

# **Soil and Crop Responses to Normal and Shear Loading: Measurements and Discrete Element Modelling**

By

Ernest Owusu-Sekyere

A Thesis submitted to the Faculty of Graduate and Postdoctoral Studies

University of Manitoba

In partial fulfilment of the requirements for the degree of

Doctor of Philosophy

Department of Biosystems Engineering

Price Faculty of Engineering

University of Manitoba

Winnipeg, MB, Canada

copyright@2026byErnestOwusu-Sekyere

---

## General abstract

---

Understanding how soils and crops respond to mechanical loading is essential for enhancing agricultural productivity, optimising field operations, and mitigating soil degradation. Mechanical interactions between agricultural machinery and soil, wind and soil erosion involve loading soil with normal and shear forces. However, their impacts on soil and crop have not been systematically quantified. This study examined the dynamic properties of agricultural soils and crop growth (focused on canola, *Brassica napus L.*) under normal and shear loading. It employed laboratory experiments, field measurements, and Discrete Element Method (DEM) modelling. Laboratory surface shear tests revealed that soil shear strength generally increased in both sandy loam and clay soils when subjected to higher normal stresses. In clay soils, elevated moisture content reduced particle detachment, thereby improving erosion resistance. Laboratory compression and shear experiments showed that bulk density increased across all four soil types (sandy loam, sandy clay loam, clay loam, and clay soils) with increasing normal stress, resulting in greater mechanical impedance. The DEM simulations successfully reproduced observed shear strength trends, confirming the validity of using particle-bonding models for soil-stress interactions. Field cone index tests indicated that compaction consistently raised penetration resistance, with smaller cones exaggerating cone index than larger cones. Laboratory and field studies on canola demonstrated that moderate soil compaction enhanced seedling emergence. However, excessive compaction reduced emergence rate, plant height, and aboveground biomass, constraining crop establishment and growth under field conditions. The integrated experimental and modelling framework advanced the understanding of soil responses and crop interactions under various loading conditions, providing a basis for sustainable soil management strategies.

## Acknowledgments

---

I deeply express my heartfelt gratitude to the Almighty God for His grace and mercies throughout the course of this work.

My sincere appreciation goes to my PhD advisor, Dr. Ying Chen, for her excellent guidance, unwavering support, and dedication to my academic growth.

I deeply appreciate the valuable insights and support from the rest of my PhD committee members, Dr. Qi Long and Dr. Zhiwei Zeng, whose advice greatly contributed to the refinement of my research. Much appreciation to Dr. Vijaya Raghavan who served as the external examiner for the thesis.

I sincerely appreciate the funding provided by NSERC and the GETS awards for my research.

Special thanks to Dr. Silvio Tessier for his generous technical support during all my field activities. I truly appreciate and enjoyed working with you. I also extend my heartfelt thanks to my lab colleagues, Kobby Acquah, Peng Wu, Zach Yarechewski, Hannah Mooney, and Hunter Slobodian, for their support during data collection and fieldwork.

To my mother and brothers, who have always been supportive, I pray that God continues to keep you close and bless you abundantly. To my number one fan, Priscilla Yaa Asantewaa Akonnor, thank you for keeping me grounded, and for your constant motivation and encouragement.

Thank you all for the strength and support you offered me through your words, kindness, and presence.

## Declaration

---

I hereby declare that the project titled “*Soil and Crop Responses to Normal and Shear Loading: Measurements and Discrete Element Modelling*”, submitted to the Department of Biosystems Engineering, Faculty of Agricultural and Food Sciences, University of Manitoba, Winnipeg, MB, Canada, is an original work carried out by me under the supervision of Dr. Ying Chen, Professor at the aforementioned institution.

This thesis is submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Biosystems Engineering. The results presented in this thesis have not been submitted to any other university or institution for the award of any degree or diploma.

## Dedication

---

Keep your dreams alive. Understand that achieving anything requires faith and belief in yourself, with vision, hard work, determination, and dedication. Remember, all things are possible for those who believe.

I dedicate this project to my mother, Theresah Oppong; my brothers, Prince Owusu Sekyere and Justice Owusu Sekyere; and a dear friend, Priscilla Y.A. Akonnor, each of whom continually reminds me of the true meaning of these words.

## Table of contents

---

|                                                                                        |       |
|----------------------------------------------------------------------------------------|-------|
| General abstract .....                                                                 | i     |
| Acknowledgments .....                                                                  | ii    |
| Declaration .....                                                                      | iii   |
| Dedication .....                                                                       | iv    |
| Table of contents .....                                                                | v     |
| List of tables .....                                                                   | xiv   |
| List of figures .....                                                                  | xv    |
| Contribution of authors .....                                                          | xxii  |
| Nomenclature .....                                                                     | xxv   |
| Thesis structure .....                                                                 | xxvii |
| Chapter 1 .....                                                                        | 1     |
| General introduction and literature review .....                                       | 1     |
| 1.1. Introduction .....                                                                | 1     |
| 1.2. Field traffic and soil compaction .....                                           | 3     |
| 1.2.1. The effect of soil type and texture on compaction .....                         | 5     |
| 1.2.2. The influence of tillage on soil compaction .....                               | 6     |
| 1.2.3. Variation in the physical properties of agricultural soils due to loading ..... | 6     |
| 1.3. Soil and crop responses to soil compaction .....                                  | 7     |
| 1.3.1. Soil water dynamics as affected by compaction .....                             | 8     |
| 1.3.2. Plant root penetration as affected by soil bulk density .....                   | 9     |
| 1.3.3. Sensitivity of seedling emergence to soil compaction .....                      | 10    |

|                                                                                                |    |
|------------------------------------------------------------------------------------------------|----|
| 1.3.4. Approaches to reduce soil compaction effects .....                                      | 11 |
| 1.4. Soil erodibility .....                                                                    | 12 |
| 1.4.1. Influencing factors and effects .....                                                   | 12 |
| 1.4.2. Soil packing density effect on soil aggregate stability and erosion resistance          | 12 |
| 1.5. Experimental methods in quantifying soil properties .....                                 | 13 |
| 1.5.1. Soil surface shear test.....                                                            | 13 |
| 1.5.1.1. Influence of soil surface friction and adhesion on surface soil detachment .....      | 15 |
| 1.5.1.2. Factors influencing soil surface friction and adhesion .....                          | 15 |
| 1.5.2. Soil shear test .....                                                                   | 16 |
| 1.5.2.1. Soil particle distribution and moisture variation effect on soil shear strength ..... | 18 |
| 1.5.2.2. Influence of compaction (bulk density) on shear strength parameters ..                | 19 |
| 1.5.2.3. Mohr-Coulomb failure criterion .....                                                  | 20 |
| 1.5.3. Soil cone index test .....                                                              | 20 |
| 1.5.3.1. Cone index variation with soil strength (compaction) .....                            | 22 |
| 1.5.3.2. Variability of cone index with soil texture, tillage and moisture content             | 23 |
| 1.6. Discrete element method (DEM) .....                                                       | 24 |
| 1.6.1. DEM approach and its applications in modelling soil .....                               | 24 |

|                                                                                                  |    |
|--------------------------------------------------------------------------------------------------|----|
| 1.6.2. DEM parameters and their influence on model outputs .....                                 | 26 |
| 1.6.3. Parameter calibrations .....                                                              | 28 |
| 1.7. Research gaps .....                                                                         | 29 |
| 1.8. General objectives .....                                                                    | 32 |
| 1.9. References .....                                                                            | 33 |
| Chapter 2 .....                                                                                  | 50 |
| Soil surface shear behaviour and particle detachment: experimental and DEM investigations* ..... | 50 |
| 2.1. Abstract .....                                                                              | 50 |
| 2.2. Introduction .....                                                                          | 51 |
| 2.3. Material and methods .....                                                                  | 53 |
| 2.3.1. Laboratory test .....                                                                     | 53 |
| 2.3.1.1. Description of soil sampling sites and soil types .....                                 | 53 |
| 2.3.1.2. Description of soil surface shear test apparatus and functionality .....                | 54 |
| 2.3.1.3. Experimental design .....                                                               | 55 |
| 2.3.1.4. Experimental procedure and measurements .....                                           | 55 |
| 2.3.1.5. Data analysis .....                                                                     | 58 |
| 2.3.2. Soil surface shear model simulation .....                                                 | 58 |
| 2.3.2.1. Model particle development .....                                                        | 58 |
| 2.3.2.2. Model-loading frame development .....                                                   | 59 |

|                                                                                                                    |    |
|--------------------------------------------------------------------------------------------------------------------|----|
| 2.3.2.3. Simulation process .....                                                                                  | 60 |
| 2.3.2.4. Model calibration .....                                                                                   | 61 |
| 2.3.2.5. Simulations of soil susceptibility to erosion .....                                                       | 62 |
| 2.4. Results and discussion .....                                                                                  | 64 |
| 2.4.1. Experimental results .....                                                                                  | 64 |
| 2.4.1.1. Soil surface shear strength as affected by the treatments .....                                           | 64 |
| 2.4.1.2. Surface shear strength envelope .....                                                                     | 66 |
| 2.4.1.3. Soil interface angle of friction ( $\delta$ ) and adhesion ( $C_a$ ) .....                                | 67 |
| 2.4.2. Model simulation results .....                                                                              | 69 |
| 2.4.2.1. Soil model calibration results .....                                                                      | 69 |
| 2.4.2.2. Soil erodibility assessment .....                                                                         | 69 |
| 2.5. Conclusion .....                                                                                              | 72 |
| 2.6. References .....                                                                                              | 73 |
| Chapter 3 .....                                                                                                    | 79 |
| Measurements and DEM modelling of soil shear behaviour under varying normal stresses<br>for different soils* ..... | 79 |
| 3.1. Abstract .....                                                                                                | 79 |
| 3.2. Introduction .....                                                                                            | 80 |
| 3.3. Materials and methods .....                                                                                   | 82 |
| 3.3.1. Laboratory experiments .....                                                                                | 82 |

|                                                                                  |    |
|----------------------------------------------------------------------------------|----|
| 3.3.1.1. Soil background information, sampling, and initial condition .....      | 82 |
| 3.3.1.2. Description of the test equipment .....                                 | 83 |
| 3.3.1.3. Soil sample preparation .....                                           | 84 |
| 3.3.1.4. Soil compression experiment .....                                       | 84 |
| 3.3.1.5. Soil shear experiment .....                                             | 85 |
| 3.3.2. Simulation of soil shearing .....                                         | 86 |
| 3.3.2.1. Model development .....                                                 | 86 |
| 3.3.2.2. Model parameters and calibration .....                                  | 88 |
| 3.3.2.3. Model validation .....                                                  | 89 |
| 3.3.2.4. Simulations of soil erosion resistance indicator .....                  | 90 |
| 3.3.3. Data analysis .....                                                       | 90 |
| 3.4. Results and discussion .....                                                | 90 |
| 3.4.1 Experimental results .....                                                 | 90 |
| 3.4.1.1. The effect of normal stress on soil axial strain and bulk density. .... | 90 |
| 3.4.1.2. Shear stress-displacement curve .....                                   | 93 |
| 3.4.1.3. Soil shear strength .....                                               | 95 |
| 3.4.1.4. Soil friction and cohesion .....                                        | 96 |
| 3.4.1.5. Soil water matrix as affected by compression and shear .....            | 97 |

|                                                                                                                                   |     |
|-----------------------------------------------------------------------------------------------------------------------------------|-----|
| 3.4.2 Soil shearing simulation results .....                                                                                      | 99  |
| 3.4.2.1 Model calibration results .....                                                                                           | 99  |
| 3.4.2.2 Model validation of soil shear strength .....                                                                             | 100 |
| 3.4.2.3. The effect of soil type and bulk density on soil erodibility .....                                                       | 101 |
| 3.5. Conclusion .....                                                                                                             | 103 |
| 3.6. References .....                                                                                                             | 104 |
| Chapter 4 .....                                                                                                                   | 111 |
| Measurement and modelling of soil cone index as affected by penetrometer cone size under<br>varying soil compaction levels* ..... | 111 |
| 4.1. Abstract .....                                                                                                               | 111 |
| 4.2. Introduction .....                                                                                                           | 112 |
| 4.3. Materials and methods .....                                                                                                  | 114 |
| 4.3.1. Filed experiment .....                                                                                                     | 114 |
| 4.3.1.1. Description of test equipment .....                                                                                      | 114 |
| 4.3.1.2. Experimental sites description .....                                                                                     | 115 |
| 4.3.1.3. Experimental design .....                                                                                                | 115 |
| 4.3.1.4. Experimental procedure and measurements .....                                                                            | 116 |
| 4.3.1.5. Data analysis .....                                                                                                      | 117 |
| 4.3.2. Simulation of soil-penetrometer interaction .....                                                                          | 118 |

|                                                                                               |     |
|-----------------------------------------------------------------------------------------------|-----|
| 4.3.2.1. Development of soil-penetrometer model .....                                         | 118 |
| 4.3.2.2. Model calibration and validation .....                                               | 119 |
| 4.3.2.3. Model applications .....                                                             | 120 |
| 4.4. Results and discussion .....                                                             | 122 |
| 4.4.1. Field experiment results .....                                                         | 122 |
| 4.4.1.1. Depth profile of soil moisture content .....                                         | 122 |
| 4.4.1.2. Soil bulk densities .....                                                            | 123 |
| 4.4.1.3. Soil cone indices (CI) of the sandy loam soil .....                                  | 123 |
| 4.4.1.4. Soil cone indices (CI) of the clay soil .....                                        | 126 |
| 4.4.2. Simulation results of soil-penetrometer interaction model .....                        | 130 |
| 4.4.2.1. Model calibration results .....                                                      | 130 |
| 4.4.2.2. Validation of soil-penetrometer interaction model in sandy loam soil .....           | 131 |
| 4.4.2.3. Validation of soil-penetrometer interaction model in clay soil .....                 | 132 |
| 4.4.2.4. Soil force-chain distribution and micro-mechanical behaviour .....                   | 133 |
| 4.4.2.5. The effect of penetration speed and penetrometer geometry on soil cone indices ..... | 134 |
| 4.5. Conclusion .....                                                                         | 139 |
| 4.6. References .....                                                                         | 140 |
| Chapter 5 .....                                                                               | 145 |

|                                                                                                                                |     |
|--------------------------------------------------------------------------------------------------------------------------------|-----|
| The effect of varying compaction levels on soil dynamic properties and the growth of canola ( <i>Brassica napus</i> L.)* ..... | 145 |
| 5.1. Abstract .....                                                                                                            | 145 |
| 5.2. Introduction .....                                                                                                        | 146 |
| 5.3. Materials and methods .....                                                                                               | 148 |
| 5.3.1. Laboratory experiment .....                                                                                             | 148 |
| 5.3.1.1. Description of soil and seed .....                                                                                    | 148 |
| 5.3.1.2. Laboratory experimental design and test procedure .....                                                               | 149 |
| 5.3.1.3. Laboratory measurements .....                                                                                         | 151 |
| 5.3.2. Field experiment .....                                                                                                  | 152 |
| 5.3.2.1. Description of the study site, soil, and seed .....                                                                   | 152 |
| 5.3.2.2. Field experimental design and test procedure .....                                                                    | 152 |
| 5.3.3. Field measurements .....                                                                                                | 154 |
| 5.3.4. Data analysis .....                                                                                                     | 155 |
| 5.4. Results and discussion .....                                                                                              | 155 |
| 5.4.1. Soil physical properties .....                                                                                          | 155 |
| 5.4.1.1. Bulk density .....                                                                                                    | 155 |
| 5.4.1.2. Soil surface resistance .....                                                                                         | 157 |
| 5.4.2. Plant emergence and growth .....                                                                                        | 159 |

|                                                           |     |
|-----------------------------------------------------------|-----|
| 5.4.2.1. Qualitative assessment of canola emergence ..... | 159 |
| 5.4.2.2. Plant count .....                                | 161 |
| 5.4.2.3. Plant emergence rate .....                       | 163 |
| 5.4.2.4. Plant height .....                               | 166 |
| 5.4.2.5. Aboveground biomass .....                        | 169 |
| 5.6. Conclusion .....                                     | 171 |
| 5.5 Reference .....                                       | 171 |
| Chapter 6 .....                                           | 178 |
| General conclusions and recommendations .....             | 178 |
| 6.1. General conclusions .....                            | 178 |
| 6.2. General recommendations .....                        | 180 |
| 6.3. Contributions to knowledge .....                     | 181 |

## List of tables

---

|                                                                                                                                    |     |
|------------------------------------------------------------------------------------------------------------------------------------|-----|
| Table 2.1. Model soil parameters .....                                                                                             | 61  |
| Table 2.2. Sandpaper grades used in model simulations .....                                                                        | 63  |
| Table 2.3. Soil surface shear properties .....                                                                                     | 68  |
| Table 2.4. Calibrated values of ( $E_{\text{mods}}$ ) and the relative errors (RE) for each soil type and moisture condition ..... | 69  |
| Table 3.1. Composition of the selected soils: sandy loam (SL), sandy clay loam (SCL), clay loam (CL), and clay (C). .....          | 83  |
| Table 3.2. Soil horizontal displacement at shear strength .....                                                                    | 95  |
| Table 3.3. Soil strength properties and regression prediction accuracy .....                                                       | 97  |
| Table 4.1. Model application parameters and ranges .....                                                                           | 121 |
| Table 4.2. ANOVA results of the effect of compaction levels and penetrometer cone sizes on CI for sandy loam soil .....            | 125 |
| Table 4.3. ANOVA results of the effect of compaction levels and cone sizes on CI for clay soil .....                               | 127 |
| Table 5.1. Soil composition and gravimetric moisture contents for the laboratory experiment. ....                                  | 149 |

## List of figures

|                                                                                                                                                                                                                                                                                                                                                                  |    |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1.1 Soil compaction from field traffic. ....                                                                                                                                                                                                                                                                                                              | 4  |
| Figure 1.2. Surface shear test diagram. ....                                                                                                                                                                                                                                                                                                                     | 14 |
| Figure 1.3. Soil shear test diagrams. ....                                                                                                                                                                                                                                                                                                                       | 18 |
| Figure 1.4. Mohr Column failure criterion diagram. ....                                                                                                                                                                                                                                                                                                          | 20 |
| Figure 1.5. Soil cone index test diagram. ....                                                                                                                                                                                                                                                                                                                   | 22 |
| Figure 1.6. Systematic approach to analyse soil compaction. ....                                                                                                                                                                                                                                                                                                 | 32 |
| Figure 2.1. Soil surface shear test apparatus: (a) Components; (b) Top; (c) and bottom view of the loading frame showing abrasive surface. ....                                                                                                                                                                                                                  | 55 |
| Figure 2.2. Soil surface shearing tests: (a) Soil sample acquired using the sample ring; (b) Sealed soil sample with lid for transportation; (c) Loading frame with a known weight placed on soil surface, showing soil and abrasive surface in contact at the initial position for shearing test; (d) Experimental set up of soil surface shear apparatus. .... | 57 |
| Figure 2.3. General relationship between surface soil strength ( $\tau$ ) and applied normal stress ( $\sigma_n$ ), showing the definitions of adhesion ( $C_a$ ) and interface friction angle ( $\delta$ ). ....                                                                                                                                                | 58 |
| Figure 2.4. Soil surface shearing model: (a) Soil particles and model loading frame; (b) Loading frame with an abrasive surface having randomly distributed spherical grains. ....                                                                                                                                                                               | 60 |
| Figure 2.5. Side views of the model loading frame with varying abrasive surface's grain sizes and the equivalent sandpaper grades. ....                                                                                                                                                                                                                          | 63 |
| Figure 2.6. Top view of the model soil sample showing the positions of soil tracers for monitoring soil displacement. ....                                                                                                                                                                                                                                       | 63 |
| Figure 2.7. Influence of normal stress and soil moisture content on the soil surface shear strength. Error bars are standard deviations. Values labelled with different letters are significantly different based on Duncan's multiple-range test at a significance level of $p < 0.05$ . ....                                                                   | 66 |

|                                                                                                                                                                                                                                                                                                                                                                                        |    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 2.8. Soil surface shear strength envelopes for sandy loam in (a) low, (b) medium, and (c) high soil moisture levels and for clay in (d) low, (e) medium and (f) high soil moisture levels. Error bars are standard deviations. Values labelled with different letters are significantly different based on Duncan's multiple-range test at a significance level of $p < 0.05$ . | 67 |
| Figure 2.9. Simulated soil particle displacements for different sandpaper grades during surface shearing for sandy loam in (a) low (b) medium and (c) high moisture levels and for clay in (d) low (e) medium and (f) high soil moisture levels.                                                                                                                                       | 72 |
| Figure 3.1. The Royal Eijkelkamp® compression and shear test apparatus.                                                                                                                                                                                                                                                                                                                | 84 |
| Figure 3.2. Soil compression and shear test process: (a) Sample preparation for measurement; (b) Height measurement of sample chamber; (c) Set up showing mounted soil sample; (d) Compressed soil sample showing the height change (axial strain); (e) Relative position of the top and bottom containers of the sample chamber at the completion of shear test.                      | 86 |
| Figure 3.3. Soil shear model: (a) Soil particles and sample chamber before and after shearing; (b) A typical model result of shear stress verses horizontal displacement.                                                                                                                                                                                                              | 88 |
| Figure 3.4. Virtual soil compression test for model calibration showing the initial and final position of the compression plate.                                                                                                                                                                                                                                                       | 89 |
| Figure 3.5. Effect of normal stress on soil axial strain. Labels are assigned based on Tukey HSD test to determine the significant different between treatment levels at a confidence level of 95% ( $p < 0.05$ ); error bars are standard deviations.                                                                                                                                 | 91 |
| Figure 3.6. Effect of normal stress on soil bulk density. Labels are assigned based on Tukey HSD test to determine the significant different between treatment levels at a confidence level of 95% ( $p < 0.05$ ); error bars are standard deviations.                                                                                                                                 | 92 |
| Figure 3.7. Shear stress relation to horizontal displacement under different normal stresses.                                                                                                                                                                                                                                                                                          | 94 |

|                                                                                                                                                                                                                                                                  |     |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 3.8. Mohr-Coulomb failure line. Labels are assigned based on Tukey HSD test to determine the significant different between treatment levels at a confidence level of 95% ( $p < 0.05$ ); error bars are standard deviations. ....                         | 96  |
| Figure 3.9. Trend of soil water matrix under varying normal stress. ....                                                                                                                                                                                         | 98  |
| Figure 3.10. Soil water matrix under compression and shearing. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ); error bars are standard deviation. .... | 99  |
| Figure 3.11. Model calibration results of average vertical soil resistance at different normal stresses. ....                                                                                                                                                    | 100 |
| Figure 3.12. Measured and simulated averages of soil shear strength per normal stress. ....                                                                                                                                                                      | 101 |
| Figure 3.13. Soil shear strength with varying bulk density per soil. ....                                                                                                                                                                                        | 102 |
| Figure 4.1. Soil cone penetrometer: (a) Parts and testing position; (b) Cone sizes (200, 333, and 500 mm <sup>2</sup> ; from left to right). ....                                                                                                                | 115 |
| Figure 4.2. Field layout of the main plots. Where C0, C1, C2, and C3, represent compaction levels zero, one, two, and three, respectively. ....                                                                                                                  | 116 |
| Figure 4.3. Compaction process with a John Deere tractor, showing wheel tracks where the soil cone index and bulk density measurements were taken. ....                                                                                                          | 117 |
| Figure 4.4. Soil-penetrometer interaction model; penetrometer model features the 100 mm <sup>2</sup> cone size. ....                                                                                                                                             | 119 |
| Figure 4.5. Modelled penetrometer: (a) Cone for model calibration (rod diameter: 8 mm); (b) Cones for model validation (rod diameter: 10 mm). ....                                                                                                               | 120 |
| Figure 4.6. Penetrometer parameters. Where (a) cone, rod and annulus surfaces, and (b) different cone dimensions. ....                                                                                                                                           | 121 |
| Figure 4.7. Initial field soil moisture content (MC) (dry basis) with depth: (a) Sandy loam; (b) Clay. ....                                                                                                                                                      | 122 |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                  |     |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 4.8. Bulk density per compaction level: (a) Sandy loam; (b) Clay. Where C0, C1, C2, and C3, represent compaction levels zero, one, two, and three, respectively. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ). .....                                                                                                          | 123 |
| Figure 4.9. Sandy loam soil CI-depth curves. Where S2, S3.33, and S5 represents cone size 200, 333 and 500 mm <sup>2</sup> respectively. ....                                                                                                                                                                                                                                                                                                    | 124 |
| Figure 4.10. Effect of (a, b) compaction level and (c, d) cone size on soil CI for clay. Where C0, C1, C2, and C3, represent compaction levels zero, one, two, and three respectively, and S2, S3.33, and S5 represents cone sizes 200, 333 and 500 mm <sup>2</sup> respectively. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ). .... | 126 |
| Figure 4.11. Clay soil CI-depth curves. Where S2, S3.33, and S5 represents cone size 200, 333 and 500 mm <sup>2</sup> respectively. ....                                                                                                                                                                                                                                                                                                         | 127 |
| Figure 4.12. Effect of (a, b) compaction level and (c, d) cone size on soil CI for clay. Where S2, S3.33, and S5 represents cone size 200, 333 and 500 mm <sup>2</sup> respectively, and C0, C1, C2, and C3, represent compaction levels zero, one, two, and three respectively. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ). ....  | 129 |
| Figure 4.13. Variation in soil CI with cone size at soil depths of 200 to 800 mm for clay soil. Where S2, S3.33, and S5 represents cone size 200, 333 and 500 mm <sup>2</sup> respectively. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ). ....                                                                                       | 130 |
| Figure 4.14. Calibrating the effective modulus at different compaction levels per soil type: (a) Sandy loam; (b) Clay. Where C0, C1, C2, and C3 are compaction zero, one, two and three respectively. ....                                                                                                                                                                                                                                       | 131 |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 4.15. Measured (M) and simulated (S) averages of soil-cone index per cone size for sandy loam soil at 100 mm depth. Where S2, S3, and S5 are cone sizes 200, 333 and 500 mm <sup>2</sup> respectively. ....                                                                                                                                                                                                                                                                              | 132 |
| Figure 4.16. Measured (M) and simulated (S) averages of soil-cone index per cone size for clay soil at 100 mm depth. Where S2, S3, and S5 are cone sizes 200, 333 and 500 mm <sup>2</sup> respectively. ....                                                                                                                                                                                                                                                                                    | 133 |
| Figure 4.17. Cross-sectional view of CI simulation showing soil (a) force-distribution, and (b) mechanical behaviour during penetration per cone size. ....                                                                                                                                                                                                                                                                                                                                     | 134 |
| Figure 4.18. CI response to varying (a) penetration speed [cone size: 100 mm <sup>2</sup> ; rod diameter: 10 mm; cone apex angle: 60°], (b) rod diameter [cone size: 100 mm <sup>2</sup> ; penetration speed: 20 mms <sup>-1</sup> ; cone apex angle: 60°], (c) cone apex angle [cone size: 100 mm <sup>2</sup> ; penetration speed: 20 mms <sup>-1</sup> ; rod diameter: 10 mm], and (d) cone size [penetration speed: 20 mms <sup>-1</sup> ; rod diameter: 10 mm; cone apex angle: 60°]. .... | 136 |
| Figure 4.19. Soil resistance as affected by varying cone size per soil type at constant penetration speed (20 mm s <sup>-1</sup> ), rod diameter (10 mm), and cone apex angle (60°). ....                                                                                                                                                                                                                                                                                                       | 138 |
| Figure 4.20. Soil CI derived from contact force on the conic surface area (A <sub>c</sub> ) at constant penetration speed (20 mm s <sup>-1</sup> ), rod diameter (10 mm), and cone apex angle (60°). ....                                                                                                                                                                                                                                                                                       | 139 |
| Figure 5.1. Laboratory experimental procedure: (a) Flow chart of the experimental design; (b) Seed positioning template; (c) Soil compaction with a proctor; (d) Covered seeded containers in the environmental chamber. ....                                                                                                                                                                                                                                                                   | 151 |
| Figure 5.2. Field experimental process: (a) Plot layout, (b) Tractor wheel tracks showing compacted and non-compacted areas; (c) Active wheel width contributing to wheel tracks. ....                                                                                                                                                                                                                                                                                                          | 154 |
| Figure 5.3. Bulk densities at varying compaction levels. Where (a–c) are lab measurements taken for the sandy loam, silt clay, and clay soils, respectively (C0 <sub>L</sub> , C1 <sub>L</sub> , C2 <sub>L</sub> , C3 <sub>L</sub> , and C4 <sub>L</sub> represent compaction levels zero, one, two, three, and four, respectively) and (d, e) are field                                                                                                                                        |     |

measurements of the sandy loam soil for first- and second-year tests, respectively ( $C0_F$ ,  $C1_F$ ,  $C2_F$ , and  $C3_F$ , represent compaction levels zero, one, two, and three, respectively). Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ). ..... 157

Figure 5.4. Soil surface resistances at varying compaction levels. Where (a–c) are lab measurements taken for the sandy loam, silt clay, and clay soils, respectively ( $C0_L$ ,  $C1_L$ ,  $C2_L$ ,  $C3_L$ , and  $C4_L$  represent compaction levels zero, one, two, three, and four, respectively) and (d, e) are field measurements on the sandy loam soil for first- and second-year tests, respectively ( $C0_F$ ,  $C1_F$ ,  $C2_F$ , and  $C3_F$  represent compaction levels zero, one, two, and three, respectively). Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ). ..... 159

Figure 5.5. Canola emergence at varying compaction levels. Where (a–c) are lab measurements taken 14 days post-seeding for the sandy loam, silt clay, and clay soils, respectively ( $C0_L$ ,  $C1_L$ ,  $C2_L$ ,  $C3_L$ , and  $C4_L$  represent compaction levels zero, one, two, three, and four, respectively;  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$  represent replicates one, two, three, and four, respectively) and (d) is field results showing emerged canola plants at compacted and non-compacted sandy loam soil areas taken 27 days post-seeding. .... 160

Figure 5.6. Plant population counts at varying compaction levels. Where (a–c) are lab measurements for the sandy loam, silt clay, and clay soils, respectively ( $C0_L$ ,  $C1_L$ ,  $C2_L$ ,  $C3_L$ , and  $C4_L$  represent compaction levels zero, one, two, three, and four, respectively) and (d, e) are field measurements using the sandy loam soil for first- and second-year tests, respectively ( $C0_F$ ,  $C1_F$ ,  $C2_F$ , and  $C3_F$  represent compaction levels zero, one, two, and three, respectively). 163

Figure 5.7. Canola emergence rate at varying compaction levels. Where (a–c) are lab measurements taken for the sandy loam, silt clay, and clay soils, respectively ( $C0_L$ ,  $C1_L$ ,  $C2_L$ ,  $C3_L$ , and  $C4_L$  represent compaction levels zero, one, two, three, and four, respectively) and (d,

e) are field measurements on the sandy loam soil for first- and second-year tests, respectively (C0<sub>F</sub>, C1<sub>F</sub>, C2<sub>F</sub>, and C3<sub>F</sub> represent compaction levels zero, one, two, and three, respectively). Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ). ..... 166

Figure 5.8. Lab measurement of plant height at varying compaction levels. Where (a–c) are increasing values with time and (d–f) are average values. Both groups are for the sandy loam, silt clay, and clay soils, respectively. C0<sub>L</sub>, C1<sub>L</sub>, C2<sub>L</sub>, C3<sub>L</sub>, and C4<sub>L</sub> represent compaction levels zero, one, two, three, and four, respectively. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ). ..... 169

Figure 5.9. Canola aboveground biomass at varying soil compaction levels. Where (a–c) are lab measurements taken 14 days post-seeding for the sandy loam, silt clay, and clay soils, respectively (C0<sub>L</sub>, C1<sub>L</sub>, C2<sub>L</sub>, C3<sub>L</sub>, and C4<sub>L</sub> represent compaction levels zero, one, two, three, and four, respectively) and (d, e) are field measurements on the sandy loam soil for first- and second-year test taken 16 weeks post-seeding, respectively (C0<sub>F</sub>, C1<sub>F</sub>, C2<sub>F</sub>, and C3<sub>F</sub>, represent compaction levels zero, one, two, and three, respectively). Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ). ..... 170

## Contribution of authors

---

This work is organized as a grouped-manuscript. Chapters 2, 3, 4, and 5 present the core research as four individual papers, each structured with its own abstract, introduction, methodology, results, discussion, conclusion, and references. The following sections outline the titles of the research articles, their review status at the time of thesis submission, author contributions, and the corresponding thesis chapters.

### 1. Chapter 2

Chapter 2 contains the work submitted to the Journal of Terramechanics (currently under revision), titled “Soil surface shear behaviour and particle detachment: experimental and DEM investigations.”. Manuscript Number: JTERRA-D-25-00156. (Submitted: September 2025)

#### Author Contributions

**Ernest Owusu-Sekyere** (Thesis author): conceptualization, methodology, software, formal analysis, investigation, data curation, validation, writing, editing, visualization, project administration.

**Kobby Acquah:** methodology, data curation, writing, project administration.

**Ying Chen:** conceptualization, methodology, investigation, data curation, validation, writing (review and editing), resources, project administration, funding acquisition.

### 2. Chapter 3

Chapter 3 includes the work submitted to Granular Matter (under revision), titled “Measurements and DEM modelling of soil shear behaviour under varying normal stresses for

different soils.”. Submission ID: cb9a3276-10d9-4bd7-8cca-8ac08665bf9e. (Submitted: 22 May 2025)

#### Author Contributions

**Ernest Owusu-Sekyere:** conceptualization, methodology, software, formal analysis, investigation, data curation, validation, writing (original draft preparation), visualization, project administration.

**Ying Chen:** supervision, conceptualization, methodology, investigation, data curation, validation, writing (review and editing), resources, project administration, funding acquisition.

### 3. Chapter 4

Chapter 4 contains the work submitted to Soil and Tillage Research (currently under revision), titled “Measurement and modelling of soil cone index as affected by penetrometer cone size under varying soil compaction levels”. Manuscript Number: STILL-D-25-00240. (Submitted: January 2025)

#### Author Contributions

**Ernest Owusu-Sekyere:** conceptualization, methodology, data curation, formal analysis, modelling, visualization, and finalizing the writing.

**Zhiwei Zeng:** validation, methodology, modelling, reviewing, and editing.

**Zack Yarechewski:** data curation, visualization, manuscript preparation.

**Kobby Acquah:** data collection and results interpretation.

**Ying Chen:** conceptualization, reviewing and editing, resources, project administration, funding acquisition.

**Xirui Zhang:** funding acquisition, resources.

#### 4. Chapter 5

Chapter 5 includes content published in Agriculture (MDPI), titled “The effect of varying compaction levels on soil dynamic properties and the growth of canola (*Brassica napus* L.).”

DOI: 10.3390/agriculture14111976. (Submitted: 9 October 2025; Accepted: 2 November 2024).

#### Author Contributions

**Ernest Owusu-Sekyere:** methodology, formal analysis, investigation, data curation, writing (original draft preparation), writing (review).

**Ying Chen:** Conceptualization, methodology, validation, resources, writing-review and editing, supervision, project administration, funding acquisition.

## Nomenclature

---

|                                                                       |                                          |
|-----------------------------------------------------------------------|------------------------------------------|
| $A_a$                                                                 | Penetrometer annulus surface area        |
| $A_c$                                                                 | Penetrometer cone surface area           |
| ANOVA                                                                 | Analysis of variance                     |
| $A_r$                                                                 | Penetrometer rod surface area            |
| $c$                                                                   | Soil cohesion                            |
| $C$                                                                   | Clay soil                                |
| $C_0, C_1, C_2$ , and $C_3$ / $C_{0F}, C_{1F}, C_{2F}$ , and $C_{3F}$ | Field compaction levels                  |
| $C_{0L}, C_{1L}, C_{2L}, C_{3L}$ , and $C_{4L}$                       | Laboratory compaction levels             |
| $C_a$                                                                 | Soil adhesion (kPa)                      |
| CAD                                                                   | Computer Aided Design                    |
| CI                                                                    | Cone Index                               |
| CL                                                                    | Clay Loam soil                           |
| DEM                                                                   | Discrete element method                  |
| $\bar{E}, E_{mod}$                                                    | Effective modulus ( $Nm^{-2}$ )          |
| $F_a$                                                                 | Resistance force on annulus surface area |
| $F_c$                                                                 | Resistance force on conical surface area |
| $F_r$                                                                 | Resistance force on rod surface area     |
| GLM                                                                   | General Linear Model                     |
| $h$                                                                   | Soil height in shear container           |
| HSD                                                                   | Highest Significance Difference          |
| $k^*$                                                                 | Normal-to-shear stiffness ratio          |
| $K_n$                                                                 | Particle normal stiffness ( $N m^{-1}$ ) |
| $K_s$                                                                 | Particle shear stiffness ( $N m^{-1}$ )  |
| $M$                                                                   | Measured values                          |
| MC                                                                    | Moisture Content (%)                     |
| $n$                                                                   | Soil porosity                            |
| $P12, P20, P30, P50, P60, P80, P100, P120, P150, P180$                | Sandpaper grades (mm)                    |

---

---

|                       |                                                |
|-----------------------|------------------------------------------------|
| PBM                   | Parallel Bond Model                            |
| $PFC^{3D}$            | Particle Flow Code in Three Dimensions         |
| R1, R2, R3, and R4    | Compaction level replicates in laboratory test |
| $R^2$                 | Coefficient of determination                   |
| $RE$                  | Relative Error (%)                             |
| RH                    | Relative Humidity                              |
| RMSE                  | Root Mean Square Error                         |
| $S$                   | Simulation values                              |
| S1, S2, S3.33, and S5 | Penetrometer cone sizes                        |
| SCL                   | Sandy Clay Loam soil                           |
| SL                    | Sandy Loam soil                                |
| $\beta_n$             | Viscous damping coefficient                    |
| $\delta$              | Soil surface friction angle (°)                |
| $\Delta h$            | Change in soil height after compression        |
| $\theta$              | Local damping coefficient                      |
| $\bar{\lambda}$       | Bond radius multiplier                         |
| $\mu$                 | Soil friction coefficient                      |
| $\rho_b$              | Soil bulk density ( $\text{kg m}^{-3}$ )       |
| $\rho_p$              | Particle density ( $\text{kg m}^{-3}$ )        |
| $\sigma$              | Bond tensile strength ( $\text{N m}^{-1}$ )    |
| $\sigma_n$            | Normal stress ( $\text{N m}^{-1}$ )            |
| $\tau$                | Shear strength                                 |
| $\tau_b$              | Bond cohesion strength ( $\text{N m}^{-1}$ )   |
| $\varphi$             | Soil internal friction angle (°)               |

---

## Thesis structure

---

This thesis is presented in a paper-based format (grouped manuscript). It comprises a general abstract, followed by an introduction and literature review in Chapter 1. Chapters 2 to 5 present the core research, organised as four individual papers, each structured with its own abstract, introduction, methodology, results, discussion, conclusion, and references. Collectively, these chapters cover various soil types and moisture conditions. The main topics include: (1) soil surface shear as influenced by normal loading (chapter 2); (2) soil shear strength under normal compression (chapter 3); (3) variation in soil cone index under wheel traffic and varying cone sizes (chapter 4); and (4) the effect of soil compaction on canola growth (chapter 5).

The projects were systematically designed to address the objective of understanding the extent to which soil compaction affects soil physical properties and crop performance. The first study (Chapter 2) established the foundation by measuring and modelling soil surface shear properties under varying moisture contents in two soil types. This initial investigation provided critical baseline data for understanding soil behaviour under mechanical stress. Building on these findings, the second study (Chapter 3) explored how compression and shearing influence the physical properties of different soil textures, sandy loam, sandy clay loam, clay loam, and clay, thereby extending the analysis from surface behaviour to internal soil structure.

The third study (Chapter 4) advanced this understanding by linking laboratory-based insights to field-scale conditions. It examined the effects of tractor wheel passes on soil resistance using cone index (CI) measurements with different cone sizes in sandy loam and clay soils. While the first two studies integrated laboratory experiments with discrete element method (DEM) simulations to model soil responses and predict erodibility, the third combined

field experiments with DEM analysis to assess CI variations under realistic traffic conditions. The final study (Chapter 5) built upon the mechanistic understanding developed in the earlier chapters by evaluating the implications of field traffic and normal compaction on crop growth, using canola as a representative small-seeded crop.

Collectively, these four studies form a coherent progression, from fundamental soil mechanical behaviour to field-scale compaction effects and crop performance, contributing to practical recommendations for sustainable tillage and traffic management practices.

Chapter 2 has been submitted to *Journal of Terramechanics* (currently under revision); Chapter 3 to *Granular Matter* (under revision); Chapter 4 to *Soil and Tillage Research* (under revision); and Chapter 5 has been published in *Agriculture (MDPI)* as Owusu-Sekyere and Chen (2024). In all submitted manuscripts and the published paper, the candidate is the first author. His contributions include conceptualisation, methodology, software, validation, formal analysis, investigation, data curation, original draft preparation, review and editing, and visualisation. The co-authors contributed to conceptualisation, methodology, validation, resources, review and editing, supervision, project administration, and funding acquisition.

## Chapter 1

---

### General introduction and literature review

#### 1.1. Introduction

The ability of agricultural soils to support crop production depends largely on their physical, mechanical, and dynamic properties. Key soil dynamic properties such as soil bulk density, shear strength, and permeability determine the soil's response to cyclic loading, influencing soil settlement and soil-structure interaction (Pavlenko, 2024). Loading to soil can be from machinery for field operations (such as soil compaction) or natural impacts from wind and water (such as soil erosion). These soil dynamic properties regulate aeration, water movement, and plant root penetration, which in turn affect plant growth and crop yield. In small seed crops like canola, excessive dynamic loading from machinery reduces soil porosity and restricts root growth, thereby limiting nutrient uptake, emergence, and overall yield performance (Gong et al., 2025). Although canola cultivation offers substantial economic benefits, its productivity is often constrained by poor crop emergence, leading to revenue losses of up to 50% (Hyatt et al., 2007). Contributing factors include inadequate soil moisture and improper seeding depth (Harker et al., 2012), as well as excessive compaction, which is widely recognized as the primary constraint (Gong et al., 2022). Addressing these soil-related challenges is therefore essential to improving crop emergence rates and maximizing its economic potential.

Soil loading conditions can be characterized as normal and shear loading. Normal loading is typically from machinery traffic, often inducing compaction. The growing mechanization of agriculture has amplified these effects, as repeated passes of heavy machinery, particularly

under moist soil conditions, exacerbate densification and hinder root growth (Gregory et al., 2015; Shaheb et al., 2021; Hamza and Anderson, 2005). Normal loading also limits water and air movement, adversely affecting microbial activity and soil fertility. Shear loading, associated with soil erosion, destabilizes soil aggregates and accelerates soil degradation processes (Horn and Baumgartl, 2002). Tillage practices and wheel traffic, further modify soil stability (Kumar et al., 2018). Studying both loading types is therefore essential, as compaction restricts crop emergence and growth, while erosion influences soil structure and nutrient availability. Together, these loading (normal and shear) underscore the importance of evaluating soil response to external forces to sustain crop performance and maintain long-term agricultural productivity (Kumar et al., 2018).

Several factors significantly influence the dynamic properties of agricultural soils, shaping their structure through compaction and affecting vulnerability to surface erosion through shearing (Horn and Baumgartl, 2002). These includes soil type, moisture content, bulk density, and external loading. Natural factors such as texture, structure, and soil moisture regulate particle distribution, cohesion, and resistance to external pressures (Balasubramanian, 2017). These factors, which are usually intertwined, affects machine-induced soil properties (Fang et al., 1992; Shah et al., 2017). Understanding the effects of these factors on soil properties is crucial for preserving soil productivity and long-term resilience.

Common experimental techniques for determining soil dynamic properties include the soil surface shear test, soil shear test, and cone index measurement. The surface shear test evaluates the topsoil strength exposed to erosive forces like raindrops, runoff, and machinery by applying a horizontal force under a controlled vertical load, assessing resistance to particle detachment and seedling emergence (Havaee et al., 2015). Soil shear tests, including direct, ring, and triaxial methods, measure maximum resistance to shear stresses, providing insights

into soil internal cohesion and friction angle, with these tests reliably aligning with the Mohr-Coulomb criterion (Al-Adhadh et al., 2021). The cone index test quantifies penetration resistance, and its applications include detecting soil compaction layers and guiding tillage and field traffic management (Chung et al., 2013). Numerical modelling techniques have been widely employed to study the dynamic behaviour of agricultural soils (Coetzee and Scheffler, 2023; Jones and Arp, 2017; Yimsiri and Soga, 2010). Among these methods, the Discrete Element Method (DEM) is a robust tool for modelling material properties. DEM is particularly suited for granular materials like soil. It enables monitoring the behaviour of individual soil particles, which is difficult, if at all possible, to measure in experiments.

This study first analyzed the influence of normal loading on soil surface shear properties, followed by investigations using the confined compression and shear apparatus to assess compaction effects on four selected soils. Penetration resistance under compaction was subsequently examined. DEM was employed to model and simulate soil behaviour under these loading conditions. Finally, the effects of compaction on canola were evaluated through laboratory and field experiments. The combination of laboratory tests, field experiments, and DEM modelling provides practical insights for managing soil compaction, improving soil health, and enhancing crop productivity.

## 1.2. Field traffic and soil compaction

Farming practices have undergone multiple phases of transformation, evolving from manual labor to advanced mechanization. The increasing demands of agricultural production have driven the widespread adoption of field mechanization, with innovations spanning the entire production cycle, from tillage and seeding to harvesting, enabled by the development of machinery such as tractors and combines. While each stage of this progression has enhanced operational efficiency, it has also introduced new challenges. Notable among them is the

detrimental effects of repeated field traffic on soil compaction, which in turn influence seedling emergence and overall crop development (Figure 1.1). Therefore, understanding the adverse effect of compaction is essential, as it helps in implementing targeted modification in reducing its effect and promoting sustainable and high-yield agricultural production.



*Figure 1.1 Soil compaction from field traffic.*

The rearrangement of soil particles under the influence of external loading, leads to reduced pore space and increased bulk density. This realignment brings particles closer to each other, increasing their contact points and overlapping ratio, thereby reducing soil permeability. The nature and direction of the applied force determine whether the particles experience compression or shearing. Both natural processes and field activities contribute to this phenomenon. Common causes include livestock grazing, mechanical loading, agronomic operations, tillage operations, and other soil-machine interactions (Hamza and Anderson, 2005; Shah et al., 2017). Compaction can occur at both the soil surface and subsoil levels, however, subsoil compaction is generally more persistent and detrimental (Kirby, 2007). It is also the most difficult form of soil degradation to detect and manage, as it typically presents no visible signs on the soil surface (Hamza and Anderson, 2005; Akker and Canarache, 2001).

The susceptibility of agricultural soils to compaction is influenced by several factors. Among them, tillage practice, soil texture and moisture content are important factors.

Accurately quantifying and assessing the impacts of these factors on soil compaction is essential for guiding the development of optimized wheel systems and innovative tillage strategies aimed at minimizing soil degradation and enhancing long-term productivity.

### *1.2.1. The effect of soil type and texture on compaction*

Soil particle size distribution has been extensively documented as a critical factor influencing soil response to compaction (Fang et al., 1992). The compaction behaviour of soils varies considerably with texture, as different particle size fractions determine the soil's capacity to rearrange under applied stress (Håkansson and Lipiec, 2000). Soils with balanced proportions of very coarse sand and silt plus clay exhibit higher compatibility, while excessive silt and clay contents reduce bulk density due to their ability to resist packing (Fang et al., 1992; Shah et al., 2017). Similarly, Oladeji, (2025) demonstrated that particle size distribution affects soil compaction primarily through its influence on bulk density and aggregate stability. Coarse-textured soils dominated by sand tend to compact more readily, whereas soils with finer particles or a balanced particle distribution retain better structural integrity and exhibit reduced compaction potential.

This particle distribution also governs the shearing behaviour of soils. Vangla and Latha, (2015) reported that increasing the coarse fraction and particle elongation while reducing particle convexity significantly improves the constant volume friction angle, thereby enhancing shear strength. Li, (2013) further explained that this improvement results from shear zone dilation, rougher shear surfaces, and increased interlocking of particles, which collectively enhance soil resistance to deformation under loading.

### *1.2.2. The influence of tillage on soil compaction*

The primary objective of tillage is to improve soil physical conditions by reducing bulk density, enhancing porosity, promoting aeration, water infiltration, and root penetration (Okorie and Niraj, 1996). By loosening the topsoil, tillage facilitates seedbed preparation, improves germination conditions, and supports early crop development (Angon et al., 2023). However, the benefits of tillage can be offset when operations are performed repeatedly or under unfavorable soil moisture conditions, particularly with the use of heavy agricultural machinery. Typically, the tips of the tillage tools tend to compress the soils below it in the process of pulverizing the surface soils. Evident of this is explained by Romaneckas et al. (2022). Such practices often result in hard-pan soil compaction, with more severe effects occurring in the subsoil (Angon et al., 2023). The negative impacts are high when tillage is conducted on wet soils (Hamza and Anderson, 2005). Under such conditions, soil aggregates are more susceptible to breakdown, leading to increased particle packing, densification in deeper soil layers, and breakdown of organic matter (Alam et al., 2014; Ramzan et al., 2019).

### *1.2.3. Variation in the physical properties of agricultural soils due to loading*

Bulk density and porosity are critical soil physical parameters widely used to evaluate the degree of compaction in agricultural soils. Bulk density, defined as the mass of dry soil per unit volume, typically increases with higher levels of compaction, whereas porosity, which represents the fraction of soil volume occupied by air and water-filled pores, correspondingly decreases (Shah et al., 2017). Compaction induced by the repeated passage of heavy agricultural machinery exerts substantial vertical stress on the soil profile (Acquah and Chen, 2022). This pressure causes compression, rearrangement, and shrinkage of soil aggregates,

thereby altering the pore-size distribution and degrading soil structure (Pagliai and Vignozzi, 2002; Ferreira et al., 2021).

Macropores, which are the larger soil pores essential for aeration and hydraulic conductivity, are particularly susceptible to compaction. Their reduction significantly impedes gaseous exchange, water infiltration, and drainage, thereby restricting root elongation and proliferation (Hasan et al., 2025). This deterioration in pore continuity also heightens soil mechanical impedance, making it more difficult for roots to penetrate compacted layers and access moisture and nutrients. Consequently, it adversely affects plant growth, water-use efficiency, and overall soil productivity.

The extent of vertical compression is linearly correlated with the intensity of the applied pressure, leading to measurable changes, including increased resistance to deformation, and reduced erosion resistance due to heightened bulk density. Empirical studies have demonstrated that compaction effects are more pronounced in subsoil layers than in surface horizons due to the transmission of wheel-induced pressure to greater depths (Acquah and Chen, 2022; Ferreira et al., 2021). This results in higher bulk densities and reduced porosity in deeper soil profiles, particularly when soils are more susceptible to plastic deformation.

### **1.3. Soil and crop responses to soil compaction**

Soil compaction increases soil strength, which significantly restricts crop growth and development (Shaheb et al., 2021). Plant stress induced by compaction is often manifested through physiological responses such as reduced stomatal conductance, decreased photosynthesis, and increased membrane injury, which are typical early indicators of environmental stress in plants (Ripley et al., 2007). These stresses mostly arise from the poor

soil aeration and restricted gas exchange caused by high levels of compaction, leading to anaerobic conditions detrimental to plant establishment (Sidhu and Duiker, 2006).

Empirical studies have demonstrated the negative effects of compaction on various crops. For instance, in barley, compaction reduced plant establishment by 36%, root mass by 42%, and total biomass by 59% (Millington et al., 2016). Similarly, soybean emergence declined significantly under high compaction ( $17.25 \text{ kJ m}^{-3}$ ), where 25% of seedlings failed to emerge, and early seedling height was reduced to 24 mm (La et al., 2013). Such reductions in early growth stages limit overall crop vigor and potential yield.

Slight compaction can be beneficial under certain conditions. Sivarajan et al. (2018) reported that moderate compaction in a no-till field enhanced early corn emergence by 175% in trafficked rows, likely due to improved seed-to-soil contact. These findings underscore that while excessive compaction is detrimental, controlled or minimal compaction may enhance germination and early growth in specific crops.

### *1.3.1. Soil water dynamics as affected by compaction*

Soil compaction degrades soil hydraulic and water-retention properties by reducing air-filled porosity, collapsing macro- and mesopores, and disrupting pore continuity (Horn et al., 2024; Huang et al., 2022; Li et al., 2023). When compaction stresses increase, especially cyclic loading, pore connectivity and air permeability decline further, severely limiting water movement through the soil profile (Horn et al., 2024). Although structured soils generally resist compaction better due to their greater pore rigidity and permeability, once their pre-compression strength is exceeded, they experience pore collapse and substantial losses in hydraulic conductivity. In loess soils, compaction preferentially compresses mesopores, which govern the saturated permeability coefficient (Li et al., 2023), and this effect intensifies

under elevated molding moisture as mesopore size and connectivity decrease. The soil water characteristic curve further illustrates this behaviour: increased compaction reduces void size distribution and compresses mesopores, lowering matric potential and water retention capacity (Bakhshi et al., 2023; Fredlund et al., 2012). This not only reduces plant-available water storage but also shifts pore-size distribution towards finer pores, diminishing both hydraulic conductivity and unsaturated water retention, effects that are particularly pronounced in clay-rich or weakly aggregated sub-soils.

### *1.3.2. Plant root penetration as affected by soil bulk density*

Crop root development is a critical determinant of crop productivity and is strongly influenced by soil physical properties, particularly bulk density. Numerous studies have demonstrated that soils with high bulk density impede root penetration and elongation due to increased mechanical impedance. For instance, He et al. (2022) reported significant reductions in root length, root tip angle, and elongation rate for rape, deep rape, lucerne, and vetiver at a bulk density of  $1.6 \text{ g cm}^{-3}$ , whereas these parameters improved markedly when bulk density was reduced to  $1.4 \text{ g cm}^{-3}$ . Similarly, Yu et al. (2024) observed that higher compaction ( $1.7 \text{ g cm}^{-3}$ ) significantly decreased root length, volume, and surface area of wheat in both sandy loam and sandy clay loam soils, while also reducing root growth angle in sandy clay loam, irrespective of moisture content.

Further, Popova et al. (2016) found that increased bulk density reduced root growth rate by 50% and root gravitropic response by 23%, while increasing root diameter by 15% and tortuosity by 10% in mixed sand. In addition, in sandy loam, root gravity response increased by 39% and tortuosity decreased by 3%. These findings demonstrate that elevated bulk density not only restricts root elongation but also alters root trajectory, with tortuosity reflecting both passive mechanical deflection and active root responses to soil impedance.

These studies highlight that optimal root development occurs in soils with bulk densities at or below  $1.4 \text{ g cm}^{-3}$ , emphasizing the need to manage soil compaction to facilitate root penetration and improve crop growth.

### *1.3.3. Sensitivity of seedling emergence to soil compaction*

Seedling emergence rate is strongly influenced by the physical characteristics of the growth medium. In agricultural soils, particularly in regions such as the Canadian Prairies, high soil strength and compaction frequently impede seedling emergence and establishment. Soil compaction increases mechanical impedance, making it difficult for seedlings to exert sufficient force to penetrate the soil surface. Gong et al. (2022) modelled the resistance forces encountered by emerging canola seedlings, reporting an increase in emergence resistance from 4.04 N at the lowest compaction level to 9.36 N at the highest level. Compaction caused unacceptably low emergence rates, thereby underscoring the detrimental effects of high soil strength on canola establishment. The sensitivity of emerging seedlings to soil mechanical impedance has been investigated through other simulations. Zeng et al. (2020) demonstrated that smaller seeds experience reduced resistance forces compared to larger seeds, while higher soil particle density further increased impedance to seedling emergence. Similar findings have been reported for other crop species, including *Quercus robur* (Cambi et al., 2018), chestnut-leaved oak (Jourgholami et al., 2016), and soybean (Capobiango et al., 2024), highlighting the broad relevance of soil compaction effects. These findings emphasize that soil compaction and particle characteristics critically influence seedling emergence forces and trajectories.

#### *1.3.4. Approaches to reduce soil compaction effects*

The impact of soil compaction on crop production remains a significant challenge in modern agriculture. As emphasized above, compaction limits root growth and reduces water infiltration, ultimately leading to lower yields and declining soil health. Much of this problem stems from intensive tillage practices and the use of heavy field machinery, highlighting the need for sustainable solutions. Current research emphasizes on innovative strategies such as controlled traffic farming, precision agriculture, and the integration of cover crops. These approaches not only help maintain soil structure but also promote long-term productivity, resilience, and environmental sustainability in farming systems.

Precision agriculture is widely recognized for its adoption of global navigation satellite systems (GNSS), geographic information systems (GIS), yield monitoring, and remote sensing to enhance data-driven decision-making and achieve greater economic efficiency in crop production (Shaheb et al., 2022). Beyond crop management, its application has also transformed tillage practices, making them more targeted, sustainable, and efficient. Traditional tillage methods often disturb entire fields uniformly, regardless of soil conditions, which can intensify compaction problems. In contrast, precision agriculture employs global positioning system (GPS) guidance, soil sensors, and yield mapping to detect site-specific areas where compaction is evident and tillage is required (Deng et al., 2025). Another notable practice is controlled traffic farming, which uses GNSS-guided equipment to restrict machinery movement to permanent traffic lanes, thereby reducing random wheel passes and preventing widespread compaction across the field (Antille et al., 2019). Cover cropping is an effective method for alleviating soil compaction through improvements in soil structure and biological activity. Their extensive root systems penetrate compacted layers and create continuous biopores, which enhance water infiltration, gas exchange, and root development

for subsequent crops (Ogilvie et al., 2021). Deep-rooted species, such as radish, are particularly efficient in loosening compacted zones and lowering bulk density (Chen and Weil, 2011). Additionally, continuous ground cover reduces soil surface sealing from raindrop impact and limits vulnerability to traffic-induced compaction (Li and Freebairn, 2001). These innovations demonstrate how precision agriculture, controlled traffic, and cover crops not only enhance productivity but also contributes to long-term soil health.

## 1.4. Soil erodibility

### *1.4.1. Influencing factors and effects*

Soil erodibility is a significant contributor to land degradation in the Canadian Prairies (Zarrinabadi, 2023). The susceptibility of agricultural soils to erosion is governed by a combination of intrinsic and extrinsic factors, including soil texture, packing density, moisture content, organic matter content, and external mechanical pressures such as wheel traffic (Fattahi et al., 2023). Erosion disrupt soil structure, leading to the depletion of essential nutrients and the displacement or loss of soil microbial communities, thereby impairing soil functionality (Fattahi et al., 2023; Orgiazzi and Panagos, 2018). These structural and biological alterations negatively affect root penetration, water and nutrient uptake, and ultimately diminish overall plant growth and productivity (Zhang et al., 2021).

### *1.4.2. Soil packing density effect on soil aggregate stability and erosion resistance*

The resistance of soils to erosion is strongly influenced by their packing density, which also affects their shearing characteristics. Higher packing density enhances aggregate stability and soil cohesion, thereby reducing particle detachment under erosive forces; while loosely packed soils with low structural integrity are more susceptible to erosion due to their ease of

shear deformation (Agrono and Wakindiki, 2014). Low-density soils are more readily sheared (Verma et al., 2023), allowing erosion agents such as wind and water to detach and transport surface particles, ultimately accelerating land degradation. Therefore, compacted soils demonstrate greater resistance to erosion due to their reduced shear susceptibility and stronger aggregate stability. However, excessive compaction, while beneficial for erosion control, poses detrimental challenges for crop growth by restricting root penetration, limiting water infiltration, and reducing aeration, which collectively impair plant development and yield (Imtiaz et al., 2024). Therefore, effective soil management necessitates maintaining an appropriate packing density that enhances resistance to erosive forces and provides favorable conditions for proper root development. This is crucial in cultivated agricultural systems, where external pressures, including machinery traffic and increase soil degradation underscore the need for management practices that improve soil structural integrity while mitigating erosion risk.

## 1.5. Experimental methods in quantifying soil properties

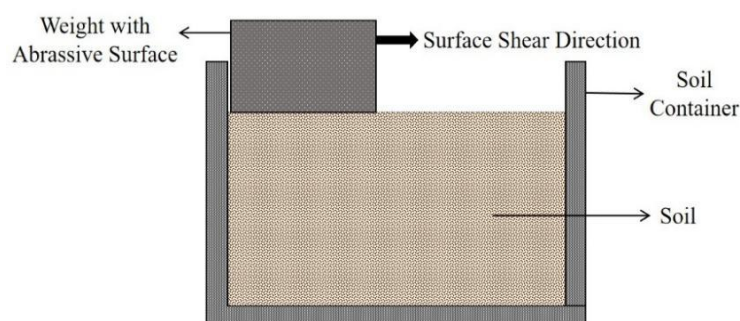
Various scientific experimental methods are employed to quantify soil compaction and evaluate changes in soil strength properties under mechanical loading. Three main methods are: (1) the surface shear test, which measures the resistance of soil surface to horizontal shearing; (2) the shear test, which evaluates the soil's internal shear strength along a failure plane; (3) the cone index test, which quantifies soil penetration resistance, used for assessing compaction over the depth profile of soil.

### 1.5.1. *Soil surface shear test*

The surface shear test is designed to evaluate the strength of the uppermost soil layer, which is directly exposed to erosive agents like raindrop impact, surface runoff, and

agricultural machinery. In this method, an instrument applies a measured horizontal force to the soil surface, typically under a predetermined vertical load, to replicate the shear stresses imposed by environmental or mechanical actions (Figure 1.2).

This approach is adopted in research studies to analyze the susceptibility of surface soils to wind erosion, as soil surface strength is a key factor influencing particle detachment and transport (Havaee et al., 2015; Zhang et al., 2018). Soil surfaces with coarse particles are less vulnerable to erosion by wind forces (Zou et al., 2022). Also, excessive mechanical impedance can hinder seedling emergence and establishment (Gong et al., 2025). Therefore, in addition to its relevance in erosion studies, it is also utilized to assess the resistance that surface soils pose to emerging seedlings. Measuring the shear strength or penetration resistance of soil surfaces provides insight into both the stability of the soil against erosive forces and its suitability for plant growth. These measurements are usually carried out using a pocket penetrometer (Gong et al., 2025), which applies a controlled force to determine penetration resistance, or a surface shearing apparatus (Havaee et al., 2015; Zhang et al., 2018), which quantifies the tangential force required to initiate soil particle movement. These tools provide standardized and repeatable data, allowing for comparative assessments across soil types, management practices, and environmental conditions, thus making the method a valuable tool in both agricultural and environmental soil research.



*Figure 1.2. Surface shear test diagram.*

#### 1.5.1.1. Influence of soil surface friction and adhesion on surface soil detachment

The interplay between soil surface frictions, the resistance encountered when soil particles slide or roll over one another or against a contacting medium, and adhesion, the bonding forces between soil particles and other surfaces, is a critical factor influencing the detachment of agricultural soils by erosive forces. Ding and Huang, (2017) observed that higher soil surface roughness increases surface friction, which in turn reduces soil loss and modifies particle selectivity during detachment. In contrast, smoother, lower friction surfaces exhibited greater losses of sand-sized particles and experienced less selective erosion. This suggests that increased surface friction not only delays particle detachment but also influences the size distribution of eroded material. The combined presence of high surface friction and strong adhesion provides maximum resistance to erosion, whereas soils with low friction and weak adhesion are more susceptible to rapid particle detachment and transport (Zou et al., 2022; Abbaspour-Gilandeh et al., 2018).

#### 1.5.1.2. Factors influencing soil surface friction and adhesion

The physical characteristics of agricultural soils, particularly surface friction and adhesion, are influenced by multiple interrelated factors. Key determinants include moisture content and texture (Abbaspour-Gilandeh et al., 2018), organic matter content (Canakci et al., 2016), and bulk density (Zhang et al., 2001).

According to Abbaspour-Gilandeh et al. (2018), soil moisture content initially enhanced surface friction and adhesion by increasing the thickness of moisture films and strengthening adhesive forces between soil particles and contacting surfaces. However, beyond a critical lubrication threshold, excessive water content diminished both properties due to the lubricating effect of water films. Soil texture further modulates these effects by influencing

the moisture levels at which soils shift from predominantly frictional behaviour to adhesive and ultimately lubricated phases. In general, finer-textured soils maintain higher adhesion coefficients than coarser-textured soils at comparable moisture contents.

Organic matter also plays a significant role. Canakci et al. (2016) reported that organic soils with approximately 70% organic content exhibited relatively low adhesion and interface friction angles compared to their surface friction angle ( $43^\circ$ ). Their study found maximum friction coefficients of around 0.67 for rough surfaces and minimum values near 0.39 for smooth surfaces.

For bulk density, Zhang et al. (2001) observed that increasing soil bulk density from 1.1 to  $1.6 \text{ Mg m}^{-3}$  generally raised both friction and adhesion values. For example, in sandy loam, friction coefficients on steel surfaces increased from approximately 0.46 to 0.66 as density rose, with adhesion forces also increasing due to greater particle-to-particle contact and reduced pore space. These findings highlight the complex interactions among soil moisture, texture, organic content, and bulk density in determining surface strength properties.

### *1.5.2. Soil shear test*

The shear strength of agricultural soils is commonly assessed through various shear test methods, including direct, ring, and triaxial shear tests. Stefanow and Dudziński, (2021) further highlighted the distinctions among several direct shear methods, such as simple shear, double shear, shear vane, shearing grouser, and ring shear (Figure 1.3). These methods are used to determine the maximum soil resistance or shear strength that increase draft forces of tillage tools (Hariri et al., 2023; Infante et al., 2016; Stacho and Sulovska, 2022). Ring shear tests, for example, have been applied to analyze the shear behaviour of sliding zone soils by Zhu et al. (2022), where results demonstrated that optimum moisture content yields maximum

strength. However, high shear rates reduce the internal friction angle, generating weak slurry-like layers that enable long-runout, high-speed reactivation of landslides (Zhu et al., 2022). Some methods, such as shear vanes, only provides the maximum shear force, making it unsuitable for fully applying the Mohr-Coulomb criterion across all displacements. Yin et al., (2022) observed that direct shear tests on grouted clay tend to overestimate cohesion and yield unreliable shear strength parameters due to the formation of secondary shear surfaces. By contrast, triaxial shear tests offer more consistent and reliable results that align better with the Mohr-Coulomb criterion. In this thesis, the confined compression and shear test apparatus, suitable for both drained and undrained soils, was used as the primary shear testing method because of its reliability and its ability to evaluate soils under varying moisture and loading conditions.

Regardless the testing methods, soil shear behaviour is also strongly influenced by its physical composition and other conditions. Al-Adhadh et al. (2021) reported that factors such as moisture and loading conditions, mineral composition, and void ratio significantly affect shear resistance. Effects of some of these factors are discussed below.

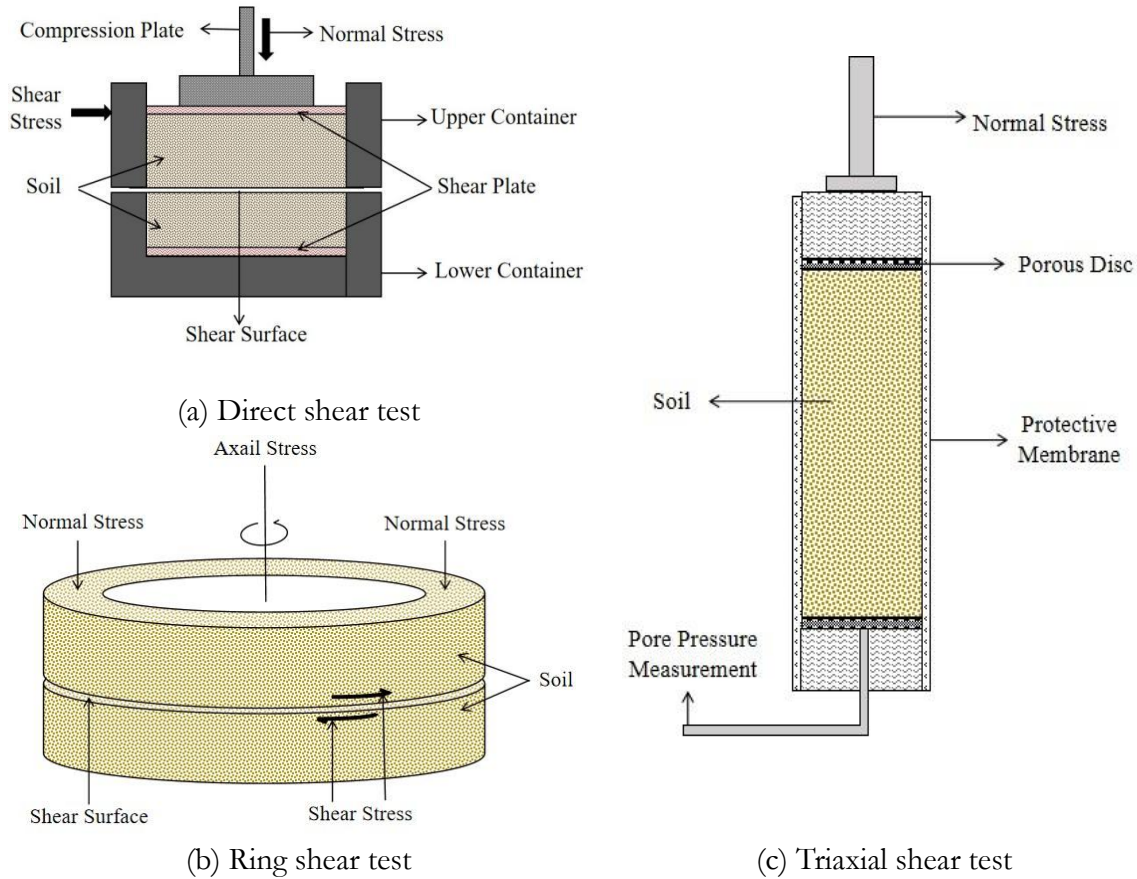


Figure 1.3. Soil shear test diagrams.

#### 1.5.2.1. Soil particle distribution and moisture variation effect on soil shear strength

Particle size distribution (PSD) is a critical factor governing soil shear strength due to its influence on soil packing density, inter-particle contact, and inter-granular void ratios (Xu et al., 2025). Well-graded soils, or those containing an optimal proportion of fines (high clay content), generally achieve denser packing and reduced void ratios, resulting in higher shear strength due to enhanced frictional resistance (Ahmad and Uchimura, 2023; Alshameri et al., 2017). However, when the fine content becomes excessive, the inter-granular void ratio increases, reducing the effective friction surface between coarse particles and thereby lowering the shear strength (Afrazi and Yazdani, 2021; Li, 2013). Moisture content interacts with PSD in influencing soil behaviour. In unsaturated soils, a reduction in moisture from

saturation initially increases matric suction, improving shear strength up to an optimum level; beyond this point, further drying does not enhance and may even diminish strength (Ahmad and Uchimura, 2023). At low fines content, increasing moisture typically reduces cohesion and friction angle, whereas at high fines content, moderate moisture may temporarily increase cohesion due to water molecular attraction before decreasing it at higher contents (Alshameri et al., 2017). In certain mixtures with very high fines content, once voids are completely filled, shear strength can increase slightly due to improved particle interlock despite the higher fines proportion (Afrazi and Yazdani, 2021).

#### 1.5.2.2. Influence of compaction (bulk density) on shear strength parameters

Compaction modifies soil structure by rearranging particles and reducing pore spaces, which directly influences packing density, void ratio, and, in turn, shear resistance. Changes in bulk density resulting from compaction directly impact soil shear behaviour. A study by Rosli et al. (2019) showed that increasing compaction energy by six-folds from 596 kJ/m<sup>3</sup> led to a 5 to 15% rise in maximum dry density, an 82 to 122% increase in shear strength under 20 kPa normal stress, and a 48 to 70% increase under 40 kPa normal stress. Pre-compaction stress is strongly and linearly related to shear strength ( $R^2 = 0.95$ ), with values surpassing the shear strength at the pre-compaction point, suggesting a high potential for failure at this stage (Hemmat et al., 2009). As noted by Fagundes and Rodrigues, (2015), compacted soils typically reach a distinct peak stress at small strains, with an initial slight volume decrease followed by an increase as shearing continues. In contrast, undisturbed soils undergo continuous strain with minimal stress gain and show a volume reduction before shearing. Furthermore, compacted soils possess higher shear strength when unsaturated, underscoring the effectiveness of compaction in such conditions for enhancing the engineering performance of soils.

### 1.5.2.3. Mohr-Coulomb failure criterion

The soil strength test is a widely used experimental method for evaluating fundamental soil strength parameters, particularly cohesion and the surface friction angle (Hariri et al., 2023). Cohesion represents the soil's inherent ability to bind particles together, while the internal friction angle characterizes the resistance to sliding between soil particles. Together, these parameters determine the soil's capacity to withstand detachment and displacement under applied loads. Using trigonometric relationships, cohesion and friction angle are incorporated into linear equations that define the stress conditions at which soil failure occurs (Labuz and Zang, 2012). This set of equations forms the Mohr-Coulomb failure criterion, a key theoretical framework in geotechnical and agricultural engineering. Figure 1.4 illustrates the relationships of the variables based on triaxial shear data. By applying this criterion, shear tests enable accurate prediction and analysis of soil shear strength under varying field conditions, supporting design, stability assessment, and soil-machine interaction studies.

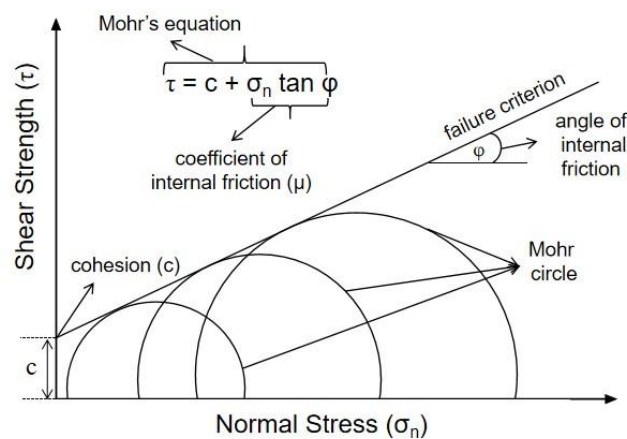


Figure 1.4. Mohr Column failure criterion diagram.

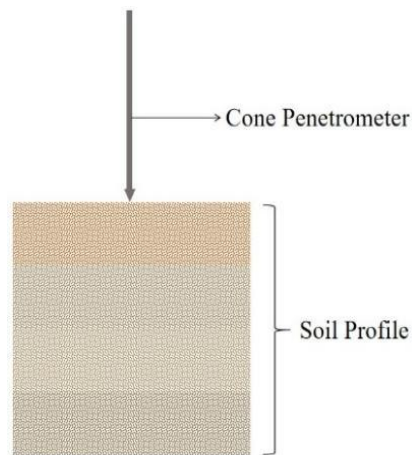
### 1.5.3. Soil cone index test

Soil cone index (CI) provides a quantitative measure of soil strength, which is directly linked to soil compaction levels and plant root growth (Chung et al., 2013). It is determined

using a cone penetrometer, an instrument generally composed of a cone attached to a probe, connected to a load cell. During operation, the cone is inserted into the soil at a constant rate, and the resistance encountered is recorded by the load cell (Figure 1.5). Mathematically, CI is expressed as the ratio of the penetration resistance force to the base area of the cone.

Cone penetrometers are available in various configurations to suit field and laboratory applications. The designs include dynamic cone penetrometers, which determine penetration resistance from the depth achieved per hammer blow, and manual/static cone penetrometers, where the cone is manually and steadily pushed into the soil at a constant speed (Kameistu et al., 2023). Specialized modifications also exist for targeted applications, such as micro-penetrometers for small-scale studies, such as detecting seed-furrow compaction. For example, Wang et al. (2016) evaluated the effects of wetting-drying cycles on the soil strength profile of silty clay using micro-penetrometer tests. These researchers also demonstrated the sensitivity of CI measurements to moisture fluctuations. Therefore, it is suggested to monitor soil moisture content while measuring CI, regardless of the type of penetrometer used.

Measuring CI offers several agronomic and engineering advantages. It enables the identification of compaction layers that restrict root growth and water infiltration, supports decision-making for tillage management to avoid unnecessary soil disturbance, aiding in trafficability assessments for field machinery (Liu, 2024). Furthermore, CI data integrated into precision agriculture systems help optimize site-specific soil management, ultimately enhancing crop productivity and soil health sustainability (Belal et al., 2021).



*Figure 1.5. Soil cone index test diagram.*

#### 1.5.3.1. Cone index variation with soil strength (compaction)

Cone index (CI) is used to quantify soil strength, particularly in hard pan layers (Tekeste et al., 2008). A higher resistance force measured by a cone penetrometer corresponds to a higher CI value, indicating greater soil strength (Zein, 2017). Field traffic, through soil compaction, influences the packing density of soils and thereby affects their CI, a principle widely documented in agricultural soil studies.

Botta et al. (2012) investigated the effect of field traffic on soil compaction by measuring CI. They reported that: (1) field traffic increased the CI in all soil conditions. The front-wheel-assist tractor producing greater CI increases in the topsoil (0–150 mm) and the four-wheel-drive tractor generating higher CI values in the subsoil (150–600 mm) due to its greater total axle load. (2) Most pronounced CI increases occurred in low-bearing-capacity soils, such as ploughed soil, highlighting their heightened susceptibility to compaction under vehicular traffic. Similar findings were reported by Alesso et al. (2020); and Chehaibi et al. (2012). Alesso et al., (2020) observed that field traffic did not significantly affect the proportion of soil with a CI greater than 2 MPa, as variability was high and values averaged only  $4.9 \pm 4.5\%$  across treatments; however, penetration resistance remained consistently

higher in wheeled zones than in non-wheeled zones, particularly along the rut centre line. Chehaibi et al. (2012) further demonstrated that the shear strength of a lateritic tropical soil increased hyperbolically with rising suction for both undisturbed and compacted samples, with the compacted soil showing a greater rate of strength gain. The combined effect of compaction and suction substantially enhanced soil strength.

#### 1.5.3.2. Variability of cone index with soil texture, tillage and moisture content

The physical characteristics of the soil medium play a critical role in determining its response during cone index (CI) measurements. Soil particle size distribution and variations in moisture content largely governs this resistance to penetration. Moisture content has been shown to exert a strong influence on CI, with higher soil moisture generally reducing penetration resistance across different sites and depths (Jones and Arp, 2017). This relationship is further observed in the influence by soil texture, as demonstrated by Kumar et al. (2012), who reported that CI values decrease with increasing clay content and increase with higher sand and silt fractions under both no-tillage and conventional tillage systems. Additionally, tillage practices significantly affect CI, with no-tillage systems typically exhibiting higher values than conventional tillage systems, especially in the topsoil layer (Bueno et al., 2006; Chen et al., 2004). Soil CI also varies along the soil depth profile, with lower values often found in the tilled layer near the surface and higher values occurring in compacted subsurface layers (Doan et al., 2005). These variations highlight the combined influence of soil moisture, texture, and management practices on soil strength, which are essential considerations when interpreting CI measurements for soil compaction assessment and management.

## 1.6. Discrete element method (DEM)

The Discrete Element Method (DEM) is a numerical technique widely applied to simulate the behaviour of granular and discrete materials such as soils, sands, and rock particles. It has proven useful in geotechnics, mining, agriculture, and material science for modelling soil compaction, particle breakage, and granular flow. DEM represents materials as assemblies of individual particles characterized by properties such as size, shape, stiffness, and density, while contact mechanics and Newton's laws of motion govern particle interactions. Through discretization, DEM generates interacting particles that form bulk structures, enabling the study of deformation, movement, and bonding at the particle scale. Although computationally demanding, particularly for large or detailed simulations, DEM is uniquely suited for processes where particle-scale behaviour strongly influences macroscopic responses. In soil mechanics and dynamics, it provides critical insights into tillage, compression, shearing, and penetration, offering a powerful tool for predicting and understanding soil behaviour with improved accuracy.

### *1.6.1. DEM approach and its applications in modelling soil*

Soil structure is inherently scale-dependent and dynamic, capable of transitioning from a granular-like assembly to a continuum-like material under the combined influence of pressure, external stresses, and capillary forces (Keller et al., 2013). Accurately capturing these behaviours is essential for both agricultural and geotechnical applications. The Discrete Element Method (DEM) has emerged as a robust numerical approach for simulating particle-scale behaviour under different loading conditions in agriculture, including soil-root, soil-machine, and soil-residue interactions. These applications provide accurate predictions of soil resistance, which are essential for optimizing field machinery performance, saving energy,

and improving crop growth (Liu et al., 2024; Tian et al., 2024). For example, Kim et al. (2021) used DEM to simulate draft force requirements of a mould-board plow at varying tillage depths with high predictive accuracy, and De Pue and Cornelis, (2019) modelled stress transmission under field traffic, showing that tyre radius, inflation pressure, and velocity significantly influence subsoil stress.

Beyond field applications, DEM is widely used to replicate laboratory tests such as triaxial and direct shear, enabling detailed investigation of soil response under compression, shear, and penetration. By capturing micro-mechanical processes such as force transmission, contact deformation, and shear band formation, DEM improves prediction of soil strength, stability, and flow behaviour (Kianoosh et al., 2017). In soil compaction studies, DEM reproduces elastic-plastic stress-strain behaviour, visualizes force chains and pore structure evolution, and enhances understanding of soil densification and deformation under normal loading (Sadek et al., 2017; Yimsiri and Soga, 2010; Chen et al., 2023). Similarly, in shearing applications, DEM replicates direct shear and triaxial tests to evaluate friction angle, cohesion, and shear band development while accounting for particle size distribution, shape, and moisture effects (De Pue and Cornelis, 2019; Jiang et al., 2014). Bernhardt et al. (2016) examined the sensitivity of DEM simulation results to sample size, contact model parameters, particle stiffness, and ring wall boundary effects during direct simple shear tests. They found that samples with fewer, larger particles had high packing-sensitive. Although increasing particle numbers improved response agreement, DEM samples remained stiffer due to the reduced inter-particle friction used to achieve higher density (Bernhardt et al., 2016). DEM therefore provides a powerful framework for bridging particle-scale interactions with field-scale soil behaviour, making it indispensable for soil analysis under complex loading scenarios.

DEM application extends to modelling shearing between soil and structure interface behaviour at the particle scale mostly for civil engineering purposes. Interface shear simulations allow visualization of shear band formation and particle displacement fields that cannot be directly observed in experiments (Jing et al., 2017; Ma et al., 2023). Calibrated micro-parameters ensure that numerical results replicates the essential macroscopic behaviour of particle morphology on granular soil-structure shearing (Ma et al., 2023). Jing et al., (2017) demonstrated that interface roughness significantly influences shear strength, and shear band thickness, with rougher surfaces exhibiting higher peak shear stresses and thicker shear bands. These findings provide insight into particle interlocking and mobilized friction mechanisms, contributing to improved modelling of soil-structure interaction problems in geotechnical and agricultural applications.

Furthermore, DEM has also been successfully applied to simulate cone penetrometer tests for evaluating soil strength. Kotrocz et al., (2016) developed a 3D DEM model using parallel bond and linear contact models to reproduce cone penetration resistance in loamy sand soils, achieving good agreement with field data. Similarly, Khosravi et al., (2020) employed virtual calibration chambers to study the effects of particle properties, chamber boundaries, and probe-particle interactions on tip resistance and sleeve friction. These simulations provided both macro-scale measurements and micro-scale particle interaction data, enhancing understanding of penetration mechanisms and soil classification. DEM thus offers a robust framework for optimizing penetrometer design and interpreting field measurements.

#### *1.6.2. DEM parameters and their influence on model outputs*

In DEM simulations, various properties and attributes are assigned to model soil particles. These include damping, friction, porosity, particle density, shape and size, as well as normal and shear stiffness. Among these, the most sensitive and frequently calibrated parameters are

the normal and shear stiffness, as they govern particle contact behaviour and strongly influence macroscopic responses (Acquah and Chen, 2021; Wu et al., 2024). In addition, particle size plays a critical role in modelling agricultural soils, since it determines the number of soil-soil and soil-tool contacts and therefore directly affects bulk strength and interaction forces.

Investigations into the effect of particle size on soil shear behaviour have shown that both peak and post-liquefaction undrained strength ratios, together with the friction angle, increase with larger particle diameters (Zeraati-Shamsabadi and Sadrekarimi, 2025). This suggests that scaling particle sizes in DEM simulations may not adequately reproduce the natural soil fabric and the complexity of inter-particle interactions (Zeraati-Shamsabadi and Sadrekarimi, 2025). Similar findings were reported by Cil et al. (2019), who observed that larger particles generally exhibit higher strength and greater resistance to fragmentation, confirming the size dependency of soil particles as a fundamental factor influencing particle-scale failure and assembly-scale mechanical responses in granular soils. In contrast, Wang et al. (2021) concluded that particle size has an insignificant effect on soil resistance when particle diameters are below 10 mm, thereby providing a useful threshold for DEM simulations on soil strength and tillage characteristics.

Equally important is the influence of particle stiffness on DEM simulation outcomes. Several studies have demonstrated that stiffness (normal and shear) exerts a major impact on soil strength analyzes (Lommen et al., 2014; Paulick et al., 2015). Both studies show that bulk compression tests reveal a linear relationship between particle stiffness and bulk modulus, with excessively low stiffness values leading to unrealistic compaction behaviour. In penetration tests, reduced stiffness systematically underestimates penetration resistance; however, reliable results are still obtained if normal overlaps remain below approximately

0.3% of the particle radius (Lommen et al., 2014). For angle of repose simulations, particle stiffness has little influence above a critical threshold of about  $10^7$  Pa, enabling significant computational efficiency gains (Lommen et al., 2014). Also, they concluded that overly soft particles result in marked reductions in the angle of repose, leading to unrealistic flow characteristics.

While reductions in particle stiffness may decrease computational costs, careful calibration is essential. Both particle size and stiffness must be appropriately selected to ensure that DEM simulations produce realistic soil behaviour at both the particle and bulk scales.

### *1.6.3. Parameter calibrations*

Calibration of DEM models is essential to ensure accurate representation of system behaviour. This process involves systematically varying the most sensitive model parameters and comparing the simulated responses with results from physical experiments. According to Coetzee and Scheffler, (2023), calibration of non-cohesive granular materials relies on angle-based measurements, particularly the angle of repose. However, this approach becomes less reliable for cohesive materials, where cohesion produces inconsistent or unrealistically steep angles that show little sensitivity to further parameter adjustments (Coetzee and Scheffler, 2023). To overcome these limitations, calibration of cohesive systems typically combines multiple experimental approaches and systematic procedures, ensuring that the complex behaviours induced by inter-particle cohesion are adequately captured (Karkala et al., 2019).

In soil mechanics, calibration generally targets material parameters such as particle normal stiffness, shear stiffness, cohesion, and friction angle. These parameters are often adjusted

individually or in pairs to achieve realistic soil responses under laboratory or field conditions (Acquah and Chen, 2021; Wu et al., 2024; De Pue et al., 2019). Beyond parameter selection, the choice of contact models is also critical in reproducing realistic soil behaviour. Commonly applied contact models include the linear contact bond, parallel bond, Hertz-Mindlin, and rolling resistance models (Zhao et al., 2024). For agricultural soils, parallel bond model is the most widely adopted, as it effectively capture cohesion and cementation effects at the particle scale (Acquah and Chen, 2021; Wu et al., 2024; Potyondy and Cundall, 2004).

### 1.7. Research gaps

The interplay between soil moisture levels and the dynamic response of soils to loading and surface shearing is a critical yet underexplored area in agricultural research. Soil moisture significantly influences how soil particles interact under stress, affecting its ability to resist deformation and maintain structure during field operations. Excessive moisture can weaken soil cohesion, making it more prone to compaction and erosion, while insufficient moisture may increase soil brittleness and resistance to shearing forces. Investigating the relationship between varying moisture levels and soil response under dynamic loading and surface shearing is essential to develop strategies that optimise soil conditions and reduce structural degradation. But little research has been done in this regard. In addition, how soil compression and shear behaviour vary with soil types have not been well documented.

In addition, quantifying soil shear strength is fundamental to effective agricultural soil management, particularly in evaluating soil resistance to erosion and mechanical stresses. Despite its importance, most existing studies on soil shear properties used disturbed soil samples. Relatively few studies have focused on surface shear strength measurements of intact soil samples from field surface as an indicator of soil erodibility. Shear strength of field surface soil directly correlates with the soil's ability to withstand disruptive forces such as

water flow, wind, and equipment traffic. Understanding these properties enables better predictions of erosion risk and supports the development of targeted soil conservation strategies.

Although Discrete Element Method (DEM) simulations have advanced the understanding of soil shearing behaviour. However, significant gaps remain in evaluating the combined effects of compression stresses and shearing across different soil types. Most studies investigate these factors independently, overlooking the complex interactions that occur when soils are subjected to simultaneous compressive and shear forces. This limitation constrains the ability to accurately replicate real field conditions. Expanding DEM research to incorporate these combined stresses across a range of soil types would yield critical insights into soil mechanical responses during field operations and inform the development of more effective soil management strategies for the Canadian Prairies. Likewise, DEM-based interface shearing characteristic tests have been widely used to study soil-structure interaction (SSI) behaviour in civil engineering applications, focusing primarily on particle morphology (e.g., soil particle size distribution) and structural surface roughness, either individually or in combination. However, these methods have not been adapted to represent the dynamic effects of moisture variation and normal loading that are unique to agricultural soil surfaces. Therefore, addressing these gaps is imperative for improving the prediction of soil particle detachment and susceptibility to wind erosion, thereby enabling better erosion control strategies and supporting sustainable land management in the Prairie region.

Despite extensive research using both physical experiments and Discrete Element Method (DEM) simulations to study soil cone index (CI), limited work has examined how varying wheel traffic patterns interact with different penetrometer cone sizes in agricultural soils of the Canadian Prairies, including sandy loam and clay fields. Most existing studies focus on

either soil physical properties or cone geometry in isolation, neglecting their combined effects under realistic field traffic conditions. This gap limits accurate interpretation of CI data, as wheel-induced compaction generates heterogeneous soil structures that may exaggerate or underestimate penetration resistance depending on cone size. An integrated approach, combining experimental testing on Prairie soils with DEM modelling, is therefore needed to standardize CI measurement and improve its reliability under field-relevant conditions.

In canola research, the impact of post-seeding soil compaction on the emergence of small seeds remains an under explored yet critical area of study. Canola seeds are particularly sensitive to soil resistance, requiring optimal conditions to achieve high emergence rates. Post-seeding compaction, often resulting from press wheels of seeder or field traffic, can create excessive resistance, impeding seedling growth and establishment. Investigating this issue is essential to inform the design of seeders with adjustable down-pressure mechanisms and to optimize the timing of field traffic to minimize compaction. Moreover, determining the ideal soil compaction level for canola emergence is crucial, as it would enable farmers to balance soil structural integrity with adequate porosity for seedling development. These specific knowledge gaps highlight the need for focused research to address the challenges of normal loading on agricultural fields. Advancing understanding in this area will not only protect soil health but also improve agricultural practices, ultimately improving canola yields and sustainability.

## 1.8. General objectives

As illustrated in Figure 1.6, to address the research gaps, the study focused on the following general objectives:

1. Determine the effect of normal stresses on soil surface strength, including its influence on adhesion and the surface angle of friction, using laboratory studies and DEM modelling.
2. Examine the soil shear behaviour under varying normal stresses across different soil types, using laboratory studies and DEM modelling.
3. Investigate soil cone index as influenced by penetrometer cone size under varying soil compaction levels, using field studies and DEM modelling.
4. Analyze the impact of varying compaction levels on soil dynamic properties and the growth of canola, using laboratory and field studies.

This comprehensive approach provided insights into the interplay between soil loading, soil conditions, and crop performance, offering valuable implications for optimizing agricultural practices in the Canadian Prairies.

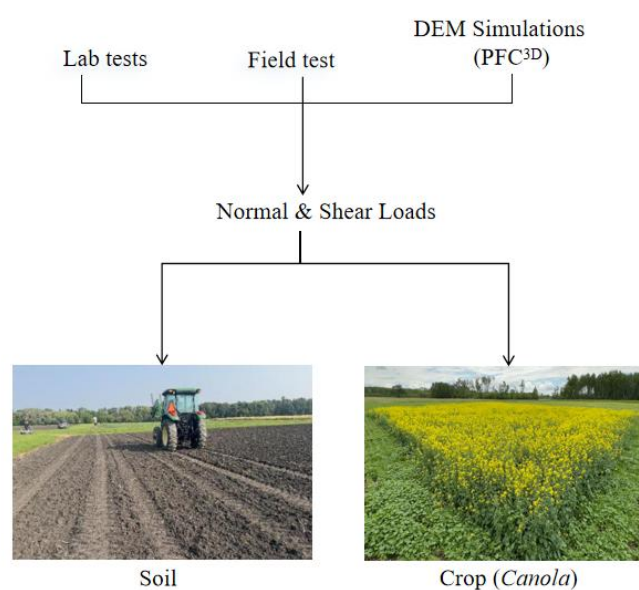


Figure 1.6. Systematic approach to analyse soil compaction.

## 1.9. References

- A. S. Gregory, Ritz, K., McGrath, S. P., Quinton, J. N., Goulding, K. W. T., Jones, R. J. A., Harris, J. A., Bol, R., Wallace, P., Pilgrim, E. S., and Whitmore, A. P. (2015). A review of the impacts of degradation threats on soil properties in the UK. *Soil Use and Management*, 31(suppl.1), 1–15. <https://doi.org/doi.org/10.1111/sum.12212>
- Abbaspour-Gilandeh, Y., Hasankhani-Ghavam, F., Shahgoli, G., Shrabian, V. R., and Abbaspour-Gilandeh, M. (2018). Investigation of the Effect of Soil Moisture Content, Contact Surface Material and Soil Texture on Soil Friction and Soil Adhesion Coefficients. *Acta Technologica Agriculturae*, 21(2), 44–50. <https://doi.org/10.2478/ata-2018-0009>
- Acquah, K., and Chen, Y. (2021). Discrete element modelling of soil compaction of a press-wheel. *AgriEngineering*, 3, 278–293. <https://doi.org/doi.org/10.3390/agriengineering3020019>.
- Acquah, K., and Chen, Y. (2022). Soil compaction from wheel traffic under three tillage systems. *Agriculture*, 12(2), 219. <https://doi.org/doi.org/10.3390/agriculture12020219>
- Afrazi, M., and Yazdani, M. (2021). Determination of the Effect of Soil Particle Size Distribution on the Shear Behavior of Sand. *Journal of Advanced Engineering and Computation*, 5(2), 125. <https://doi.org/10.25073/jaec.202152.331>
- Agrono, A. D., and Wakindiki, I. I. C. (2014). Physical indicators of soil erosion, aggregate stability and erodibility. *Archives of Agronomy and Soil Science*, 61(6), 827–842. <https://doi.org/doi.org/10.1080/03650340.2014.956660>
- Ahmad, W., and Uchimura, T. (2023). The Effect of Moisture Content at Compaction and Grain Size Distribution on the Shear Strength of Unsaturated Soils. *Sustainability (Switzerland)*, 15(6). <https://doi.org/10.3390/su15065123>
- Al-Adhadh, A. R., Abbas, B. J., and Ali, A. M. (2021). Factors Influencing the Shear Strength

- of Clays: A review. *IOP Conference Series: Materials Science and Engineering*, 1090(1), 012009. <https://doi.org/10.1088/1757-899x/1090/1/012009>
- Alam, M. K., Islam, M. M., Salahin, N., and Hasanuzzaman, M. (2014). Effect of tillage practices on soil properties and crop productivity in wheat-mungbean-rice cropping system under subtropical climatic conditions. *Scientific World Journal*, 2014. <https://doi.org/10.1155/2014/437283>
- Alesso, C. A., Cipriotti, P. A., Masola, M. J., Carrizo, M. E., Imhoff, S. C., Rocha-Meneses, L., and Antille, D. L. (2020). Spatial distribution of soil mechanical strength in a controlled traffic farming system as determined by cone index and geostatistical techniques. *Agronomy Research*, 18(Special Issue 2), 1115–1126. <https://doi.org/10.15159/AR.20.133>
- Alshameri, B., Madun, A., and Bakar, I. (2017). Assessment on the effect of fine content and moisture content towards shear strength. *Geotechnical Engineering*, 48(4), 76–86.
- Angon, P. B., Anjum, N., Akter, M. M., Kc, S., Suma, R. P., and Jannat, S. (2023). An Overview of the Impact of Tillage and Cropping Systems on Soil Health in Agricultural Practices. *Advances in Agriculture*, 2023. <https://doi.org/10.1155/2023/8861216>
- Antille, D. L., Peets, S., Galambošová, J., Botta, G. F., Rataj, V., Macak, M., Tullberg, J. N., Chamen, W. C. T., White, D. R., Misiewicz, P. A., Hargreaves, P. R., Bienvenido, J. F., and Godwin, R. J. (2019). Review: Soil compaction and controlled traffic farming in arable and grass cropping systems. *Agronomy Research*, 17(3), 653–682. <https://doi.org/10.15159/AR.19.133>
- Bakhshi, A., Alamdari, P., Heidari, A., and Mohammadi, M. H. (2023). Estimating soil–water characteristic curve (SWCC) using machine learning and soil micro-porosity analysis. *Earth Science Informatics*, 16(4), 3839–3860. <https://doi.org/10.1007/s12145-023-01131-3>

- Balasubramanian, A. (2017). Soil Erosion- Causes and Effects Soil Erosion – Causes and Effects By Prof . A . Balasubramanian Centre for Advanced Studies in Earth Science , University of Mysore , Mysore. *Centre for Advanced Studies in Earth Science, March, 7*.  
<https://doi.org/10.13140/RG.2.2.26247.39841>
- Belal, A. A., EL-Ramady, H., Jalhoum, M., Gad, A., and Mohamed, E. S. (2021). Precision Farming Technologies to Increase Soil and Crop Productivity. In *Springer Water* (Issue October). Springer International Publishing.  
[https://doi.org/10.1007/978-3-030-78574-1\\_6](https://doi.org/10.1007/978-3-030-78574-1_6)
- Bernhardt, M. L., Biscontin, G., and O'Sullivan, C. (2016). Experimental validation study of 3D direct simple shear DEM simulations. *Soils and Foundations*, 56(3), 336–347.  
<https://doi.org/10.1016/j.sandf.2016.04.002>
- Botta, G. F., Tolon-Becerra, A., Tourn, M., Lastra-Bravo, X., and Rivero, D. (2012). Agricultural traffic: Motion resistance and soil compaction in relation to tractor design and different soil conditions. *Soil and Tillage Research*, 120, 92–98.  
<https://doi.org/10.1016/j.still.2011.11.008>
- Bueno, J., Amiama, C., Hernanz, J. L., and Pereira, J. M. (2006). Penetration resistance, soil water content, and workability of grasslands soils under two tillage systems. *Transactions of the ASABE*, 49(4), 875–882. <https://doi.org/doi:10.13031/2013.21727>
- Cambi, M., Mariotti, B., Fabiano, F., Maltoni, A., Tani, A., Foderi, C., Laschi, A., and Marchi, E. (2018). Early response of *Quercus robur* seedlings to soil compaction following germination. *Land Degradation and Development*, 29(4), 916–925.  
<https://doi.org/doi.org/10.1002/ldr.2912>
- Canakci, H., Hamed, M., Celik, F., Sidik, W., and Eviz, F. (2016). Friction characteristics of organic soil with construction materials. *Soils and Foundations*, 56(6), 965–972.  
<https://doi.org/10.1016/j.sandf.2016.11.002>

- Capobianco, N. P., Bessa, G. B., Peris, G. C. de O., Silva, F. L. da, Dias, D. C. F. dos S., Fernandes, R. B. A., Silva, M. F. da, and Silva, L. J. da. (2024). Performance of seedlings and yield of soybean genotypes under soil compaction. *Journal of Agronomy and Crop Science*, 210(2). <https://doi.org/doi.org/10.1111/jac.12699>
- Chehaibi, S., Khelifi, M., Boujelban, A., and Abrougui, K. (2012). Effects of tire inflation pressure and field traffic on compaction of a sandy clay soil as measured by cone index and permeability. *Canadian Biosystems Engineering / Le Genie Des Biosystems Au Canada*, 54(1985), 9–15. <https://doi.org/10.7451/cbe.2012.54.2.9>
- Chen, G., and Weil, R. R. (2011). Root growth and yield of maize as affected by soil compaction and cover crops. *Soil and Tillage Research*, 117, 17–27. <https://doi.org/10.1016/j.still.2011.08.001>
- Chen, H., Gao, L., Li, M., Liao, Y., and Liao, Q. (2023). Effect of soil surface roughness on emergence rate and yield of mechanized direct-seeded rapeseed based on 3D laser scanning. *International Journal of Agricultural and Biological Engineering*, 16(3), 110–119. <https://doi.org/10.25165/J.IJABE.20231603.7276>
- Chen, Y., Monero, F. V., Lobb, D., Tessier, S., and Cavers, C. (2004). Effects of six tillage methods on residue incorporation and crop performance in a heavy clay soil. *Transactions of the ASABE*, 47(4), 1003–1010. <https://doi.org/doi:10.13031/2013.16570>
- Chung, S. O., Sudduth, K. A., Motavalli, P. P., and Kitchen, N. R. (2013). Relating mobile sensor soil strength to penetrometer cone index. *Soil and Tillage Research*, 129, 9–18. <https://doi.org/10.1016/j.still.2012.12.004>
- Cil, M. B., Sohn, C., and Giuseppe Buscarnera, M. A. (2019). DEM Modeling of Grain Size Effect in Brittle Granular Soils. *Journal of Engineering Mechanics*, 146(3), 04019138. [https://doi.org/doi.org/10.1061/\(ASCE\)EM.1943-7889.0001713](https://doi.org/doi.org/10.1061/(ASCE)EM.1943-7889.0001713)
- Coetzee, C. J., and Scheffler, O. C. (2023). Review: The Calibration of DEM Parameters for

- the Bulk Modelling of Cohesive Materials. *Processes*, 11(1).  
<https://doi.org/10.3390/pr11010005>
- De Pue, J., and Cornelis, W. M. (2019). DEM simulation of stress transmission under agricultural traffic Part 1: Comparison with continuum model and parametric study. *Soil and Tillage Research*, 195(March). <https://doi.org/10.1016/j.still.2019.104408>
- Deng, Y., Zhang, W., Qi, B., Wang, Y., Ding, Y., and Zhang, H. (2025). Research Progress and Prospects of Intelligent Measurement and Control Technology for Tillage Depth in Subsoiling Operations. *Sensors*, 25(12). <https://doi.org/10.3390/s25123821>
- Ding, W., and Huang, C. (2017). Effects of soil surface roughness on interrill erosion processes and sediment particle size distribution. *Geomorphology*, 295, 801–810.  
<https://doi.org/doi.org/10.1016/j.geomorph.2017.08.033>
- Doan, V., Chen, Y., and Irvine, B. (2005). Effect of residue type on the performance of no-till seeder openers. *Canadian Biosystems Engineering / Le Genie Des Biosystems Au Canada*, 47, 29–35.
- Fagundes, L. S., and Rodrigues, R. A. (2015). Shear Strength of a Natural and Compacted Tropical Soil. *Electronic Journal of Geotechnical Engineering*, 20(1), 47–58.  
[https://web.archive.org/web/20180422075945id\\_/http://www.ejge.com/2015/Ppr2015.0004ma.pdf](https://web.archive.org/web/20180422075945id_/http://www.ejge.com/2015/Ppr2015.0004ma.pdf)
- Fang, Z., Patterson, B. R., and Turner, M. E. (1992). Influence of particle size distribution on coarsening. *Acta Metallurgica Et Materialia*, 40(4), 713–722.  
[https://doi.org/10.1016/0956-7151\(92\)90013-5](https://doi.org/10.1016/0956-7151(92)90013-5)
- Fattahi, S. M., Soroush, A., Huang, N., Zhang, J., Abbasi, S. J., and Yu, Y. (2023). Soil properties affecting erosion induced by saltating particles. *Environmental Geotechnics*, 10(4), 252–265. <https://doi.org/doi.org/10.1680/jenge.19.00230>
- Fredlund, D. G., Rahardjo, H., and Fredlund, M. D. (2012). Measurement and Estimation of

- State Variables. In *Unsaturated Soil Mechanics in Engineering Practice*.  
<https://doi.org/10.1002/9781118280492.ch4>
- Gong, H., Chen, Y., Wu, S., Tang, Z., Liu, C., Wang, Z., Fu, D., Zhou, Y., and Qi, L. (2022). Simulation of canola seedling emergence dynamics under different soil compaction levels using the discrete element method (DEM). *Soil and Tillage Research*, 223. <https://doi.org/doi.org/10.1016/j.still.2022.105461>
- Gong, H., Tang, Z., Cai, Y., Zhang, Y., Yang, S., Chen, Y., and Qi, L. (2025). Emergence of Soybean and Canola Plants as Affected by Soil Compaction from a Seeder Press Roller. *Agronomy*, 15(5). <https://doi.org/10.3390/agronomy15051076>
- Håkansson, I., and Lipiec, J. (2000). A review of the usefulness of relative bulk density values in studies of soil structure and compaction. *Soil and Tillage Research*, 53(2), 71–85. [https://doi.org/10.1016/S0167-1987\(99\)00095-1](https://doi.org/10.1016/S0167-1987(99)00095-1)
- Hamza, M. A., and Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research*, 82(2), 121–145. <https://doi.org/doi.org/10.1016/j.still.2004.08.009>.
- Hariri, A. El, Ahmed, A. E. E., and Kiss, P. (2023). Review on soil shear strength with loam sand soil results using direct shear test. *Journal of Terramechanics*, 107, 47–59. <https://doi.org/doi.org/10.1016/j.jterra.2023.03.003>
- Harker, K. N., O'Donovan, J. T., Blackshaw, R. E., Johnson, E. N., Lafond, G. P., and May, W. E. (2012). Seeding Depth and Seeding Speed Effects on No-till Canola Emergence, Maturity, Yield and Seed Quality. *Canadian Journal of Plant Science*, 92(4), 795–802. <https://doi.org/10.4141/cjps2011-189>
- Hasan, M. M., Liu, X. D., Rahman, M. A., Hazzazi, Y., Wassem, M., Ghimire, S., Alabdallah, N. M., Alharbi, B. M., Kabir, A. H., Yao, G., and Fang, X. W. (2025). Plants breathing under pressure: mechanistic insights into soil compaction-induced physiological,

- molecular and biochemical responses in plants. *Planta*, 261(3).  
<https://doi.org/10.1007/s00425-025-04624-1>
- Havaee, S., Mosaddeghi, M. R., and Ayoubi, S. (2015). In situ surface shear strength as affected by soil characteristics and land use in calcareous soils of central Iran. *Geoderma*, 237, 137–148. <https://doi.org/10.1016/j.geoderma.2014.08.016>
- He, Y., Wu, Z., Zhao, T., Yang, H., Ali, W., and Jiazhou Chen. (2022). Different plant species exhibit contrasting root traits and penetration to variation in soil bulk density of clayey red soil. *Agronomy Journal*, 114(1), 867–877. <https://doi.org/doi.org/10.1002/agj2.20972>
- Hemmat, A., Tahmasebia, M., Vafaeianb, M., and Mosaddeghic, M. . (2009). Relationship between pre-compaction stress and shear strength under confined and semi-confined loadings for a sandy loam soil. *Biosystems Engineering*, 102(2), 219–226. <https://doi.org/doi:10.1016/j.biosystemseng.2008.11.001>
- Horn, R., and Baumgartl, T. (2002). Dynamic properties of soils. *Soil Physics Companion*, 389, 17. <https://books.google.ca/books?hl=en&lr=&id=kYPLBQAAQBAJ&oi=fnd&pg=PA17&dq=Several+factors+significantly+influence+the+dynamic+physical+properties+of+agricultural+soils,+shaping+their+behavior,+structure,+and+vulnerability+to+surface+erosion.+&ots=UA3BWRGR>
- Horn, R., Mordhorst, A., and Fleige, H. (2024). The impact of arable soil management on physical functions – The ratio of air capacity and air permeability or hydraulic conductivity as a document of harmful soil compaction. *Soil and Tillage Research*, 244(July), 106221. <https://doi.org/10.1016/j.still.2024.106221>
- Huang, X., Horn, R., and Ren, T. (2022). Soil structure effects on deformation, pore water pressure, and consequences for air permeability during compaction and subsequent shearing. *Geoderma*, 406(August 2021), 115452.

<https://doi.org/10.1016/j.geoderma.2021.115452>

- Hyatt, J., Wendroth, O., Egli, D. B., and TeKrony, D. M. (2007). Soil compaction and soybean seedling emergence. *Crop Sci*, 47(6), 2495. <https://doi.org/10.2135/cropsci2007.03.0171>
- Imtiaz, S., Shahid, S., Ishfaq, T., Ilyas, M., Nawaz, A. F., Shamshad, J., Fiaz, S., and Arif, M. (2024). Impact of Climate Change on Agriculture. In *Environment, Climate, Plant and Vegetation Growth*. [https://doi.org/10.1007/978-3-031-69417-2\\_10](https://doi.org/10.1007/978-3-031-69417-2_10)
- Infante, D. J. U., Martinez, G. M. A., Arrua, P. A., and Eberhardt, M. (2016). Shear Strength Behavior of Different Geosynthetic Reinforced Soil Structure from Direct Shear Test. *International Journal of Geosynthetics and Ground Engineering*, 2(2). <https://doi.org/10.1007/s40891-016-0058-2>
- Jiang, M. J., Li, T., Hu, H. J., and Thornton, C. (2014). DEM analyses of one-dimensional compression and collapse behaviour of unsaturated structural loess. *Computers and Geotechnics*, 60, 47–60. <https://doi.org/10.1016/j.compgeo.2014.04.002>
- Jing, X. Y., Zhou, W. H., and Li, Y. (2017). Interface Direct Shearing Behavior between Soil and Saw-tooth Surfaces by DEM Simulation. *Procedia Engineering*, 175, 36–42. <https://doi.org/10.1016/j.proeng.2017.01.011>
- Jones, M.-F., and Arp, P. A. (2017). Relating Cone Penetration and Rutting Resistance to Variations in Forest Soil Properties and Daily Moisture Fluctuations. *Open Journal of Soil Science*, 07(07), 149–171. <https://doi.org/10.4236/ojss.2017.77012>
- Jourgholami, M., Khoramizadeh, A., and Zenner, E. K. (2016). Effects of soil compaction on seedling morphology, growth, and architecture of chestnut-leaved oak (*Quercus castaneifolia*). *IForest - Biogeosciences and Forestry*, 10(1), 145–153. <https://doi.org/doi.org/10.3832/ifor1724-009>
- Kameistu, P., Priadi, E., and Widodo, S. (2023). Correlation of Based Soil Carrying Capacity

- Results of Cone Penetration Test, Dynamic Cone Penetrometer (Dcp), Plate Bearing Test, and Hand Penetrometer. *Jurnal Teknik Sipil*, 23(3), 318. <https://doi.org/10.26418/jts.v23i3.64107>
- Karkala, S., Davis, N., Wassgren, C., Shi, Y., Liu, X., Riemann, C., Yacobian, G., and Ramachandran, R. (2019). Calibration of discrete-element-method parameters for cohesive materials using dynamic-yield-strength and shear-cell experiments. *Processes*, 7(5), 1–16. <https://doi.org/10.3390/pr7050278>
- Keller, T., Lamandé, M., Peth, S., Berli, M., Delenne, J. Y., Baumgarten, W., Rabbel, W., Radjaï, F., Rajchenbach, J., Selvadurai, A. P. S., and Or, D. (2013). An interdisciplinary approach towards improved understanding of soil deformation during compaction. *Soil and Tillage Research*, 128, 61–80. <https://doi.org/10.1016/j.still.2012.10.004>
- Khosravi, A., Martinez, A., and Dejong, J. T. (2020). Discrete element model (DEM) simulations of cone penetration test (CPT) measurements and soil classification. *Canadian Geotechnical Journal*, 57(9), 1369–1387. <https://doi.org/10.1139/cgj-2019-0512>
- Kianoosh, T., Combe, G., and Luding, S. (2017). DEM applied to soil mechanics. *ALERT Doctoral School*, 218. <https://ris.utwente.nl/ws/portalfiles/portal/23891303/ALERT.pdf#page=135>
- Kim, Y. S., Siddique, M. A. A., Kim, W. S., Kim, Y. J., Lee, S. D., Lee, D. K., Hwang, S. J., Nam, J. S., Park, S. U., and Lim, R. G. (2021). DEM simulation for draft force prediction of moldboard plow according to the tillage depth in cohesive soil. *Computers and Electronics in Agriculture*, 189(July), 106368. <https://doi.org/10.1016/j.compag.2021.106368>
- Kirby, M. (2007). Whither soil compaction research? Letter to the editor. *Soil and Tillage Research*, 93(2), 472–475. <https://doi.org/doi.org/10.1016/j.still>

- Kotroc, K., Mouazen, A. M., and Kerényi, G. (2016). Numerical simulation of soil-cone penetrometer interaction using discrete element method. *Computers and Electronics in Agriculture*, 125, 63–73. <https://doi.org/10.1016/j.compag.2016.04.023>
- Kumar, A., Chen, Y., Sadek, A., and Rahman, S. (2012). Soil cone index in relation to soil texture, moisture content, and bulk density for no-tillage and conventional tillage. *Agricultural Engineering International: CIGR Journal*, 14(1), 26–37.
- Kumar, V., Sharma, K., Singh, G., Kumar, R., Khajuria Krishi Vigyan Kendra, S., Sher-e-, S., Balbir Dhotra, I., Kumar Arora, R., Kumar Yadav, N., Singh Choudhary, R., Samanta, A., Singh Butter, T., Singh, V., Khajuria, S., and Dhotra, B. (2018). Soil structure and their management in farming system: A review. 280 ~ *International Journal of Chemical Studies*, 6(4), 280–287.
- La, A., Brown, J., Chen, Y., Kumaravelayutham, P., Munch, G., Nandanvar, M., Panditharatne, M., Peranantham, T., Sharma, U., Sadek, M., and Chen, Y. (2013). Effect of Soil Compaction on Early Soybean Plant Growth in Sandy Loam Manitoba Soil. *CSBE/SCGAB 2013 Annual Conference, Saskatoon, SK. CSBE*, 12. <http://www.csbe-scgab.ca/docs/meetings/2013/CSBE13071.pdf>
- Labuz, J. F., and Zang, A. (2012). Mohr-Coulomb failure criterion. *Rock Mechanics and Rock Engineering*, 45(6), 975–979. <https://doi.org/10.1007/s00603-012-0281-7>
- Li, P., Pan, Z., Xiao, T., and Wang, J. (2023). Effects of molding water content and compaction degree on the microstructure and permeability of compacted loess. *Acta Geotechnica*, 18(2), 921–936. <https://doi.org/10.1007/s11440-022-01592-8>
- Li, Y. (2013). Effects of particle shape and size distribution on the shear strength behavior of composite soils. *Bulletin of Engineering Geology and the Environment*, 72(3–4), 371–381. <https://doi.org/10.1007/s10064-013-0482-7>
- Liu, K. (2024). *Parameters Optimisation of Agricultural Machinery for Soil Compaction*

- Mitigation and Crop Yield Enhancement* [University of Padova].  
<https://www.research.unipd.it/handle/11577/3508890>
- Liu, X., Shi, R., Zhao, W., Sun, W., Li, P., Li, H., Zhang, H., Wang, J., Wang, G., and Dai, F. (2024). Study on the Characteristics of Residual Film–Soil–Root Stubble Complex in Maize Stubble Fields of the Hexi Corridor and Establishment of a Discrete Element Model. *Agriculture (Switzerland)*, 14(9). <https://doi.org/10.3390/agriculture14091542>
- Lommen, S., Schott, D., and Lodewijks, G. (2014). DEM speedup: Stiffness effects on behavior of bulk material. *Particuology*, 12(1), 107–112.  
<https://doi.org/10.1016/j.partic.2013.03.006>
- Ma, X., Lei, H., and Kang, X. (2023). Examination of interface roughness and particle morphology on granular soil–structure shearing behavior using DEM and 3D printing. *Engineering Structures*, 290(May). <https://doi.org/10.1016/j.engstruct.2023.116365>
- Millington, W. A. J., Misiewicz, P. A., Dickin, E. T., White, D. R., and Godwin, R. J. (2016). An investigation into the effect of soil compaction and tillage on plant growth and yield of winter barley (*Hordeum vulgare* L.). 2016 American Society of Agricultural and Biological Engineers Annual International Meeting, ASABE 2016, 1–12.  
<https://doi.org/10.13031/aim.20162461725>
- Ogilvie, C. M., Ashiq, W., Vasava, H. B., and Biswas, A. (2021). Quantifying root-soil interactions in cover crop systems: A review. *Agriculture (Switzerland)*, 11(3).  
<https://doi.org/10.3390/agriculture11030218>
- Okorie, B. O., and Niraj, Y. (1996). Effects of different tillage practices on soil fertility properties: A review. *International Journal of Agriculture and Environmental Research*, 8(1), 176–193. <https://doi.org/10.22004/ag.econ.333826>
- Oladeji, N. O. (2025). SOIL PHYSICAL PROPERTIES, ORGANIC CARBON DYNAMICS, AND MAIZE PERFORMANCE UNDER LONG-TERM GRAZING AND

CONTINUOUS CULTIVATION IN ADO EKITI, SOUTHWEST NIGERIA.

*International Journal of Organic Agricultural Research and Development*, 20(1), 36–42.

<https://ijoardjournal.org/index.php/ijoardjournal/article/view/387>

Orgiazzi, A., and Panagos, P. (2018). Soil biodiversity and soil erosion: It is time to get married: Adding an earthworm factor to soil erosion modelling. *Global Ecology and Biogeography*, 27(10), 1155–1167. <https://doi.org/10.1111/geb.12782>

Pagliai, M., and Vignozzi, N. (2002). The soil pore system as an indicator of soil quality. *Advances in GeoEcology*, 35, 69–80.

Paulick, M., Morgeneyer, M., and Kwade, A. (2015). Review on the influence of elastic particle properties on DEM simulation results. *Powder Technology*, 283, 66–76. <https://doi.org/10.1016/j.powtec.2015.03.040>

Pavlenko, O. V. (2024). Seismic Waves in Soil Layers. In *Seismic Waves in Soil Layers*. <https://doi.org/10.1007/978-3-031-52338-0>

Popova, L., Van Dusschoten, D., Nagel, K. A., Fiorani, F., and Mazzolai, B. (2016). Plant root tortuosity: An indicator of root path formation in soil with different composition and density. *Annals of Botany*, 118(4), 685–698. <https://doi.org/10.1093/aob/mcw057>

Ramzan, S., Wani, M. A., Jeelani, J., Ashraf, I., Auyoub Bhat, M., Maqbool, M., and Rasool, R. (2019). Soil health: Looking for the effect of tillage on soil physical health. *International Journal of Chemical Studies*, 7(1), 1731–1736.

Ripley, B. S., Gilbert, M. E., Ibrahim, D. G., and Osborne, C. P. (2007). Drought constraints on C4 photosynthesis: Stomatal and meta\_bolic limitations in C3 and C4 subspecies of *Alloteropsis semi\_alata*. *Journal of Experimental Botany*, 58(6), 1351–1363. <https://doi.org/doi.org/10.1093/jxb/erl302>

Romaneckas, K., Kimbirauskienė, R., and Sinkevičienė, A. (2022). Impact of Tillage Intensity on Planosol Bulk Density, Pore Size Distribution, and Water Capacity in Faba

- Bean Cultivation. *Agronomy*, 12(10). <https://doi.org/10.3390/agronomy12102311>
- Rosli, R. N., Selamat, M. R., and Ramli, M. H. (2019). ScienceDirect Shear strength and permeability properties of lateritic soils from North West Malaysia due to extended compaction. *Materials Today: Proceedings*, 17, 630–639. <https://doi.org/10.1016/j.matpr.2019.06.344>
- Sadek, M. A., Tekeste, M., and Naderi, M. (2017). Calibration of soil compaction behavior using Discrete Element Method (DEM). *ASABE Annual International Meeting. American Society of Agricultural and Biological Engineers.*, 1. <https://doi.org/doi:10.13031/aim.201700777>
- Shah, A. N., Tanveer, M., Shahzad, B., Yang, G., Fahad, S., Ali, S., Bukhari, M. A., Tung, S. A., Hafeez, A., and Souliyanonh, B. (2017). Soil compaction effects on soil health and crop productivity: an overview. *Environmental Science and Pollution Research*, 24(11), 10056–10067. <https://doi.org/10.1007/s11356-017-8421-y>
- Shaheb, M. R., Sarker, A., and Shearer, S. A. (2022). *Precision Agriculture for Sustainable Soil and Crop. Soil Science: Emerging Technologies, Global Perspectives and Applications.*
- Shaheb, M. R., Venkatesh, R., and Shearer, S. A. (2021). A review on the effect of soil compaction and its management for sustainable crop production. *Journal of Biosystems Engineering*, 46, 417–439. <https://doi.org/doi.org/10.1007/s42853-021-00117-7>
- Sidhu, D., and Duiker, S. W. (2006). Soil compaction in conservation tillage: Crop impacts. *Agronomy Journal*, 98(5), 1257–1264. <https://doi.org/doi.org/10.2134/agronj2006.0070>
- Sivarajan, S., Maharlooei, M., Bajwa, S. G., and Nowatzki, J. (2018). Impact of soil compaction due to wheel traffic on corn and soybean growth, development and yield. *Soil and Tillage Research*, 175, 234–243. <https://doi.org/doi.org/10.1016/j.still.2017.09.001>

- Stacho, J., and Sulovska, M. (2022). Shear Strength Properties of Coarse-Grained Soils Determined Using Large-Size Direct Shear Test. *Civil and Environmental Engineering*, 18(1), 244–257. <https://doi.org/10.2478/cee-2022-0023>
- Stefanow, D., and Dudziński, P. A. (2021). Soil shear strength determination methods – State of the art. *Soil and Tillage Research*, 208(November 2020). <https://doi.org/10.1016/j.still.2020.104881>
- Tekeste, M. Z., Raper, R. L., and Schwab, E. B. (2008). Soil Drying Effects on Soil Strength and Depth of Hardpan Layers as Determined from Cone Index Data. *Agricultural Engineering International: CIGR Journal*, X, 1–17.
- Tian, Y., Zeng, Z., and Xing, Y. (2024). *A Review of Discrete Element Method Applications in Soil – Plant Interactions : Challenges and Opportunities*. 1–20.
- Vangla, P., and Latha, G. M. (2015). Influence of Particle Size on the Friction and Interfacial Shear Strength of Sands of Similar Morphology. *International Journal of Geosynthetics and Ground Engineering*, 1(1). <https://doi.org/10.1007/s40891-014-0008-9>
- Verma, A. K., Prasad, A., and Bonal, N. S. (2023). Investigation of the long-term shear strength behavior of municipal solid waste fines stabilized with biopolymer: An experimental study. *Journal of Environmental Chemical Engineering*, 11(3), 109805. <https://doi.org/10.1016/j.jece.2023.109805>
- Wang, D. Y., Tang, C. S., Cui, Y. J., Shi, B., and Li, J. (2016). Effects of wetting-drying cycles on soil strength profile of a silty clay in micro-penetrometer tests. *Engineering Geology*, 206, 60–70. <https://doi.org/10.1016/j.enggeo.2016.04.005>
- Wang, X., Wei, W., He, J., and Huang, Y. (2021). Effect of soil particle-size distribution (Psd) on soil-subsoiler interactions in the discrete element model. *Spanish Journal of Agricultural Research*, 19(1), 1–13. <https://doi.org/10.5424/sjar/2021191-16584>
- Wu, P., Zhang, X., Zeng, Z., and Chen, Y. (2025). DEM simulation of subsoiling for soil

- disturbance as affected by soil layering and working speed. *Smart Agricultural Technology*, 7(100385). <https://doi.org/doi.org/10.1016/j.atech.2023.100385>
- Xu, S., Hu, L., Sun, H., Wang, B., Gao, F., and Wang, M. (2025). Investigating peak strength of gap-graded soils through discrete element method: mechanisms and prediction. *Granular Matter*, 27(2). <https://doi.org/10.1007/s10035-025-01511-0>
- Yimsiri, S., and Soga, K. (2010). Dem analysis of soil fabric effects on behaviour of sand. *Geotechnique*, 60(6), 483–495. <https://doi.org/10.1680/geot.2010.60.6.483>
- Yin, Z., Zhang, Q., Zhang, X., Zhang, J., and Li, X. (2022). Shear strength of grouted clay: comparison of triaxial tests to direct shear tests. *Bulletin of Engineering Geology and the Environment*, 81(7). <https://doi.org/10.1007/s10064-022-02739-3>
- Yu, C., Mawodza, T., Atkinson, B. S., Atkinson, J. A., Sturrock, C. J., Whalley, R., Hawkesford, M. J., Cooper, H., Zhang, X., Zhou, H., and Mooney, S. J. (2024). The effects of soil compaction on wheat seedling root growth are specific to soil texture and soil moisture status. *Rhizosphere*, 29(100838). <https://doi.org/doi.org/10.1016/j.rhisph.2023.100838>
- Yuxia Li, J. N. T., and Freebairn, D. M. (2001). No Title. *Australian Journal of Soil Research*, 39(2), 239–247. <https://doi.org/doi.org/10.1071/SR00017>
- Zarrinabadi, E. (2023). *Soil erosion and fluxes of sediment within landscapes of the Canadian Prairies* [University of Manitoba]. <https://mspace.lib.umanitoba.ca/server/api/core/bitstreams/265f8a8e-130d-4866-8933-2a1bda211073/content>
- Zein, A. K. M. (2017). Estimation of undrained shear strength of fine grained soils from cone penetration resistance. *International Journal of Geo-Engineering*, 8(1). <https://doi.org/10.1186/s40703-017-0046-y>
- Zeng, Z., Chen, Y., and Qi, L. (2020). Simulation of cotyledon-soil dynamics using the

- discrete element method (DEM). *Computers and Electronics in Agriculture*, 174(February), 105505. <https://doi.org/10.1016/j.compag.2020.105505>
- Zeraati-Shamsabadi, M., and Sadrekarimi, A. (2025). A DEM study on the effects of specimen and particle sizes on direct simple shear tests. *Granular Matter*, 27(2). <https://doi.org/10.1007/s10035-025-01513-y>
- Zhang, B., Zhao, Q. G., Horn, R., and Baumgartl, T. (2001). Shear strength of surface soil as affected by soil bulk density and soil water content. *Soil and Tillage Research*, 59(3–4), 97–106. [https://doi.org/10.1016/S0167-1987\(01\)00163-5](https://doi.org/10.1016/S0167-1987(01)00163-5)
- Zhang, C., Wang, X., Zou, X., Tian, J., Liu, B., Li, J., Kang, L., Chen, H., and Wu, Y. (2018). Estimation of surface shear strength of undisturbed soils in the eastern part of northern China's wind erosion area. *Soil and Tillage Research*, 178(19), 1–10. <https://doi.org/10.1016/j.still.2017.12.014>
- Zhang, L., Huang, Y., Rong, L., Duan, X., Zhang, R., Li, Y., and Guan, J. (2021). Effect of soil erosion depth on crop yield based on topsoil removal method: a meta-analysis. *Agronomy for Sustainable Development*, 41(5), 1–13. <https://doi.org/10.1007/s13593-021-00718-8>
- Zhao, Z., Wu, M., and Jiang, X. (2024). A Review of Contact Models' Properties for Discrete Element Simulation in Agricultural Engineering. *Agriculture (Switzerland)*, 14(2). <https://doi.org/10.3390/agriculture14020238>
- Zhu, R., Xie, W. li, Liu, Q., Yang, H., and Wang, Q. (2022). Shear behavior of sliding zone soil of loess landslides via ring shear tests in the South Jingyang Plateau. *Bulletin of Engineering Geology and the Environment*, 81(6), 1–15. <https://doi.org/10.1007/s10064-022-02719-7>
- Zou, X., Li, H., Kang, L., Zhang, C., Jia, W., Gao, Y., Zhang, J., Yang, Z., Zhang, M., Xu, J., Cheng, H., and Wu, X. (2022). Soil wind erosion rate on rough surfaces: A dynamical

model derived from an invariant pattern of the shear-stress probability density function of the soil surface. *Catena*, 219(106633).  
<https://doi.org/doi.org/10.1016/j.catena.2022.106633>

## Chapter 2

---

### Soil surface shear behaviour and particle detachment: experimental and DEM investigations\*

*\*Submitted to Journal of Terramechanics (under revision)*

#### 2.1. Abstract

Soil shear behaviour and particle detachment at the surface play a critical role in soil stability and resistance to wind erosion, yet their dependence on moisture and loading conditions remains insufficiently understood. This study measured soil surface properties (surface shear strength, adhesion, and interface friction angle) of sandy loam and clay soils under three moisture conditions (low, medium, high) using a soil surface shear apparatus. Discrete Element Models (DEM) were developed to replicate the surface soil shear tests, calibrated using the measurements, and applied to assess wind erosion through simulations of soil particle displacements. Test results showed that interface friction angle and adhesion increased with soil moisture content. The DEM models replicated the measured shear responses across the soil types and moisture levels, with relative errors in the range of 2.1-18.4%. Simulation results indicated decreasing particle displacement with higher soil moisture, reflecting enhanced aggregate stability and reduced detachment of the soil particles. Horizontal particle displacement was dominated in sandy loam, while clay showed greater vertical displacement at higher moisture level. This numerical approach provides a reliable approach for predicting soil stabilities for erosion prevention.

**Keywords:** Soil shear strength; adhesion; friction angle; DEM model; erosion

## 2.2. Introduction

Tillage, wind and runoff are significant contributors to agricultural soil erosion in the Canadian Prairies (Zarrinabadi et al., 2023). Several forms of erosion, such as rill flow and splash erosion, are primarily influenced by the shearing properties of the soil surface (Rauws and Govers, 1988). The susceptibility of surface soils to erosion is also dependent on other physical properties, such as porosity, bulk density, texture and moisture content (Holz et al., 2015; Stanchi et al., 2013). Soil shear strength is a critical shear property, as it reflects surface resistance, affected by loading. Also, it serves as a critical indicator of soil erodibility and directly impacts seedling emergence (Owusu-Sekyere and Chen, 2024). Quantifying surface shear strength is therefore essential for effective control of soil erosion in agriculture.

The surface shear strength characteristics of soils are influenced by various physical parameters, including particle distribution, soil structure and moisture content. Soils with higher clay content exhibit resistance to shearing due to their high cohesion, whereas soils with high sand content resist shearing primarily through friction (Yin et al., 2021). Additionally, Li et al. (2021) demonstrated that increasing soil moisture content enhances shear deformation, while reducing moisture content has the opposite effect. External factors such as compaction and normal loading on soil surface decrease soil void spaces and enhance particle interlocking, thereby increasing the soil shear resistance (Huang et al., 2022). In addition, the formation of soil crusts has been observed to enhance soil surface strength while reducing infiltration rates and the detachment of surface soils (Moore and Singer, 1990). However, these crusts lead to the decrease in soil's ability to absorb nutrients, which negatively affects seedling emergence (Moore and Singer, 1990; Nakagawa et al., 2024). While these factors are well documented, the interplay between varying soil moisture levels

and the dynamic response of soil to loading and surface shearing remains an area with significant potential for further exploration.

Different techniques have been developed to measure soil surface resistance and assess its shearing behaviour. These include the torvane test, the pocket penetrometer test, and the hand vane test. Zimbone et al. (1996) reported that the pocket penetrometer recorded higher shear values compared to the torvane and hand vane testers. To improve in situ measurements, Havaee et al. (2015) developed a shear box capable of measuring surface shear cohesion and the friction angle of clay soils. Their study utilised multi-linear regression to predict soil surface shear strength. Similarly, Brunori et al. (1989) used a drop-cone penetrometer to test the shear resistance of soils with varying textures. While this method demonstrated low repeatability, it was more sensitive to minor variations in soil texture. Besides tests, soil erodibility prediction models, such as USLE, RUSLE, and WEPP, were developed using data from these surface resistance studies (Akbarzadeh et al., 2016; Guo et al., 2021; Zarrinabadi, 2023). These models are empirical, based on experimental observations only, lacking the ability to explicitly capture the mechanistic processes of soil particle detachment and transport under varying mechanical loading conditions. For example, the USLE and RUSLE focus primarily on average annual soil loss without accounting for micro-scale heterogeneity in soil structure (Akbarzadeh et al., 2016). Similarly, the WEPP model, though process-based, does not adequately represent particle-scale mechanics governing soil strength and erosion thresholds (Guo et al., 2021). In contrast, Discrete Element Method (DEM) simulations can overcome these shortcomings by modelling soil as an assembly of discrete particles, enabling the direct representation of particle contacts, friction, cohesion, under applied normal stresses (Jia et al., 2023; Liu et al., 2021).

The DEM is a robust tool for analysing soil dynamic properties and the macro-behaviour of soil-structure interfaces. Extensive research has resulted in the development of various soil behaviour models to study soil shearing. For instance, Jia et al. (2023) utilized DEM to investigate the anisotropic tensile behaviour of biaxial geogrid-soil interfaces, accounting for particle shape irregularities. Their findings revealed a reduction in interface shear strength as geogrid anisotropy increased, primarily due to decreased overall geogrid strength. Similarly, Liu et al. (2021) examined the interfacial behaviour of unsaturated soil structures using DEM to perform direct shear tests, finding that capillary cohesion diminished with increasing normal load. Salazar et al. (2015) studied coarse sand using 3D DEM modelling, revealing that up-scaled particle sizes reduced accuracy but significantly shortened computational time. However, existing models were limited to shearing and compaction mechanisms, lacking a detailed representation of soil surface detachment governed by particle-scale interactions.

The objectives of this study were to: (1) determine the surface shear properties (adhesion and interface friction angle) of two soils from the Canadian Prairies under three moisture conditions and varying normal loads; (2) develop and calibrate DEM models to simulate the surface shearing behaviour of these soils across various moisture levels; (3) use the developed models to assess the susceptibility of the soils to surface erosion.

## **2.3. Material and methods**

### *2.3.1. Laboratory test*

#### **2.3.1.1. Description of soil sampling sites and soil types**

Two soil-sampling sites were selected based on the characterization of increased soil surface erodibility. The first site is located at a farm in the municipality of Piney, Manitoba,

Canada. It is situated 134 km southeast from Winnipeg. The soil texture is sandy loam with 70% sand, 16% silt, and 14% clay. The second site is at a research farm of the University of Manitoba, Winnipeg, Canada. The soil texture is clay with 62% clay, 35% silt, and 3% sand (ASTM, 2007). Typical tillage practice in both farms was conventional tillage.

### 2.3.1.2. Description of soil surface shear test apparatus and functionality

The shear properties of the soil surface were measured using a soil surface shear test apparatus (M1-0866e, Royal Eijkelkamp Giesbeek, Netherlands). The apparatus is the final variation of the earlier prototype developed by Wójciga et al. (2009) and Zhang et al. (2001). The apparatus consists of a loading frame, a digital force transducer, a winding mechanism, a measuring ruler, a soil container, soil sample rings, and calibrated weights (Figure 2.1a). The loading frame (diameter: 68 mm and height: 30 mm) in Figure 2.1b is coated with abrasive material (sandpaper grade P40) at its bottom (Figure 2.1c) to mimic the interlocking nature between soil aggregates. The apparatus measures soil surface shear resistance by applying a horizontal force via the winding mechanism to the loading frame (with calibrated weight within) placed on top of the soil sample. This mechanism moves the loading frame horizontally on the soil surface. The digital force transducer monitors the maximum surface shear resistance and registers it as the force needed to initiate movement of the loading frame.

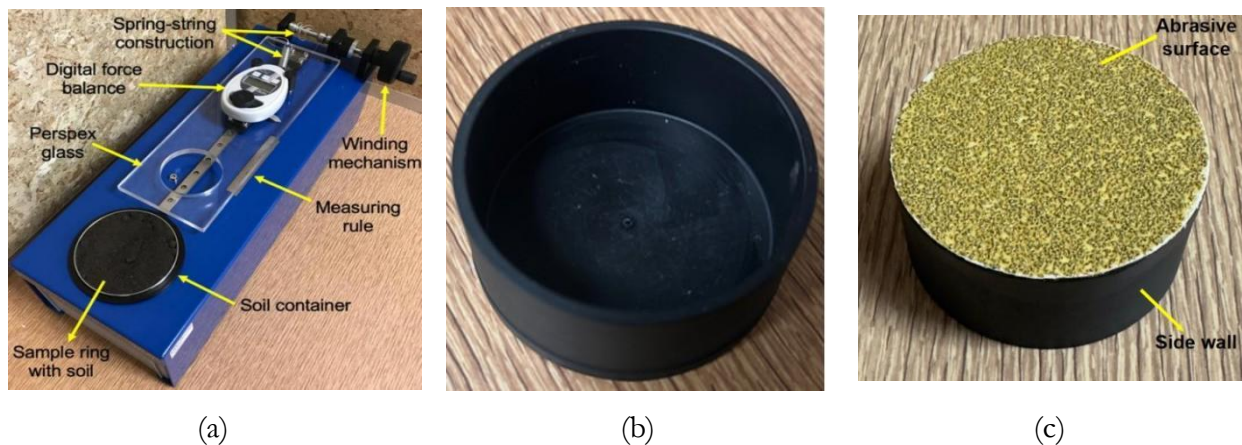


Figure 2.1. Soil surface shear test apparatus: (a) Components; (b) Top; (c) and bottom view of the loading frame showing abrasive surface.

### 2.3.1.3. Experimental design

The soil surface shear test apparatus was used to measure soil shear properties that can be used to assess surface soil detachment by wind. The experiment was a split plot design with a factorial treatment layout. The two soil types (sandy loam and clay soils) served as the whole-plot factor and three soil moisture content (MC) levels served as the subplot factor for the experiment. The three moisture levels were designated as low, medium, and high, further described below. Four normal loads, 40, 540, 1040 and 2040 g, were applied to determine the interface friction angle and adhesion for each soil type under different moisture levels. Four replicates were performed for each treatment combination. Ninety-six (96) individual tests (2 soils x 3 soil moisture contents x 4 normal loads x 4 replicates) were performed.

### 2.3.1.4. Experimental procedure and measurements

Undisturbed soil samples were taken from the two sampling sites using sample rings (inner diameter: 100 mm; height 30 mm) (Figure 2.2a). Soil samples were taken from the topsoil layer (from soil surface to 30 mm depth). The sample rings (with soil) were covered with lids during transportation to prevent evaporation and disintegration of the soil structure.

The cover placed on the natural undisturbed field soil surface was labelled as ‘S’ (Figure 2.2b) to ensure that the soil surface of the soil sample was in contact with the abrasive sandpaper in the shear test. For each soil type, sixteen soil samples were obtained from each of the three soil moisture levels. The soil moisture content was determined by using the oven drying method (ASTM, 1999). For sandy loam, the gravimetric moisture content was 9%, 23% and 31% (dry basis) for the low, medium, and high moisture content levels respectively. The corresponding gravimetric moisture content for clay was 18%, 24% and 35% (dry basis). These are common soil moisture contents (MCs) observed in the Canadian Prairies. The low MC was measured in mid-summer, whereas the medium and high MC were measured in spring and fall, respectively.

For the test, the sample ring (with intact soil) was placed within the soil container on the shear test apparatus with the side labelled as ‘S’ facing upward (Figure 2.2c). The Perspex glass, which was connected to the digital force transducer and winding mechanism through a spring-string construction, was drawn over the soil sample. The desired normal stresses were attained by placing the calibrated weights within the loading frame. The loading frame with the calibrated weights were then placed on top of the soil sample through the opening in the Perspex glass such that the abrasive face of the loading frame was in direct contact with the soil surface (Figure 2.2d).

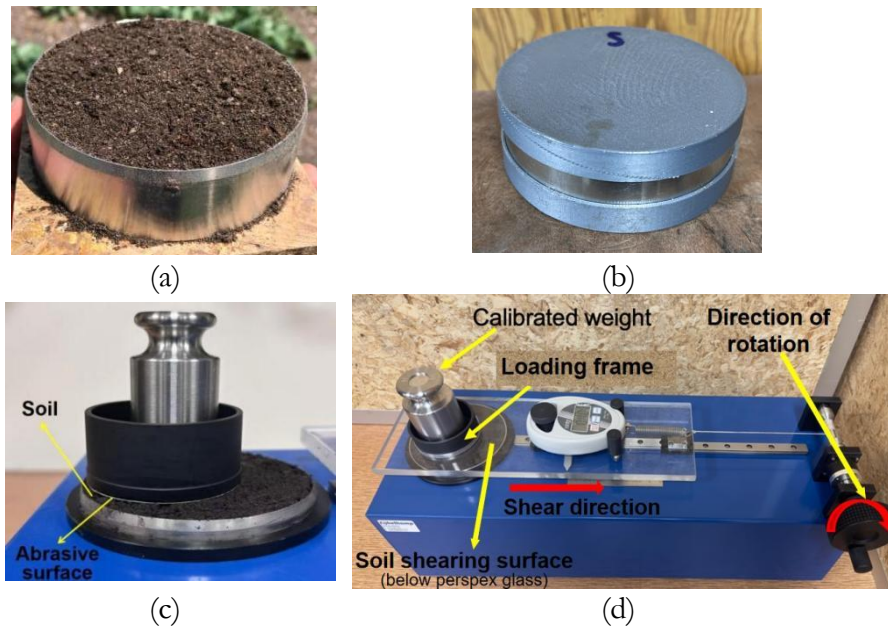


Figure 2.2. Soil surface shearing tests: (a) Soil sample acquired using the sample ring; (b) Sealed soil sample with lid for transportation; (c) Loading frame with a known weight placed on soil surface, showing soil and abrasive surface in contact at the initial position for shearing test; (d) Experimental set up of soil surface shear apparatus.

The winding mechanism operated at 1 rev/sec moved the loading frame (with the calibrated weights) horizontally across the soil surface for a distance of 30 mm, applying a horizontal (shear) force. This induced shearing between the abrasive surface and the soil surface. The digital force transducer measured the horizontal (shear) resistance and registered it as the shear force. Normal stresses of 0.11, 1.46, 2.81, and 5.50 kPa were determined using calibrated weights of 40, 540, 1040, and 2040 g, respectively. The test was repeated for each stress condition of different soil types and moisture levels.

The soil surface shear strength was calculated as the maximum shear force divided by the base area of the abrasive surface. The surface shear strength ( $\tau$ ) was plotted against the applied normal stress ( $\sigma_n$ ) to yield a linear relationship to obtain the adhesion and interface friction angle between the soil and the abrasive surface (Figure 2.3). The adhesion was determined as the intercept on the shear strength axis (y-axis) and the interface friction angle was determined from the slope of the linear line.

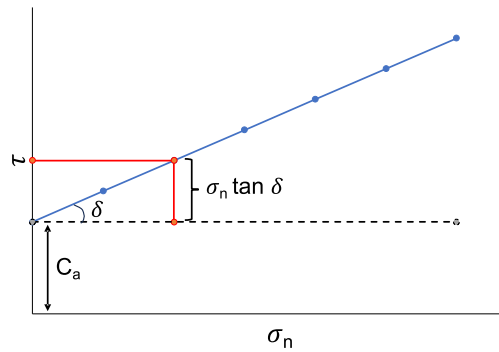


Figure 2.3. General relationship between surface soil strength ( $\tau$ ) and applied normal stress ( $\sigma_n$ ), showing the definitions of adhesion ( $C_a$ ) and interface friction angle ( $\delta$ ).

#### 2.3.1.5. Data analysis

Data analysis was conducted using R statistical software (version 4.2.2). Analysis of variance (ANOVA) was employed to evaluate the influence of soil moisture content and normal applied loads on the response variables: soil surface shear strength, adhesion, and the interface angle of friction. This statistical approach was used to determine whether variations in these independent factors significantly affected the response variables. The ‘*sp.plot*’ function from the ‘*agricolae*’ package was used for the ANOVA computations. To further examine pairwise comparisons among treatment groups, Duncan’s multiple range test was performed. This combined methodology ensured a thorough assessment of the soil’s mechanical behaviour under varying loading and moisture conditions.

### 2.3.2. Soil surface shear model simulation

#### 2.3.2.1. Model particle development

The Discrete Element Method (DEM) model for soil surface shearing was developed using Particle Flow Code in Three Dimensions (PFC<sup>3D</sup>) software (Version 6.0, Itasca Consulting Group Inc., Minneapolis, USA). The model (Figure 2.4a) had a 1:1 scale relative

to the physical experiment described above. An open-top cylindrical ring model measuring 100 mm in diameter and 35 mm in height was created to represent the soil sample ring. Spherical soil particles with radius varying randomly from 0.7 to 1 mm were generated in the ring to a height of 30 mm. This particle size range was chosen to optimize computational time while ensuring accuracy in the model soil response. The model particles were allowed to settle under gravity, and their particle density was adjusted using Equation 2.1 to match the model soil's bulk density to the bulk density of the soil in the physical experiment.

$$\frac{\rho_b}{\rho_p} = 1 - n \quad (2.1)$$

where  $\rho_b$  is the soil bulk density,  $\rho_p$  is the particle density, and  $n$  is the soil porosity.

#### 2.3.2.2. Model-loading frame development

In the model, the loading frame was simplified as a cylindrical weight with an abrasive surface at the bottom of the weight. The weight had the same dimensions as the loading frame in the physical test (68 mm in diameter and 30 mm in height). A total of 120 spherical grains was generated randomly at the bottom of the weight to form the abrasive surface (Figure 2.4b). The radius of the spherical grains was 0.00019 mm, determined from the average radius of the sand paper grain size for grade P40 (You et al., 2024). The spherical grains were assigned a low resolution of 0.9 to depict the irregular shape of the grain sizes in the sandpaper. The grains were assigned a surface friction coefficient of 1 to mimic the high abrasive surface and the interlocking behaviour (Adajar et al., 2021).

### 2.3.2.3. Simulation process

For the simulation, the model-loading frame was given a vertical velocity ( $0.003 \text{ mm}^{-1}$ ) to settle on the model soil at one end of the soil sample ring. As the loading frame moved down, the normal load of soil was monitored, and the vertical movement of the model-loading frame was stopped when the normal load in the simulation matched the normal load in the physical test. The model-loading frame was then made to move horizontally at a speed of  $0.003 \text{ mms}^{-1}$  across the model soil surface until it reached the other end of the soil sample, replicating the physical test. The speed of travel was consistent with the average speed in the physical test, determined as the total distance travelled divided by the average time taken. The horizontal resistance (contact force) of the model soil to the loading frame's abrasive surface was monitored, as the shear force as in the physical test. The surface shear strength was determined as the maximum horizontal force divided by the base area of the model-loading frame's abrasive surface.

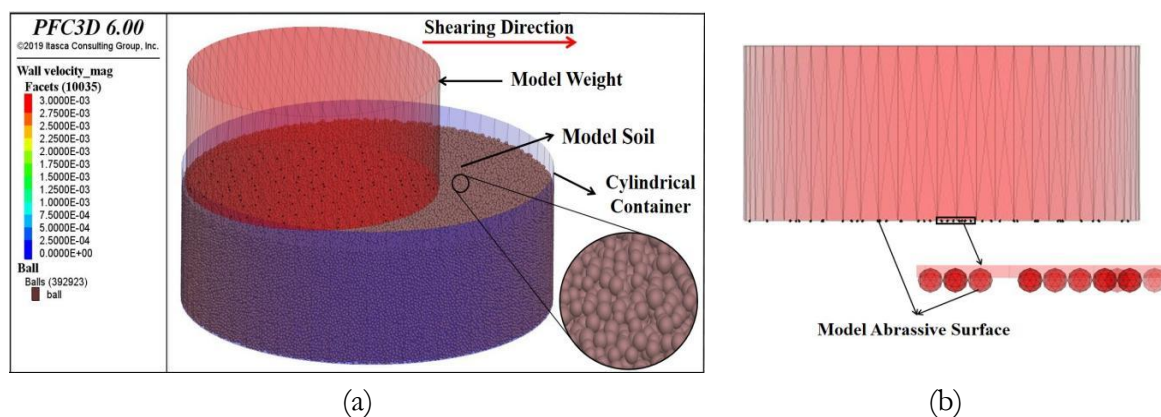


Figure 2.4. Soil surface shearing model: (a) Soil particles and model loading frame; (b) Loading frame with an abrasive surface having randomly distributed spherical grains.

To simulate the cohesive behaviour of agricultural soils, a parallel bond model (PBM) was applied between the soil particles, based on Potyondy and Cundall (2004). Parameters for the PBM are summarised in Table 2.1. Through preliminary simulations using the model, the soil

effective modulus ( $E_{mod}$ ) was found to be the most sensitive parameter and was therefore calibrated, while other parameters were taken from literature (Table 2.1).

Table 2.1. Model soil parameters

| Model Parameter     | Description                     | Unit             | Value               | Reference                  |
|---------------------|---------------------------------|------------------|---------------------|----------------------------|
| Particle Parameters |                                 |                  |                     |                            |
| $K_n$               | Particle normal stiffness       | N/m              | $9.0 \times 10^3$   | (Acquah and Chen, 2023)    |
| $K_s$               | Particle shear stiffness        | N/m              | $2.52 \times 10^4$  | (Nandanwar and Chen, 2017) |
| $\beta_n$           | Viscous damping coefficient     | -                | 1.0                 | (Sadek and Chen, 2015)     |
| $\theta$            | Local damping coefficient       | -                | 0.5                 |                            |
| Bond Parameters     |                                 |                  |                     |                            |
| $\bar{E}$           | Effective modulus               | N/m <sup>2</sup> | To be calibrated    |                            |
| $\sigma$            | Tensile strength                | Pa               | $1.5 \times 10^7$   | (Ju et al., 2016)          |
| $\tau$              | Cohesion strength               | Pa               | $5.244 \times 10^7$ |                            |
| $\mu$               | Friction coefficient            | -                | 0.5                 | (Acquah and Chen, 2023)    |
| $\bar{\lambda}$     | Bond radius multiplier          | -                | 0.5                 |                            |
| $k^*$               | Normal-to-shear stiffness ratio | -                | 0.5                 |                            |

#### 2.3.2.4. Model calibration

The soil model parameter  $E_{mod}$  was calibrated by matching the simulation results of adhesion and interface friction angle with those measured in the physical test. For each combination of soil type and moisture level, the calibration was performed in the following steps: (1) running the model with an assumed value of  $E_{mod}$ ; (2) obtaining the simulated soil surface shear strengths for each of the four normal stresses; (3) determining the adhesion and interface friction angle from the simulated shear strengths through regression analysis; (4) calculating the relative errors (defined in Equation 2.2) between the simulated and measured adhesion and interface friction angles. These steps were repeated with more assumed values of  $E_{mod}$  until the simulated adhesion and interface friction angle agreed with those measured in

the physical experiment. This process was repeated for each of the six combinations of two soil types and three moisture conditions, and thus, six calibrated values of  $E_{mod}$  were obtained.

$$RE = \frac{|M-S|}{M} \times 100 \quad (2.2)$$

where, RE is the relative error, M and S are measured and simulated data, respectively.

#### 2.3.2.5. Simulations of soil susceptibility to erosion

The calibrated model was used to simulate surface shear strengths at the interface between soil and surfaces of varying abrasiveness. Results of such simulations can be used to assess soil resistances to wind in various conditions. The degrees of abrasiveness were determined according to the sandpaper grading listed in Table 2.2 (You et al., 2024). Accordingly, the sandpaper grain sizes were incorporated into the abrasive surfaces of the model loading frame, as shown in Figure 2.5. Simulations were performed for both sandy loam and clay soils at their three moisture levels (low, medium, and high). To understand soil susceptibility to surface erosion, soil particle displacements were monitored to evaluate the extent of surface soil detachment. Five tracers, matching the average size of the model soil particles, were positioned atop the soil model, under the loading frame, in the manner as shown in Figure 2.6. Their movement in horizontal, lateral, and vertical directions were tracked as soil particle displacements in x-, y-, and z-directions respectively. The 540 g loading condition was maintained for all the simulations at a shearing speed of 0.003 mms<sup>-1</sup>.

Table 2.2. Sandpaper grades used in model simulations

| Grading | Grain Size/Radius (mm) |
|---------|------------------------|
| P12     | 0.9075                 |
| P20     | 0.5000                 |
| P30     | 0.3210                 |
| P50     | 0.1680                 |
| P60     | 0.1345                 |
| P80     | 0.1005                 |
| P100    | 0.0810                 |
| P120    | 0.0625                 |
| P150    | 0.0500                 |
| P180    | 0.0390                 |

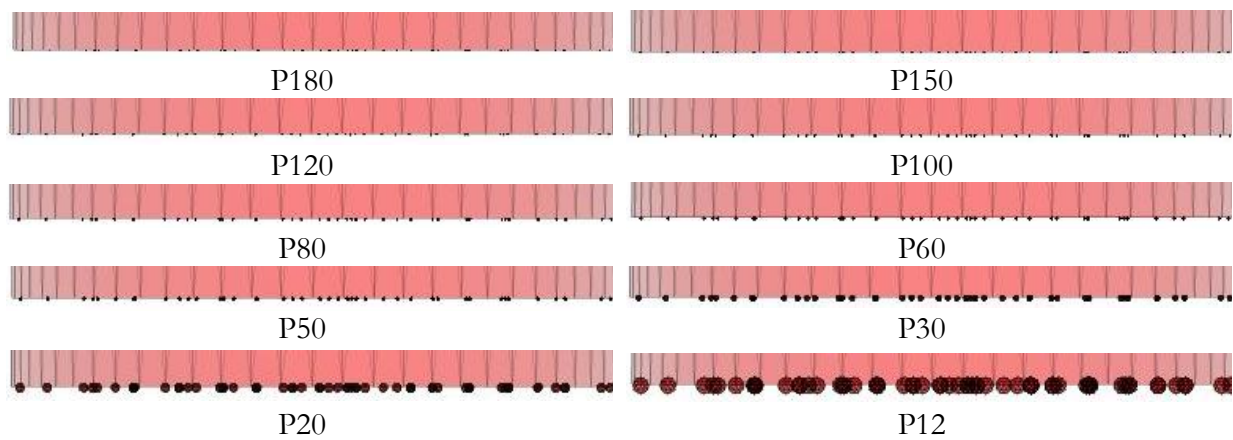


Figure 2.5. Side views of the model loading frame with varying abrasive surface's grain sizes and the equivalent sandpaper grades.

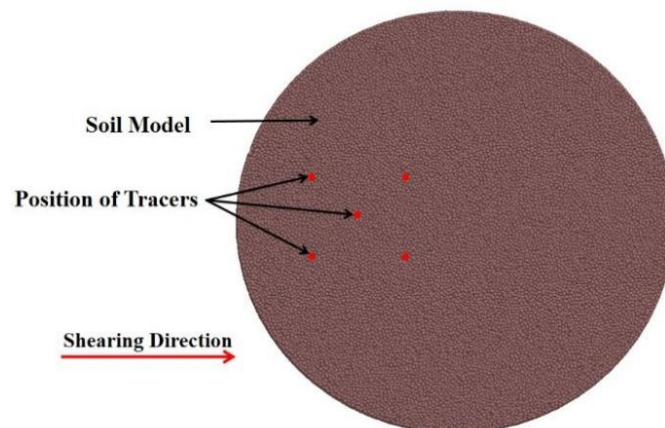


Figure 2.6. Top view of the model soil sample showing the positions of soil tracers for monitoring soil displacement.

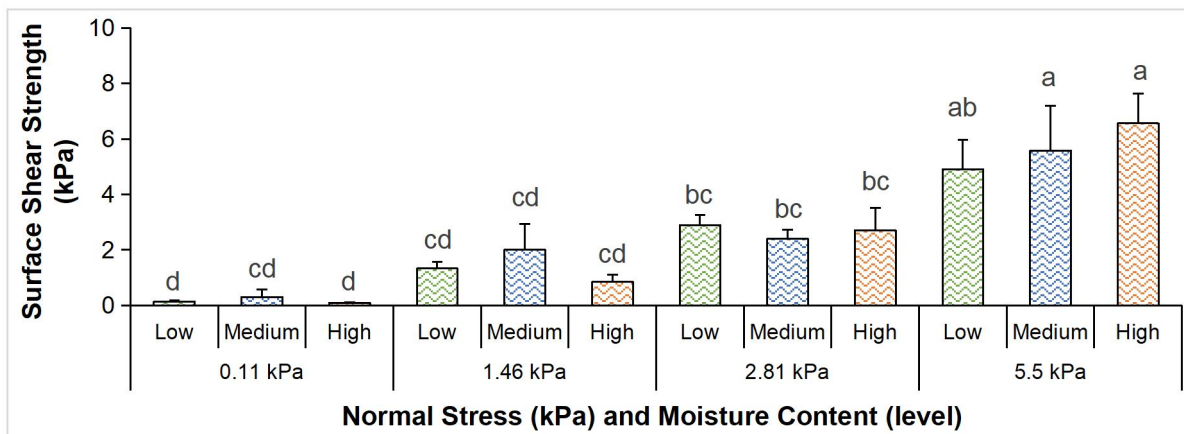
## 2.4. Results and discussion

### 2.4.1. *Experimental results*

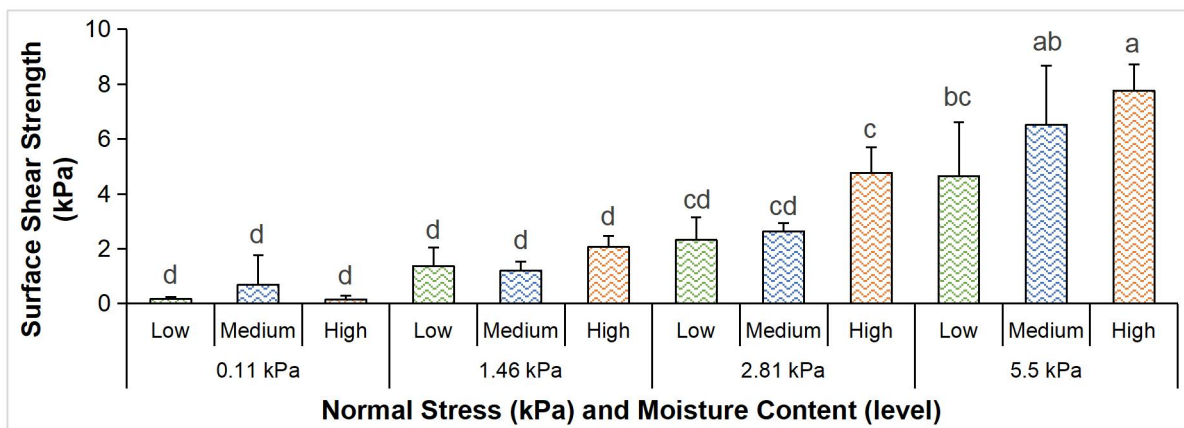
#### 2.4.1.1. Soil surface shear strength as affected by the treatments

For the sandy loam soil, the surface shear strength under different moisture conditions (MC) and varying normal stresses is illustrated in Figure 2.7a. Effects of MC was more critical than the effect of normal loading. The results showed a non-linear increase in shear strength with increasing normal stress. Under the 0.11 kPa normal stress, the low soil MC exhibited a slightly higher shear strength compared to the high soil MC, with a difference of 0.05 kPa. However, the medium MC recorded the highest shear strength at the 0.31 kPa normal stress, though the difference was not statistically significant compared to the low and high MC. When the normal stress increased to 1.46 kPa, the shear strength rose significantly, with an average increase of 672%. The shear strength behaviour under the 1.46 kPa stress was similar to that observed under the 0.11 kPa stress. However, at 2.81 kPa normal stress, the shear strength increased by an average of 91.3% compared to the 1.46 kPa stress. In this case, the low soil MC exhibited 17.1% and 6.2% higher surface shear strengths than the medium and wet soil MCs, respectively. Under the 5.5 kPa stress, the surface shear strength increased further, with an average percentage difference of 112.9% compared to the 2.81 kPa stress. Unlike the lower stresses, the surface shear strength increased with moisture content under the 5.5 kPa stress. The differences in shear strength were 13.9% between the low and medium MC and 17.5% between the medium and high MC, although these differences were not statistically significant. The gritty nature of the sand particles resulted in the observed increasing surface shear resistance with increasing moisture level and loading (Li et al., 2021; Yin et al., 2021).

For the clay soil, a non-linear increase in surface shear strength was observed with increasing normal load and moisture content (MC) (Figure 2.7b), a behaviour evident in the work done by Wei et al. (2015 ). Under the 0.11 kPa normal stress, the surface shear strength of clay exhibited a similar pattern to that of sandy loam, with no significant differences. When the stress level was increased to 1.46 kPa, the surface shear strength rose by 359.2%. Although soil strength increased with rising MC, the differences were not statistically significant. Under the 2.81 kPa normal stress, changes in shear strength of 13.5% and 81.1% were observed between the low and medium MC and the medium and high MC, respectively. The highest surface shear strength was recorded under the 5.5 kPa normal stress. Similar to the sandy loam soil, clay soil displayed a linear increase in surface shear strength with increasing MC under this stress. The low soil MC recorded a surface shear strength of 4.66 kPa. The medium MC had a soil strength of 6.52 kPa while high MC had 7.76 kPa. The cohesive behaviour of clay soil at higher moisture levels enhanced its shearing resistance (Yin et al., 2021).



(a) Sandy loam



(b) Clay

Figure 2.7. Influence of normal stress and soil moisture content on the soil surface shear strength. Error bars are standard deviations. Values labelled with different letters are significantly different based on Duncan's multiple-range test at a significance level of  $p < 0.05$ .

#### 2.4.1.2. Surface shear strength envelope

The soil surface shear strength envelopes fit linear lines across all soil types and moisture conditions (MC) (Figures 2.8a-f). For the low MC of sandy loam soil, percentage changes of 833.3%, 117.5%, and 69.5% were recorded between 0.11 and 1.46 kPa, 1.46 and 2.81 kPa, and 2.81 and 5.5 kPa normal stresses, respectively. Significant differences in soil surface shear strength were observed among the normal stresses. At the medium MC, the maximum percentage change was 554.6% between 0.11 and 1.46 kPa, while the minimum change was 19.6% between 1.46 and 2.81 kPa. At high MC, sandy loam soil exhibited the highest shear

strength, reaching 6.56 kPa under the 5.5 kPa normal stress. The trend in surface shear strength for sandy loam soil was consistent with that of clay soil. Maximum percentage changes of 714.9%, 74.6%, and 1255.7% were observed between the lower normal stresses (0.11 and 1.46 kPa) for low, medium, and high MC of clay soil, respectively. Under the 5.5 kPa normal stress, both soils exhibited higher standard errors across all moisture conditions. This variability likely resulted from challenges in maintaining consistent motion while operating the winding mechanism of the shear test apparatus under higher loads.

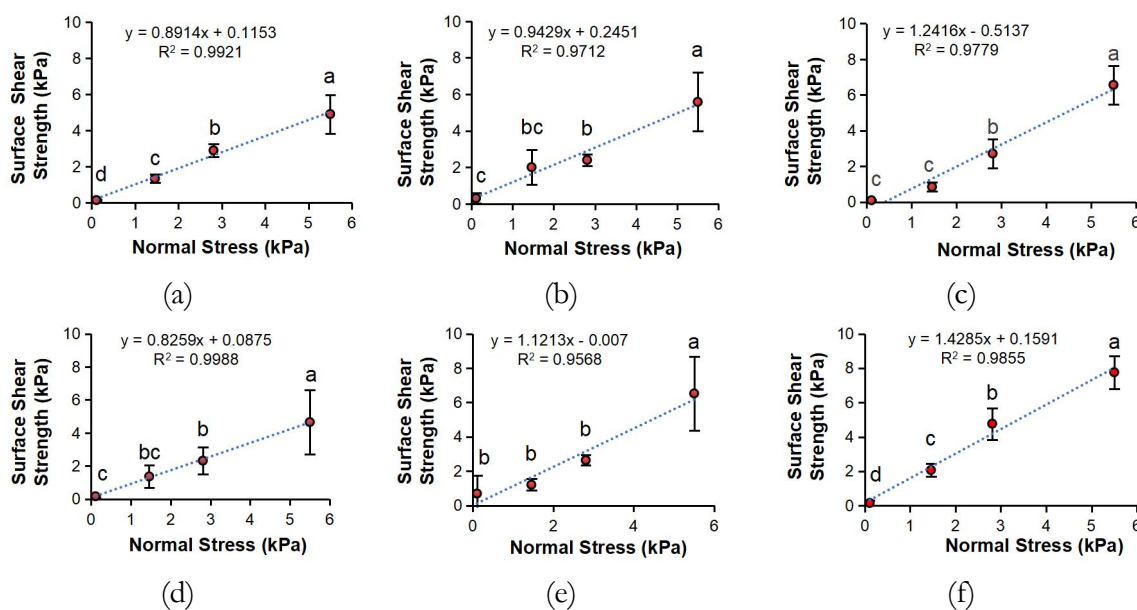


Figure 2.8. Soil surface shear strength envelopes for sandy loam in (a) low, (b) medium, and (c) high soil moisture levels and for clay in (d) low, (e) medium and (f) high soil moisture levels. Error bars are standard deviations.

Values labelled with different letters are significantly different based on Duncan's multiple-range test at a significance level of  $p < 0.05$ .

#### 2.4.1.3. Soil interface angle of friction ( $\delta$ ) and adhesion ( $C_a$ )

Table 2.3 shows the interface angle of friction ( $\delta$ ) and adhesion ( $C_a$ ) for sandy loam and clay soils under the three moisture conditions (MC): low, medium, and high. A general increase in  $\delta$  and  $C_a$  with increasing MC for both soil types is consistent with the trend reported by Wei et al. (2015). Under low MC, sandy loam recorded  $\delta$  and  $C_a$  values of  $41.7^\circ$

and 0.115 kPa, respectively, while clay showed lower values ( $\delta = 39.6^\circ$ ,  $C_a = 0.088$  kPa) due to its finer texture and reduced inter-particle friction (Amiri Khaboushan et al., 2018). The gritty texture of sandy loam particles likely contributed to its slightly higher  $\delta$  under dry conditions.

At medium MC, sandy loam exhibited a  $\delta$  of  $43.3^\circ$ , approximately  $5^\circ$  lower than clay, but its  $C_a$  was 0.238 kPa higher, indicating a greater tendency for particle bonding at this moisture level. This alternation suggested increased variability in shear parameters under intermediate moisture conditions for both soils. As MC increased to high levels,  $\delta$  and  $C_a$  continued to rise in both soil types, highlighting the strong influence of moisture on inter-particle bonding. Clay displayed a  $\delta$  value of 7.42% higher than sandy loam at high MC, reflecting its greater capacity to develop cohesive forces as water content increased (Abbaspour-Gilandeh et al., 2018).

Soil adhesion dropped at high MC for sandy loam and at medium MC for clay, likely because of natural heterogeneity in field soils and uneven pore-water distribution. This variability emphasized the need to account for spatial differences when modelling soil shear behaviour. RMSE values ranging from 0.578 to 1.219 indicated high precision in determining these parameters. These results underscored the importance of considering soil type and MC when predicting surface shear properties, as both significantly influenced  $\delta$  and  $C_a$ .

*Table 2.3. Soil surface shear properties*

| Soil Type  | Moisture Condition | Interface Friction Angle, $\delta$ ( $^\circ$ ) | Adhesion, $C_a$ (kPa) | RMSE  |
|------------|--------------------|-------------------------------------------------|-----------------------|-------|
| sandy loam | low                | 41.7                                            | 0.115                 | 0.578 |
|            | medium             | 43.3                                            | 0.245                 | 0.955 |
|            | high               | 51.2                                            | -0.513                | 0.689 |
| clay       | low                | 39.6                                            | 0.088                 | 1.117 |
|            | medium             | 48.3                                            | -0.007                | 1.219 |
|            | high               | 55.0                                            | 0.159                 | 0.695 |

### 2.4.2. Model simulation results

#### 2.4.2.1. Soil model calibration results

The calibrated effective modulus ( $E_{mod}$ ) for each soil type and moisture condition (MC) is shown in Table 2.4. For sandy loam soil at low MC, an  $E_{mod}$  of  $7.5 \times 10^6$  yielded relative errors (REs) of 6% for adhesion ( $C_a$ ) and 4.3% for interface friction angle ( $\delta$ ). At medium MC, an  $E_{mod}$  of  $6.5 \times 10^6$  resulted in RE values of 14.9% and 7.4% for  $C_a$  and  $\delta$ , respectively. At high MC, using an  $E_{mod}$  of  $5 \times 10^6$ , RE values were 18.4% for  $C_a$  and 2.1% for  $\delta$ .

Clay soil exhibited comparatively higher REs at low MC, with values of 15.8% for  $C_a$  and 5.3% for  $\delta$ . A similar trend was observed at medium MC, where the RE for  $C_a$  was 2.2% higher than that of sandy loam, whereas the RE for  $\delta$  was 2.4% lower. At high MC, REs for  $C_a$  and  $\delta$  were 15.7% and 2.2%, respectively. The corresponding  $E_{mod}$  values were  $9 \times 10^6$  for low MC,  $8.5 \times 10^6$  for medium MC, and  $7 \times 10^6$  for high MC. All the determined  $E_{mod}$ s values demonstrated reasonably good accuracy and fell within acceptable simulation ranges (Acquah and Chen, 2023; Wu et al., 2025).

Table 2.4. Calibrated values of ( $E_{mod}$ s) and the relative errors (RE) for each soil type and moisture condition

| Soil Type  | Moisture Level | $E_{mod}$ s | Adhesion, $C_a$ (kPa) |           | RE (%) | Friction Angle, $\delta$ (°) |           | RE (%) |
|------------|----------------|-------------|-----------------------|-----------|--------|------------------------------|-----------|--------|
|            |                |             | Measured              | Simulated |        | Measured                     | Simulated |        |
| Sandy loam | low            | 7.5e6       | 0.115                 | 0.108     | 6.0    | 41.7                         | 43.7      | 4.3    |
|            | medium         | 6.5e6       | 0.245                 | 0.281     | 14.9   | 43.3                         | 40.1      | 7.4    |
|            | high           | 5.0e6       | -0.513                | -0.418    | 18.4   | 51.2                         | 50.1      | 2.1    |
| clay       | low            | 9.0e6       | 0.088                 | 0.102     | 15.8   | 39.6                         | 41.7      | 5.3    |
|            | medium         | 8.0e6       | -0.007                | -0.008    | 17.1   | 48.3                         | 50.7      | 5.0    |
|            | high           | 7.0e6       | 0.159                 | 0.184     | 15.7   | 55.0                         | 53.8      | 2.2    |

#### 2.4.2.2. Soil erodibility assessment

Simulated soil particle displacements are shown in Figure 2.9. Comparing the sandpaper grades, the coarser textures with larger abrasive particles produced greater soil particle

displacements in all directions. This occurred because larger grains provided a wider interaction area and imparted higher shearing forces. As the sandpaper grade increased (finer grains), the magnitude of displacement became relatively uniform, likely due to the reduced contact area and lower transfer of shear energy.

Between the two soils tested, sandy loam exhibited consistently greater displacement in all directions than clay soil. This trend can be attributed to the relatively higher adhesion forces in sandy loam compared to clay (Table 2.2). These findings align with Shahabinejad et al. (2019), who reported that soils dominated by larger sand particles are more susceptible to detachment and subsequent wind erosion. For sandy loam (Figures 2.9a–c), soil particles at low MC displayed further than those at medium or high MC. Across all conditions, horizontal displacement (x-direction) was dominant, followed by lateral displacement (y-direction), while vertical movement (z-direction) remained comparatively lower. At lower sandpaper grades (coarser surface), lateral displacements were higher, but vertical displacement showed minimal variation across the sandpaper grades. At the medium and high MC, vertical displacement increased relative to lateral movement, likely due to higher soil sinkage as water content increased (Figure 2.9c). For clay soil (Figures 2.9d–f), soil particle displacement was also highest at low MC. However, unlike the sandy loam, the displacement magnitude decreased progressively with increasing sandpaper grade. As with sandy loam, horizontal displacement dominated over lateral and vertical movements. At low MC, the normal stress had little effect on dry clay particles, leading to reduced z-direction displacement. As MC increased, clay became more susceptible to the normal stress, reducing horizontal displacement while slightly increasing vertical sinkage.

The results confirm that increasing MC reduces the susceptibility of both sandy loam and clay soils to wind erosion. The observed reduction in particle displacement with increasing

MC reflects field-scale dynamics where soil moisture and clay content enhance aggregate stability, and raises the threshold shear velocity required for wind erosion (Nourzadeh et al., 2013). Maintaining optimal soil moisture in the Canadian Prairies can serve as a natural mitigation strategy against surface erosion and soil loss. Soil susceptibility to surface erosion depends on both moisture condition and wind intensity. Using sandpaper of varying grades to simulate wind forces proved effective for replicating shear stresses. Coarser grades displaced more particles, reflecting stronger winds, while higher moisture reduced displacement, confirming that increasing soil MC enhances aggregate stability and raises the threshold shear velocity required for particle detachment.

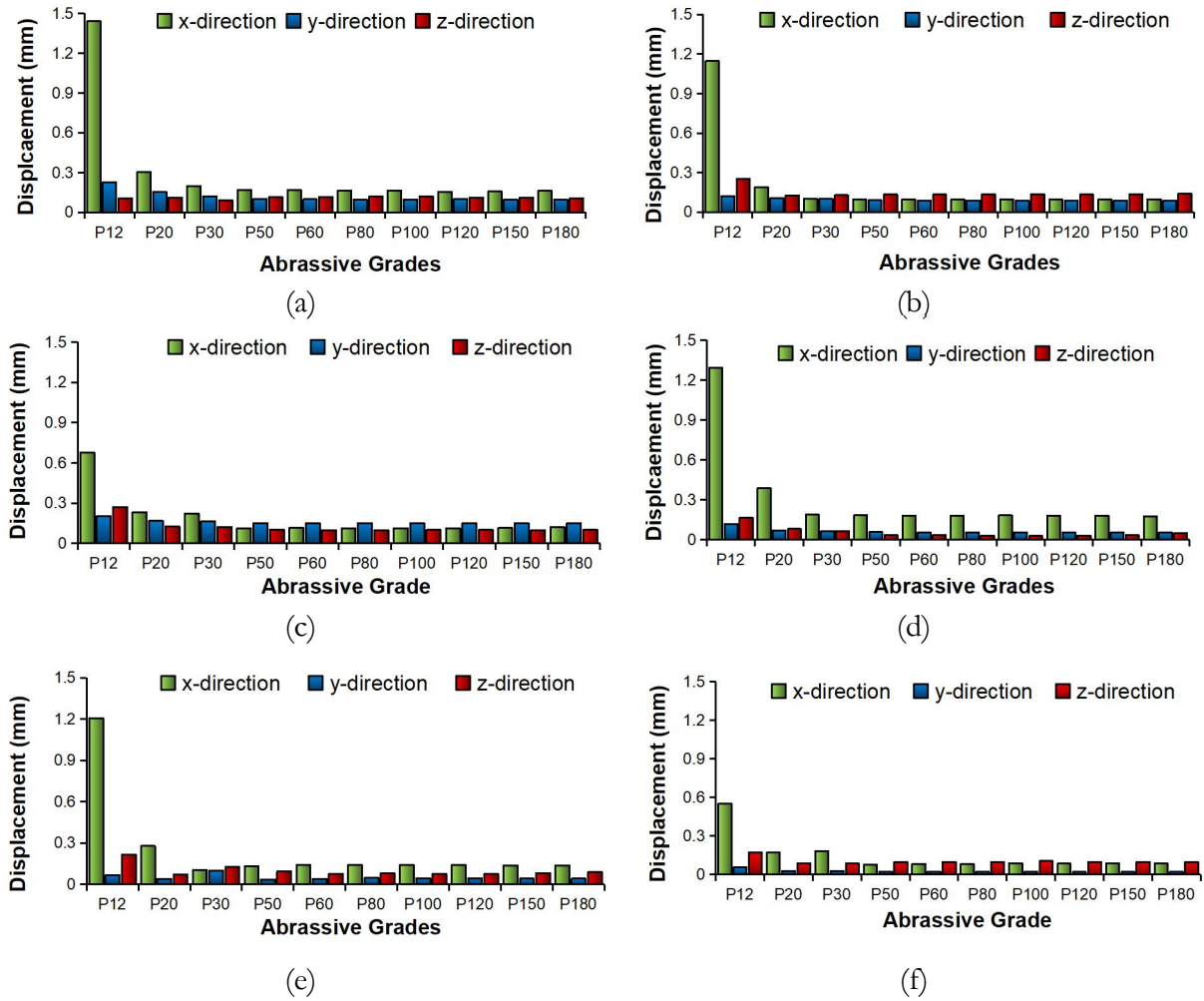


Figure 2.9. Simulated soil particle displacements for different sandpaper grades during surface shearing for sandy loam in (a) low (b) medium and (c) high moisture levels and for clay in (d) low (e) medium and (f) high soil moisture levels.

## 2.5. Conclusion

This study investigated the surface shear behaviour of sandy loam and clay soils under varying normal loads and moisture contents, combining laboratory testing with DEM modelling to assess erosion susceptibility. Results revealed that shear strength increased with applied load and moisture, with clay soils exhibiting higher adhesion-driven resistance, whereas sandy loam relied more on frictional resistance. Adhesion and interface friction angle both increased with moisture content, confirming the stabilizing role of soil water in aggregate bonding. The DEM model successfully captured the shear response, with effective

modulus calibration yielding close agreement between simulated and measured values. The particle displacement simulations highlighted that sandy loam soils were more prone to detachment than clay, particularly under low moisture conditions. Horizontal displacement dominated erosion dynamics for sandy soil, but clay exhibited higher vertical displacements at increased moisture, suggesting a shift toward sinkage rather than lateral detachment. These findings reinforce the importance of soil moisture as a key determinant of erosion resistance. Increasing moisture raised the threshold shear velocity, stabilized aggregates, and minimized soil particle displacement. However, there is a geographical limitation to this work, as the findings are limited to soils in southern Manitoba. Site-specific strategies should consider soil texture, as sandy loam soils require greater protection under dry conditions. DEM surface shear modelling can be employed as a predictive tool to support erosion risk assessment.

While this study provides valuable insights into surface shear behaviour and erosion susceptibility, understanding soil internal shear properties remains essential for a more complete characterisation of soil mechanical response under compaction and loading. Internal shear governs subsurface structural integrity, influencing stress transmission, root penetration, and moisture retention, factors that surface measurements alone cannot fully quantify. Further investigation into internal shear strength and deformation mechanisms would enable more accurate prediction of subsurface failure, enhance the calibration of DEM models for three-dimensional soil behaviour, and support the development of comprehensive soil stability and erosion control frameworks across different soil types and loading conditions. Therefore, Chapter three of this study estimates the shear behaviour of the soils under normal and shear loading.

## 2.6. References

Abbaspour-Gilandeh, Y., Hasankhani-Ghavam, F., Shahgoli, G., Shrabian, V. R., and

- Abbaspour-Gilandeh, M. (2018). Investigation of the Effect of Soil Moisture Content, Contact Surface Material and Soil Texture on Soil Friction and Soil Adhesion Coefficients. *Acta Technologica Agriculturae*, 21(2), 44–50. <https://doi.org/10.2478/ata-2018-0009>
- Acquah, K., and Chen, Y. (2023). Discrete element modelling of soil pressure under varying number of tire passes. *Journal of Terramechanics*, 107, 23–33. <https://doi.org/10.1016/j.jterra.2023.02.003>
- Adajar, J. B., Alfaro, M., Chen, Y., and Zeng, Z. (2021). Calibration of discrete element parameters of crop residues and their interfaces with soil. *Computers and Electronics in Agriculture*, 188(July), 106349. <https://doi.org/10.1016/j.compag.2021.106349>
- Akbarzadeh, A., Ghorbani-Dashtaki, S., Naderi-Khorasgani, M., Kerry, R., and Taghizadeh-Mehrjardi, R. (2016). Monitoring and assessment of soil erosion at micro-scale and macro-scale in forests affected by fire damage in northern Iran. *Environmental Monitoring and Assessment*, 188(12). <https://doi.org/10.1007/s10661-016-5712-6>
- American Society for Testing and Materials ASTM D 422-63. (2007). Standard test method for particle\_size analysis of soils. In *Annual Book of ASTM Standards*, 1–8. <https://www.astm.org/standards/d422>
- American Society for Testing and Materials D2216-10. (1999). Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass. *ASTM International*, West Conshohocken, PA: ASTM, 1–5. <https://doi.org/10.1109/WiCom.2008.1574>
- Amiri Khaboushan, E., Emami, H., Mosaddeghi, M. R., and Astarai, A. R. (2018). Estimation of unsaturated shear strength parameters using easily-available soil properties. *Soil and Tillage Research*, 184(July), 118–127.

<https://doi.org/10.1016/j.still.2018.07.006>

Brunori, F., Penzo, M. C., and Torri, D. (1989). *Soil Shear Strength: Its Measurement and Soil Detachability*. 16, 59–71.

Guo, T., Srivastava, A., and Flanagan, D. C. (2021). Improving and calibrating channel erosion simulation in the Water Erosion Prediction Project (WEPP) model. *Journal of Environmental Management*, 291(April), 112616. <https://doi.org/10.1016/j.jenvman.2021.112616>

Havaee, S., Mosaddeghi, M. R., and Ayoubi, S. (2015). In situ surface shear strength as affected by soil characteristics and land use in calcareous soils of central Iran. *Geoderma*, 237, 137–148. <https://doi.org/10.1016/j.geoderma.2014.08.016>

Holz, D. J., Williard, K. W. J., Edwards, P. J., and Schoonover, J. E. (2015). Soil Erosion in Humid Regions: A Review. *Journal of Contemporary Water Research and Education*, 154(1), 48–59. <https://doi.org/10.1111/j.1936-704x.2015.03187.x>

Huang, X., Horn, R., and Ren, T. (2022). Geoderma Soil structure effects on deformation , pore water pressure , and consequences for air permeability during compaction and subsequent shearing. *Geoderma*, 406(January 2021), 115452. <https://doi.org/10.1016/j.geoderma.2021.115452>

Jia, Y., Zhang, J., Chen, X., Miao, C., and Zheng, Y. (2023). DEM study on shear behavior of geogrid-soil interfaces subjected to shear in different directions. *Computers and Geotechnics*, 156(December 2022). <https://doi.org/10.1016/j.compgeo.2023.105302>

Ju, Y., Liu, P., Chen, J., Yang, Y., and Ranjith, P. G. (2016). CDEM-based analysis of the 3D initiation and propagation of hydrofracturing cracks in heterogeneous glutenites. *Journal of Natural Gas Science and Engineering*, 35, 614–623. <https://doi.org/10.1016/j.jngse.2016.09.011>

Li, M., Li, Y., and Islam, R. (2021). Effects of water content and interface roughness on the

- shear strength of silt – cement mortar interface. *Soils and Foundations*, 61(6), 1615–1629. <https://doi.org/10.1016/j.sandf.2021.08.011>
- Liu, X., Zhou, A., Shen, S. L., Li, J., and Arulrajah, A. (2021). Modelling unsaturated soil-structure interfacial behavior by using DEM. *Computers and Geotechnics*, 137(June). <https://doi.org/10.1016/j.compgeo.2021.104305>
- Moore, D. C., and Singer, M. J. (1990). Crust Formation Effects on Soil Erosion Processes. *Soil Science Society of America Journal*, 54(4), 1117–1123. <https://doi.org/doi.org/10.2136/sssaj1990.03615995005400040033x>
- Nakagawa, A. C. S., Iseki, K., and Ikazaki, K. (2024). Development of a simple evaluation method of soybean seedling emergence against soil crust. *Plant Production Science*, 27(4), 265–271. <https://doi.org/10.1080/1343943X.2024.2392296>
- Nandanwar, M., and Chen, Y. (2017). Modeling and measurements of triaxial tests for a sandy loam soil. *Canadian Biosystems Engineering / Le Genie Des Biosystems Au Canada*, 59, 1–8. <https://doi.org/10.7451/CBE.2017.59.2.1>
- Nourzadeh, M., Bahrami, H. A., Goossens, D., and Fryrear, D. W. (2013). Determining soil erosion and threshold friction velocity at different soil moisture conditions using a portable wind tunnel. *Zeitschrift Für Geomorphologie*, 57(1), 97–109. <https://doi.org/10.1127/0372-8854/2012/0089>
- Owusu-Sekyere, E., and Chen, Y. (2024). The Effect of Varying Compaction Levels on Soil Dynamic Properties and the Growth of Canola (*Brassica napus* L.). *Agriculture (Switzerland)*, 14(11). <https://doi.org/10.3390/agriculture14111976>
- Potyondy, D. O., and Cundall, P. A. (2004). A bonded-particle model for rock. *International Journal of Rock Mechanics and Mining Sciences*, 41(8 SPEC.ISS.), 1329–1364. <https://doi.org/10.1016/j.ijrmms.2004.09.011>
- Rauws, G., and Govers, G. (1988). Hydraulic and soil mechanical aspects of rill generation on

- agricultural soils. *Journal of Soil Science*, 39(1), 111–124.  
<https://doi.org/doi.org/10.1111/j.1365-2389.1988.tb01199.x>
- Sadek, M. A., and Chen, Y. (2015). Feasibility of using PFC3D to simulate soil flow resulting from a simple soil-engaging tool. *Transactions of the ASABE*, 58(4), 987–996.  
<https://doi.org/10.13031/trans.58.10900>
- Salazar, A., Sáez, E., and Pardo, G. (2015). Modeling the direct shear test of a coarse sand using the 3D Discrete Element Method with a rolling friction model. *Computers and Geotechnics*, 67, 83–93. <https://doi.org/10.1016/j.compgeo.2015.02.017>
- Shahabinejad, N., Mahmoodabadi, M., Jalalian, A., and Chavoshi, E. (2019). The fractionation of soil aggregates associated with primary particles influencing wind erosion rates in arid to semiarid environments. *Geoderma*, 356(August), 113936.  
<https://doi.org/10.1016/j.geoderma.2019.113936>
- Stanchi, S., Freppaz, M., Godone, D., and Zanini, E. (2013). Assessing the susceptibility of alpine soils to erosion using soil physical and site indicators. *Soil Use and Management*, 29(4), 586–596. <https://doi.org/10.1111/sum.12063>
- Wei, Y., Wu, X., and Cai, C. (2015). Splash erosion of clay-sand mixtures and its relationship with soil physical properties: The effects of particle size distribution on soil structure. *Catena*, 135, 254–262. <https://doi.org/10.1016/j.catena.2015.08.003>
- Wójciga, A., Bolte, K., Horn, R., Stepniewski, W., and Bajuk, E. (2009). Surface shear resistance of soils on the micro- To mesoscale. *International Agrophysics*, 23(4), 391–398.  
<https://agro.icm.edu.pl/agro/element/bwmeta1.element.agro-article-f2b4215c-fb73-4164-9b2f-cb328eb698cf>
- Wu, P., Zhang, X., Zeng, Z., and Chen, Y. (2025). DEM simulation of subsoiling for soil disturbance as affected by soil layering and working speed. *Smart Agricultural*

- Technology*, 7(100385). <https://doi.org/doi.org/10.1016/j.atech.2023.100385>
- Yin, K., Fauchille, A.-L., Di Filippo, E., Kotronis, P., and Sciarra, G. (2021). A Review of Sand–Clay Mixture and Soil–Structure Interface Direct Shear Test. *Geotechnics*, 1(2), 260–306. <https://doi.org/10.3390/geotechnics1020014>
- You, S., Lee, K., and Hong, G. (2024). Influence of Fines Content and Pile Surface Characteristics on the Pullout Resistance Performance of Piles. *Materials*, 17(1). <https://doi.org/10.3390/ma17010124>
- Zarrinabadi, E. (2023). *Soil erosion and fluxes of sediment within landscapes of the Canadian Prairies* [University of Manitoba]. <https://mspace.lib.umanitoba.ca/server/api/core/bitstreams/265f8a8e-130d-4866-8933-2a1bda211073/content>
- Zarrinabadi, E., Lobb, D. A., Li, S., Koiter, A. J., and Badiou, P. (2023). Agricultural activities lead to sediment infilling of wetlandscapes in the Canadian Prairies: Assessment of contributions by tillage, water and wind erosion. *Geoderma*, 438(July), 116621. <https://doi.org/10.1016/j.geoderma.2023.116621>
- Zhang, B., Zhao, Q. G., Horn, R., and Baumgartl, T. (2001). Shear strength of surface soil as affected by soil bulk density and soil water content. *Soil and Tillage Research*, 59(3–4), 97–106. [https://doi.org/10.1016/S0167-1987\(01\)00163-5](https://doi.org/10.1016/S0167-1987(01)00163-5)
- Zimbone, S. M., Vickers, A., Morgan, R. P. C., and Vella, P. (1996). Field investigations of different techniques for measuring surface soil shear strength. *Soil Technology*, 9(1–2), 101–111. [https://doi.org/10.1016/0933-3630\(96\)00002-5](https://doi.org/10.1016/0933-3630(96)00002-5)

## Chapter 3

---

### Measurements and DEM modelling of soil shear behaviour under varying normal stresses for different soils\*

*\*Submitted to Granular Mater (Springer Nature) (under review)*

#### 3.1. Abstract

Understanding soil shear behaviour improves insights into how soil responds to shear forces caused by machinery, tillage, and seeding, as well as natural processes. This study investigated the compression and shear properties of sandy loam (SL), sandy clay loam (SCL), clay loam (CL), and clay (C) soils. Soil samples were tested under normal stresses ranging from 0 to 200 kPa using a compression and shear test apparatus (Royal Eijkelkamp®), measuring bulk density, shear stress, soil cohesion, internal friction angles, and soil water matrix. A discrete element model (DEM) was developed to simulate the shearing behaviour of these soils under the same normal stresses. Experimental results showed that SL soil exhibited the highest bulk density change from compression, while C soil had the highest shear strength. Internal friction angle was lowest for CL soil (39.42°) and highest for C soil (49.19°). Soil cohesion followed the order: CL > SCL > SL > C. DEM simulations revealed that increasing normal stress enhanced particle packing and shear resistance, while higher bulk densities reduced soil erosion susceptibility. The relative errors between measured and simulated shear strength values ranged from 1.10% to 12.71%. These findings enhance the understanding of shear behaviour of different soil types.

**Key words:** soil type; compression; shear stress; cohesion; internal friction angle; DEM model.

### 3.2. Introduction

The process of soil shearing plays a key role in various agricultural field operations including tillage, seeding, and wheel-soil interactions caused by machine traffic. Understanding soil shear behaviour is critical for improving soil structure and designing more efficient agricultural machinery. This knowledge is crucial for optimizing tillage practices, minimizing soil compaction (Gregory et al., 2010; Shaheb et al., 2021), managing soil water (Keesstra et al., 2012), and enhancing crop root penetration (Zhang et al., 2007). Soil compression affects crucial soil properties including bulk density (Lepore et al., 2024), ultimately impeding agricultural productivity by reducing crop yields. The influence of this becomes more pronounced when tilling the soil under high moisture conditions (Hamza and Anderson, 2005). Therefore, understanding the far-reaching effects of soil behaviour on key agricultural properties essential for crop production across different soil conditions is imperative for sustainable agriculture.

Not only does soil compression affect soil structural properties, but also influences the energy potential of soils in absorbing moisture for crop development (Zhang et al., 2024). The energy bound between agricultural soil and water comprises of potential and kinetic energies (Or et al., 2002). The matric potential of soils exerts the greatest influence among the equilibrium forces affecting the potential energy of soil-water bonds (Hanks, 2012; Or et al., 2002). Therefore, in soil response to compression and shearing, analyzing compression and shearing effect on soil-water matrix is of great significance, as it affects the hydraulic properties of soils in crop development (Romero-Ruiz et al., 2021). Soil shear strength represents soil's inherent property that influences its ability to resist detachment under erosive forces (J. Liu et al., 2024). Thus, soil shear strength and soil erodibility are closely related. Existing research on soil erodibility focused on using models like the Universal Soil Loss

Equation (USLE) to predict soil erosion. These studies mostly utilized wind tunnels (applying wind to soil) to measure the soil particle detachment and transport rates, or indirectly measuring soil erodibility, such as aggregate stability, infiltration rate, and dispersion ratio (Adesina et al., 2024; Benavidez et al., 2018; Bonakdari et al., 2024). However, few studies have explored the use of soil shear strength as a means to evaluate soil erodibility.

Various researchers have conducted experimental studies on the strength properties of agricultural soils. Schjønning, (2024) interpreted uniaxial confined compression test data from selected Danish soils and concluded on a hyperbolic elastic and plastic deformation from the stress-strain relationship. Also, Toledo et al. (2021) evaluated unsaturated soils from sugarcane fields in Brazil and revealed lower compressibility and elasticity, as well as higher shear strength, with increasing compactness. Furthermore, Huang et al. (2023) studied unsaturated soils and found that compaction and shearing increased the chi factor and the soil effective stress. The aforementioned research studies focused on the structural properties of the soils at specific matric potentials, overlooking the impact of compression on soil water matrix.

DEM modelling has also been conducted to investigate the shearing characteristics of varied soils. For example, Xiaofeng et al. (2013) examined the effect of coarse gravel content on soil direct shearing behaviour using DEM simulations. Their findings revealed that under the same vertical stress conditions, increase in coarse gravel content enhanced soil shearing stress due to higher particle stiffness and friction coefficients. Gu et al. (2014) studied the macro structure of granular soils during shearing using DEM. They concluded that the contact force at the critical shearing state was influenced by the mean normal effective stress, while the evolution path of shear stress depended on the bulk density and compression stress. A decrease in roundness of coarse particles increased both the peak and critical friction angle

when Zhu et al. (2021) used DEM to study the shear behaviour of cohesionless and mixed-sized soil particles. While DEM simulations have greatly enhanced the understanding of soil shearing characteristics, the combined influence of varying compression stresses and shearing on different soil types with DEM remains largely unexplored.

Therefore, the objectives of this study were to (1) investigate the compression and shear properties of different soils, (2) develop, calibrate, and validate a DEM model to simulate the soils' compression and shearing behaviour, and (3) use the DEM model to simulate the erodibility of the soils at varying bulk densities.

### **3.3. Materials and methods**

#### *3.3.1. Laboratory experiments*

Two experiments were conducted: soil compression and soil shear experiments to examine soil properties of different soils. In the soil compression experiment, the effect of normal stress on soil bulk density was examined, and in the soil shear experiment, the effects of normal stress on soil shear behaviour were investigated. These two experiments are described below.

##### **3.3.1.1. Soil background information, sampling, and initial condition**

The study utilized four soil types: sandy loam (SL), sandy clay loam (SCL), clay loam (CL), and clay soils (C) from Manitoba, Canada. The SCL and CL soils were sampled from the Ian N. Morrison research station in Carman. The C and SL soils were obtained from The Point, a research station at the University of Manitoba in Winnipeg, and Piney respectively, the same locations as used in the soil surface shear test. Table 3.1 shows their particle size distribution (ASTM, 2007). The target soil moisture contents were adjusted to near field

capacities (Karmeli and Keller, 1975; Mohammad and Ismail, 2006; Saxton et al., 1986) by either drying the soil or spraying it with water. The final soil moisture contents, measured using the oven-drying method (ASTM, 2019), were 17.56% for SL, 22.89% for SCL, 24.23% for CL and 22.01% for C.

*Table 3.1. Composition of the selected soils: sandy loam (SL), sandy clay loam (SCL), clay loam (CL), and clay (C).*

| Soil type | % gravel<br>(< 4.5 mm) | % sand<br>(0.075 - 4.5 mm) | % silt<br>(0.005 - 0.075 mm) | % clay<br>(< 0.005 mm) |
|-----------|------------------------|----------------------------|------------------------------|------------------------|
| SL        | 0                      | 69.8                       | 17.2                         | 13.0                   |
| SCL       | 0                      | 53.9                       | 23.2                         | 22.9                   |
| CL        | 0                      | 37.3                       | 30.5                         | 32.2                   |
| C         | 0.6                    | 2.5                        | 34.9                         | 62.0                   |

### 3.3.1.2. Description of the test equipment

The Royal Eijkelkamp® shear and compression test apparatus (08.68, Nijverheidsstraat, Netherlands) shown in Figure 3.1 was used in the experiment. The apparatus was designed to assess soil susceptibility to confined vertical compression and horizontal shearing for drained and undrained soils. It can apply normal stresses from 0 to 600 kPa, and horizontal stress from 0 to 400 kPa. The actuator of the load cell, with capacity 500 kg, operates under air pressure of 0.7 MPa, a force of 5 kN, and a maximum speed of 2 mm/min. An air compressor facilitates the movement of the actuator. The movement of the load cell and the vertical compression sensor is computer controlled, utilizing multifunctional software (Eijkelkamp Physical Soil Test, version 2.1.1) to execute accurate stress applications and display correct output data. The sample chamber has a cylindrical geometry measuring 100 mm in diameter and 30 mm in height. The instruments for soil property measurements include the load cell for soil shear strength measurement (kPa), a tensiometer to register soil water matrix (hPa), and a vertical stress sensor for measuring normal compression stress (kPa).

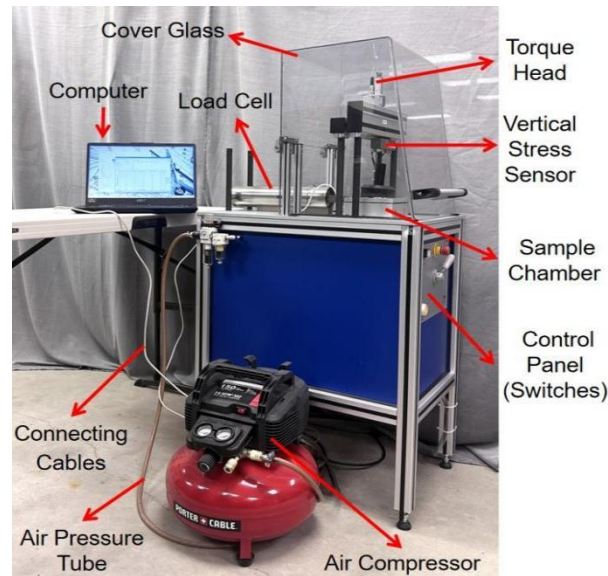


Figure 3.1. The Royal Eijkkelkamp<sup>®</sup> compression and shear test apparatus.

### 3.3.1.3. Soil sample preparation

The soil sample preparation process involved inverting the sample, covering the turned blunt side with the centering tool, and placing the gouge auger at the center of the centering tool (Figure 3.2a). The extruder was gently pushed into the soil sample to create the tensiometer hole. The centering tool, gouge auger, and the extruder were gently removed from the soil core. The soil core was carefully turned upside down and gently mounted in the sample chamber, aligning the tensiometer with the extruded hole. The soil core was pushed into the sample chamber with the rod and sample transfer stamp.

### 3.3.1.4. Soil compression experiment

In the soil compression experiment, five normal stress levels (0, 50, 100, 150, and 200 kPa) were applied in a completely randomized design for each of the four soil types, without shearing the soil. This experiment involved 100 tests (4 soil types  $\times$  5 normal stress  $\times$  5 replicates). Soil bulk density was measured through measuring the axial strain (change in height of the soil sample before and after compression). The original height ( $h$ ) of the soil

sample chamber was recorded (Figure 3.2b). Soil sample mounted in the sample chamber was compressed for five minutes after ascertaining compression time had no influence on the compression process in a preliminary study. The selected normal stress was applied to the sample, without activating the shearing action of the apparatus (Figure 3.2c). Then, the change in height ( $\Delta h$ ) of the soil sample was measured at four locations of the soil surface (Figure 3.2d). The average was used to calculate the final soil bulk density after compression with the final height ( $h - \Delta h$ ), the known soil sample diameter, and the mass of the soil.

#### 3.3.1.5. Soil shear experiment

This experiment also employed a completely randomized design with five replicates. The same five levels of normal stress as in the compression experiment were used. However, soil samples were sheared during this test. In total, 100 tests (4 soil types  $\times$  5 normal stress  $\times$  5 replicates) were performed in the experiment. After the normal stress was applied, the soil sample was sheared by engaging the actuator of the test apparatus to move at a forward speed of 1 mm/min for 40 minutes at a data logging rate of five seconds. After the test run, the actuator was retracted at a speed of 2 mm/min, revealing the sheared soil sample with the maximum horizontal displacement (Figure 3.2e). During the test, soil shear stress-horizontal displacement curve was recorded. The strain of the soil sample in the vertical direction and the soil-water matrix were also registered. From the curve, the soil shear strength was obtained. The angle of internal friction ( $\varphi$ ) and the soil cohesion forces ( $c$ ) were deduced from the normal stresses used in the tests and the soil shear strengths obtained.

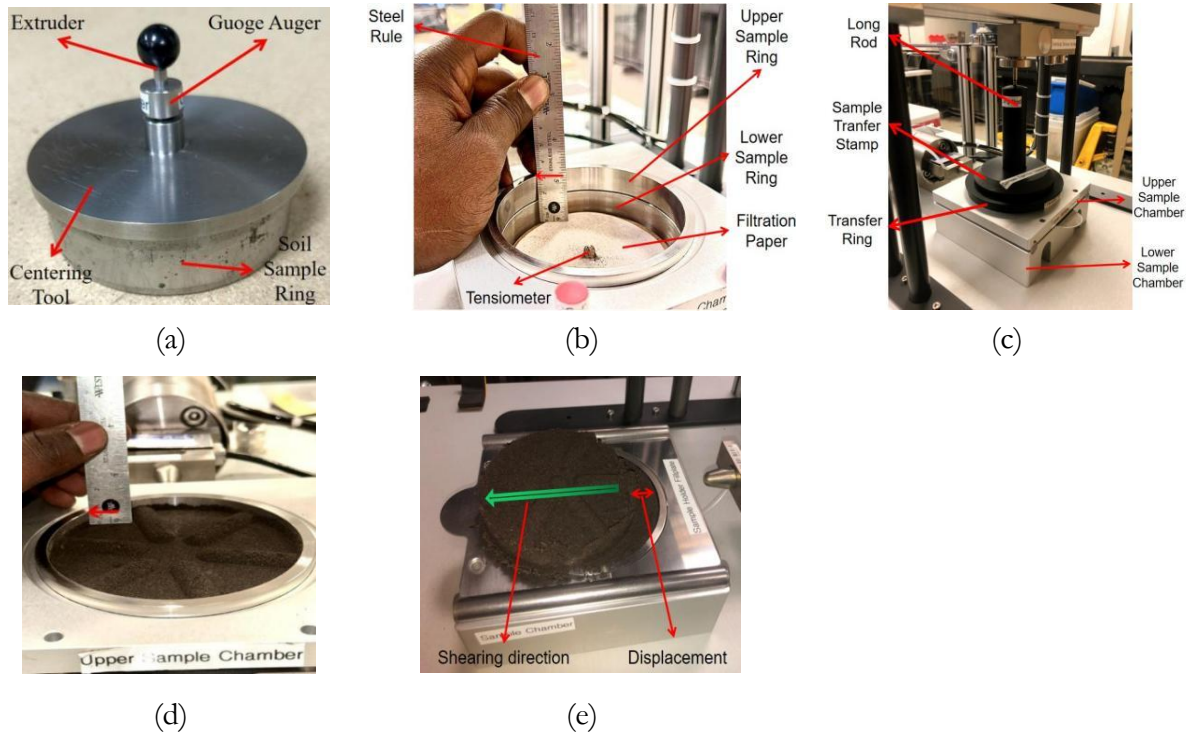


Figure 3.2. Soil compression and shear test process: (a) Sample preparation for measurement; (b) Height measurement of sample chamber; (c) Set up showing mounted soil sample; (d) Compressed soil sample showing the height change (axial strain); (e) Relative position of the top and bottom containers of the sample chamber at the completion of shear test.

### 3.3.2. Simulation of soil shearing

#### 3.3.2.1. Model development

The soil shearing model (Figure 3.3a) was developed in Particle Flow Code in Three Dimensions (PFC<sup>3D</sup>, version 6.0, Itasca Consulting Group Inc., Minneapolis, USA), DEM software. The model simulated the soil shear test described above in a scale ratio of 1:1. The model sample chamber consisted of two cylinders: an open-top cylinder served as the bottom container, and an open-end cylinder served as the top container. Both cylinders measured 100 mm in diameter and 15 mm in height. Spherical soil particles (varied from 1 to 2 mm in diameter) were generated in the model sample chamber. Parallel bond model (PBM) were

added between model soil particles (Potyondy and Cundall, 2004) to simulate the cohesive behaviour of agricultural soils.

Before shearing the soil, the soil particles were allowed to settle in the sample chamber under gravity until they were stable (reflected by their maximum unbalanced force being less than  $1 \times 10^{-3}$  N). The particle density of the model soil was adjusted until the bulk density of the model soil matched the soil bulk density observed in the laboratory experiment for the corresponding normal stress and soil type. The bulk density of the model soil was calculated using the relationship given in Equation 2.1.

For shearing the model soil, the top container was moved in the horizontal direction. It would be ideal if the shearing speed in the model was the same as that in the experiment. However, using the same speed, the computing time would be unpractical. Preliminary test runs of the model were performed to examine how shearing speed affected the model output and computing time. Results indicated no significant effect of the selected speeds (25, 50, 75, and  $100 \text{ mm s}^{-1}$ ) on the model outputs. Therefore,  $100 \text{ mm s}^{-1}$  was used for simulation to obtain a practical computing time.

During shearing, the contact force between the soils in the top and bottom containers in the horizontal direction was monitored as the shearing force of the model soil. The shear stress was recorded until the horizontal displacement matched the average maximum horizontal displacement observed in the laboratory test for the specific soil type and normal stress (Figure 3.3b). The soil strength was taken as the value at the maximum horizontal displacement.

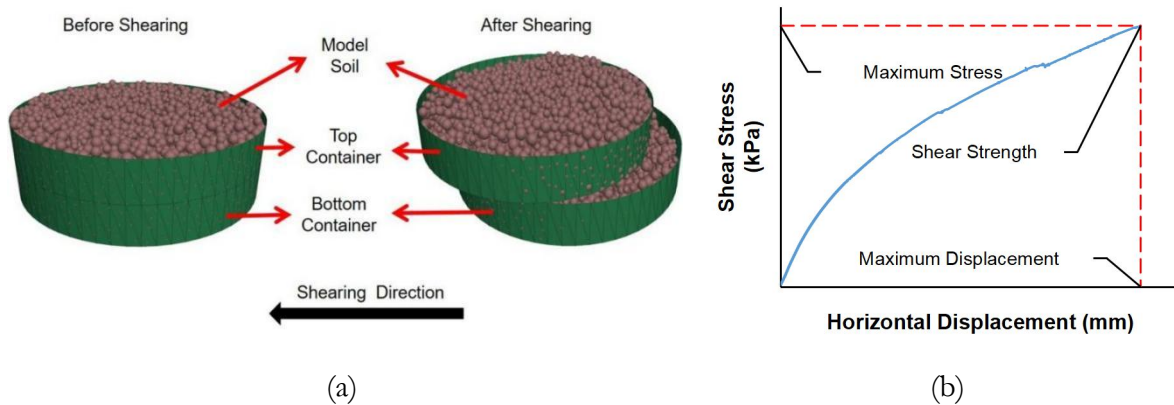


Figure 3.3. Soil shear model: (a) Soil particles and sample chamber before and after shearing; (b) A typical model result of shear stress versus horizontal displacement.

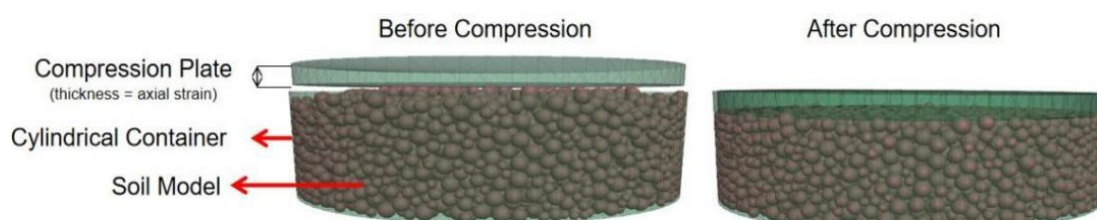
### 3.3.2.2. Model parameters and calibration

Preliminary analysis was performed on the sensitivity of the soil shear force to the model parameters for the parallel bond contact model. The results showed that the effective modulus ( $E_{mod}$ ) of the soil particles had the greatest influence on the soil shear force. Therefore,  $E_{mod}$  was calibrated, while the other model parameters were taken from existing literature (Table 2.1).

The model parameter  $E_{mod}$  was calibrated using the results from the compression experiment mentioned above. The compression test was simulated using a virtual test. A cylindrical container measuring  $30 \times 100$  mm in height and diameter respectively was filled with soil particles (Figure 3.4). The model soil particles had the same parameters listed in Table 2.1 and assumed values of  $E_{mods}$ . A compression plate measuring 100 mm in diameter was created atop the container to compress the soil to the same axial strain observed in the compression experiment. In the experiment, the axial strain varied with the normal stresses. For an easy control of the axial strain in the model, the thickness of the compression plate was varied to match the experimental axial strain for each normal stress. Thus, in the virtual test,

soil was compressed until the top surface of the compression plate aligned with the upper edge of the cylindrical container.

For each soil type, the virtual compression test was performed for each of the four normal stresses (50, 100, 150, and 200 kPa). During the virtual test, the vertical soil resistance to the plate was recorded, and the  $E_{mods}$  were adjusted until their average vertical resistance force matched the applied normal force (N) in the laboratory experiment. The agreement between the simulated and the experimental values was evaluated using the relative error method.



*Figure 3.4. Virtual soil compression test for model calibration showing the initial and final position of the compression plate.*

### 3.3.2.3. Model validation

The calibrated model was validated using the data from the soil shear experiment for all the soils at the different normal stresses. The shear stress of the model soil was calculated from the contact force at the shearing surface between the soils in the top and bottom containers in the horizontal direction. The simulations were stopped when the horizontal displacement matched the horizontal displacement at which the maximum shear force was recorded in the shear experiment. The simulated shear strengths were compared with the measured averages to assess the model's accuracy, evaluated using their relative errors.

### 3.3.2.4. Simulations of soil erosion resistance indicator

Simulations were performed using the validated model to examine the effect of bulk density (ranging from 500 to 2000 kg m<sup>-3</sup> in intervals of 150 kg m<sup>-3</sup>) on the erodibility for all the soils. These bulk densities were achieved by adjusting the particle density of the model soil using Equation 2.1. In the simulations, soil shearing was performed without the application of normal stress, as agricultural fields are typically not subjected to normal forces from overlying materials. The simulated soil shear strengths were defined as soil erosion resistance indicators that could be used to assess how soil resists wind erosion.

### 3.3.3. Data analysis

A General Linear Model (GLM) and Analysis of Variance (ANOVA) were performed utilizing the ‘car’ package in the R statistical software (R-Studio), to assess the effect of the normal stress on the soil properties. The significant differences between the normal stresses for each measured parameter were evaluated using Tukey's HSD in the same software. For the model simulation, significant differences between the shearing speeds were determined using Tukey's HSD test in the same software.

## 3.4. Results and discussion

### 3.4.1 Experimental results

#### 3.4.1.1. The effect of normal stress on soil axial strain and bulk density.

The vertical deformation (axial strain) of the soils under compression showed a linear trend (Figure 3.5a, b, c, and d). For sandy loam, the highest deformation change (12.08%) occurring between 0 and 50 kPa. As the normal stress increased, deformation changes reduced

to 6.57% from 50 to 100 kPa, 3.23% from 100 to 150 kPa, and 2.18% from 150 to 200 kPa. Sandy clay loam exhibited a similar trend, with an initial deformation of 21.67% from 0 to 50 kPa. Changes decreased to 9.68% between 50 and 100 kPa but increased slightly at higher stresses due to soil non-homogeneity. Clay loam followed the same pattern, with the largest deformation of 19% observed between 0 and 50 kPa. Clay soil showed the least change in deformation, with an initial change of 10.31% from 0 to 50 kPa, attributed to its small particle sizes (Tang et al., 2018). Clay's minimal deformation reflects their particle size distribution and low pore space, leading to greater resistance to axial deformation.

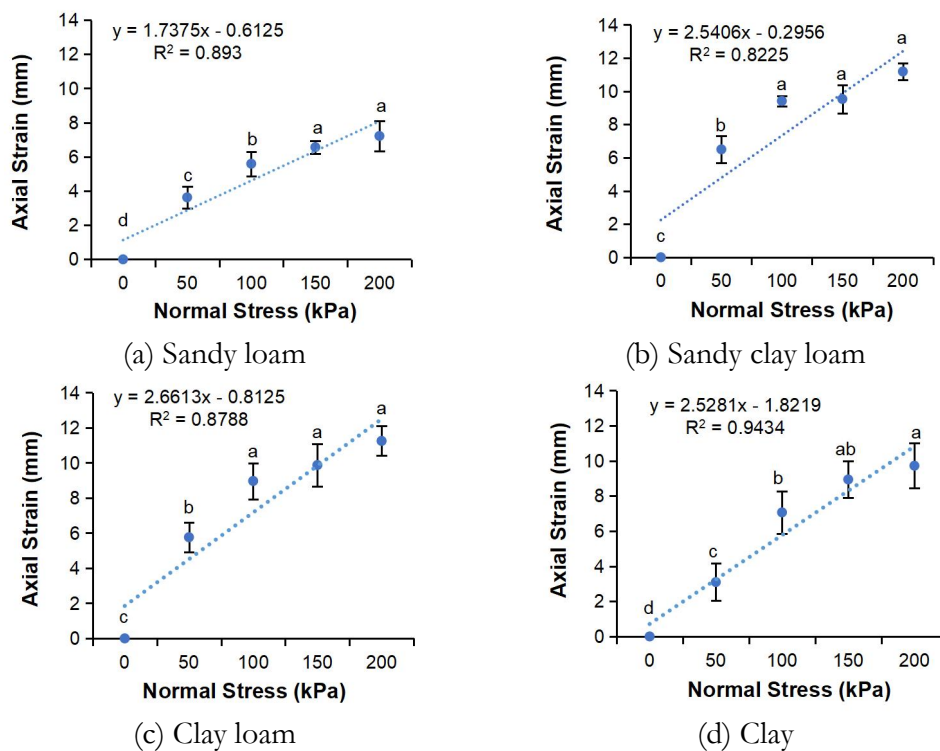


Figure 3.5. Effect of normal stress on soil axial strain. Labels are assigned based on Tukey HSD test to determine the significant different between treatment levels at a confidence level of 95% ( $p < 0.05$ ); error bars are standard deviations.

Soil bulk density exhibited an increasing trend with increasing normal stress (Figure 3.6). For sandy loam, higher and significant changes in magnitude were observed between normal stresses from 0 to 100 kPa (Figure 3.6a). Lower densities were recorded for sandy clay loam than sandy loam at zero normal stress (Figure 3.6b). Increasing normal stress resulted in

significant effect on bulk density from 0 to 150 kPa for sandy clay loam. Clay loam also followed the same trend (Figure 3.6c). However, all stress levels registered significantly different bulk densities. Clay soil showed lower bulk density under normal stresses than all the other soils (Figure 3.6d). Similar trend of change in magnitude with increasing stress levels as elaborated for clay loam was the same for clay. The general trend shows sandy loam soil with higher bulk densities compared to sandy clay loam, clay loam, and clay soils.

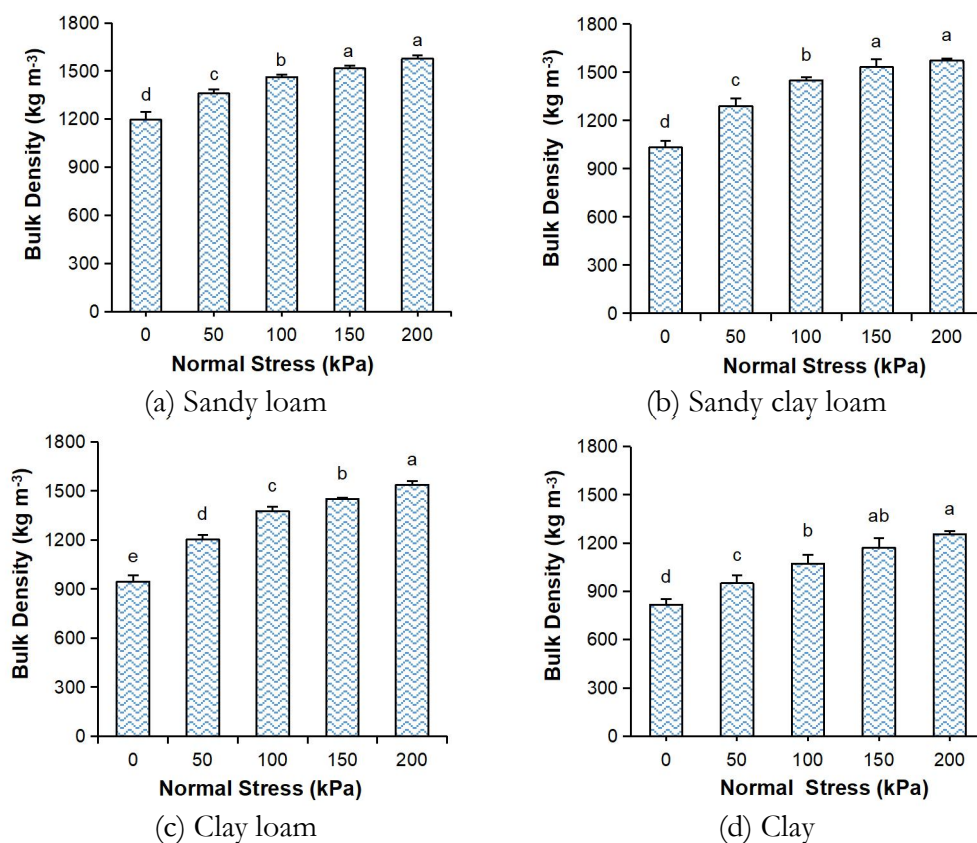


Figure 3.6. Effect of normal stress on soil bulk density. Labels are assigned based on Tukey HSD test to determine the significant different between treatment levels at a confidence level of 95% ( $p < 0.05$ ); error bars are standard deviations.

The trend in soil vertical deformation and bulk density was a result of the normal stresses impacting soil structure by forcing the closure of soil pore spaces through the downward pressure on soil particles, aligning them in close proximity (Alaoui et al., 2011). The higher the normal force, the closer soil particles are aligned. Also, highly porous soils are easily susceptible to deformation caused by compression (Shah et al., 2017). The response of the

soils to normal stress, as indicated by its bulk density, varied based on their particle size distribution (Alaoui and Diserens, 2018). Soils exhibiting small particle size (clay) have less variation in bulk density in response to soil compaction, whereas soils with larger sizes (sand) show higher variation in magnitude (Osman, 2013). This explains why sandy loam was highly influenced by compression than the other soils high in clay content. Furthermore, the insignificant effect among the higher normal stresses (150 and 200 kPa) could be due to the closure of soil pores at high densities, where further deformation from normal stress has less effect on the soil structure. The soils had attained maximum deformation where additional compression could not cause significant difference. All or large amount of soil air had been filled or removed at this state.

#### 3.4.1.2. Shear stress-displacement curve

The soil shear stress-displacement curves showed hyperbolic trends across all tests (Figure 3.7). This relationship aligns with the findings by Guo-xiong et al. (2010). Slightly small differences in shear stress magnitudes compared to normal stresses were noted, attributable to the elastic-plastic behaviour of surface soils, similar to observations by Gitau et al. (2006) and Zhang et al. (2001). Sandy loam displayed a sharp rise in shear stress between 0-4 mm displacements from 50 to 200 kPa. It stabilized afterwards until failure at 12 mm (Figure 3.7a). Sandy clay loam exhibited smoother shear stress inclinations up to 6 mm, with steadier behaviour at lower stress levels and earlier peaks at higher stress levels (Figure 3.7b). Clay loam showed sharp initial rises at higher stresses, transitioning to steady states before failure (Figure 3.7c). It recorded lower shear stress due to its high moisture condition. Clay soil required higher shear forces due to finer particle sizes, showing steep stress increases before yielding (Figure 3.7d). Elevated bulk density during shearing contributed to increased frictional forces, enhancing resistance under higher normal stresses. The soils under no

normal stress exhibited some level of shear resistance. This was due to the natural arrangement of the individual particles causing them to slide over each other and experiencing a lower form of friction (Mitchell and Soga, 2005). Similar shear behaviour trends were reported by Gitau et al. (2006), Infante et al. (2016), and Yin et al. (2021).

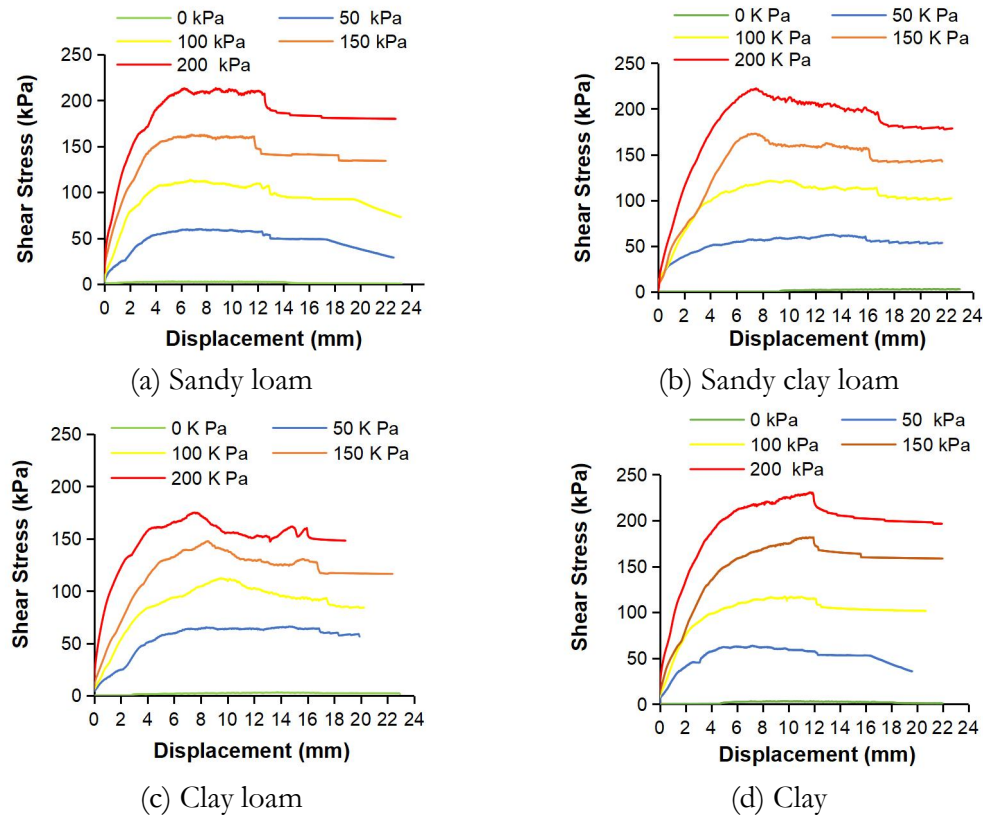


Figure 3.7. Shear stress relation to horizontal displacement under different normal stresses.

Shear strength was reached at different displacements. The displacement at shear strength depended on the soil type and the normal pressure within each soil type (Table 3.2). Sandy loam exhibited alternating displacements with maximum and minimum values of 8.7 mm and 7.0 mm, respectively, at 100 and 200 kPa. Sandy clay loam and clay loam showed an increasing trend with rising normal stress. Horizontal displacement for sandy clay loam decreased from 13.3 mm at 50 kPa to 7.4 mm at 200 kPa, while for clay loam, it decreased from 14.3 mm at 50 kPa to 7.6 mm at 200 kPa. In contrast, clay exhibited an increasing trend,

with displacement decreasing from 7.2 mm at 50 kPa to 1.6 mm at 200 kPa. These variations were due to the soils' differing compositions and responses to normal stress.

*Table 3.2. Soil horizontal displacement at shear strength*

| Normal Stress<br>(kPa) | Horizontal Displacement (mm) |                 |           |      |
|------------------------|------------------------------|-----------------|-----------|------|
|                        | Sandy Loam                   | Sandy Clay Loam | Clay Loam | Clay |
| 50                     | 7.5                          | 13.3            | 14.3      | 7.2  |
| 100                    | 7.0                          | 10.1            | 9.5       | 9.7  |
| 150                    | 7.5                          | 7.4             | 8.5       | 11.6 |
| 200                    | 8.7                          | 7.4             | 7.6       | 11.6 |

#### 3.4.1.3. Soil shear strength

Figures 3.8a, b, c, and d illustrate the shear strength behaviour of the soils under normal stresses. A linear increasing trend with increasing normal stress was observed for all soils, with significant differences between the stress levels. The general trend is similar to that observed in the axial strain and bulk density measurements. For sandy loam, percentage changes of 1715%, 87%, 46%, and 31% were recorded between 0 and 50 kPa, 50 and 100 kPa, 100 and 150 kPa, and 150 and 200 kPa, respectively. A maximum percentage change of 1961% was recorded between 0 and 50 kPa, while a minimum change of 26% was calculated between 150 and 200 kPa for sandy clay loam. Clay loam exhibited a similar trend, with minimum and maximum shear strengths of 2.5 kPa and 170.9 kPa, respectively. Clay recorded the highest shear strength of 233 kPa at a normal stress of 200 kPa, possibly due to the same reasons provided for the bulk density.

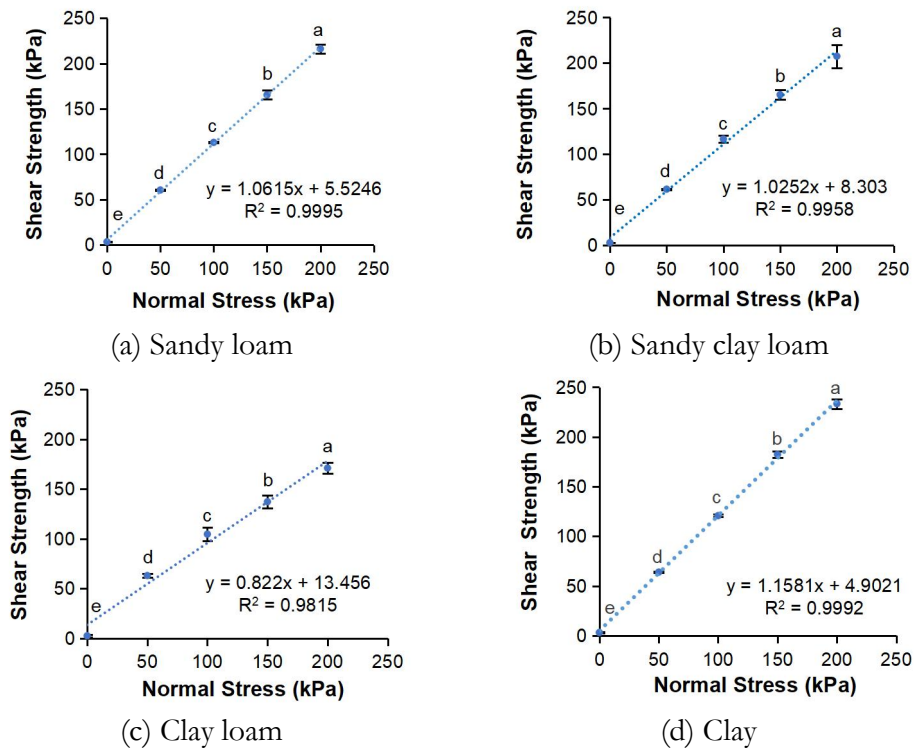


Figure 3.8. Mohr-Coulomb failure line. Labels are assigned based on Tukey HSD test to determine the significant different between treatment levels at a confidence level of 95% ( $p < 0.05$ ); error bars are standard deviations.

#### 3.4.1.4. Soil friction and cohesion

From the regression linear relationships in Figure 3.8, the soil internal friction angle was taken as the slope of the line and the cohesion was taken as the intersection of the line based on the Mohr-Coulomb Failure Criterion. Table 3.3 shows the results with strong  $R^2$  values of higher than 0.98 and RMSE values from 1.601 to 7.994. Clay loam had a reduction in its internal angle of friction of  $6.29^\circ$  less than sandy clay loam and an increase in cohesion force with a magnitude of 5.153 kPa more than sandy clay loam. Clay soil had the highest internal friction angle of  $49.19^\circ$ , which was  $2.48^\circ$  higher than sandy loam. Its cohesion was 0.62 kPa lower than sandy loam. A higher magnitude of shear strength led to a higher internal friction angle. Deviations from the linearity caused the increase in RMSE and a decrease in  $R^2$ . This deviation may have caused the higher internal friction angle and cohesion in the clay.

*Table 3.3. Soil strength properties and regression prediction accuracy*

| Soil Type | Angle of Internal Friction (°) | Cohesion (kPa) | R <sup>2</sup> | RMSE  |
|-----------|--------------------------------|----------------|----------------|-------|
| SL        | 46.71                          | 5.52           | 0.999          | 1.601 |
| SCL       | 45.71                          | 8.30           | 0.995          | 4.724 |
| CL        | 39.42                          | 13.46          | 0.981          | 7.994 |
| C         | 49.19                          | 4.90           | 0.999          | 2.349 |

#### 3.4.1.5. Soil water matrix as affected by compression and shear

The water matrix of the tested soils under varying normal stresses showed distinct trends (Figure 3.9). Sandy loam showed sharp reductions at 150 and 200 kPa during compression, with 150 kPa maintaining the highest potential (Figure 3.9a). During shearing, 150 kPa stabilized after 23 minutes, while 200 kPa reached a steady state after 12 minutes. Lower forces (0, 50, and 100 kPa) achieved steady states earlier, with 100 kPa maintaining the highest potential among them. Water potential in sandy clay loam remained steady (8-12 hPa) throughout the test (Figure 3.9b). The lowest potential occurred at 200 kPa, with 0 kPa showing the highest. Clay loam exhibited a smooth negative slope during normal stress application, with sharp declines observed at 50 and 200 kPa (Figure 3.9c). Steady states were observed for 100 and 150 kPa, while 150 kPa peaked at 29 minutes before declining. Clay showed the steadiest water matrix, except for 50 kPa. During the test, 0 and 200 kPa recorded the highest potentials, followed by 150, 100, and 50 kPa in descending order (Figure 3.9d). Sandy loam, with larger particles and more pore spaces, showed higher reduction in water matrix during compression, consistent with the findings by Cui et al. (2010). Clay loam showed the highest water matrix, influenced by the impact of normal stress on pore structures (Faloye et al., 2021; Gregory et al., 2010; Lu et al., 2022).

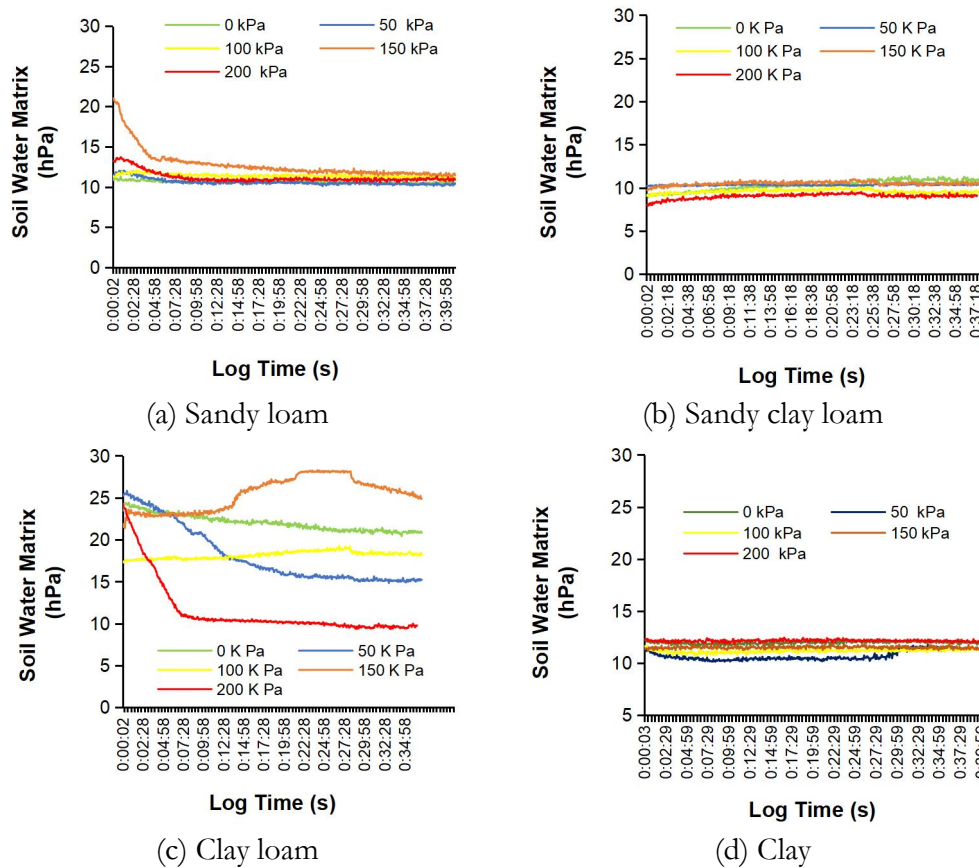


Figure 3.9. Trend of soil water matrix under varying normal stress.

The average soil water matrix during compression and shearing revealed alternating soil responses to normal stress (Figure 3.10). Sandy loam exhibited potentials between 9.52–11.66 hPa, showing no significant difference with increased normal stress (Figure 3.10a). Sandy clay loam showed alternating potentials, ranging from 7.44 - 10.38 hPa, likely due to its non-homogeneous nature (Figure 3.10b). Clay loam showed an alternating pattern, with the highest potential at zero normal stress (17.91 hPa), reducing under stress (Figure 3.10c). Clay exhibited decreasing water matrix with no significant differences, aligning with studies indicating reduced suction potential under normal stress (Gregory et al., 2010; Huang et al., 2021) (Figure 3.10d). Therefore, the applied normal stress resulted in low and insignificant effect on the water matrix of the studied soils. This may be due to the chosen moisture content. Where high soil moisture content results in low soil water potential (Saxton et al., 1986).

Larger portions of the soil pore spaces were filled, affecting the samples' potential to absorb moisture.

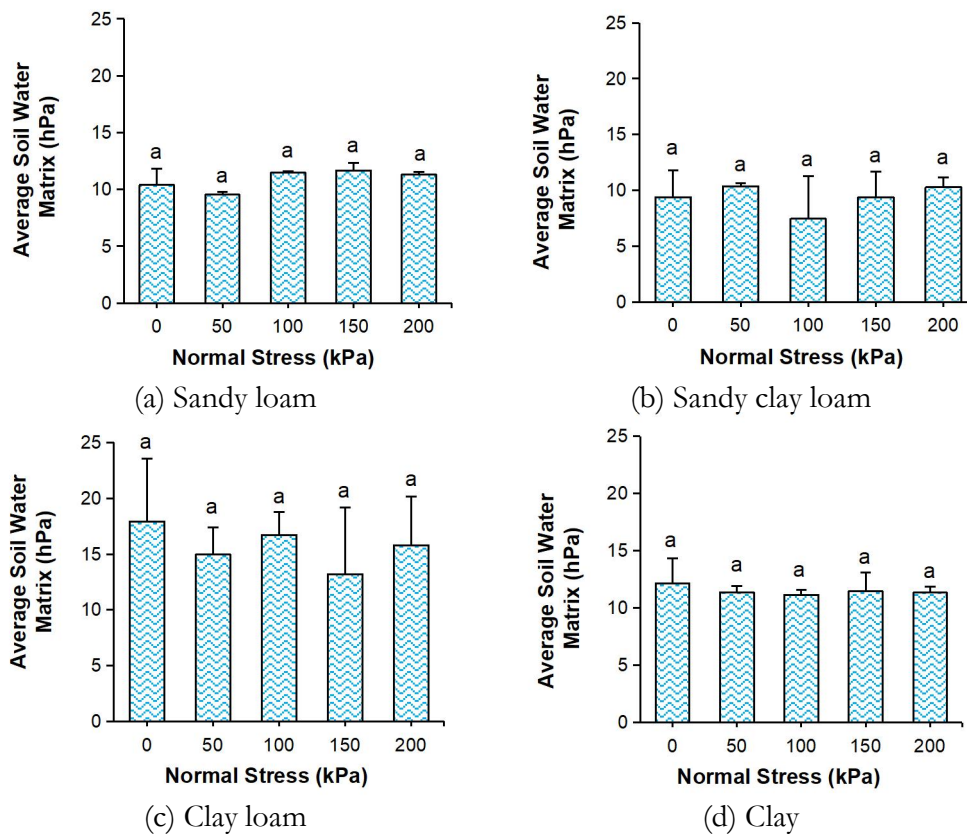


Figure 3.10. Soil water matrix under compression and shearing. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ); error bars are standard deviation.

### 3.4.2 Soil shearing simulation results

#### 3.4.2.1 Model calibration results

The virtual soil compression test was run with  $E_{mod}$  values varying from  $1e5$  to  $1e7$  at intervals of  $0.5e5$  using the 50, 100, 150, and 200 kPa normal stresses. The least mean relative error between the measured and simulated vertical soil resistance was found at  $2.5e6$  for sandy loam,  $3e6$  for sandy clay loam,  $1e6$  for clay loam, and  $1.5e6$  for clay. Using these values of  $E_{mod}$ , the resultant simulated values against the measured values are shown in

Figure 3.11a, b, c, and d. The overall relative errors were 6.66% for sandy loam, 9.06% for sandy clay loam, 9.22% for clay loam, and 7.12% for clay. The low particle stiffness value adopted from literature may have contributed to the observed errors, as Acquah and Chen, (2023) and De Pue and Cornelis, (2019) explained that lower particle stiffness reduces pressure transmission in model simulation. However, the errors observed were minimal and within acceptable limits for DEM parameter calibration (Wang, et al., 2021; Zeng et al., 2020).

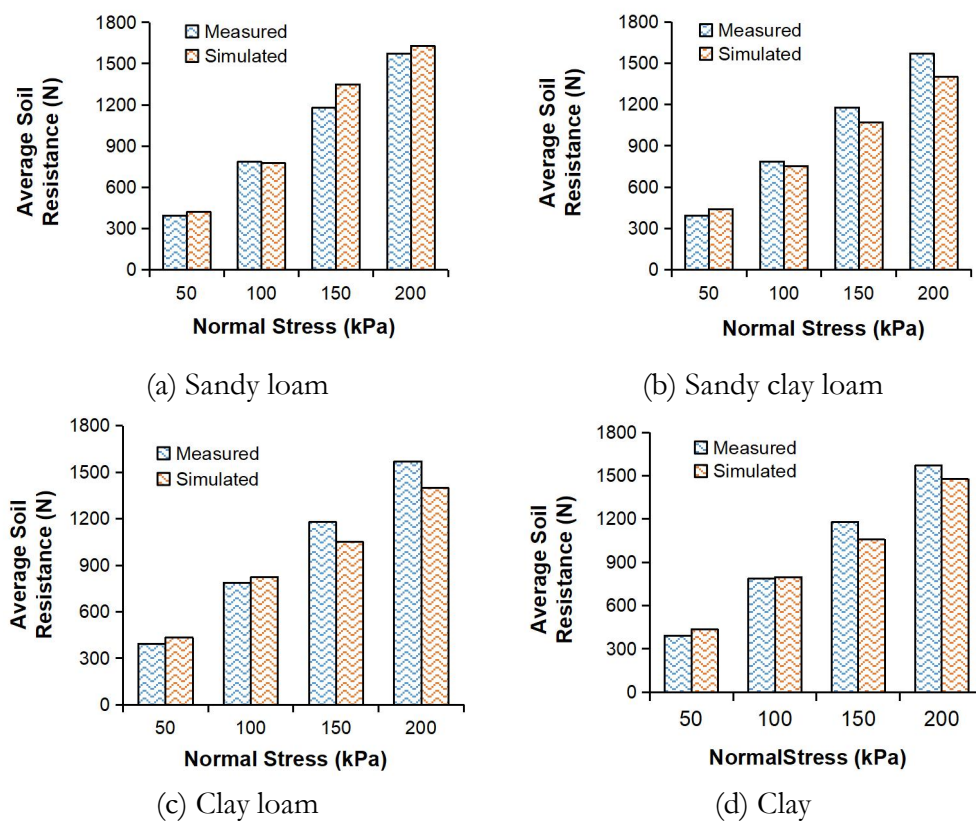


Figure 3.11. Model calibration results of average vertical soil resistance at different normal stresses.

#### 3.4.2.2 Model validation of soil shear strength

An increasing trend in soil shear strength was observed from the simulations, which was consistent with the measured values (Figure 3.12a, b, c, and d). Higher shear strengths were recorded for clay, followed by sandy clay loam, clay loam, and sandy loam, consistent with

the explanation provided for the measured shear stress-displacement data. The simulated values at the highest normal pressure had higher relative errors with the measured values across all soil types. The model's deviations reflect the limitations of the calibrated model. Relative errors ranged from 1.10% to 12.71% for sandy loam, 1.61% to 6.96% for sandy clay loam, 2.36% to 12.58% for clay loam, and 3.96% to 5.98% for clay. These errors fall within the acceptable range, as demonstrated in the study by Wu et al. (2024).

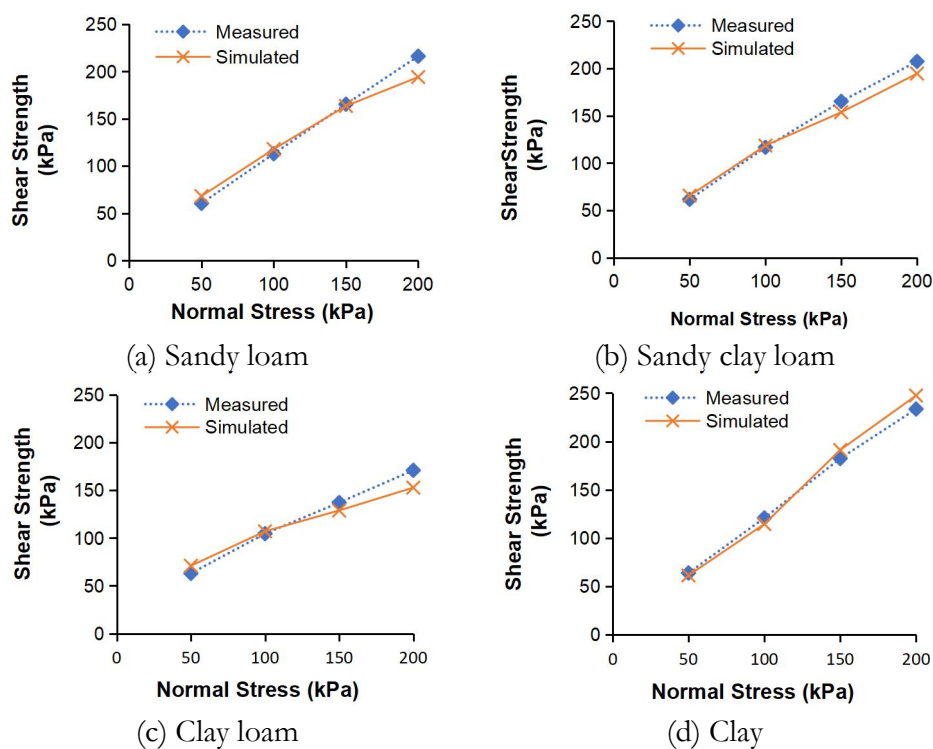


Figure 3.12. Measured and simulated averages of soil shear strength per normal stress.

### 3.4.2.3. The effect of soil type and bulk density on soil erodibility

This simulation was conducted without the application of normal stress, which simulated the soil resistance to shear in an agricultural field, reflecting the soil resistance to erosion. Thus, simulated soil shear strengths without adding normal stresses are presented as erosion resistance indicator. Results revealed that erosion resistance indicator increased with bulk density across all soil types (Figure 3.13). Among the soil types, clay demonstrated the highest erosion resistance with increasing bulk density, making it the least susceptible to

erosion under the soil condition the model was calibrated. Results showed a positive correlation across all soil types. However, a nonlinear trend was observed, with a more pronounced increase in erosion resistance at higher bulk density values. A noticeable change in the rate of increase occurred at a soil bulk density of approximately 1000-1200  $\text{kg m}^{-3}$  for all soils. Below this range, the erosion resistance indicator increased gradually, while above this range, it increased more rapidly. This may be attributed to the relatively loose soil packing at lower bulk densities, which results in lower cohesion. In contrast, higher bulk densities are associated with more compact soil packing, greater cohesion, and, consequently, a higher erosion resistance indicator.

These findings provide valuable insights into soil erodibility, aiding in the identification of vulnerable soils and the implementation of targeted conservation practices. By integrating these results with other field observations and predictive models, soil erodibility can be assessed and mitigated in both agricultural and non-agricultural contexts.

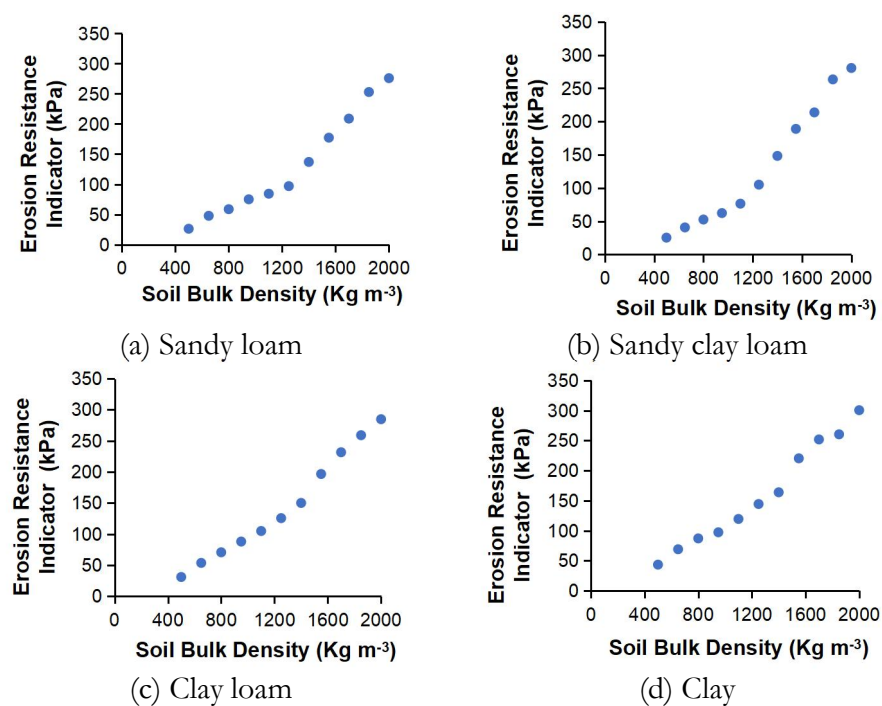


Figure 3.13. Soil shear strength with varying bulk density per soil.

### 3.5. Conclusion

The study evaluated the response of sandy loam (SL), sandy clay loam (SCL), clay loam (CL) and clay (C) soils to varying normal stress. The bulk density of the soils increased linearly with normal stress, with significant changes at lower levels, but increased at 150-200 kPa. Soils with high sand content was more susceptible to compression than soils with high clay content. Shear stress exhibited a hyperbolic pattern, varying slightly with normal stress. The angle of internal friction ( $\phi$ ) decreased with smaller particle sizes, ranging from  $46.71^\circ$  (SL) to  $39.42^\circ$  (CL), except for C at  $49.19^\circ$ . Cohesion varied inconsistently, lowest in C. Normal stress had a more pronounced effect on the soil shear strength than the soil water matrix. The DEM model revealed an increase in soil shear resistance with increasing soil bulk density. Soils susceptibility to shearing and erosion was low at higher normal stress and bulk density respectively. The lower shear strengths and the insignificant effect of normal stress on the soil matrix may have been caused by the nature of the surface soil and the influence of soil moisture, respectively. Therefore, further studies into the effect of normal stress on the shearing properties of the soils at different moisture levels is recommended. This result provides valuable insights for crop producers, enhancing the understanding of the response of agricultural soils under normal stress.

The current study enhances the understanding of soil deformation and shear behaviour under normal stress, further research into soil cone index (CI) is essential to extend these findings to field-scale conditions. The CI provides a direct measure of soil penetration resistance, integrating the effects of bulk density, moisture, and internal shear strength on root growth. Investigating the relationship between normal stress, internal shear parameters, and CI would establish a quantitative link between laboratory-measured mechanical properties

and in situ soil strength. Therefore, chapter four of this thesis evaluated soil cone index in relation to field traffic.

### 3.6. References

- Acquah, K., and Chen, Y. (2023). Discrete element modelling of soil pressure under varying number of tire passes. *Journal of Terramechanics*, 107, 23–33. <https://doi.org/10.1016/j.jterra.2023.02.003>
- Adesina, E., Ajayi, O., Odumosu, J., and Illah, A. (2024). *Assessing the risk of soil loss using geographical information system ( GIS ) and the revised universal soil loss equation ( RUSLE )*. 4(2), 42–53. <http://publish.mersin.edu.tr/index.php/agis/index>
- Alaoui, A., and Diserens, E. (2018). Mapping soil compaction – A review. *Current Opinion in Environmental Science and Health*, 5, 60–66. <https://doi.org/10.1016/j.coesh.2018.05.003>
- Alaoui, A., Lipiec, J., and Gerke, H. H. (2011). A review of the changes in the soil pore system due to soil deformation: A hydrodynamic perspective. *Soil and Tillage Research*, 115–116, 1–15. <https://doi.org/10.1016/j.still.2011.06.002>
- American Society for Testing and Materials. (2007). ASTM D422-63: Standard test method for particle\_size analysis of soils. In *Annual book of ASTM standards* (pp. 1–8). <https://www.astm.org/standards/d422>
- American Society for Testing and Materials. (2019). ASTM D2216: Standard Test Methods for Laboratory Determination of Water (Moisture). In *Content of Soil and Rock by Mass*. <https://store.accuristech.com/standards/astm-d2216-19>
- Benavidez, R., Jackson, B., Maxwell, D., and Norton, K. (2018). A review of the (Revised) Universal Soil Loss Equation ((R)USLE): With a view to increasing its global applicability and improving soil loss estimates. *Hydrology and Earth System Sciences*,

- 22(11), 6059–6086. <https://doi.org/10.5194/hess-22-6059-2018>
- Bonakdari, H., Ebtehaj, I., and Gumiere, S. (2024). *Future Trajectories of Soil Erosion in Canadian Agricultural Lands: Runoff-Induced Impacts and Sustainability*. <https://doi.org/10.21203/rs.3.rs-5367697/v1>
- Cui, K., Défossez, P., Cui, Y. J., and Richard, G. (2010). Quantifying the effect of matric suction on the compressive properties of two agricultural soils using an osmotic oedometer. *Geoderma*, 156(3–4), 337–345. <https://doi.org/10.1016/j.geoderma.2010.03.003>
- De Pue, J., and Cornelis, W. M. (2019). DEM simulation of stress transmission under agricultural traffic Part 1: Comparison with continuum model and parametric study. *Soil and Tillage Research*, 195(March). <https://doi.org/10.1016/j.still.2019.104408>
- Faloye, O. T., Ajayi, A. E., Zink, A., Fleige, H., Dörner, J., and Horn, R. (2021). Effective stress and pore water dynamics in unsaturated soils: Influence of soil compaction history and soil properties. *Soil and Tillage Research*, 211(February). <https://doi.org/10.1016/j.still.2021.104997>
- Gitau, A. N., Gumbe, L. O., and Biamah, E. K. (2006). Influence of soil water on stress-strain behaviour of a compacting soil in semi-arid Kenya. *Soil and Tillage Research*, 89(2), 144–154. <https://doi.org/10.1016/j.still.2005.07.008>
- Gregory, A. S., Bird, N. R. A., Whalley, W. R., Matthews, G. P., and Young, I. M. (2010). Deformation and Shrinkage Effects on the Soil Water Release Characteristic. *Soil Science Society of America Journal*, 74(4), 1104–1112. <https://doi.org/10.2136/sssaj2009.0278>
- Gu, X., Huang, M., and Qian, J. (2014). *DEM investigation on the evolution of microstructure in granular soils under shearing*. 91–106. <https://doi.org/10.1007/s10035-013-0467-z>
- Guo-xiong, M., Qi-ming, C., and Peng-ming, J. (2010). *Stress–strain relationship of*

- unsaturated cohesive soil MEI. 4*, 1139–1143. <https://doi.org/10.1007/s11771>
- Hamza, M. A., and Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research*, 82(2), 121–145. <https://doi.org/doi.org/10.1016/j.still.2004.08.009>.
- Hanks, R. J. (2012). Applied soil physics: soil water and temperature applications. In *Springer Science and Business Media*. (Vol. 8). <https://link.springer.com/book/10.1007/978-1-4612-2938-4>
- Huang, X., Horn, R., and Ren, T. (2021). Deformation and pore water pressure change during static and cyclic loading with subsequent shearing on soils with different textures and matric potentials. *Soil and Tillage Research*, 209(September 2020), 104909. <https://doi.org/10.1016/j.still.2020.104909>
- Huang, X., Ren, T., and Rainer, H. (2023). Effective stress and shear strength parameters of unsaturated soils as affected by compaction and subsequent shearing. *European Journal of Science*, 74(3), e12284. <https://doi.org/https://doi.org/10.1111/ejss.13384>
- Infante, D. J. U., Martinez, G. M. A., Arrua, P. A., and Eberhardt, M. (2016). Shear Strength behaviour of Different Geosynthetic Reinforced Soil Structure from Direct Shear Test. *International Journal of Geosynthetics and Ground Engineering*, 2(2). <https://doi.org/10.1007/s40891-016-0058-2>
- Karmeli, D., and Keller, J. (1975). Trickle irrigation design (No. 04; TC805, K3.). *Glendora, CA: Rain Bird Sprinkler Manufacturing Corporation*. [https://doi.org/https://pdf.usaid.gov/pdf\\_docs/PNAAA949.pdf](https://doi.org/https://pdf.usaid.gov/pdf_docs/PNAAA949.pdf)
- Keesstra, S. D., Geissen, V., Mosse, K., Piirainen, S., Scudiero, E., Leistra, M., and van Schaik, L. (2012). Soil as a filter for groundwater quality. *Current Opinion in Environmental Sustainability*, 4(5), 507–516. <https://doi.org/10.1016/j.cosust.2012.10.007>
- Lepore, E., Schmidt, O., Fenton, O., Tracy, S., Bondi, G., and Wall, D. P. (2024). Traffic

- induced compaction and physical quality of grassland soil under different soil moisture deficits. *Soil and Tillage Research*, 244(October 2023), 106205. <https://doi.org/10.1016/j.still.2024.106205>
- Liu, J., Chen, L., Wang, B., and Peng, X. (2024). Effects of physical crust on soil detachment by overland flow in the Loess Plateau region of China. *International Soil and Water Conservation Research*, 12(1), 107–120. <https://doi.org/10.1016/j.iswcr.2023.05.006>
- Lu, N., Luo, S., and Zhou, B. (2022). Water Adsorption–Induced Pore–Water Pressure in Soil. *Journal of Geotechnical and Geoenvironmental Engineering*, 148(6), 1–16. [https://doi.org/10.1061/\(asce\)gt.1943-5606.0002814](https://doi.org/10.1061/(asce)gt.1943-5606.0002814)
- Mitchell, J. K., and Soga, K. (2005). Fundamentals of Soil behaviour. In *Wiley, New York*. <https://doi.org/10.1097/00010694-199407000-00009>
- Mohammad, E. N., and Ismail, S. M. (2006). *Subsurface Drip Irrigation System Development and Modeling of Wetting Pattern Distribution* [Alexandria University]. <https://www.researchgate.net/publication/319006457>
- Or, D., Wraith, J. M., and Warrick, A. W. (2002). Soil water content and water potential relationships. *Soil Physics Companion*, 1, 49–84. <https://api.semanticscholar.org/CorpusID:128579839>
- Osman, K. T. (2013). *Physical Properties of Soil, In Soils: Principles, Properties and Management*,. Springer. [https://doi.org/doi.org/10.1007/978-94-007-5663-2\\_5](https://doi.org/doi.org/10.1007/978-94-007-5663-2_5)
- Potyondy, D. O., and Cundall, P. A. (2004). A bonded-particle model for rock. *International Journal of Rock Mechanics and Mining Sciences*, 41(8 SPEC.ISS.), 1329–1364. <https://doi.org/10.1016/j.ijrmms.2004.09.011>
- Romero-Ruiz, A., Linde, N., Baron, L., Solazzi, S. G., Keller, T., and Or, D. (2021). Seismic signatures reveal persistence of soil compaction. *Vadose Zone Journal*, 20(4), 1–15. <https://doi.org/10.1002/vzj2.20140>

- Saxton, K. E., Rawls, W. J., Romberger, J. S., and Papendick, R. I. (1986). Estimating Generalized Soil-water Characteristics from Texture. *Soil Science Society of America Journal*, 50(4), 1031–1036. <https://www.soils.org/publications/sssaj/abstracts/50/4/SS0500041031>
- Schjønning, P. (2024). Interpretation of uniaxial, confined compression test data for agricultural topsoils. *Soil and Tillage Research*, 235(April 2023). <https://doi.org/10.1016/j.still.2023.105866>
- Shah, A. N., Tanveer, M., Shahzad, B., Yang, G., Fahad, S., Ali, S., Bukhari, M. A., Tung, S. A., Hafeez, A., and Souliyanonh, B. (2017). Soil compaction effects on soil health and cropproductivity: an overview. *Environmental Science and Pollution Research*, 24(11), 10056–10067. <https://doi.org/10.1007/s11356-017-8421-y>
- Shaheb, M. R., Venkatesh, R., and Shearer, S. A. (2021). A review on the effect of soil compaction and its management for sustainable crop production. *Journal of Biosystems Engineering*, 46, 417–439. <https://doi.org/doi.org/10.1007/s42853-021-00117-7>
- Tang, L., Cong, S., Ling, X., Xing, W., and Nie, Z. (2018). A unified formulation of stress-strain relations considering micro-damage for expansive soils exposed to freeze-thaw cycles. *Cold Regions Science and Technology*, 153(May), 164–171. <https://doi.org/10.1016/j.coldregions.2018.05.006>
- Toledo, M. P. S., Rolim, M. M., de Lima, R. P., Cavalcanti, R. Q., Ortiz, P. F. S., and Cherubin, M. R. (2021). Strength, swelling and compressibility of unsaturated sugarcane soils. *Soil and Tillage Research*, 212(April). <https://doi.org/10.1016/j.still.2021.105072>
- Van Genuchten, M. V., Leij, F. J., and Yates, S. R. (1991). *The RETC code for quantifying the hydraulic functions of unsaturated soils*. <https://doi.org/https://www.pc-progress.com/Documents/programs/retc.pdf>
- Wang, X., Li, B., Xia, R., and Ma, H. (2021). *Engineering Applications of Discrete Element*

*Method: Operation Analysis and Optimization Design of Coal and Agricultural Machinery* (Vol. 4). <https://doi.org/10.1007/978-981-15-7977-6>

- Wu, P., Zhang, X., Zeng, Z., and Chen, Y. (2025). DEM simulation of subsoiling for soil disturbance as affected by soil layering and working speed. *Smart Agricultural Technology*, 7(100385). <https://doi.org/doi.org/10.1016/j.atech.2023.100385>
- Xiaofeng, X., Houzhen, W., Qingshan, M., Changfu, W., and Yanghe, L. (2013). DEM Simulation on Effect of Coarse Gravel Content to Direct Shear Strength and Deformation Characteristics of Coarse-Grain soil. *Journal of Engineering Geology*, 21(2), 311–316. [https://doi.org/1004-9665/2013/21\(2\)-311-316](https://doi.org/1004-9665/2013/21(2)-311-316)
- Yin, K., Fauchille, A.-L., Di Filippo, E., Kotronis, P., and Sciarra, G. (2021). A Review of Sand–Clay Mixture and Soil–Structure Interface Direct Shear Test. *Geotechnics*, 1(2), 260–306. <https://doi.org/10.3390/geotechnics1020014>
- Zeng, Z., Ma, X., Chen, Y., and Qi, L. (2020). Modelling residue incorporation of selected chisel ploughing tools using the discrete element method (DEM). *Soil and Tillage Research*, 197(November 2019). <https://doi.org/10.1016/j.still.2019.104505>
- Zhang, B., Jia, Y., Fan, H., Guo, C., Fu, J., Li, S., Li, M., Liu, B., and Ma, R. (2024). Soil compaction due to agricultural machinery impact: A systematic review. *Land Degradation and Development*. <https://doi.org/https://doi.org/10.1002/ldr.5144>
- Zhang, B., Zhao, Q. G., Horn, R., and Baumgartl, T. (2001). Shear strength of surface soil as affected by soil bulk density and soil water content. *Soil and Tillage Research*, 59(3–4), 97–106. [https://doi.org/10.1016/S0167-1987\(01\)00163-5](https://doi.org/10.1016/S0167-1987(01)00163-5)
- Zhang, W., Ricketts, T. H., Kremen, C., Carney, K., and Swinton, S. M. (2007). Ecosystem services and dis-services to agriculture. *Ecological Economics*, 64(2), 253–260. <https://doi.org/10.1016/j.ecolecon.2007.02.024>
- Zhu, Y., Gong, J., and Nie, Z. (2021). Particuology Shear behaviours of cohesionless mixed

soils using the DEM : The influence of coarse particle shape. *Particuology*, 55, 151–165.

<https://doi.org/10.1016/j.partic.2020.07.002>

## Chapter 4

---

### Measurement and modelling of soil cone index as affected by penetrometer cone size under varying soil compaction levels\*

*\*Submitted to Soil and Tillage Research (under revision)*

#### 4.1. Abstract

Soil compaction significantly impacts soil structure and crop root health, emphasizing the importance of accurately measuring the soil cone index (CI). This study investigated the influence of penetrometer geometry on soil CI in sandy loam and clay fields under varying compaction levels. Four compaction levels: C0, C1, C2, and C3, corresponding to zero, one, two, and three tractor passes, respectively, were applied to each field. Using a soil cone penetrometer (Royal Eijkelkamp) with cone base areas of 200, 333, and 500 mm<sup>2</sup>, CI was measured across the soil depth profile. A discrete element method (DEM) model was developed to simulate soil-penetrometer interactions and calibrated and validated with field data. Results showed that in the 0-100 mm soil depth range, CI increased from 0.38 MPa (C0) to 0.54 MPa (C3) in the sandy loam soil and from 0.43 MPa (C0) to 0.65 MPa (C3) in the clay soil. Smaller cone sizes consistently yielded higher CI values than larger cone sizes under identical conditions, a trend also confirmed by the DEM model results. The model results revealed that penetrometer cone size and rod diameter significantly influenced CI values. To mitigate these effects, it is recommended that the rod of cone penetrometers be equipped with a sleeve matching the cone base diameter. Simulations using the DEM model supported this recommendation. These findings highlight the need to revisit standards for measuring soil CI and the importance of minimizing excessive soil compaction in agricultural practices.

**Keywords:** soil; compaction; penetrometer; cone size; rod; cone index; DEM model.

## 4.2. Introduction

Soil cone index (CI) is an important mechanical property used in both agricultural and civil engineering to quantify soil's resistance to penetration, providing valuable assessment on soil compactness. Soil compaction, occurs when soil particles are forced together, resulting in the compression of soil air pores that would otherwise be used to transport water and nutrients to crop roots (Shah et al., 2017). Specifically, excessive soil compaction can negatively affect various number of soil properties, such as porosity, volumetric water content, hydraulic conductivity, and water infiltration, thereby altering root penetration (Taylor and Brar, 1991; Zhang et al., 2024) and nutrient uptake. Soils with excessive compaction cannot properly support crop production, leading to significant crop losses and reduced yield (Zhang et al., 2024).

Soil CI indicates the ease at which crop roots can grow and penetrate soil media. Lampurlanés et al. (2001) studied root growth of barley under different tillage/compaction levels on two soils in semi-arid conditions. Their results showed that Root Length Density (RLD) was significantly greater for no-tillage/no compaction than for sub-soiler or minimum tillage. Therefore, soil CI and root growth follow a direct relationship – minimal soil CI allows crop roots to move easily reaching a more nutrient rich soil, promoting root growth and, subsequently, plant growth (Jayaraman et al., 2021).

While greater soil compaction typically relates to increased soil CI, other soil mechanical properties directly affect its compaction level. According to literature, soil texture influences CI. More specifically, values of CI decreases with increasing clay fraction, and increase with an increase in sand and silt fractions (Kumar et al., 2012). Adeniran and Babatunde (2010) found that soil CI and shear vane strength of highly fertile soils increased with depth and decreased with an increase in moisture content. This is also evident in the study conducted by

Kumar et al. (2012). In summary, soil CI is related to soil physical properties such as soil textural parameters (e.g., sand, silt, and clay content), moisture content, and bulk density (Kumar et al., 2012; Negiş, 2024).

In addition, literature shows that CI values in the same soil composition vary with penetrometer properties including rod diameter and cone sizes (Whiteley and Dexter, 1981; Zhuang and Yu, 2018). Whiteley and Dexter (1981) studied the effect of micro-penetrometer probe diameter on soil CI and concluded that the 1 mm probe required 45-55% more pressure to penetrate the material compared to the 2 mm probe. This was due to the increased localized shearing resistance at the sand-probe interface for smaller cones. Zhuang and Yu (2018) reported a decrease in CI with increasing cone sizes. The standard cone size for industrial testing is 1000–1500 mm<sup>2</sup> with apex angle of 60°, primarily intended for very soft soils (Ameratunga et al., 2016; ASTM, 2019). Conversely, smaller cone sizes, such as 100 mm<sup>2</sup>, are utilized in specialized laboratory and research applications (ASTM, 2019). As noted by the Royal Eijkelpamp (2022), the 100 mm<sup>2</sup> cone is recommended for agricultural soil studies, as both smaller and larger cone sizes may lead to over- or underestimation of CI values.

Varying inter-particle contact parameters, container boundary conditions, and void ratio under different sand particle configurations affected the tip resistance of a cone penetrometer in a three-dimensional discrete element method (DEM) study by Khosravi et al. (2020). Wu et al. (2023) also studied the micro-behaviour and tip resistance of model soil to cone penetration as influenced by soil void ratio and particle shape using the DEM. Cone tip resistance was found to vary with changes in particle parameters, including a reduction in initial porosity and an increase in the friction coefficient. Furthermore, particles closer to the cone penetrometer model exhibited higher displacement. Song et al. (2022) studied the mechanics of soil-cone interaction by coupling the DEM with the finite difference method

(FDM). Their results showed that cone tip resistance correlated positively with the number of particle contacts during penetration.

The dynamics of measuring soil CI in relation to varying cone geometry and field traffic remains insufficiently documented. Therefore, the objectives of this study were to (1) conduct field experiments to determine the effects of penetrometer cone size and soil compaction level on the soil CI of sandy loam and clay fields. (2) Develop, calibrate, and validate a DEM model to simulate the soil-penetrometer interaction. (3) Apply the model to investigate the effects of various geometrical and operational parameters of the cone penetrometer.

### 4.3. Materials and methods

#### 4.3.1. Field experiment

##### 4.3.1.1. Description of test equipment

A soil cone penetrometer (Royal Eijkelkamp, 615SA, Nijverheidsstraat, Netherlands) was used to measure the soil cone indices in two experimental fields. The penetrometer is equipped with a water-resistant housing, a 1,000-N capacity load cell, three cone sizes, a communication port, a GPS antenna, a control panel LCD screen, a depth reference plate, and a level plate (Figure 4.1a). The cone sizes (the basal areas of the cones) are 200, 333, and 500 mm<sup>2</sup>, and all cones have an apex angle of 60° (Figure 4.1b). The probing rod has a diameter of 10 mm, and a length of 970 mm. The maximum measurement depth was 800 mm below the soil surface. For model calibration discussed later in the paper, a different cone size (100-mm<sup>2</sup>) and rod diameter (8-mm) was also used to measure cone index data.

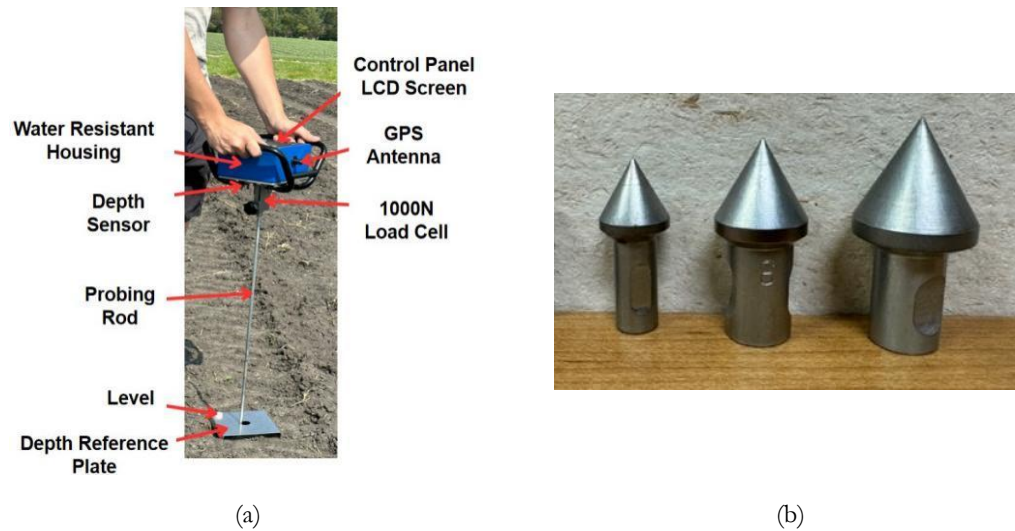


Figure 4.1. Soil cone penetrometer: (a) Parts and testing position; (b) Cone sizes (200, 333, and 500 mm<sup>2</sup>; from left to right).

#### 4.3.1.2. Experimental sites description

The two experimental fields were located at a farm in the Rural Municipality of Piney, Manitoba, Canada, and at a research station of the University of Manitoba in Winnipeg, Canada. The soil texture at Piney was sandy loam with 70% sand, 16% silt, and 14% clay, while the soil texture at Winnipeg was clay with 62% clay, 35% silt, and 3% sand. Prior to the experiment, the experimental fields underwent standard tillage operation with a disc plough.

#### 4.3.1.3. Experimental design

The experiment had a split plot design with the factor of compaction levels as the main plot and the factor of penetrometer cone sizes as the sub-plot. The response variable was the different values of soil CI obtained from the penetrometer. The factor levels for the cone sizes were 200, 333, and 500 mm<sup>2</sup> basal areas, denoted by S2, S3.33, and S5 respectively. The factor levels for the compaction magnitude were created by the number of tractor passes in the fields, denoted by C0, C1, C2, and C3 for compaction levels zero, one, two, and three

respectively. Each treatment was replicated five times constituting 20 plots (four compaction levels  $\times$  five replicates) in each experimental field (Figure 4.2).

| Plot 1 | Plot 2 | Plot 3 | Plot 4 | Plot 5 | Plot 6 | Plot 7 | Plot 8 | Plot 9 | Plot 10 | Plot 11 | Plot 12 | Plot 13 | Plot 14 | Plot 15 | Plot 16 | Plot 17 | Plot 18 | Plot 19 | Plot 20 |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| C2     | C0     | C1     | C3     | C0     | C2     | C3     | C3     | C1     | C2      | C1      | C0      | C2      | C3      | C2      | C3      | C0      | C1      | C0      | C1      |

Figure 4.2. Field layout of the main plots. Where C0, C1, C2, and C3, represent compaction levels zero, one, two, and three, respectively.

#### 4.3.1.4. Experimental procedure and measurements

At each of the two experimental fields, a tractor (selected based on availability at the farms) was used to create different soil compaction levels. The sandy loam field was compacted with a John Deere 1023e, weighing approximately 656 kg, while the clay field was compacted with a John Deere 5425 with a bucket, with a total weight of approximately 3,814 kg. The tractor traveled at a constant speed of 2 km h<sup>-1</sup>. Each field plot received either zero, one, two, or three tractor passes along the same track corresponding to compaction levels zero (C0), one (C1), two (C2), and three (C3), respectively (Figure 4.3).

Prior to the soil compaction process, ten random soil samples were taken from the field with a soil core sampler (20 mm diameter) to a depth of 200 mm at a 40-mm interval. The soil moisture condition of the fields were determined after oven drying the samples at 105 °C for 24 hours (ASTM, 2021).

After compaction, soil bulk density and cone index were measured in each field plots. Three soil cores measuring 30 x 100 mm in diameter and height respectively were taken from three random locations on the wheel tracks for each plot. The bulk densities of the fields were determined by weighing the mass of the samples and the given sample volume (ASTM, 2021).

Cone indices were measured using the penetrometer with different cone sizes. The penetrometer was pushed into the soil at a constant velocity of  $20 \text{ mm s}^{-1}$ , perpendicular to the ground (Ameratunga et al., 2016; ASTM, 2018). The penetrometer was pushed until it was impossible to push further or the maximum depth was obtained. Two sets of data were measured. The first dataset was obtained using the penetrometer with three different cone sizes (S200, S333, and S500) and the 10 mm rod diameter. For each experimental field, three penetrations per cone size were taken on each of the 20 plots. This totaled to 180 measurements (*i.e.* 3 cone sizes  $\times$  4 compaction levels  $\times$  5 replicates  $\times$  3 penetrations per plot). Data of the second set were obtained using the penetrometer with the cone size of  $100 \text{ mm}^2$  and the 8 mm rod diameter. Measurements were taken on the same compaction plots as in the first test. This totaled to 60 measurements (*i.e.* 1-cone sizes  $\times$  4 compaction levels  $\times$  5 replicates  $\times$  3 penetrations per plot). This second set of data was used only for model calibration discussed under section 2.2 below.



*Figure 4.3. Compaction process with a John Deere tractor, showing wheel tracks where the soil cone index and bulk density measurements were taken.*

#### 4.3.1.5. Data analysis

The ‘*sp.plot*’ function in the ‘*agricolae*’ package of R programming software (version 4.2.2) was used to analyze the effects of the treatments. The interaction effect between

compaction level and cone size was analyzed to determine if they depended on each other. Tukey HSD test in the same software was utilized to determine the significant differences between the treatment levels at a confident level of 95%.

#### *4.3.2. Simulation of soil-penetrometer interaction*

##### *4.3.2.1. Development of soil-penetrometer model*

The soil-penetrometer interaction model (Figure 4.4) was developed in Particle Flow Code in Three Dimensions (PFC<sup>3D</sup>, version 6.0, Itasca Consulting Group Inc., Minneapolis, USA), DEM software. Spherical soil particles were generated in an open-top cylindrical wall measuring 0.1 m and 0.12 m in diameter and height respectively. Wang et al. (2021) concluded that soil particle size had an insignificant effect on soil resistance when using particles with diameter less than 10 mm. Acquah and Chen (2023) emphasized the likelihood of obtaining inaccurate information about bulk granular material responses when using uniform particle size. Therefore, in this study, the soil particle diameter was set to vary from 3 to 7 mm to ensure the model's accuracy while optimizing computational time.

The soil particles were allowed to settle in the cylinder under gravity until the maximum unbalanced force of soil particles was less than  $1 \times 10^{-3}$  N. To represent the soil condition at various soil compaction levels, the particle density of the model soil was adjusted until the soil matched the soil bulk density for each compaction level in the experiment. The relationship provided in Equation 2.1 was used to compute the dry soil bulk density for each compaction level.

The CAD model of the penetrometer rods and cones were developed in SolidWorks (2019 version, Dassault Systèmes Solidworks Corporation, Waltham, Massachusetts, USA). The

CAD model was imported into the simulation model above the soil surface at the centre. For simulation, the model penetrometer was made to move downward to penetrate the model soil at a constant velocity of  $20 \text{ mm s}^{-1}$  as used in the field test. As the model penetrometer moved down, the contact force between the penetrometer and the soil in the vertical direction was monitored. The force divided by the base area of the penetrometer cone determined the soil cone index (CI).

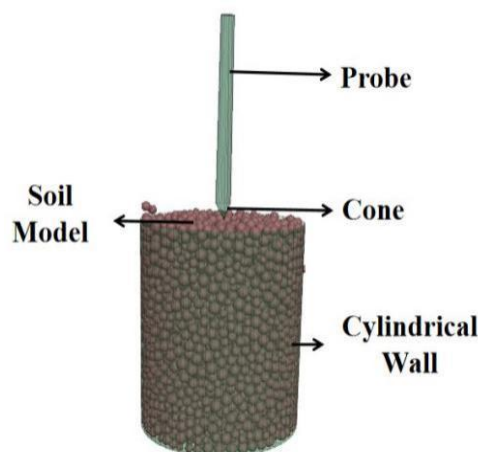


Figure 4.4. Soil-penetrometer interaction model; penetrometer model features the  $100 \text{ mm}^2$  cone size.

Bonds were added between soil particles, known as the parallel bond model (PBM) (Potyondy and Cundall, 2004) to simulate the cohesive behaviour of agricultural soils. A preliminary analysis on the sensitivity of soil cone index to the model parameters showed that the effective modulus of soil particle ( $E_{mod}$ ) had the greatest influence on the soil cone index. Therefore,  $E_{mod}$  was calibrated, as discussed below, and the remaining model parameters were taken from existing literature (Table 2.1).

#### 4.3.2.2. Model calibration and validation

The model parameter  $E_{mod}$  was calibrated using the second set of experimental data from both soils (sandy loam and clay) at the C0 compaction level using the penetrometer with the  $100\text{-mm}^2$  cone size and 8-mm rod. Using the same penetrometer and soil compaction level,

the penetrometer-soil model (Figure 4.5a) was run to obtain the simulated cone indices. In the simulation, the value of  $E_{mod}$  was adjusted until the simulated cone indices matched the measured indices from the experiment. The agreement between simulations and measurements was evaluated using the relative error (RE) described in Equation 2.2.

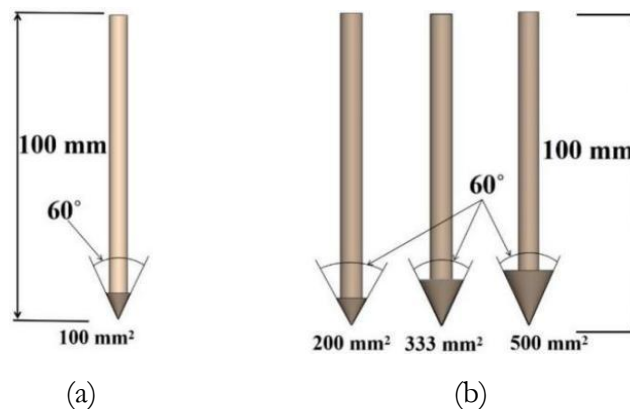


Figure 4.5. Modelled penetrometer: (a) Cone for model calibration (rod diameter: 8 mm); (b) Cones for model validation (rod diameter: 10 mm).

The calibrated model was validated using cone index data from the first set of experimental data for the two soil types (sandy loam and clay) and the three penetrometer cone sizes (200, 333, and 500 mm²) (Figure 4.5b). Using the same cone sizes and soil conditions, the penetrometer-soil model was run to obtain the simulated cone indices. The simulated cone indices were compared with the measured values to assess the model accuracy, evaluated using the relative error (RE) method described in Equation 2.2.

#### 4.3.2.3. Model applications

A cone penetrometer consists of a cone and a rod. These form several surfaces, including the cone base surface, conical surface, cylindrical rod surfaces ( $A_r$ ), and annulus surfaces as shown in Figure 4.6a. How each of these surfaces affects CI and their interactions are important for developing a guide for soil CI measurements. Also, how the apex angle and penetration speeds affect the measured CI values is also important. Therefore, effects of these

parameters were investigated using simulations. The cone base area ( $A$ ) was a primary dimension as it is the area used in determining cone index. As the base area changes, the conical area ( $A_c$ ) and the annulus surface area ( $A_a$ ) also changes (Figure 4.6b). As a result, the contact forces between the penetrometer and the soil also change, ultimately affecting the CI measured.

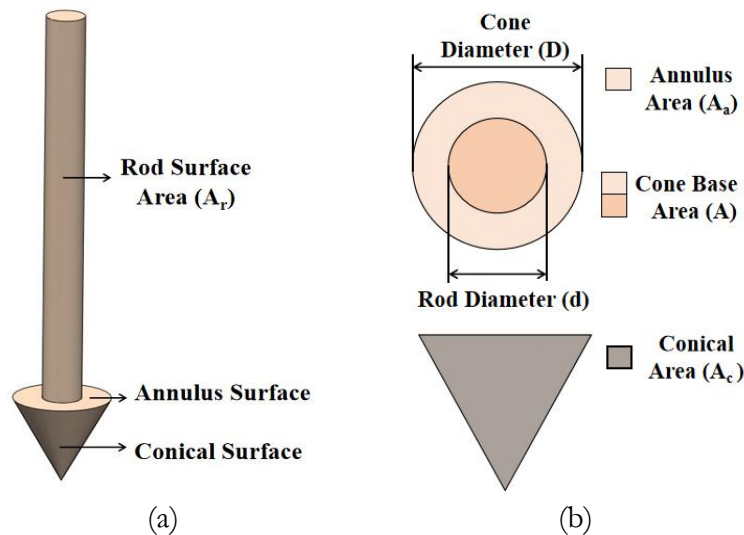


Figure 4.6. Penetrometer parameters. Where (a) cone, rod and annulus surfaces, and (b) different cone dimensions.

Simulations were performed using the validated model to examine the effects of the above parameters. The base value and range of each parameter were set as listed in Table 4.1. In the simulations, when examining one parameter, its value was varied within the range, while the other parameters were kept constant at the base values.

Table 4.1. Model application parameters and ranges

| Parameter         | Unit               | Base value | Intervals | Range     |
|-------------------|--------------------|------------|-----------|-----------|
| Cone base area    | mm <sup>2</sup>    | 100        | 100       | 100-1,000 |
| Rod diameter      | mm                 | 10         | 2         | 8-16      |
| Penetration speed | mm s <sup>-1</sup> | 20         | 20        | 20-100    |
| Cone apex angle   | °                  | 60         | 15        | 30-90     |

## 4.4. Results and discussion

### 4.4.1. Field experiment results

#### 4.4.1.1. Depth profile of soil moisture content

For both soils, the gravimetric moisture content generally decreased with soil depth (Figure 4.7), similar to that observed by other researchers (Zhao et al., 2020). Sandy loam (Figure 4.7a) had a significantly lower gravimetric moisture content as compared to the clay soil (Figure 4.7b), due to clay particles having better soil retention capacity than sand particles (Zhao et al., 2020). The higher moisture content in the top layers of the sandy soil was due to the rainfall prior to the measurements. For clay soil, the gravimetric moisture content increased from 0-40mm to 40-80mm, before dropping with soil depth. This was due to the lack of rain prior to the measurement, which allowed for cracks to form on the top of the soil upper layer, preventing moisture at the deeper sublayers from evaporating, as demonstrated in the review by Wei et al. (2020).

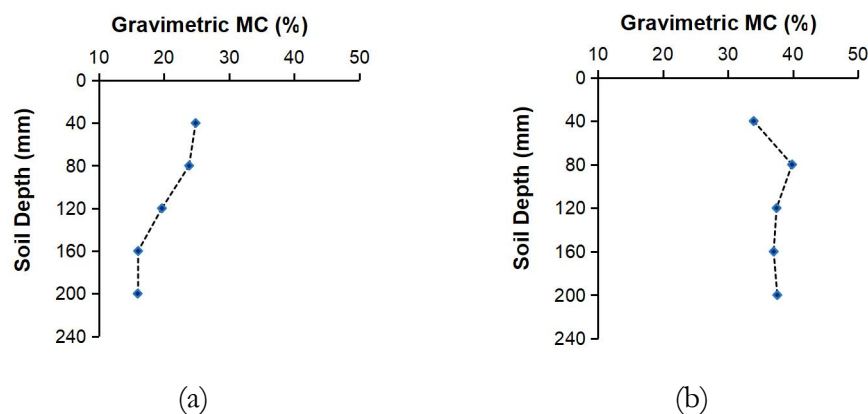


Figure 4.7. Initial field soil moisture content (MC) (dry basis) with depth: (a) Sandy loam; (b) Clay.

#### 4.4.1.2. Soil bulk densities

Both soils experienced a general increasing trend in bulk density as compaction increased, although there were no significant differences between treatments (Figure 4.8). Clay soil consistently had a slightly higher bulk density than sandy loam soil at each compaction level. Sandy loam had an 8.96% difference in magnitude between C0 and C3 (Figure 4.8a), while clay soil had a difference of 6.67% between the same compaction levels (Figure 4.8b). Similar results were reported by Li et al. (2016). This was an expected outcome, as increased bulk density typically relates to more compacted soils. Highly compacted soils have less total porosity, equivalent to less pores for water and air incorporation within the soil, resulting in greater bulk density. Increased bulk density may lead to mineral and nutrient depletion, resulting in poor root performance in water and nutrient absorption (Shaheb et al., 2021). This results in significant yield reduction (McPhee et al., 2020).

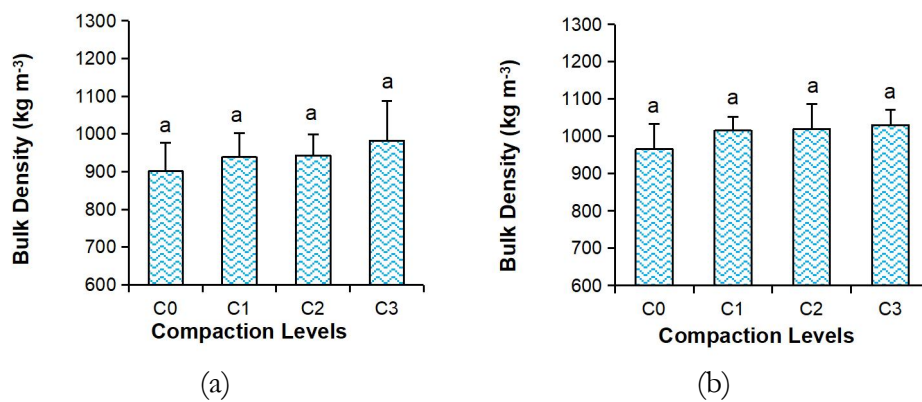


Figure 4.8. Bulk density per compaction level: (a) Sandy loam; (b) Clay. Where C0, C1, C2, and C3, represent compaction levels zero, one, two, and three, respectively. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ).

#### 4.4.1.3. Soil cone indices (CI) of the sandy loam soil

The CI results were plotted against soil depth, showing how CI changes with each treatment (Figure 4.9). Soil CI increased with greater soil depth, due to deeper soil sub-layers

having different coarseness with increasing depth (Hudson et al., 2023). For C0, A similar and gentle slope of increasing CI with depth was observed for all cone sizes with alternating magnitudes (Figure 4.9a). The S2 cone had higher CI at the start of penetration until 50 mm where it recorded lower CI than S3.33 and S5 cones. The S3.33 cone recorded similar CI as S5 down to 70 mm where S3 values rose in CI than S5 until end of penetration. The S2 cone recorded the highest CI, with overlapping magnitudes with S3.33 and S5 cones at 70 mm and 120 mm respectively. This behaviour occurred at 130 mm between S2 and S3.33 and, at 160 mm between S2 and S5 for C2 (Figure 4.9b, c). For C3, S3.33 recorded higher magnitudes than S2 and S5 until 150 mm, where it alternated with S2 until end of penetration (Figure 4.9d). It had similar values with S5 down to 140 mm. The maximum penetration depth decreased with increasing cone size at all compaction levels. This may be due to the gritty, stony and dry nature of the sandy particles causing large cones to experience high resistance force (Hudson et al., 2023), preventing deeper penetration.

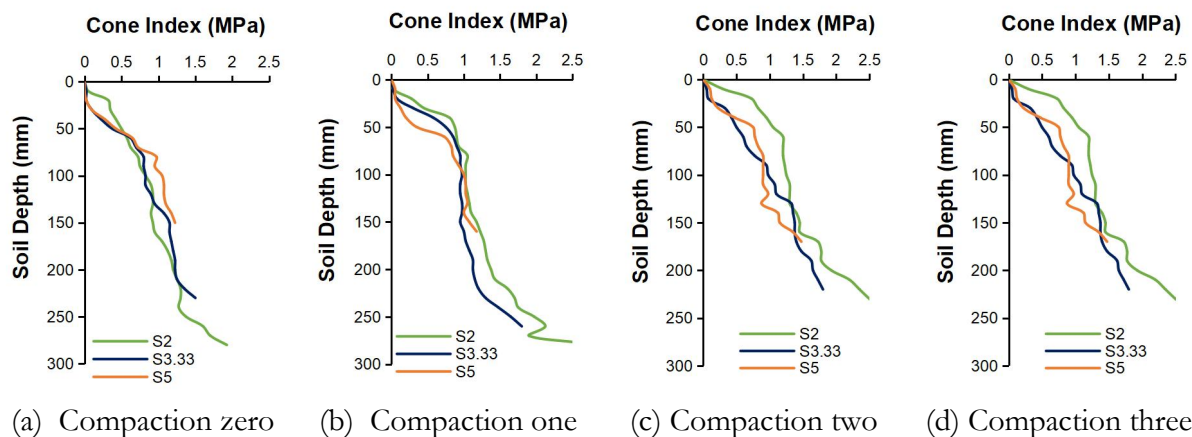


Figure 4.9. Sandy loam soil CI-depth curves. Where S2, S3.33, and S5 represents cone size 200, 333 and 500  $\text{mm}^2$  respectively.

To examine the effects of soil compaction level and penetrometer cone size on soil cone indices, cone index data were averaged over 100 mm depth intervals: 0-100 mm and 100-200 mm. The treatment effects on the average CI were examined at each depth range. The ANOVA results in Tables 4.2 indicate no significant interaction effect between compaction

level and cone size at any of the two depth ranges. However, their individual effects were significant.

*Table 4.2. ANOVA results of the effect of compaction levels and penetrometer cone sizes on CI for sandy loam soil*

| Penetration depth (mm) | Source of variation              | DoF | Sum Sq.  | Mean Sq. | F-value | P-value  |
|------------------------|----------------------------------|-----|----------|----------|---------|----------|
| 0 - 100                | Replicate                        | 3   | 0.02428  | 0.008093 | 0.2880  | 0.833319 |
|                        | Compaction levels                | 3   | 0.17588  | 0.058627 | 13.3546 | 0.001156 |
|                        | Main plot error                  | 9   | 0.03951  | 0.004390 |         |          |
|                        | Cone sizes                       | 2   | 0.04726  | 0.023628 | 0.8407  | 0.452053 |
|                        | Compaction levels:<br>Cone sizes | 6   | 0.17046  | 0.028411 | 1.0109  | 0.456755 |
|                        | Split plot error                 | 31  | 0.39346  | 0.028104 |         |          |
| 100 - 200              | Replicate                        | 3   | 0.093753 | 0.031251 | 1.4917  | 0.2599   |
|                        | Compaction levels                | 3   | 0.165933 | 0.055311 | 1.9781  | 0.1879   |
|                        | Main plot error                  | 9   | 0.251656 | 0.027962 |         |          |
|                        | Cone sizes                       | 2   | 0.025281 | 0.012640 | 0.6034  | 0.5606   |
|                        | Compaction levels:<br>Cone sizes | 6   | 0.293304 | 0.018776 | 0.8962  | 0.5240   |
|                        | Split plot error                 | 31  | 0.293304 | 0.020950 |         |          |

For the 0-100 mm range, there was a significant magnitude change in CI between C0 and the other compaction levels (Figure 4.10a), which may correspond to the high magnitude change in bulk density between them (Figure 8a). No apparent trend existed between the different compaction levels for the depth range of 100-200 mm (Figure 4.10b). In general, the CI values decreased slightly with larger cones (Figures 4.10c, d), a trend supported by previous studies (Whiteley and Dexter, 1981; Zhuang and Yu, 2018). However, the decreasing trend was not statistically significant.

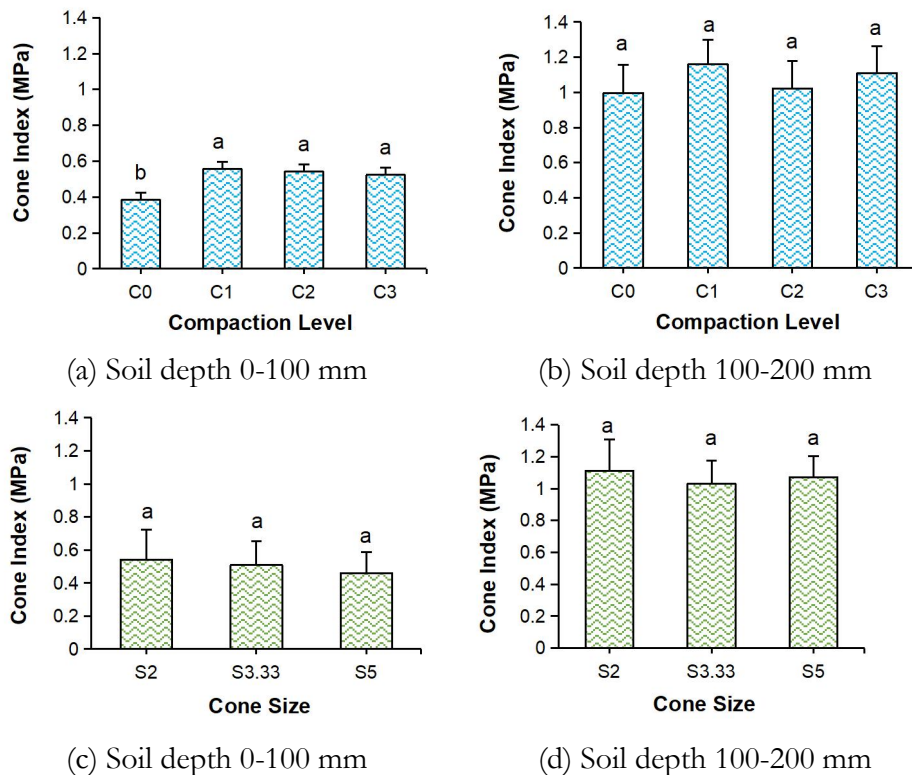


Figure 4.10. Effect of (a, b) compaction level and (c, d) cone size on soil CI for clay. Where C0, C1, C2, and C3, represent compaction levels zero, one, two, and three respectively, and S2, S3.33, and S5 represents cone sizes 200, 333 and 500 mm<sup>2</sup> respectively. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ).

#### 4.4.1.4. Soil cone indices (CI) of the clay soil

A trend of increasing CI with depth was recorded for all cone sizes and compaction levels until 800 mm (Figure 4.11). Sudden horizontal or vertical constant lines of data signify either a brief loss in connection from the depth sensor to the data acquisition system of the penetrometer, or inconsistent penetration speed. This could also be either due to extreme resistance from the soil or a stone in the soil (Mahore et al., 2024). A peak CI was recorded within the first 100 mm of soil depth from C1 to C3 (Figures 4.11b-d). At this depth, CI did not peak for the zero compaction (C0) (Figures 4.11a). Thus, one could conclude that peaks of CI for C1 to C3 were the result of tractor wheel compaction. The soil natural behaviour

caused the trend between 200-800 mm where relatively same CI recorded in each compaction level.

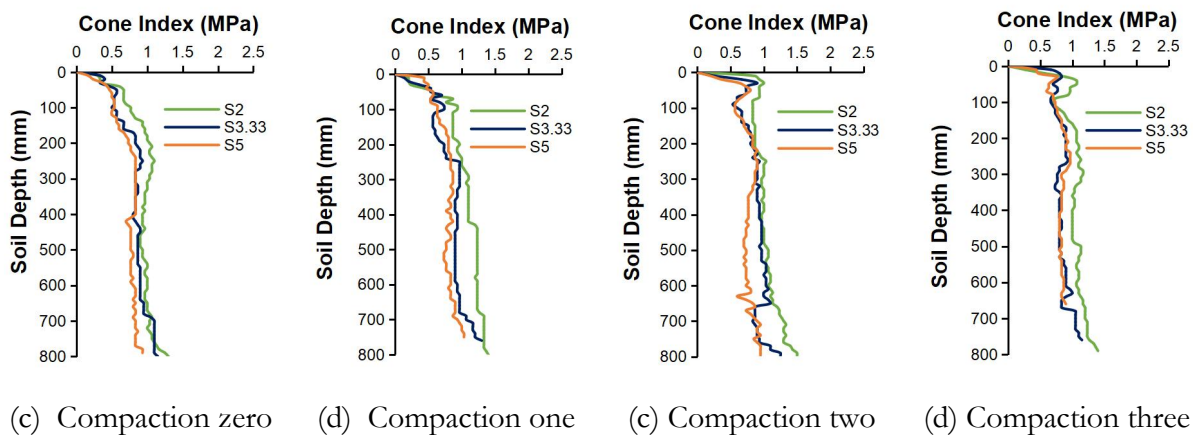


Figure 4.11. Clay soil CI-depth curves. Where S2, S3.33, and S5 represents cone size 200, 333 and 500 mm<sup>2</sup> respectively.

To examine the effects of soil compaction level and penetrometer cone size on soil cone indices of the clay soil, cone index data were averaged over 100 mm depth intervals: 0-100 mm and 100-200 mm. ANOVA results showed a significant individual effect of compaction and cone size on soil CI (Table 4.3), but their interaction effects were not statistically significant.

Table 4.3. ANOVA results of the effect of compaction levels and cone sizes on CI for clay soil

| Penetration depth (mm) | Source of variation           | DoF | Sum Sq.  | Mean Sq. | F-value  | P-value  |
|------------------------|-------------------------------|-----|----------|----------|----------|----------|
| 0 - 100                | Replicate                     | 3   | 0.01051  | 0.002628 | 0.5350   | 0.7110   |
|                        | Compaction levels             | 3   | 0.40471  | 0.13904  | 27.32652 | 1.213e-5 |
|                        | Main plot error               | 9   | 0.05937  | 0.004948 |          |          |
|                        | Cone sizes                    | 2   | 0.13323  | 0.066616 | 13.5627  | 5.867e-5 |
|                        | Compaction levels: Cone sizes | 6   | 0.03620  | 0.006033 | 1.2283   | 0.3188   |
|                        | Split plot error              | 31  | 0.15226  | 0.004912 |          |          |
| 100 - 200              | Replicate                     | 3   | 0.021099 | 0.005275 | 1.8959   | 0.13613  |
|                        | Compaction levels             | 3   | 0.086917 | 0.028972 | 4.0188   | 0.03414  |
|                        | Main plot error               | 9   | 0.086511 | 0.007209 |          |          |
|                        | Cone sizes                    | 2   | 0.177872 | 0.088936 | 31.9654  | 2.926e-8 |
|                        | Compaction levels: Cone sizes | 6   | 0.029856 | 0.004976 | 1.7885   | 0.13411  |
|                        | Split plot error              | 31  | 0.086250 | 0.002782 |          |          |

For the 0-100 mm range, the average soil CI increased significantly with higher compaction levels (Figure 4.12a) (Kumar et al., 2012). However, the rate of change decreased with increasing compaction level with values of 0.12, 0.07, and 0.02 MPa respectively between C0 and C1, C1 and C2, and C2 and C3. Similar to the 0-100 mm depth range, the data for the 100-200 mm depth range showed an increasing trend in CI with higher compaction Figure 4.12b, where significant differences in soil CI were observed between C0 and C3.

In terms of the effect of penetrometer cone size, soil CI in the 0-100 mm range decreased with larger cone sizes, showing significant differences between the cone sizes (Figure 4.12c). For the 100-200 mm range, measured CI using the cone size S2 differed significantly from those using S3.33 and S5 (Figure 4.12d). This may be attributed to the inconsistent increase in manually applied pressure with larger cone sizes, as the greater surface area of larger cones encounters higher resistance in compacted soils (Royal Eijkelpamp, 2022). At the same penetration depth, smaller cones experience higher tip resistance than larger cones (Zhuang and Yu, 2018). This variation may be influenced by the normalized surface roughness ( $R_a/d_{50}$ ) of the cone and decreases with greater depth (Zhuang and Yu, 2018). In addition, the effective rod diameter during penetration may be larger than the true diameter, leading to variations in the resultant cone index (Whiteley and Dexter, 1981).

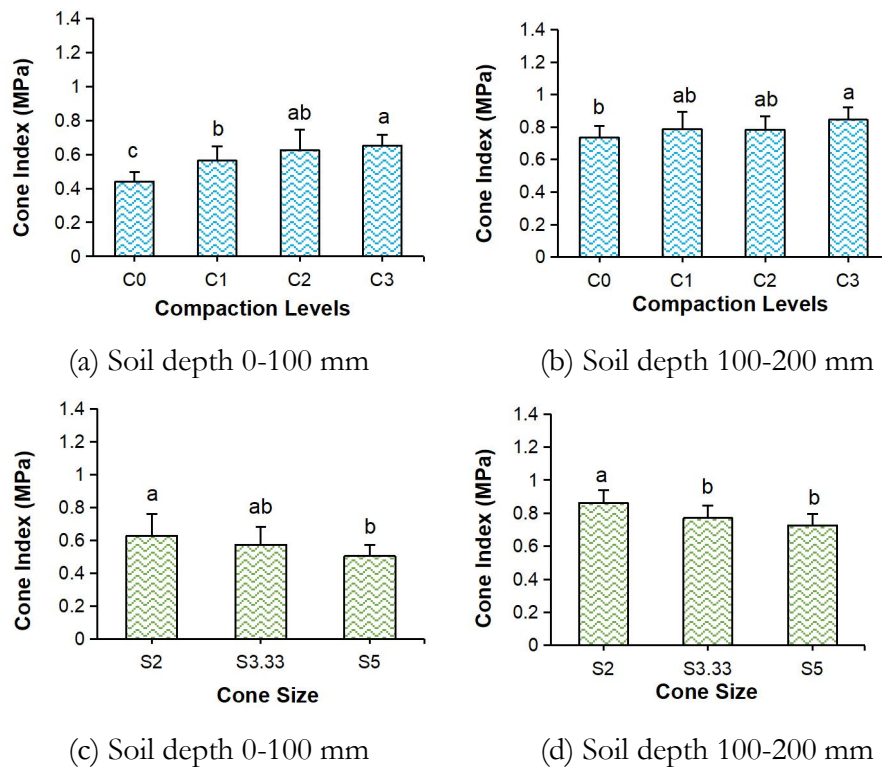


Figure 4.12. Effect of (a, b) compaction level and (c, d) cone size on soil CI for clay. Where S2, S3.33, and S5 represents cone size 200, 333 and 500 mm<sup>2</sup> respectively, and C0, C1, C2, and C3, represent compaction levels zero, one, two, and three respectively. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ).

Beyond 200 mm, the trend observed reflected only the soil's natural composition, devoid of compaction effect. Therefore, effects of soil compaction on CI are not presented beyond this depth. Variation in CI with cone size was examined at 100 mm intervals from 200 to 800 mm soil depth (Figure 4.13). For each of the six different depth ranges, CI constantly decreased with increasing cone size, with significant differences between all the cone sizes, except for the 600-700 mm interval where only S3.33 and S5 experienced similar CI. Measurements showed a minimum CI of 0.77 MPa between 400 and 500 mm (Figure 4.13c) for S5 and a maximum CI of 1.25 MPa between 700 and 800 mm (Figure 4.13f) for S2. The average change in magnitude between S2 and S3.33 was 0.15 MPa, and between S3.33 and S5 was 0.088 MPa. This trend of decreasing soil cone index with increasing cone size is evident in prior research (Whiteley and Dexter, 1981), and explained above.

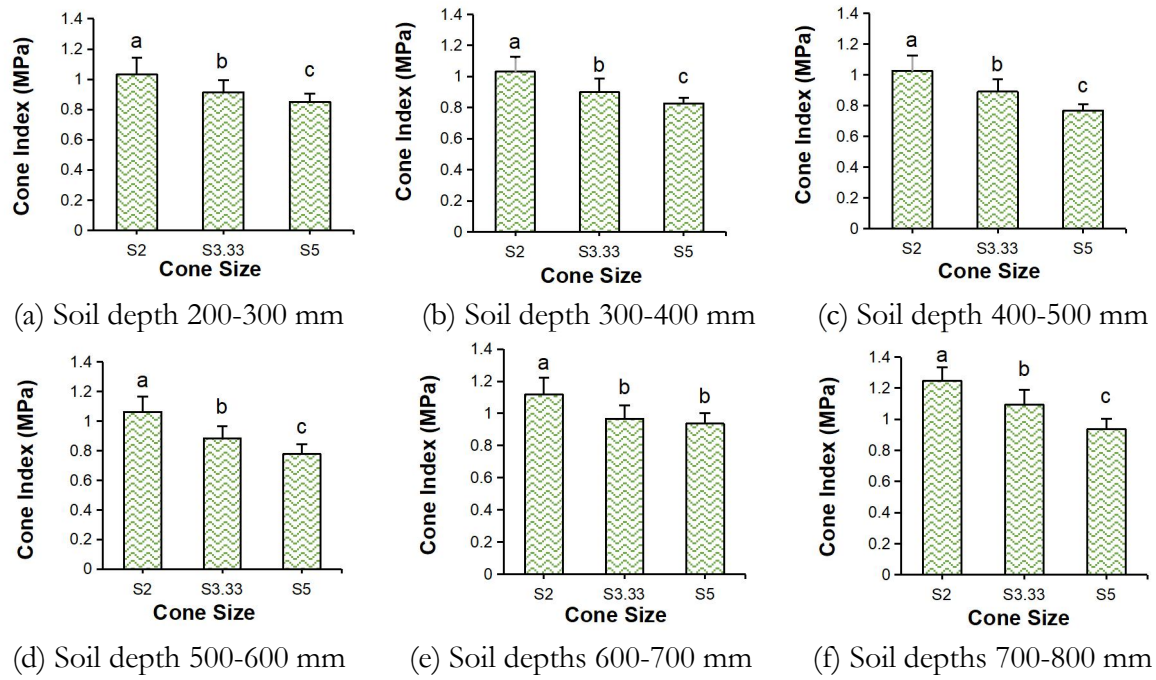


Figure 4.13. Variation in soil CI with cone size at soil depths of 200 to 800 mm for clay soil. Where S2, S3.33, and S5 represents cone size 200, 333 and 500 mm<sup>2</sup> respectively. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ).

#### 4.4.2. Simulation results of soil-penetrometer interaction model

##### 4.4.2.1. Model calibration results

The calibration simulation was run using a range of  $E_{mod}$  values from  $1e5$  to  $2e5$  Pa, with intervals of  $0.1e5$ . The resultant CI values were compared with the measurements. The best match between the simulated and measured CI values was found when  $E_{mod}$  value was  $1.6e5$  Pa for sandy loam and  $1.1e5$  Pa for clay. With these  $E_{mod}$  values, the simulated CI values under different soil compaction levels are shown in Figure 4.14, together with the measured values. The relative errors for sandy loam were between 0.32 and 10.98%, and those for clay were between 0.09 and 13.94%. These observed errors may be attributed to the selected particle stiffness, where low stiffness values may result in reduced pressure transmission in the models, as observed by both (Acquah and Chen, 2023; De Pue and Cornelis, 2019).

However, the relative errors were low and acceptable in DEM parameter calibrations (Wang, et al., 2021; Zeng et al., 2020).

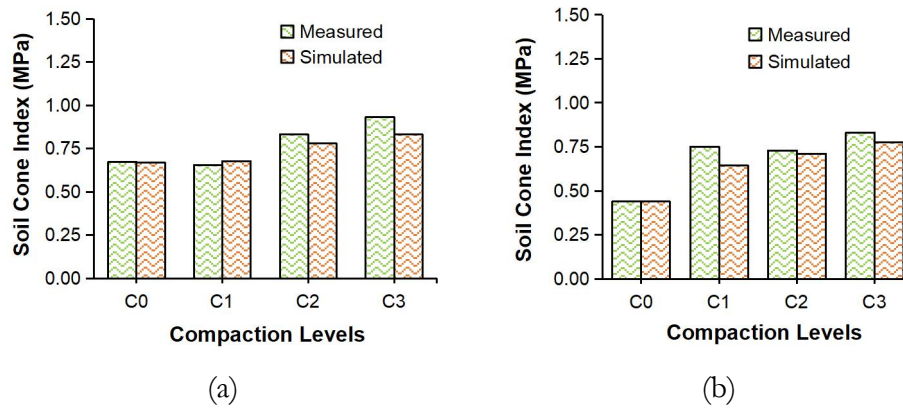


Figure 4.14. Calibrating the effective modulus at different compaction levels per soil type: (a) Sandy loam; (b) Clay. Where C0, C1, C2, and C3 are compaction zero, one, two and three respectively.

#### 4.4.2.2. Validation of soil-penetrometer interaction model in sandy loam soil

Figure 4.15 shows both simulated and measured average cone indices. At C0 (Figure 4.15a), the model performed well, with REs of 0.36, 0.85, and 8.31% for the 200, 333, and 500 mm<sup>2</sup> cones, respectively. The corresponding REs were 7.19, 6.43, and 16.09% (Figure 4.15b) for C1, and 8.22, 11.83, and 14.78% for C2. For C3, the highest RE was 16.84% for the 333-mm<sup>2</sup>, while the 200 and 500 mm<sup>2</sup> cones had REs of 6.09 and 12.45%, respectively (Zeng, Ma, et al., 2020). In general, the model performed better at the zero compaction level than at the other compaction levels.

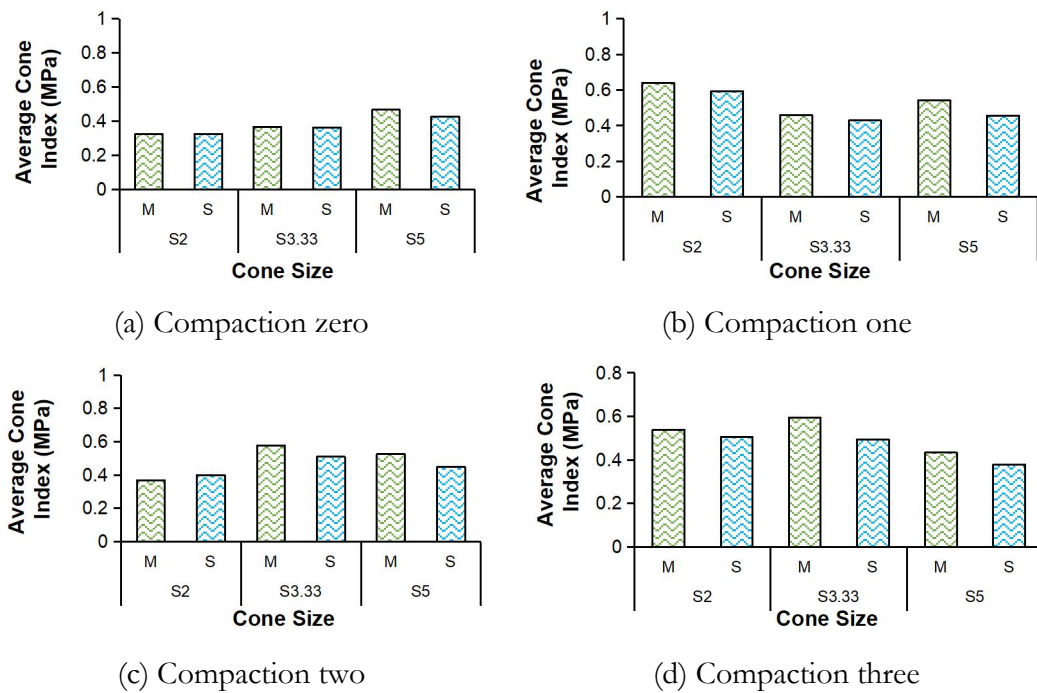


Figure 4.15. Measured (M) and simulated (S) averages of soil-cone index per cone size for sandy loam soil at 100 mm depth. Where S2, S3, and S5 are cone sizes 200, 333 and 500 mm<sup>2</sup> respectively.

#### 4.4.2.3. Validation of soil-penetrometer interaction model in clay soil

Measured averages (Figure 4.16a-d) showed a general decreasing trend in CI with increasing cone size as explained for the field test. This trend appeared in both the simulation and the physical test. The REs increased with increasing compaction levels, with minimum and maximum averages of 4.61% and 16.36%, respectively, calculated for C2 (200 mm<sup>2</sup>) and C1 (333 mm<sup>2</sup>). This falls within acceptable range also recorded in the study conducted by (Zeng, Ma, et al., 2020).

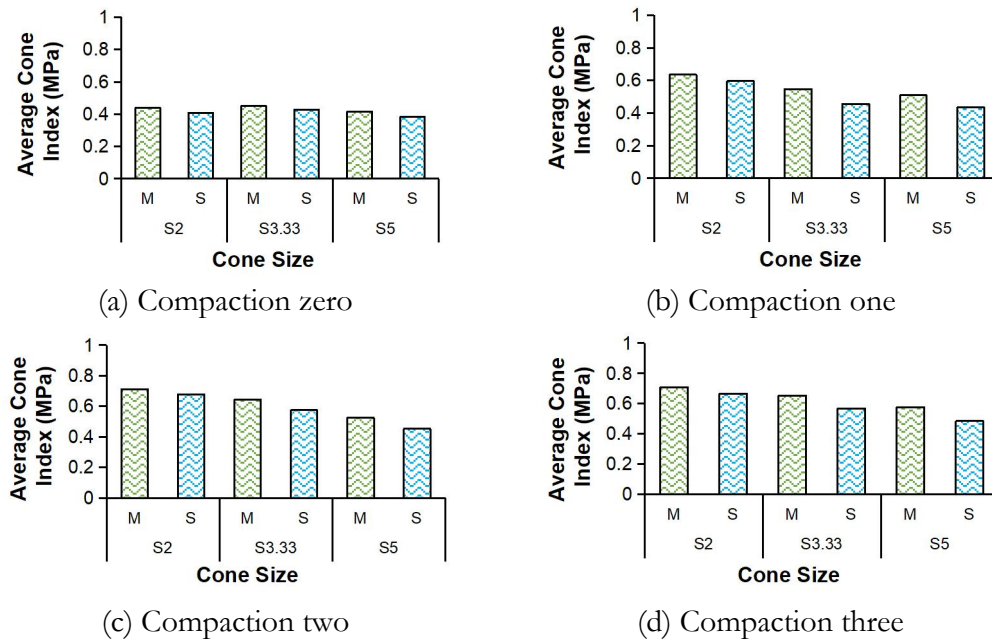


Figure 4.16. Measured (*M*) and simulated (*S*) averages of soil-cone index per cone size for clay soil at 100 mm depth. Where *S2*, *S3*, and *S5* are cone sizes 200, 333 and 500 mm<sup>2</sup> respectively.

#### 4.4.2.4. Soil force-chain distribution and micro-mechanical behaviour

The velocity contour of the model soil (Figure 4.17a) represents the kinetic energy exerted by the penetrometer cone and rod during penetration, with constant soil model parameters but varying cone sizes. As the cone size increased, demonstrated in Figure 4.17a from left to right, there was an increase in the particle velocities within the soil model. The surface area of the cones represents the extent and magnitude of soil interaction interface. Larger cone surface area resulted in greater interaction with the soil particles, leading to higher ball-velocity (force distribution). This behaviour is also reflected in the trend of the penetrometer breaking soil bonds and displacing particles (Figure 4.17b). The 500-mm<sup>2</sup> cone caused the most bond breaking and particle displacement, followed by the 333, 200, and 100 mm<sup>2</sup> cones.

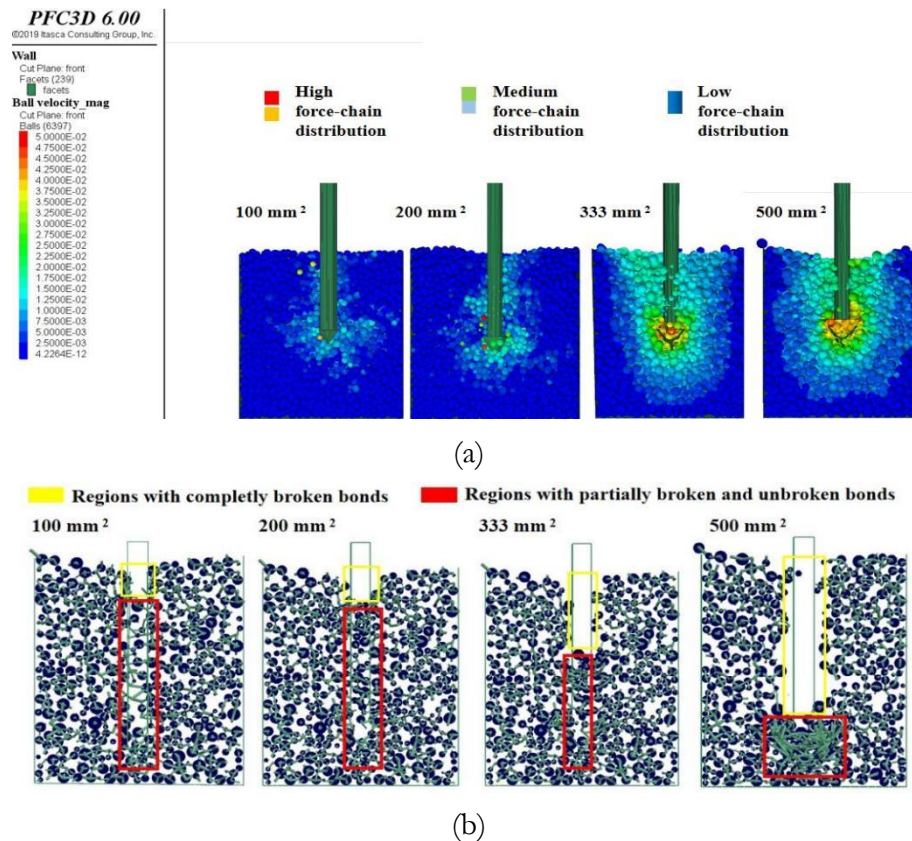


Figure 4.17. Cross-sectional view of CI simulation showing soil (a) force-distribution, and (b) mechanical behaviour during penetration per cone size.

#### 4.4.2.5. The effect of penetration speed and penetrometer geometry on soil cone indices

The response of the soil model to variations in a single penetrometer model parameter, while keeping the other parameters at their base values (Table 4.1), is shown in Figure 4.18. Penetration speed minimally affected cone index (CI) in sandy loam and clay soils (Figure 4.18a). Changes in CI were minor at higher speeds, with a 0.1 MPa increase observed between 80 and 100 mms<sup>-1</sup> for sandy loam. Clay soil showed CI increasing up to 60 mms<sup>-1</sup>, then decreases. The data fit linear relationships, with coefficients of determination ( $R^2$ ) of 0.7898 for sandy loam and 0.6254 for clay. Both soils showed a more rapid increase in CI with varying rod diameters (Figure 4.18b), indicating that the rod and cones did not function

independently (Ingling et al., 1977). For sandy loam, CI increased from 0.67 to 0.72, 0.85, 1.00, and 1.26 MPa for rod diameters of 8, 12, 14, 16, and 18 mm, respectively, with a strong  $R^2$  of 0.9399. For clay, a similar but slightly lower increasing trend was observed, with CI values of 0.44, 0.61, 0.69, 0.84, and 1.06 MPa respectively for the same rod diameters, and a prediction accuracy of 97.75%. There were minimal changes in CI with increasing cone apex angle. For sandy loam, CI ranged between 0.67 and 0.72 MPa at 60 and 75°, respectively, while for clay soil, CI ranged between 0.44 and 0.61 MPa respectively at 60 and 90° (Figure 4.18c). Both soils had lower CI at 60°. In summary, penetrometer rod diameter had the greatest influence on both soil's CI (Zhuang and Yu, 2018), likely due to the increased rod surface area, which caused greater interaction with model particles during penetration.

Effects of cone sizes (base area) showed non-constant values (Figure 4.18d). The 100-mm<sup>2</sup> cone resulted in CI values of 0.67 MPa and 0.45 MPa for the sandy loam and clay soils, respectively. The cone size (1000-mm<sup>2</sup>) reduced CI values to 0.29 MPa and 0.18 MPa for the sandy loam and clay soils, respectively. With the same rod diameter, smaller cones that have lower cone-rod diameter ratios had more rod-soil interactions that increase the soil resistances, and therefore, increase the soil cone indices. The non-linear decreasing trends of the CIs can be explained by the non-linear relationship between base areas and rod diameters. In general, lower CI magnitudes were observed in clay compared to sandy loam across all tested parameters, corresponding to the lower values seen in both the field and model validation.

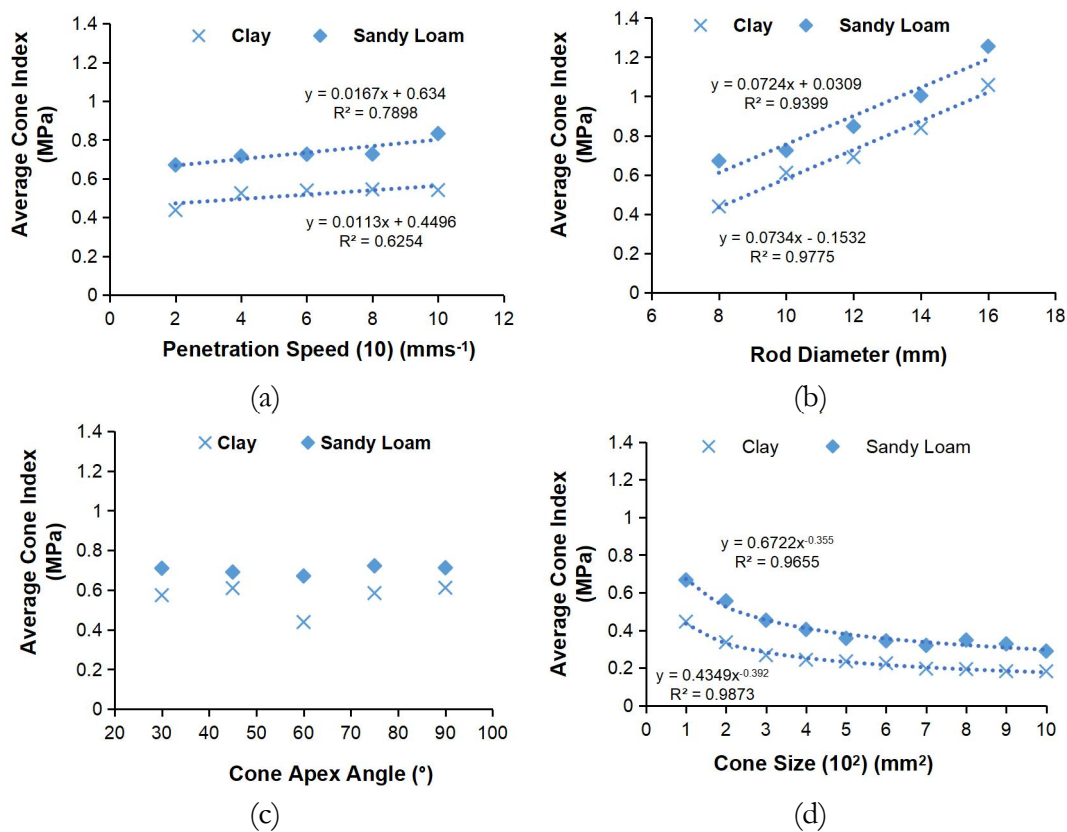
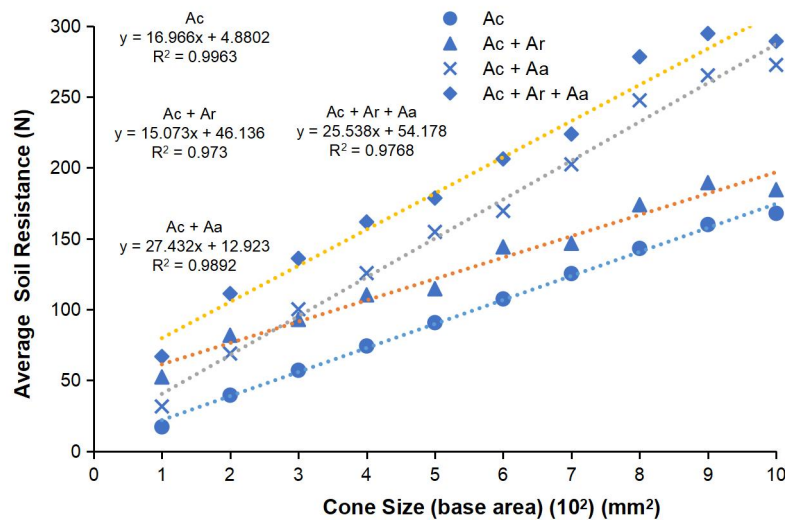


Figure 4.18. CI response to varying (a) penetration speed [cone size: 100 mm<sup>2</sup>; rod diameter: 10 mm; cone apex angle: 60°], (b) rod diameter [cone size: 100 mm<sup>2</sup>; penetration speed: 20 mms<sup>-1</sup>; cone apex angle: 60°], (c) cone apex angle [cone size: 100 mm<sup>2</sup>; penetration speed: 20 mms<sup>-1</sup>; rod diameter: 10 mm], and (d) cone size [penetration speed: 20 mms<sup>-1</sup>; rod diameter: 10 mm; cone apex angle: 60°].

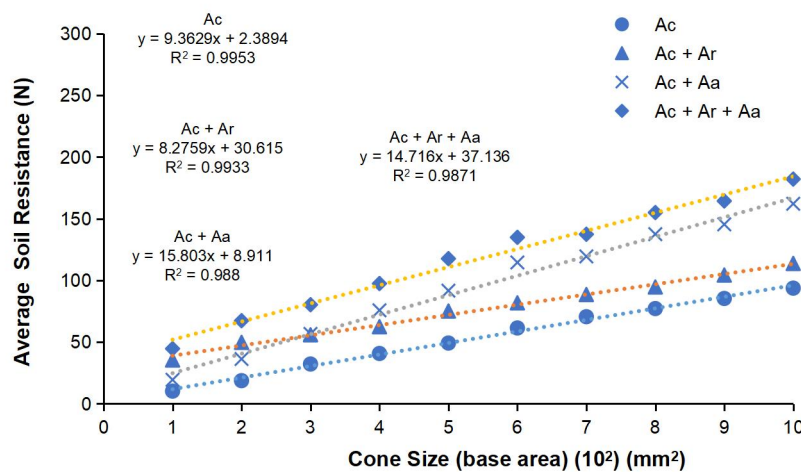
For a given cone penetrometer, the measured cone index value depends on the resistance force (in the vertical direction) exerted by the soil on the cone penetrometer for the specified area of the cone base. Thus, soil resistance forces between the cone penetrometer and the soil were analyzed for several different contact surfaces as illustrated in Figure 4.6a. This included four scenarios: (1) soil resistance acting only on the conical surface ( $F_c$ ), (2) soil resistance acting on both the conical and rod surfaces ( $F_c + F_r$ ), (3) soil resistance acting on both the conical and annulus surfaces ( $F_c + F_a$ ), and (4) soil resistance acting on all the three surfaces ( $F_c + F_r + F_a$ ). The results are shown in Figure 4.19. Soil resistance force in sandy loam increased sharply with cone size, with average increases of 25.37%, 70.64%, and 96.99%,

respectively, between  $A_c$  and  $A_c + A_r$ ,  $A_c$  and  $A_c + A_a$ , and  $A_c$  and  $A_c + A_r + A_a$  (Figure 4.19a). Clay showed a similar trend, with smoother slopes and increases of 55.08%, 865.43%, and 139.27%, respectively, for the same penetrometer surface area combinations (Figure 4.19b). The increase in soil resistance forces for both soils was due to the larger particle-penetrometer contact areas of the larger cone. Regression analysis revealed strong correlations, with  $R^2$  values ranging from 0.9768 to 0.9963 for sandy loam and 0.9871 to 0.9953 for clay.

The results showed that all surfaces of the penetrometer in contact with the soil model, including  $A_c$ ,  $A_r$ , and  $A_a$  contributed to the soil resistance forces. The soil resistance consists of the friction and adhesion forces between penetrometer surface and soil in the vertical direction (Okello, 1991). Cone penetrometers were developed to measure soil cone index that should be the vertical pressure exerted on  $A_c$ . Therefore, cone penetrometers should record only the soil resistance force on  $A_c$ . Soil resistance forces on  $A_r$  and  $A_a$  are unwanted forces and should be eliminated in cone index measurements. This can be achieved through using a sleeve on penetrometer rod. Both penetrometers, with and without sleeves, have been used to measure soil cone indices (Kumar et al., 2012; Robertson and Cabal, 2015; Zeng and Chen, 2016). However, the outputs from both penetrometer types would be different under the same soil conditions. Industrial penetrometers equipped with pushing equipment are mostly designed with sleeves (Robertson and Cabal, 2015). However, there are no standards on sleeve designs or their inclusion in handheld penetrometers.



(a) Sandy loam



(b) Clay

Figure 4.19. Soil resistance as affected by varying cone size per soil type at constant penetration speed ( $20 \text{ mm s}^{-1}$ ), rod diameter ( $10 \text{ mm}$ ), and cone apex angle ( $60^\circ$ ).

Results from this study confirmed the need for sleeves in penetrometer rod designs to eliminate the effects of the rod. Additionally, the diameter of the sleeve should match the diameter of the cone base to eliminate the effects of the annulus. This conclusion was further demonstrated by simulating the cone indices of a cone penetrometer with a sleeve that has the same diameter as the cone base. In the simulation, instead of adding a sleeve in the penetrometer model, the cone index was determined as the simulated soil resistance on the conic surface ( $F_c$ ) divided by the cone base area ( $A_c$ ), based on the definition of soil cone

index. Results showed that the CI values were consistent for both soil types as cone size increased (Figure 4.20). This aligns with the theory of soil mechanics, where soil cone index (in pressure units) should not vary with the contact surface. Therefore, there is the need to include sleeves in penetrometer rod designs to ensure accuracy in soil resistance measurement.

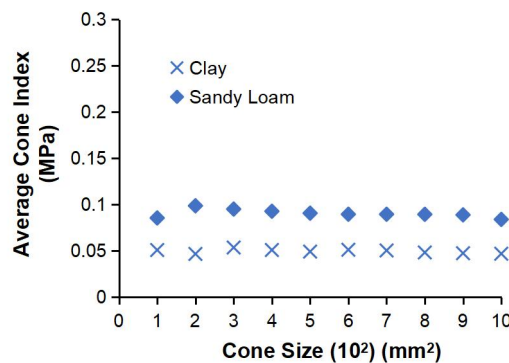


Figure 4.20. Soil CI derived from contact force on the conic surface area ( $A_c$ ) at constant penetration speed ( $20 \text{ mm s}^{-1}$ ), rod diameter ( $10 \text{ mm}$ ), and cone apex angle ( $60^\circ$ ).

## 4.5. Conclusion

The study evaluated the effects of field traffic-induced soil compaction in clay and sandy loam soils and penetrometer geometry on soil cone index (CI) through measurements and modelling. The following conclusions are drawn. Field measurements showed that soil CI was influenced by both soil compaction level and penetrometer geometry, increasing with compaction level and decreasing with cone size. The clay soil showed higher CI differences between compaction levels than the sandy loam. The DEM model results supported the field data, while revealing additional insights as following. The CI values increased linearly with the penetration speed and rod diameter. Cone apex angle had little effect on the CI. Varying the penetrometer rod diameter had a greater effect on CI than penetration speed. There was a non-linear decreasing trend in CI as the cone size decreased from  $100$  to  $1000 \text{ mm}^2$ . This was due to the complex effects of the relative dimensions between the penetrometer cone and rod,

proved by the model results. To avoid these effects, a penetrometer design incorporating a sleeve is recommended. The outer diameter of the sleeve should be equal to the base diameter of the corn base. The results from this study have important implications on managing field traffic and developing cone penetrometer standards.

The study provides critical insights into how soil compaction influence soil cone index (CI). Further research was needed to understand how these mechanical changes translate into crop response and productivity. Soil CI reflects penetration resistance, which directly affects root growth, and water infiltration. These are key factors determining plant establishment. Investigating crop physiological responses under varying compaction levels would help identify tolerance thresholds for different soil types. Such research would bridge the gap between mechanical soil behaviour and biological performance, enabling the development of integrated soil management practices that balance traffic efficiency with optimal crop growth and sustainability. Therefore, the concluding chapter of this thesis investigated the effect of soil compaction on crop performance.

#### 4.6. References

- Acquah, K., and Chen, Y. (2023). Discrete element modelling of soil pressure under varying number of tire passes. *Journal of Terramechanics*, 107, 23–33. <https://doi.org/10.1016/j.jterra.2023.02.003>
- Adeniran, K. A., and Babatunde, O. O. (2010). Investigation of wetland soil properties affecting optimum soil cultivation. *Journal of Engineering Science and Technology Review*, 3(1), 23–26. <https://doi.org/10.25103/jestr.031.04>
- Ameratunga, J., Sivakugan, N., and Das, B. M. (2016). *Cone Penetrometer Test*. 2(4), 115–157. [https://doi.org/10.1007/978-81-322-2629-1\\_5](https://doi.org/10.1007/978-81-322-2629-1_5)
- ASTM D7263-21. (2021). *Standard Test Methods for Laboratory Determination of Density*

and Unit Weight of Soil Specimens. <https://doi.org/2021>

ASTM Standard. (2019). *ASTM Standard Cone Penetrometer Sizes: Which is Best for Your Application?* Geotill Engineering, Inc.

<https://geotill.com/astm-standard-cone-penetrometer-sizes-which-is-best-for-your-application/#:~:text=Most CPT cones range from 5 cm2 to,accurate cone resistance values in very soft soils.>

ASTM Standard D3441-16. (2018). Standard Test Method for Mechanical Cone Penetration Testing of Soils. *ASTM International*. <https://www.astm.org/d3441-16.html>

De Pue, J., and Cornelis, W. M. (2019). DEM simulation of stress transmission under agricultural traffic Part 1: Comparison with continuum model and parametric study. *Soil and Tillage Research*, 195(March). <https://doi.org/10.1016/j.still.2019.104408>

Eijkelpamp, R. (2022). *Penetroviewer* (V6.08). <https://www.royaleijkelpamp.com/media/nrwjyah3/m-0615sae-penetrologger.pdf>

Hudson, K. S., Ulmer, K. J., Zimmaro, P., Kramer, S. L., Stewart, J. P., and Brandenberg, S. J. (2023). Unsupervised machine learning for detecting soil layer boundaries from cone penetration test data. *Earthquake Engineering and Structural Dynamics*, 52(11), 3201–3215. <https://doi.org/10.1002/eqe.3961>

Ingling, C. R., Lewis, A. L., Loose, D. R., and Myers, K. J. (1977). Cones change rod sensitivity. *Vision Research*, 17(4), 555–563. [https://doi.org/10.1016/0042-6989\(77\)90054-2](https://doi.org/10.1016/0042-6989(77)90054-2)

Jayaraman, S., Dalal, R. C., Patra, A. K., and Chaudhari, S. K. (2021). *Conservation agriculture. Conservation Agriculture for Sustainable Agriculture*. [https://doi.org/10.1007/978-981-16-0827-8\\_1](https://doi.org/10.1007/978-981-16-0827-8_1)

Khosravi, A., Martinez, A., and Dejong, J. T. (2020). Discrete element model (DEM) simulations of cone penetration test (CPT) measurements and soil classification.

- Canadian Geotechnical Journal*, 57(9), 1369–1387.  
<https://doi.org/10.1139/cgj-2019-0512>
- Kumar, A., Chen, Y., Sadek, A., and Rahman, S. (2012). Soil cone index in relation to soil texture, moisture content, and bulk density for no-tillage and conventional tillage. *Agricultural Engineering International: CIGR Journal*, 14(1), 26–37.  
<https://cigrjournal.org/index.php/Ejournal/article/view/1413/1552>
- Lampurlanés, J., Angás, P., and Cantero-Martínez, C. (2001). Root growth, soil water content and yield of barley under different tillage systems on two soils in semiarid conditions. *Field Crops Research*, 69(1), 27–40. [https://doi.org/10.1016/S0378-4290\(00\)00130-1](https://doi.org/10.1016/S0378-4290(00)00130-1)
- Li, B., Chen, Y., and Chen, J. (2016). Modeling of soil-claw interaction using the discrete element method (DEM). *Soil and Tillage Research*, 158, 177–185.  
<https://doi.org/10.1016/j.still.2015.12.010>
- Mahore, V., Soni, P., Patidar, P., and Machavaram, R. (2024). An IoT-enabled penetrometer with constant-rate penetration for accurate measurement of soil cone index. *Cogent Engineering*, 11(1). <https://doi.org/10.1080/23311916.2024.2372088>
- McPhee, J. E., Antille, D. L., Tullberg, J. N., Doyle, R. B., and Boersma, M. (2020). Managing soil compaction – A choice of low-mass autonomous vehicles or controlled traffic? *Biosystems Engineering*, 195, 227–241.  
<https://doi.org/10.1016/j.biosystemseng.2020.05.006>
- Negiş, H. (2024). Using Models and Artificial Neural Networks to Predict Soil Compaction Based on Textural Properties of Soils under Agriculture. *Agriculture (Switzerland)*, 14(1).  
<https://doi.org/10.3390/agriculture14010047>
- Okello, A. (1991). A review of soil strength measurement techniques for prediction of terrain vehicle performance. *Journal of Agricultural Engineering Research*, 50(C), 129–155.  
[https://doi.org/10.1016/S0021-8634\(05\)80010-1](https://doi.org/10.1016/S0021-8634(05)80010-1)

- Potyondy, D. O., and Cundall, P. A. (2004). A bonded-particle model for rock. *International Journal of Rock Mechanics and Mining Sciences*, 41(8 SPEC.ISS.), 1329–1364. <https://doi.org/10.1016/j.ijrmms.2004.09.011>
- Robertson, P. K., and Cabal, K. . L. (2015). *Guide to Cone Penetration testing for Geotechnical Engineering*. [https://cpt-robertson.com/PublicationsPDF/CPT Guide 6th 2015.pdf](https://cpt-robertson.com/PublicationsPDF/CPT%20Guide%206th%202015.pdf)
- Shah, A. N., Tanveer, M., Shahzad, B., Yang, G., Fahad, S., Ali, S., Bukhari, M. A., Tung, S. A., Hafeez, A., and Souliyanonh, B. (2017). Soil compaction effects on soil health and cropproductivity: an overview. *Environmental Science and Pollution Research*, 24(11), 10056–10067. <https://doi.org/10.1007/s11356-017-8421-y>
- Shaheb, M. R., Venkatesh, R., and Shearer, S. A. (2021). A review on the effect of soil compaction and its management for sustainable crop production. *Journal of Biosystems Engineering*, 46, 417–439. <https://doi.org/doi.org/10.1007/s42853-021-00117-7>
- Song, Y., Gu, X. Q., and Hu, J. (2022). DEM-FDM coupling simulation of cone penetration tests in a virtual calibration chamber. *Cone Penetration Testing 2022 - Proceedings of the 5th International Symposium on Cone Penetration Testing, CPT 2022*, 703–707. <https://doi.org/10.1201/9781003308829-103>
- Taylor, H. M., and Brar, G. S. (1991). Effect of soil compaction on root development. *Soil and Tillage Research*, 19(2–3), 111–119. [https://doi.org/10.1016/0167-1987\(91\)90080-H](https://doi.org/10.1016/0167-1987(91)90080-H)
- Wang, X., Li, B., Xia, R., and Ma, H. (2021). *Engineering Applications of Discrete Element Method: Operation Analysis and Optimization Design of Coal and Agricultural Machinery* (Vol. 4). <https://doi.org/10.1007/978-981-15-7977-6>
- Wang, X., Wei, W., He, J., and Huang, Y. (2021). Effect of soil particle-size distribution (Psd) on soil-subsoiler interac-tions in the discrete element model. *Spanish Journal of Agricultural Research*, 19(1), 1–13. <https://doi.org/10.5424/sjar/2021191-16584>

- Wei, X., Gao, C., and Liu, K. (2020). A Review of Cracking behaviour and Mechanism in Clayey Soils Related to Desiccation. *Advances in Civil Engineering*, 2020, 19–27. <https://doi.org/10.1155/2020/8880873>
- Whiteley, G. M., and Dexter, A. R. (1981). The dependence of soil penetrometer pressure on penetrometer size. *Journal of Agricultural Engineering Research*, 26(6), 467–476. [https://doi.org/10.1016/0021-8634\(81\)90080-9](https://doi.org/10.1016/0021-8634(81)90080-9)
- Wu, K., Sun, W., Liu, S., and Yang, D. (2023). Study of cone penetration test in granular soil considering realistic particle shapes by discrete element method in 3D. *European Journal of Environmental and Civil Engineering*, 27(16), 4629–4645. <https://doi.org/10.1080/19648189.2023.2194955>
- Zeng, Z., and Chen, Y. (2016). Simulation of soil-micropenetrometer interaction using the discrete element method (DEM). *Transactions of the ASABE*, 59(5), 1157–1163. <https://doi.org/https://elibrary.asabe.org/abstract.asp?aid=47484>
- Zeng, Z., Ma, X., Chen, Y., and Qi, L. (2020). Modelling residue incorporation of selected chisel ploughing tools using the discrete element method (DEM). *Soil and Tillage Research*, 197(November 2019). <https://doi.org/10.1016/j.still.2019.104505>
- Zhang, B., Jia, Y., Fan, H., Guo, C., Fu, J., Li, S., Li, M., Liu, B., and Ma, R. (2024). Soil compaction due to agricultural machinery impact: A systematic review. *Land Degradation and Development*. <https://doi.org/https://doi.org/10.1002/ldr.5144>
- Zhao, W., Cui, Z., and Zhou, C. (2020). Spatiotemporal variability of soil–water content at different depths in fields mulched with gravel for different planting years. *Journal of Hydrology*, 590(June). <https://doi.org/10.1016/j.jhydrol.2020.125253>
- Zhuang, Yu, P.-Z., and Hai-Sui. (2018). Size Effects in Cone Penetration Tests in Sand. *Proceedings of China-Europe Conference on Geotechnical Engineering. (SSGG)*, 283–287. [https://doi.org/doi.org/10.1007/978-3-319-97112-4\\_64](https://doi.org/doi.org/10.1007/978-3-319-97112-4_64)

## Chapter 5

---

### The effect of varying compaction levels on soil dynamic properties and the growth of canola (*Brassica napus L.*)\*

\*Published in *Agriculture* v14,10.3390/agriculture14111976

#### 5.1. Abstract

Extremely low field emergence rates for canola are primarily attributed to soil compaction from field traffic during and after planting. This study aimed to determine the critical compaction level for canola emergence across different soil types. A laboratory experiment was conducted using sandy loam, silt clay, and clay soils, compacted to five levels (zero to four) using Proctor hammer drops after sowing canola (*Brassica napus L.*). The lab results were validated through two years of field experiments in sandy loam, applying four compaction levels (zero to three) using a tractor. Soil properties (bulk density and surface resistance) and canola growth parameters (plant emergence rate, count, height, and above-ground biomass) were measured. Zero compaction resulted in lower bulk density and surface resistance across all soil types. Laboratory results showed maximum emergence rates of 95% for sandy loam, 100% for silt clay, and 60% for clay, while field emergence rates were 63% and 87.59% in the first and second years, respectively, both at zero compaction. Recommendations include light or no compaction for sandy loam, and zero compaction for silt clay, while clay soil did not achieve the 80% emergence target at any compaction level. These results can assist agricultural producers in optimizing their seeding equipment setup and managing field traffic for canola production.

**Keywords:** soil; compaction; surface resistance; canola; emergence rate; biomass

## 5.2. Introduction

Canola (*Brassica napus L.*) is a commercially significant crop in the Canadian Prairies, with uses ranging from consumable oil to biofuels. Annual revenue doubled from CAD 15.4 billion to CAD 26.7 billion between 2007 and 2015 (Rempel et al., 2014), driving an expansion of canola cultivation areas across Canada. However, emergence rates of canola as low as 50% have been reported (Hyatt et al., 2007). This implies a 50% loss in revenue. Low emergence rates may reduce the yield and cause an economic loss due to the high cost of canola seeds. Factors contributing to low crop emergence rate include inadequate soil moisture, inappropriate seeding depth (Harker et al., 2012), seed variety and size (Lamb and Johnson, 2004), and soil compaction. Among these, soil compaction is considered a major cause (Gong et al., 2022). High soil surface resistance of compacted soil prevents small seedlings from emerging (Zuo et al., 2017). Soil compaction also increases soil bulk density and surface resistance, which is detrimental to crop emergence and early growth of small seeds, like canola (Gong et al., 2022).

Soil structural properties significantly influenced by compaction include bulk density, surface resistance, and related characteristics (Sivarajan et al., 2018). These properties are associated with soil deformation resulting from induced stresses that vary according to the magnitude of the applied pressure (Schjønning et al., 2020) (such as tractor traffic) and other influencing factors (Horn et al., 2023). Previous research has shown that an increase in soil bulk density and penetration resistance with the number of tractor passes is accompanied by a notable reduction in soil porosity (Sivarajan et al., 2018). Soil properties relevant to this study were bulk density and surface resistance, as compaction was found to notably increase both (Radford et al., 2001; Singh and Ghildyal, 1977), with high values observed at high compaction levels.

The effects of soil compaction extend beyond changes in soil properties, impacting root and plant growth and reducing crop yield (Batey, 2009; Hamza and Anderson, 2005). Varying conclusions regarding the effects of compaction on crop growth and yield have been reported from different academic studies. For example, Gelder et al. (2007) reported no significant effect of traffic-induced compaction on corn yield and plant emergence. In contrast, other investigations have demonstrated a pronounced influence of compaction on crop growth and yield (Sivarajan et al., 2018). Ishaq et al. (2001) documented subsoil compaction as a factor contributing to reduced grain and straw yield, diminished fertile tillers, and compromised water and nutrient use efficiency in wheat. Excessive soil compaction increases soil resistance to emerging seedlings and compromises root development, leading to poor crop performance (Buttery et al., 1998; Hyatt et al., 2007; Singh and Ghildyal, 1977). The decrease in seedling emergence with an increase in soil compaction has been reported for many crops, such as corn (Singh and Ghildyal, 1977), sorghum, wheat (Radford et al., 2001), and soybean (Buttery et al., 1998). A study performed by Buttery et al. (1998) showed that a decrease in overall soybean and common bean growth was correlated with an increasing compaction level. The work conducted by Chan et al. (2006) revealed a 34% reduction in yield and inhibited root growth in canola due to the compaction induced by tractor wheel traffic. These findings highlight the need for further research on how compaction affects soil properties and canola growth.

Existing studies have not specifically examined the effects of post-seeding soil compaction on the emergence of small seeds, such as canola, which are sensitive to soil resistance. Therefore, studying post-seeding compaction is crucial, as the results can guide the down pressure design of press wheels of seeders and the timing management of field traffic. The ideal soil compaction level favorable for canola emergence is currently unknown, making it essential to determine the compaction level that allows seedlings to emerge at an acceptable

rate. Soil properties, such as surface resistance, vary with soil type and composition (Buttery et al., 1998; Lehmann et al., 2018). Therefore, it is important to include different soil types when investigating the effects of soil compaction levels on the emergence and growth of canola. Given that canola seeds are small relative to soil aggregates, controlled lab tests may help mitigate errors associated with highly non-homogeneous field soil conditions. However, to draw valid conclusions on the effect of compaction on soil properties and canola growth, field tests are necessary to confirm whether the lab results apply in real-world settings. This will be highly valuable to agricultural producers.

Therefore, the specific objectives of this study were (1) to evaluate in a laboratory the effect of different soil compaction levels on soil properties and canola (*Brassica napus L.*) emergence and growth under three distinct soil types, and (2) to validate the laboratory results of soil and plant responses in a field over two years. The results helped to determine the critical compaction level needed for achieving a target canola emergence rate for each soil type.

### 5.3. Materials and methods

#### 5.3.1. Laboratory experiment

##### 5.3.1.1. Description of soil and seed

The canola emergence test was first conducted under controlled laboratory conditions in 2020. The canola (*Brassica napus L.*) seed variety was Westar Canola, from a commercial seed supplier in Manitoba, Canada. Three soils, namely sandy loam, silt clay, and clay soils, were sourced from three different farms (Piney, the Ian N. Morrison research station at Carman, and a research station at the University of Manitoba Fort Garry campus, respectively)

in southern Manitoba, Canada. The average moisture level for each soil type was adjusted to near its field capacity. Table 5 shows the compositions of these soils along with their gravimetric moisture content (d.b.), determined by oven-drying the soil samples for 24 h at 105 °C (ASABE, 2012).

*Table 5.1. Soil composition and gravimetric moisture contents for the laboratory experiment.*

| Soil Type  | Clay (%) | Silt (%) | Sand (%) | Moisture Content (d.b.)% |
|------------|----------|----------|----------|--------------------------|
| Sandy Loam | 14       | 16       | 70       | 24                       |
| Silt Clay  | 54       | 42       | 4        | 33                       |
| Clay       | 77       | 19       | 4        | 36                       |

#### 5.3.1.2. Laboratory experimental design and test procedure

The laboratory experiment used a completely randomized design. The treatments were five soil compaction levels: zero compaction level/no compaction (C0<sub>L</sub>), compaction level one (C1<sub>L</sub>), level two (C2<sub>L</sub>), level three (C3<sub>L</sub>), and level four (C4<sub>L</sub>). The creation of these compaction levels is described below. Each treatment was replicated four times. Thus, 20 sample units (5 compaction levels x 4 replicates) were carried out for each soil type, totaling 60 tests for the 3 soil types in the experiment. The experimental design is illustrated in Figure 5.1a.

For each soil type, 20 cylinders (166 mm in height and 154 mm in diameter) were employed as seeding containers and filled with soil up to a height of 20 mm below the container's rim. Subsequently, five canola seeds were positioned on the seedbed following a pentagon-shaped template as a guide, with one seed placed at each corner of the pentagon (Figure 5.1b). The distance between adjacent seeds was 30 mm. A predetermined amount of soil was then used to cover the seeds in each container, ensuring an appropriate depth of soil cover. This entire procedure, from soil preparation to seeding, was consistently applied across all the three soil types.

Following seeding, the 20 containers within each soil type were subdivided into 5 groups for compaction of the seed cover. A soil proctor (ASTM/Modified Proctor Compaction Rammer, ELE International, Loveland, CO, USA) with a hammer of mass 4.5 kg and a drop height of 0.457 m, was utilized for this purpose (Figure 5.1c). The group of containers, denoted by treatment C0<sub>L</sub>, underwent no compaction. The remaining groups of containers received one, two, three, and four drops of the hammer of the proctor, corresponding to treatments C1<sub>L</sub>, C2<sub>L</sub>, C3<sub>L</sub>, and C4<sub>L</sub>, respectively. Given the hammer mass ( $m$ ) of 4.5 kg, the gravitational acceleration ( $g$ ), and the drop height ( $h$ ) of 0.457 m, the values of compaction energy (potential energy =  $mgh$ ) for the compaction levels C0<sub>L</sub>, C1<sub>L</sub>, C2<sub>L</sub>, C3<sub>L</sub>, and C4<sub>L</sub> were 0, 20.2, 40.4, 60.6, and 80.8 J, respectively. After seeding, the containers were transferred to an environmental chamber set at predetermined conditions of 19 °C, 10% RH, and an 8-16 h dark-photo-period (Figure 5.1d). To maintain soil moisture content, the containers were covered with wet clothes that were rewetted twice daily during the initial five days to mitigate soil water evaporation.

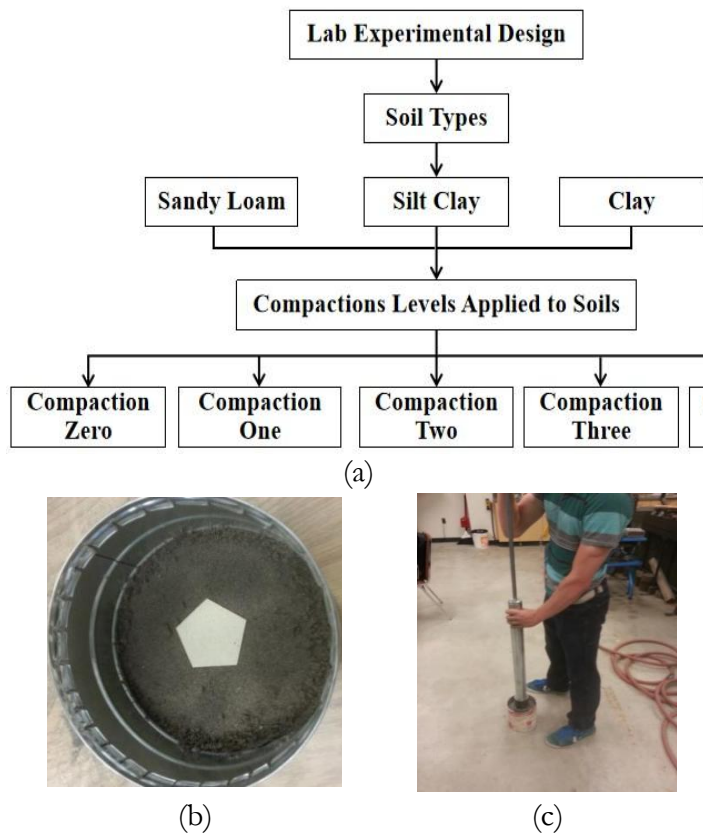


Figure 5.1. Laboratory experimental procedure: (a) Flow chart of the experimental design; (b) Seed positioning template; (c) Soil compaction with a proctor; (d) Covered seeded containers in the environmental chamber.

### 5.3.1.3. Laboratory measurements

Soil compaction levels in the containers were quantified for bulk density and surface resistance. For this, separate containers of the same soil compaction levels as used in the seeding test were prepared without seeding. A Dail Pocket Penetrometer (Model: HM-502, Gilson Company Inc., OH 43035, USA with a specified plunger surface area of  $314 \text{ mm}^2$  was used to measure the surface resistance at three random locations in each container. For each container, a soil core was taken using a  $50 \times 50 \text{ mm}$  cylindrical soil sampler. The gravimetric moisture content and soil dry bulk density were calculated after oven-drying at  $105^\circ \text{C}$  for 24 h (ASTM, 2019; ASTM, 2021).

The number of plants that emerged in each container and the height of those plants were recorded daily for a total of 14 days after seeding. At the end of the 14 days, the plants were cut off at the soil surface, and their aboveground biomass was determined by oven-drying for 72 h at 60 °C (ASABE, 2012).

### 5.3.2. *Field experiment*

#### 5.3.2.1. Description of the study site, soil, and seed

The field experiment was conducted during the summers of 2023 and 2024, from May to August. The experimental site was in Piney, Manitoba, Canada (49°07'15" N, 96°07'56" W). During the study months, the site recorded an average maximum temperature of 23.4 °C and a minimum of 10.5 °C, with 67% relative humidity, 0.8 mm/day of rainfall, and wind speeds averaging 13.31 km/h in 2023 (Manitoba Agriculture, 2024). For 2024, the site recorded an average maximum temperature of 21.9 °C and a minimum of 10 °C, with 74% relative humidity, 2.9 mm/day of rainfall, and wind speeds averaging 14.16 km/h (Manitoba Agriculture, 2024). The field had sandy loam soil with the same texture as that employed in the laboratory experiment, and the canola variety was also the same. At the time of measurements, the field soil moisture content was 19.67% and 35.58% (d.b.) for the first- and second-year tests, respectively.

#### 5.3.2.2. Field experimental design and test procedure

In the field experiment, different compaction levels were created using tractor wheels on the field. The experiment was a completely random design with four compaction levels, namely zero compaction level/no compaction (C0<sub>F</sub>), compaction level one (C1<sub>F</sub>), level two (C2<sub>F</sub>), and level three (C3<sub>F</sub>), as treatments. Each treatment was randomly replicated 5 times,

giving a total of 20 plots (4 compaction levels  $\times$  5 replications). The field plot layout is illustrated in Figure 5.2a.

Before compacting the soil, canola was seeded in the field using a disc seeder (4-row Plotter choice, Shelbyville, IN, USA). The seeding rate was 1 kg/ha and 3.8 kg/ha for the first- and second-year tests, respectively. As in the laboratory experiment, post-seeding compaction was applied to the soil by driving a tractor (John Deere 1023E tractor, weighing 656 kg, equipped with ballasts) at 2 km/h in the seeded field in the direction perpendicular to the seeding direction (Figure 5.2a). The tractor made one pass for the C1<sub>F</sub> treatment, two passes along the same track for the C2<sub>F</sub> treatment, and three passes along the same track for the C3<sub>F</sub>, creating tracks (Figure 5.2b) for each compaction level.

On the wheel tracks, measurement areas were marked (Figure 5.2b) with each area measuring  $1.8 \times 0.22$  m. The width of the measured area was the active tire width illustrated in Figure 5.2c. Six measurement areas were randomly selected in each plot, with three areas for soil property measurements and three areas for canola growth measurements. Additionally, in each plot, six random areas of the same dimensions ( $1.8 \times 0.22$  m), that did not have wheel tracks, were used for measurements of the zero compaction level (C0<sub>F</sub>).

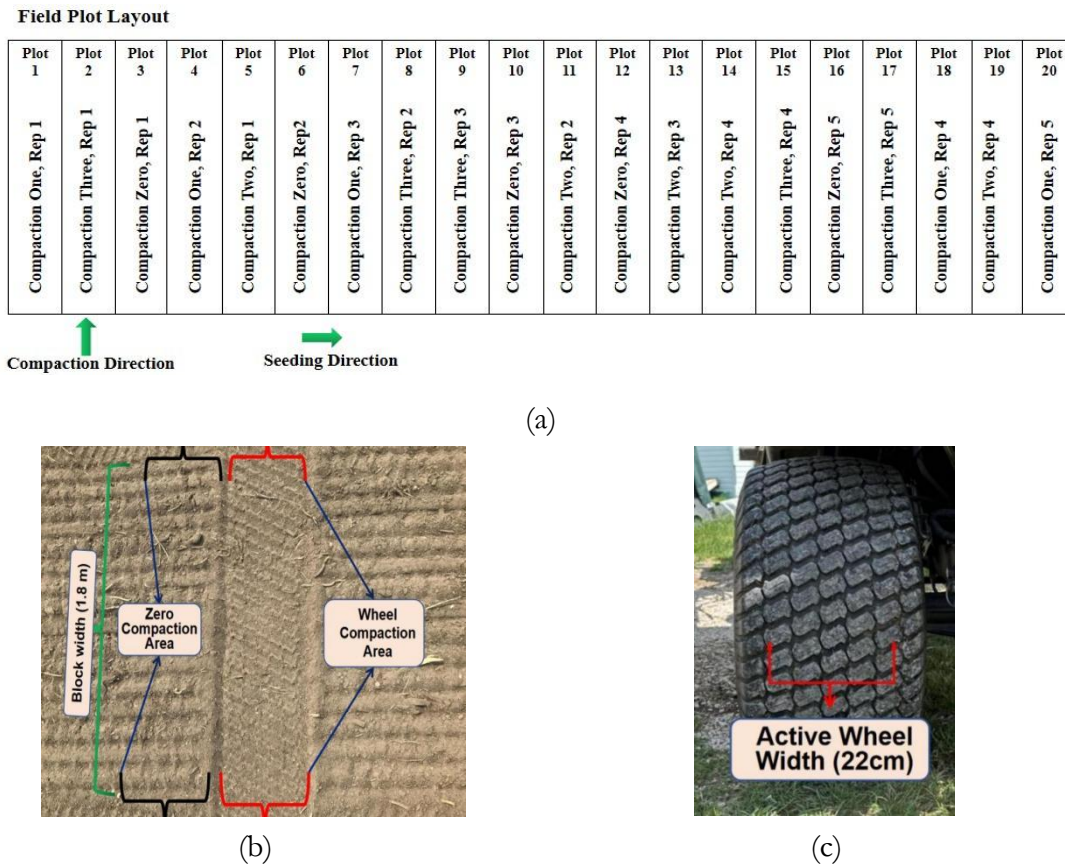


Figure 5.2. Field experimental process: (a) Plot layout, (b) Tractor wheel tracks showing compacted and non-compacted areas; (c) Active wheel width contributing to wheel tracks.

### 5.3.3. Field measurements

As in the laboratory experiment, the soil compaction levels in the field were quantified for bulk density and surface resistance. Three soil cores (diameter 50 mm and height 100 mm) were taken from each measurement area per plot to measure bulk density. The soil surface resistance was measured using the same instrument as in the laboratory test at three measurement areas in each plot.

After 48 h of seeding, plant counting was conducted in the measurement areas of each plot every 48 h for five consecutive counts. After allowing the crops to fully emerge, a final count was conducted 27 days after seeding. Subsequently, the emergence rate was determined. Fully matured aboveground plants were collected from all plots three months post-seeding. The

biomass of the plants was determined using the same oven-drying method performed in the laboratory experiment.

#### 5.3.4. *Data analysis*

One-way analysis of variance (ANOVA) was performed using R programming software version R4.2.2 and the ‘*car*’ package to analyze the effects of the treatments (soil compaction levels) on the measured parameters (soil properties and plant responses). The Tukey HSD test was utilized to determine the significant differences in the measured variables between all treatments at a confident level of 95%, using the same software.

### 5.4. Results and discussion

#### 5.4.1. *Soil physical properties*

##### 5.4.1.1. Bulk density

In the laboratory test, the initial soil bulk density without compaction ( $C0_L$ ) was the highest for the sandy loam soil (Figure 5.3a), followed by the silt clay (Figure 5.3b), and finally the clay soil (Figure 5.3c). The silt clay and clay soils had slight changes in magnitude, with no significant difference between  $C3_L$  and  $C4_L$  (Figure 5.3b,c). Similar results were reported by Li et al. (2016). However, the  $C3_L$  of the sandy loam resulted in a lower bulk density than  $C4_L$  (Figure 5.3a). Overall, soil bulk density was the highest for the sandy loam soil and lowest for the clay soil at all compaction levels. At compaction levels of  $C2_L$  and lower, all the soils had a similar response to the compaction efforts, in terms of soil bulk density. The highest compaction in the sandy loam was 35.35% greater than in the silt clay and 59.05% greater than in the clay. Field soil bulk density results did not show significant

differences between the compaction levels. In the first-year test, soil bulk density also increased when the compaction level was increased from C0<sub>F</sub> to C2<sub>F</sub>, and there was no further increase in soil bulk density for C3<sub>F</sub> (Figure 5.3d). Although this trend was not statistically significant, it did not contradict the explained patterns in the lab experiment. However, the second-year test followed an increasing trend from C0<sub>F</sub> to C3<sub>F</sub> with small changes between compaction levels (Figure 5.3e). It registered lower bulk densities than the first-year test at all levels.

The trend in bulk density observed in the lab test was expected, as sand particles have a higher density than silt clay and clay particles (Campbell, 1986). The observed increased trend in both the lab and field test was consistent with the findings of Phakdee and Suvanjumrat (2023), who reported that soil compaction exhibits a positive linear relationship with soil bulk density. Lower compaction levels had less effect on soil porosity. Bulk density exhibits an inverse relationship with the porosity of soil samples of equal volume (de Jesus Duarte et al., 2019). The lower values observed in the second-year test compared to the first year across all compaction levels may be due to differences in field locations, as there is no homogeneity among them (Figure 5.3d,e). The common lack of a further increase in soil bulk density beyond the third compaction level could likely be attributed to the limited number of soil pores which restricted further soil deformation under compaction (Saljnikov et al., 2022).

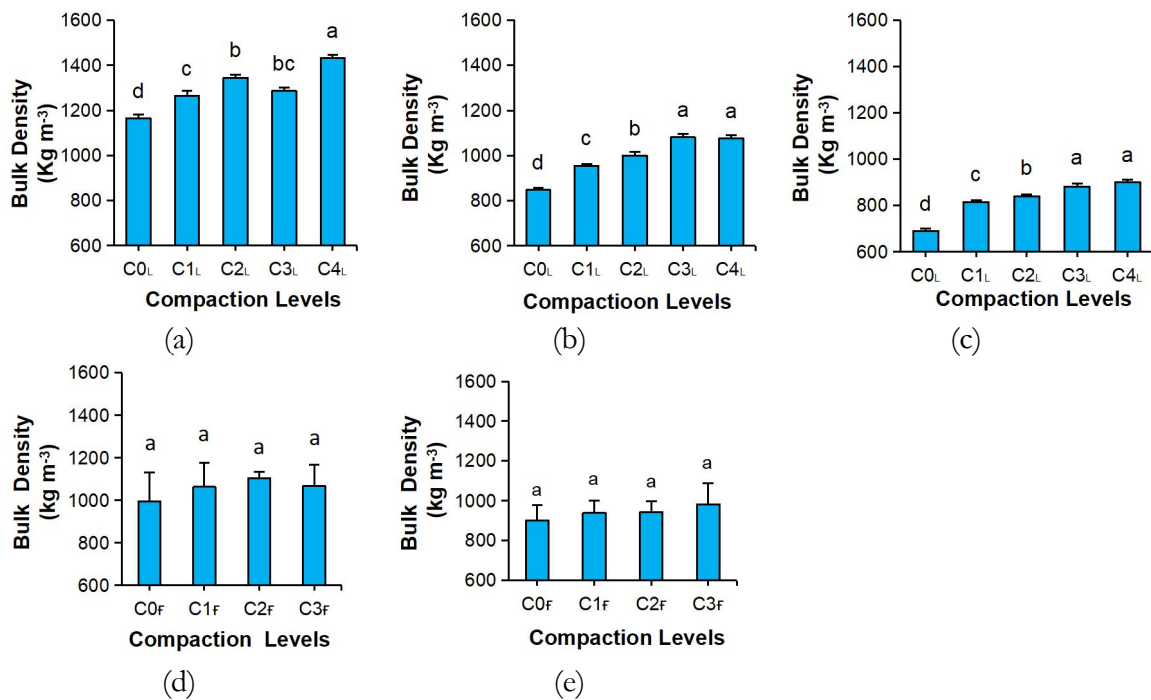


Figure 5.3. Bulk densities at varying compaction levels. Where (a–c) are lab measurements taken for the sandy loam, silt clay, and clay soils, respectively (C0<sub>L</sub>, C1<sub>L</sub>, C2<sub>L</sub>, C3<sub>L</sub>, and C4<sub>L</sub> represent compaction levels zero, one, two, three, and four, respectively) and (d, e) are field measurements of the sandy loam soil for first- and second-year tests, respectively (C0<sub>F</sub>, C1<sub>F</sub>, C2<sub>F</sub>, and C3<sub>F</sub>, represent compaction levels zero, one, two, and three, respectively). Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ).

#### 5.4.1.2. Soil surface resistance

The laboratory test revealed an increasing trend in surface resistance with increasing compaction levels for all the three soil types (Figure 5.4a–c). All three soils had a very low resistance at C0<sub>L</sub>. However, the rate of increase was different among the different soil types. When the compaction level was increased from C0<sub>L</sub> to C3<sub>L</sub>, the soil resistance increased 29 times for the sandy loam soil (Figure 5.4a), 19 times for the silt clay soil (Figure 5.4b), and only 5 times for the clay soil (Figure 5.4c). For the sandy loam and silt clay soils, there was no further increase in resistance for C4<sub>L</sub>. The change in the surface resistance of the clay soil between C3<sub>L</sub> and C4<sub>L</sub> was significant. Comparing the magnitudes of surface resistance at C4<sub>L</sub>,

the resistance of the sandy loam was 54% higher than that of silt clay, and 76% higher than that of clay.

The first-year field test exhibited significantly lower soil surface resistance at the C0<sub>F</sub>. There were significant disparities between compaction levels zero and one (Figure 5.4d). However, the differences in soil resistance between C1<sub>F</sub>, C2<sub>F</sub>, and C3<sub>F</sub> were not statistically significant. Also, there was a general increasing trend of surface resistance with the soil compaction level (Figure 5.4d). This trend from the field was consistent with those obtained from the laboratory test (Gong et al., 2022). However, the second-year test showed an increasing pattern with significant differences among all compaction levels (Figure 5.4e). This trend is consistent with the general trend in bulk density.

The increase in compaction level caused a significant increase in surface resistance, as also recorded in the work carried out by Mileusnić et al. (2022). A similar trend in bulk density by soil type was translated into the trend in surface resistance, indicating that soil resistance was highly variable with soil type. The coarser the soil type, the higher its surface resistance, and vice versa (Lehmann et al., 2018). Overall, different soils had different responses to the compaction efforts, in terms of soil resistance. The different behaviours of soil in response to compaction demonstrated the significance of investigating crop emergence and critical compaction levels for different soil types.

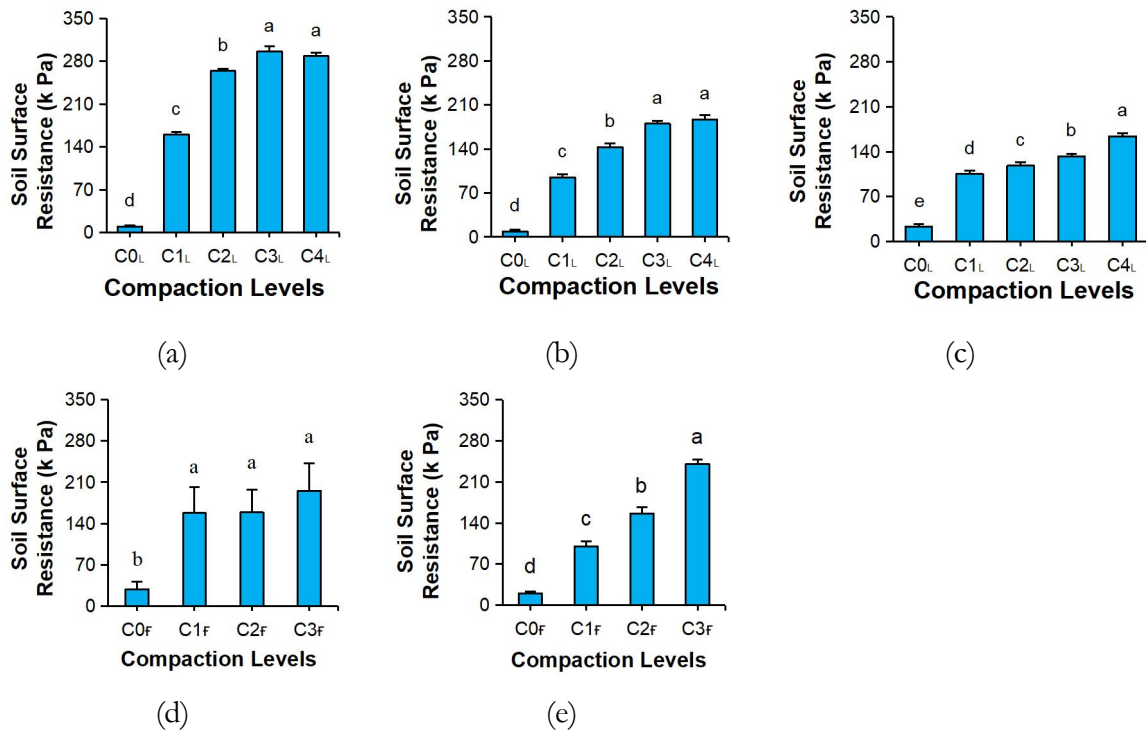


Figure 5.4. Soil surface resistances at varying compaction levels. Where (a–c) are lab measurements taken for the sandy loam, silt clay, and clay soils, respectively (C0<sub>L</sub>, C1<sub>L</sub>, C2<sub>L</sub>, C3<sub>L</sub>, and C4<sub>L</sub> represent compaction levels zero, one, two, three, and four, respectively) and (d, e) are field measurements on the sandy loam soil for first- and second-year tests, respectively (C0<sub>F</sub>, C1<sub>F</sub>, C2<sub>F</sub>, and C3<sub>F</sub> represent compaction levels zero, one, two, and three, respectively). Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ).

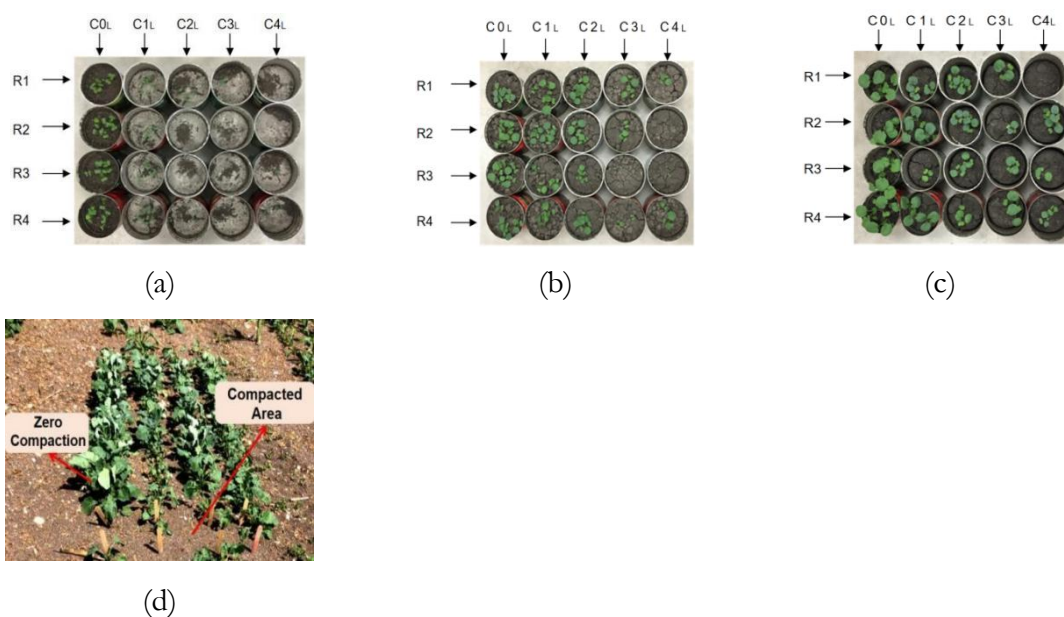
#### 5.4.2. Plant emergence and growth

##### 5.4.2.1. Qualitative assessment of canola emergence

In the lab experiment, canola emergence and growth can be visualized from the photographs taken at the end of the two-week study (Figure 5.5a–c). These photos show 3 groups of 20 containers, with 1 group for each soil type. Within a group, the five containers in a row represent the five compaction levels (C0<sub>L</sub>, C1<sub>L</sub>, C2<sub>L</sub>, C3<sub>L</sub>, and C4<sub>L</sub>), while the four containers in a column represent the four replicates (R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub>, and R<sub>4</sub>) of the treatment. Three visual comparisons were made from these photos. Row-wise comparison within each

group showed that better canola emergence was observed at a lower compaction level for all three soils. Column-wise comparison within each group showed that the four replications had consistent emergence, indicating low experimental errors. Comparison between the groups showed that the sandy loam soil had the worst plant growth, while clay soil had the best growth.

Analogous results to those shown in the lab test were noticed in the field test for the same sandy loam soil (Figure 5.5a, d). Field plots on tractor wheel tracks (distinguished by popsicle sticks) exhibited a significant reduction in canola plants, while a greater number of plants were evident in the no compaction areas for same reasons as stated above. Generally, higher soil bulk density and surface resistance were associated with a lower growth rate of canola (Acquah and Chen, 2022; H. Chen et al., 2023).



*Figure 5.5. Canola emergence at varying compaction levels. Where (a–c) are lab measurements taken 14 days post-seeding for the sandy loam, silt clay, and clay soils, respectively (C0L, C1L, C2L, C3L, and C4L represent compaction levels zero, one, two, three, and four, respectively; R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub>, and R<sub>4</sub> represent replicates one, two, three, and four, respectively) and (d) is field results showing emerged canola plants at compacted and non-compacted sandy loam soil areas taken 27 days post-seeding.*

#### 5.4.2.2. Plant count

In the lab test, the numbers of canola plants that emerged in each pot were counted daily over the entire observation period. The daily total number of plants of all the replicates are presented here. For the sandy loam soil, the first emergence was observed for C0<sub>L</sub>. For this compaction level, canola seedlings started to emerge on the fifth day after seeding (Figure 5.6a). Increasing the compaction level to C1<sub>L</sub> resulted in a one-day delay in emergence. Further increase in compaction level to C2<sub>L</sub>, C3<sub>L</sub>, and C4<sub>L</sub> resulted in a delay by another day. At the early stages of observation, the two lower compaction levels (C0<sub>L</sub> and C1<sub>L</sub>) demonstrated a steep increase in seedling emergence, and seedlings emerged over a 10-day period. There was no increase in plant count afterwards. The emergence rate for treatments C2<sub>L</sub>, C3<sub>L</sub>, and C4<sub>L</sub> increased much slower over time than the rates for the lower compaction levels, and then emergence ceased on the 8th day. At the end of the observation period, the plant count was reduced by 5% for C0<sub>L</sub>, 20% for C1<sub>L</sub>, 80% for C2<sub>L</sub> and C4<sub>L</sub>, and 95% for C3<sub>L</sub>.

For the silt clay soil, the first emergence was also observed on the fifth day, which was for C0<sub>L</sub>, followed by C1<sub>L</sub> and C2<sub>L</sub> on the sixth day, and C3<sub>L</sub> and C4<sub>L</sub> on the seventh day (Figure 5.6b). The plants of C3<sub>L</sub> and C4<sub>L</sub> emerged until the end of the observation period. C0<sub>L</sub> had the highest plant count, with all the seedlings emerging by the seventh day. The plant count for C1<sub>L</sub> also demonstrated a rapid increase initially and slowly reached its maximum count of 12 plants on the 10th day. The count for C2<sub>L</sub> was lower, and new plants did not emerge after the 11th day. C0<sub>L</sub> had a 0% reduction in plant count, while the maximum reduction was 65% for C3<sub>L</sub>.

For the clay soil, the first emergence for C0<sub>L</sub>, C1<sub>L</sub>, C2<sub>L</sub>, and C3<sub>L</sub> occurred two days later than it did for the other two soil types and occurred on the eighth day for C4<sub>L</sub> (Figure 5.6c).

No new seedlings emerged after 9 days of seeding for all the treatments. The number of plants was reduced by 40% for C0<sub>L</sub>, with a maximum reduction of 75% for C3<sub>L</sub>.

In the field test, canola emergence was assessed by the number of plants per unit field area over the observation period. Results from the two-year test showed that seedling emergence started six days after seeding for all compaction levels (Figure 5.6d, e). Both tests revealed a general increase in the number of emerging plants over time. A higher number of emerged plants were observed at the zero compaction level compared to the other compaction levels in both years. Towards the end of the twenty-seven-day period, a slight reduction in plant population was observed for C0<sub>F</sub> in the first-year test due to external environmental factors, such as nocturnal field grazing by deer. A higher number of plants were observed in the second year than the first year, due to the increased seeding rate in the second year.

Comparable findings for sandy loam soil were observed in both the field and lab tests, as both used soil with the same composition. It was expected that plant count would reduce with the increasing compaction level from C1<sub>F</sub>, to C2<sub>F</sub> and C3<sub>F</sub> for both tests, as observed by Kahlon et al. (2023) for summer moon bean. However, the reverse was the case. Plant count decreased from C1<sub>F</sub> to C3<sub>F</sub> and then to C2<sub>F</sub> in the first-year test, and from C2<sub>F</sub> to C3<sub>F</sub>, and then to C1<sub>F</sub> in the second-year test. This could be due to the heterogeneous nature of field soils (Habib-ur-Rahman et al., 2022; S. Zhang et al., 2014). Similarly, this reverse phenomenon was also observed in the laboratory tests where the highest compaction level did not always result in the lowest number of emerged plants (Figure 5.6b, c).

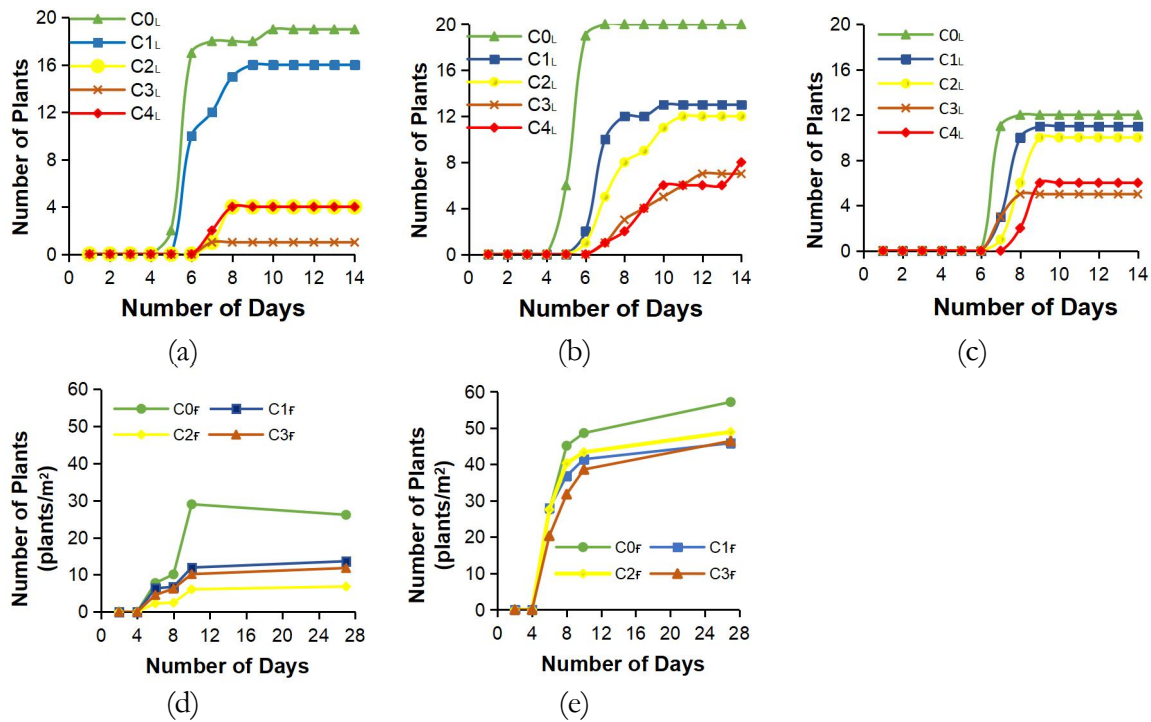


Figure 5.6. Plant population counts at varying compaction levels. Where (a–c) are lab measurements for the sandy loam, silt clay, and clay soils, respectively ( $C_{0L}$ ,  $C_{1L}$ ,  $C_{2L}$ ,  $C_{3L}$ , and  $C_{4L}$  represent compaction levels zero, one, two, three, and four, respectively) and (d, e) are field measurements using the sandy loam soil for first- and second-year tests, respectively ( $C_{0F}$ ,  $C_{1F}$ ,  $C_{2F}$ , and  $C_{3F}$  represent compaction levels zero, one, two, and three, respectively).

#### 5.4.2.3. Plant emergence rate

The emergence rate of the laboratory experiment was determined as the ratio of the total number of emerged plants to the total number of seeds sown. The results showed a decrease in seedling emergence rate with an increase in soil compaction level.

Emergence for the sandy loam soil showed two distinct groups of statistical differences (Figure 5.7a). The group with a high rate consisted of the  $C_{0L}$  and  $C_{1L}$  compaction levels, and the group with a much lower rate consisted of  $C_{2L}$ ,  $C_{3L}$ , and  $C_{4L}$ . The average emergence rate for  $C_{0L}$  was quite high (95%), while that for  $C_{1L}$  was 80%. However, the average emergence rate for the latter groups averaged to 15%, much lower than the literature-reported range of 50–60% (Harker et al., 2003).

The emergence rate of canola was also significantly different between compaction levels for the silt clay soil (Figure 5.7b). The emergence rate observed for the silt clay was 100% for C0<sub>L</sub>, meaning that all seeds emerged when the soil was not compacted. The C1<sub>L</sub> and C2<sub>L</sub> treatments had 65 and 60% rates, respectively, which were significantly lower than C0<sub>L</sub>. Very low emergence rates were observed in the higher compaction levels (C3<sub>L</sub>, and C4<sub>L</sub>).

The general trend of the clay soil was that compaction decreased the emergence rate. However, the trend was not statistically significant. None of the compaction levels had an emergence rate of 80% or higher (Figure 5.7c). Seedling emergence was delayed in clay soil due to large soil aggregates which impeded the upward movement of the canola cotyledons, as observed by Vance et al., (2024) in chickpea. As a result, some canola seeds were not able to emerge from the soil's surface.

The emergence rate of the field test was determined as the ratio of the number of emerged plants to the total seeds sown per unit area, calculated using the known seeding rate and thousand kernel weight of canola. The results revealed a general trend of an inverse relationship between emergence rate and compaction level (Figure 5.7d, e). The seeding rate of 1 kg/m<sup>2</sup> used in the first-year test resulted in a much higher and significant change in magnitude between the zero compaction (C0<sub>F</sub>) and the other compaction levels (Figure 5.7d). No significant differences were observed among compaction levels C1<sub>F</sub>, C2<sub>F</sub>, and C3<sub>F</sub>.

Increasing the seeding rate in the second-year test to 3.8 kg/m<sup>2</sup> increased the emergence rate by 24% for C0<sub>F</sub>, 42.97% for C1<sub>F</sub>, 60.6% for C2<sub>F</sub>, and 47.54% for C3<sub>F</sub> (Figure 5.7e). The 80% emergence rate was achieved only in the zero compaction level, which recorded a value of 87.59% (Figure 5.7e).

The application of compaction pressure caused the reorganization of individual soil particles, leading to the closure of soil pores (reducing soil aeration), as discussed by Gong et al., 2022; Hess et al., 2019; Otalvaro et al., 2016, potentially impeding the upward movement of seedlings. This aligns with existing studies for different crops, such as corn (Singh and Ghildyal, 1977), maize, sorghum, wheat (Radford et al., 2001), soybean (Buttery et al., 1998), winter oilseed rape (Orzech et al., 2021), and alfalfa (Yan et al., 2024). Compaction significantly reduced the canola emergence rate by 81.90% in sandy loam, 62.95% in silt clay and 45.70% in clay, consistent with studies of compaction effects on sugar cane (Barbosa et al., 2024), corn (Nawaz et al., 2023), and soybean (Capobianco et al., 2023). The significantly low averaged emergence rate for sandy loam soil at C2<sub>L</sub> and C3<sub>L</sub> (Figure 5.7a) would significantly increase seed costs. Assuming a target emergence rate of 80%, only the C0<sub>L</sub> and C1<sub>L</sub> treatments were acceptable. Thus, the critical compaction level for the sandy loam soil is C1<sub>L</sub>, which corresponded to a compaction energy of 20.2 J, bulk density of 1265 kg m<sup>-3</sup>, and surface resistance of 160 k Pa. For silt clay, the only condition that had the emergence rate of 80% and greater was C0<sub>L</sub> (Figure 5.7b). Therefore, any form of compaction is unacceptable for seeding canola. Thus, its critical compaction level was C0<sub>L</sub>, which corresponds to zero compaction energy, a soil bulk density of 848 kg m<sup>-3</sup>, and a surface resistance of 9 k Pa. For clay soil, the highest emergence rate observed at C0<sub>L</sub> meant that at least 40% more seeds would need to be sown when growing canola crops in clay soil (Figure 5.7c). This would significantly increase production costs. The results implied that clay soil severely limited canola emergence, preventing it from reaching the 80% emergence rate, regardless of the compaction level. The reasons could be similar to those that affected plant count. The highest emergence rate of 63% in the first-year field condition was within the reported range in the literature (Harker et al., 2003), but it was far below the assumed target rate of 80% (Figure

5.7d). However, the second-year emergence rate (87.59%) increased beyond the target rate (Figure 5.7e).

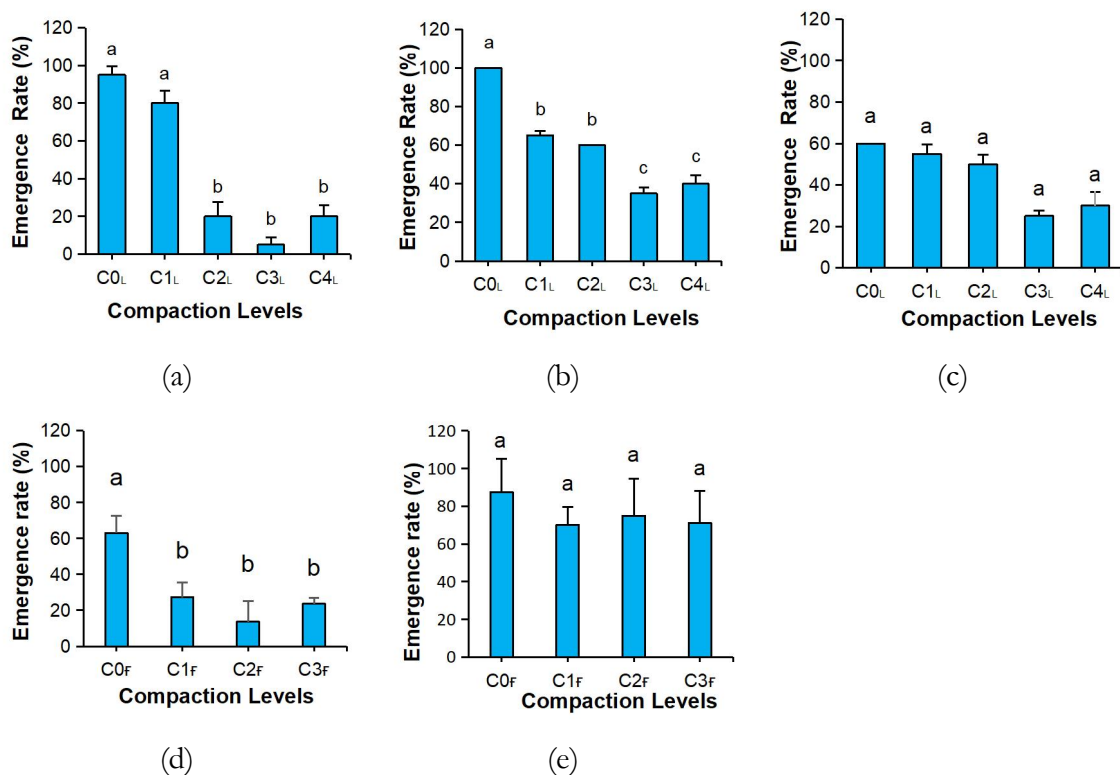


Figure 5.7. Canola emergence rate at varying compaction levels. Where (a–c) are lab measurements taken for the sandy loam, silt clay, and clay soils, respectively (C0<sub>L</sub>, C1<sub>L</sub>, C2<sub>L</sub>, C3<sub>L</sub>, and C4<sub>L</sub> represent compaction levels zero, one, two, three, and four, respectively) and (d, e) are field measurements on the sandy loam soil for first- and second-year tests, respectively (C0<sub>F</sub>, C1<sub>F</sub>, C2<sub>F</sub>, and C3<sub>F</sub> represent compaction levels zero, one, two, and three, respectively). Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ).

#### 5.4.2.4. Plant height

Plant height was measured in the lab condition, not in the field, since plant structure is not stable under weather conditions (wind and rain). In the lab experiment, an increasing trend was observed in the plant height with time, which lasted until the end of the observation period (Figure 5.8).

The initial growth rate for the sandy loam soil was similar for all the soil compaction levels, reflected by the similar slope of the plant height curves before the twelfth day (Figure 5.8a). Afterwards, there was a small increase in the plant height until the end of the observation period. However, higher heights were observed in the zero compaction level than the other compaction levels from the start of emergence until the end of the observation period. Very similar observation in plant height was observed between C2<sub>L</sub>, C3<sub>L</sub>, and C4<sub>L</sub>.

Like the sandy loam soil, plant height data for the silt clay showed that the least compacted soil had a greater height at the initial growing stage (Figure 5.8b). Between the seventh and the twelfth day, plants at all compaction levels had a similar growth rate. The plant height experienced a rapid increase during the last two days. The C3<sub>L</sub> and C4<sub>L</sub> compaction levels had similar growth rates, as shown by the overlapped growth curves.

As compared with the other two soils, where the plant height increased gradually and non-linearly, the clay soil demonstrated a more rapid increase in plant height with a more linear increasing trend for the 14 days of growth (Figure 5.8c). Irrespective of the low plant count, the clay soil had higher plant height after the 14-day period.

To further demonstrate the effects of soil compaction on plant height, the data of the plant heights at the end of the observation period were averaged at each compaction level for each soil (Figure 5.8d–f). The sandy loam soil exhibited a decreasing trend in average plant height with increasing compaction level (Figure 5.8d). The maximum plant growth was observed at the non-compacted level, C0<sub>L</sub>, with an average plant height of 37.7 cm. With slight compaction (C1<sub>L</sub>), the average plant height reduced to 23.0 cm, a 39% reduction from C0<sub>L</sub>. Additional compaction (C2<sub>L</sub>) led to significantly lower plant heights. Subsequent compactations (C3<sub>L</sub> and C4<sub>L</sub>) did not yield significant changes in average plant height.

In the silt clay soil, a similar average plant height to that observed in the sandy loam soil was seen for the C0<sub>L</sub> (Figure 5.8e). However, the change in magnitude between the compaction levels is less than that observed in the sandy loam soil. The zero compaction, C0<sub>L</sub>, had the highest plant height, followed by C1<sub>L</sub> and C2<sub>L</sub> in that order, with no significant difference between the three levels. A significantly lower plant height was observed with additional compaction at C3<sub>L</sub> and C4<sub>L</sub>. However, average plant height did not differ significantly between these two levels.

Compaction had no significant influence on the average height of canola plants within the clay soil (Figure 5.8f). The clay soil exhibited the highest plant height among all the three soils at all compaction levels. The plant emergence rate was notably less pronounced in the clay soil among all soils (Figure 5.7c). However, here, the clay soil had greater plant height than the other two soils. This observation might be due to the better water holding capacity of clay particles than sand particles in soil (Yang et al., 2023).

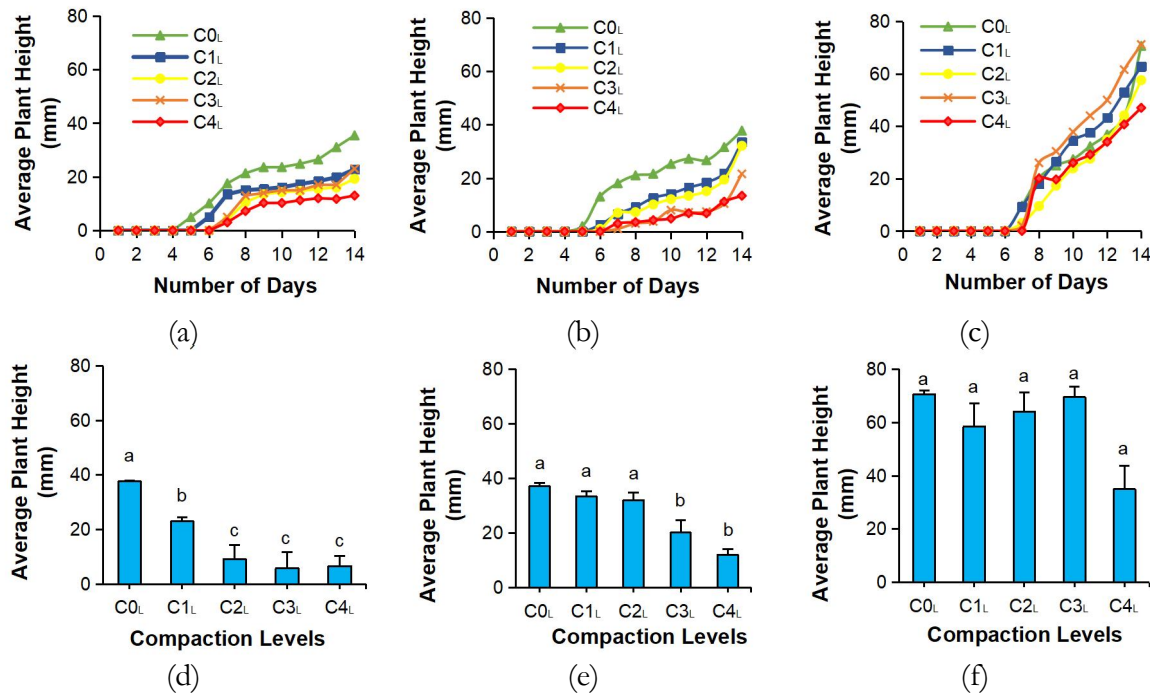


Figure 5.8. Lab measurement of plant height at varying compaction levels. Where (a–c) are increasing values with time and (d–f) are average values. Both groups are for the sandy loam, silt clay, and clay soils, respectively.  $C0_L$ ,  $C1_L$ ,  $C2_L$ ,  $C3_L$ , and  $C4_L$  represent compaction levels zero, one, two, three, and four, respectively. Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ).

#### 5.4.2.5. Aboveground biomass

The sandy loam soil in the lab test showed biomass data exhibiting a similar trend to that of the plant height data. The highest biomass value was recorded for  $C0_L$  (Figure 5.9a), which corresponded to the highest plant height. As the soil compaction level increased, significantly less biomass was produced. Biomass for the silt clay soil was much higher than the sandy loam soil and decreased with increasing compaction level (Figure 5.9b). The clay soil showed irregular trend with no significant difference in biomass with increasing compaction level (Figure 5.9c). The plant emergence data showed the worst performance in the clay soil, regardless of the soil compaction level. However, the overall amount of biomass was better than the sandy loam and as good as that of the silt clay.

In the field study, due to the shattering loss of canola pods and seeds during harvesting, the seeds could not provide a reliable reflection of yield. Therefore, above-ground biomass was used as a measure of yield. Biomass was very sensitive to soil compaction in the first-year test (Figure 5.9d). A significant effect of compaction level on the biomass was observed. The decreasing trend of biomass with increasing compaction levels observed in both the first and second-year tests was similar between the field results (Figure 5.9d, e) and the lab results (Figure 5.9a), as the soil was sandy loam in both cases. However, compaction in the second-year test had no significant effect on biomass.

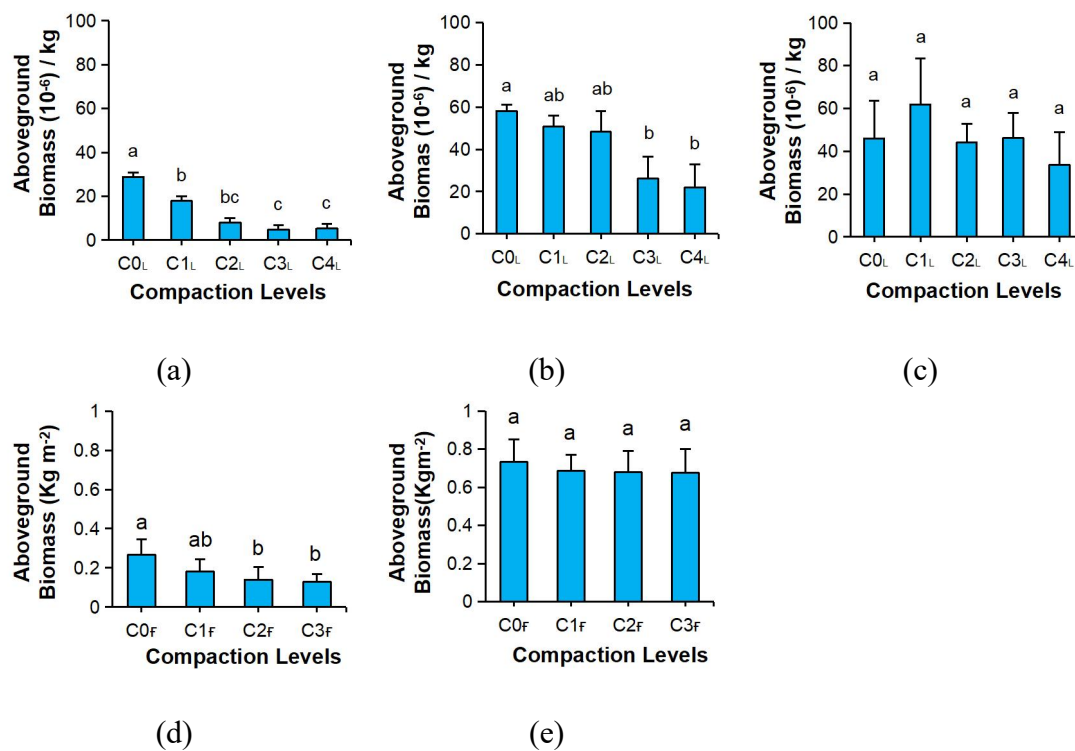


Figure 5.9. Canola aboveground biomass at varying soil compaction levels. Where (a–c) are lab measurements taken 14 days post-seeding for the sandy loam, silt clay, and clay soils, respectively (C0L, C1L, C2L, C3L, and C4L represent compaction levels zero, one, two, three, and four, respectively) and (d, e) are field measurements on the sandy loam soil for first- and second-year test taken 16 weeks post-seeding, respectively (C0F, C1F, C2F, and C3F, represent compaction levels zero, one, two, and three, respectively). Labels are assigned based on Tukey HSD test to determine the significant difference between treatment levels at a confidence level of 95% ( $p < 0.05$ ).

## 5.6. Conclusion

The study highlights the need to minimize soil compaction to optimize canola emergence and growth. Lab and field tests revealed that higher compaction increased soil bulk density and surface resistance, which negatively affected canola performance, particularly in sandy loam soils. Silt clay soils showed similar sensitivity under lab conditions, while clay soil was largely unaffected by compaction. For sandy loam, no or slight compaction is recommended, and for silt clay, compaction should be avoided altogether. Clay soil did not meet the acceptable 80% emergence rate at any compaction level. In the field conditions, the target emergence rate of 80% was achieved only under no compaction treatment in one of the two studying years. Therefore, avoiding soil compaction is recommended regardless of soil type to optimize canola production. Future studies should include measurements of canola yields. These findings provide practical guidance for agricultural producers in managing field traffic and modifying seeder equipment to prevent economic losses due to compaction-induced poor emergence. Future studies on additional soil types in field conditions, along with the application of these findings in designing and adjusting seeders, are recommended.

## 5.5 Reference

- Acquah, K., and Chen, Y. (2022). Soil compaction from wheel traffic under three tillage systems. *Agriculture*, 12(2), 219. <https://doi.org/doi.org/10.3390/agriculture12020219>
- American Society of Agricultural and Biosystems Engineering (ASABE) Standards. (2012). *Moisture Measurement, Forages, St. Joseph, MI: ASABE*. <https://elibrary.asabe.org/standards.asp>
- ASTM. (2019). *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass, D2216-19*. <https://store.accuristech.com/standards/astm-d2216-19>

- ASTM D7263-21. (2021). *Standard Test Methods for Laboratory Determination of Density and Unit Weight of Soil Specimens*. <https://doi.org/2021>
- Barbosa, L. C., Tenelli, S., Magalhães, P. S. G., Bordonal, R. O., Cherubin, M. R., de Lima, R. P., Castioni, G. A. F., Rossi Neto, J., and Carvalho, J. L. N. (2024). Linking soil physical quality to shoot and root biomass production in scenarios of sugarcane straw removal. *European Journal of Agronomy*, 152(November 2023), 1–10. <https://doi.org/10.1016/j.eja.2023.127029>
- Batey, T. (2009). Soil compaction and soil management - A review. *Soil Use and Management*, 25(4), 335–345. <https://doi.org/10.1111/j.1475-2743.2009.00236.x>
- Buttery, B. R., Tan, C. S., Drury, C. F., Park, S. J., Armstrong, R. J., and Park, K. Y. (1998). The Effects of Soil Compaction, Soil Moisture and Soil Type on Growth and Nodulation of Soybean and Common Bean. *Canadian Journal of Plant Science*, 78(4), 571–576. <https://doi.org/10.4141/P97-132>
- Campbell, G. S. (1986). Soil Physics with Basic. *Soil Science*, 142(6), 367–368.
- Capobianco, N. P., Bessa, G. B., de Oliveira Peris, G. C., da Silva, F. L., dos Santos Dias, D. C. F., Fernandes, R. B. A., and da Silva, L. J. (2023). Evaluation of soybean genotypes grown under soil compaction. *Journal of Agronomy and Crop Science*, 209(4), 517–531. <https://doi.org/doi.org/10.1111/jac.12635>
- Chan, K. Y., Oates, A., Swan, A. D., Hayes, R. C., Dear, B. S., and Peoples, M. B. (2006). Agronomic consequences of tractor wheel compaction on a clay soil. *Soil and Tillage Research*, 89(1), 13–21. <https://doi.org/doi.org/10.1016/j.still.2005.06.007>
- Chen, H., Gao, L., Li, M., Liao, Y., and Liao, Q. (2023). Effect of soil surface roughness on emergence rate and yield of mechanized direct-seeded rapeseed based on 3D laser scanning. *International Journal of Agricultural and Biological Engineering*, 16(3), 110–119. <https://doi.org/10.25165/J.IJABE.20231603.7276>

- de Jesus Duarte, S., Glaser, B., and Cerri, C. E. P. (2019). Effect of biochar particle size on physical, hydrological and chemical properties of loamy and sandy tropical soils. *Agronomy*, 9(4). <https://doi.org/10.3390/agronomy9040165>
- Gelder, B., Cruse, R., and Zhang, X. (2007). Comparison of track and tire effects of planter tractors on corn yield and soil properties. *Trans. ASABE*, 50(2), 365–370. <https://doi.org/doi:10.13031/2013.22627>
- Gong, H., Chen, Y., Wu, S., Tang, Z., Liu, C., Wang, Z., Fu, D., Zhou, Y., and Qi, L. (2022). Simulation of canola seedling emergence dynamics under different soil compaction levels using the discrete element method (DEM). *Soil and Tillage Research*, 223. <https://doi.org/doi.org/10.1016/j.still.2022.105461>
- Habib-ur-Rahman, M., Raza, A., Ahrends, H. E., Hügling, H., and Gaiser, T. (2022). Impact of in-field soil heterogeneity on biomass and yield of winter triticale in an intensively cropped hummocky landscape under temperate climate conditions. *Precision Agriculture*, 23(3), 912–938. <https://doi.org/10.1007/s11119-021-09868-x>
- Hamza, M. A., and Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research*, 82(2), 121–145. <https://doi.org/doi.org/10.1016/j.still.2004.08.009>.
- Harker, K. N., Clayton, G. W., Blackshaw, R. E., O'Donovan, J. T., and Stevenson, F. C. (2003). Seeding Rate, Herbicide Timing and Competitive Hybrids Contribute to Integrated Weed Management in Canola ( Brassica Napus). *Canadian Journal of Plant Science*, 83(2), 433–440. <https://doi.org/10.4141/P02-073>
- Harker, K. N., O'Donovan, J. T., Blackshaw, R. E., Johnson, E. N., Lafond, G. P., and May, W. E. (2012). Seeding Depth and Seeding Speed Effects on No-till Canola Emergence, Maturity, Yield and Seed Quality. *Canadian Journal of Plant Science*, 92(4), 795–802. <https://doi.org/10.4141/cjps2011-189>

- Hess, M. C., Buisson, E., and Mesléard, F. (2019). Soil compaction enhances the impact of microwave heating on seedling emergence. *Flora*, 259(151457).  
<https://doi.org/doi.org/10.1016/j.flora.2019.151457>
- Horn, R., Fleige, H., Mordhorst, A., and Dörner, J. (2023). Structure dependent changes in pore water pressure due to stress application and consequences on the effective stress. *Soil and Tillage Research*, 231, 105719.  
<https://doi.org/doi.org/10.1016/j.still.2023.105719>
- Hyatt, J., Wendroth, O., Egli, D. B., and TeKrony, D. M. (2007). Soil Compaction and Soybean Seedling Emergence. *Crop Science*, 47(6), 2495.  
<https://doi.org/10.2135/cropsci2007.03.0171>
- Ishaq, M., Hassan, A., Saeed, M., Ibrahim, M., and Lal, R. (2001). Subsoil compaction effects on crops in Punjab, Pakistan: I. Soil physical properties and crop yield. *Soil and Tillage Research*, 59(1–2), 57–65. [https://doi.org/doi.org/10.1016/S0167-1987\(00\)00189-6](https://doi.org/doi.org/10.1016/S0167-1987(00)00189-6)
- Kahlon, M. S., Singh, C. B., and Dhingra, M. (2023). Effect of compaction and irrigation regimes on soil physical characteristics, emergence, growth and productivity of summer moongbean. *Legume Research-An International Journal*, 46(4), 473–481.  
<https://doi.org/10.18805/LR-4362>
- Lamb, K. E., and Johnson, B. L. (2004). Seed Size and Seeding Depth Influence on Canola Emergence and Performance in the Northern Great Plains. *Agronomy Journal*, 96(2), 454.  
<https://doi.org/10.2134/agronj2004.4540>
- Lehmann, P., Merlin, O., Gentine, P., and Or, D. (2018). Soil texture effects on surface resistance to bare-soil evaporation. *Geophysical Research Letters*, 45(19), 10–398.  
<https://doi.org/doi.org/10.1029/2018GL078803>
- Li, B., Chen, Y., and Chen, J. (2016). Modeling of soil-claw interaction using the discrete element method (DEM). *Soil and Tillage Research*, 158, 177–185.

<https://doi.org/10.1016/j.still.2015.12.010>

Manitoba Agriculture. (2024). *Manitoba Ag-Weather Program*. Manitoba, Agriculture, Food and Rural Development. <https://web43.gov.mb.ca/climate/DailyReport.aspx>

Mileusnić, Z. I., Saljnikov, E., Radojević, R. L., and Petrović, D. V. (2022). Soil compaction due to agricultural machinery impact. *Journal of Terramechanics*, 100, 51–600. <https://doi.org/doi.org/10.1016/j.jterra.2021.12.002>

Nawaz, M. M., Noor, M. A., Latifmanesh, H., Wang, X., Ma, W., and Zhang, W. (2023). Field traffic-induced soil compaction under moderate machine-field conditions affects soil properties and maize yield on sandy loam soil. *Frontiers in Plant Science*, 14(June), 1–17. <https://doi.org/10.3389/fpls.2023.1002943>

Orzech, K., Wanic, M., and Załuski, D. (2021). The effects of soil compaction and different tillage systems on the bulk density and moisture content of soil and the yields of winter oilseed rape and cereals. *Agriculture*, 11(7), 666. <https://doi.org/doi.org/10.3390/agriculture11070666>

Otalvaro, I. F., Neto, M. P. C., Delage, P., and Caicedo, B. (2016). Relationship between soil structure and water retention properties in a residual compacted soil. *Engineering Geology*, 205, 73–80. <https://doi.org/10.1016/j.enggeo.2016.02.016>

Phakdee, S., and Suvanjumrat, C. (2023). Development of a tire testing machine for evaluating the performance of tractor tires based on the soil compaction. *Journal of Terramechanics*, 110, 13–25. <https://doi.org/doi.org/10.1016/j.jterra.2023.07.002>

Radford, B. ., Yule, D. ., McGarry, D., and Playford, C. (2001). Crop Responses to Applied Soil Compaction and to Compaction Repair Treatments. *Soil and Tillage Research*, 61(3–4), 157–166. [https://doi.org/10.1016/S0167-1987\(01\)00194-5](https://doi.org/10.1016/S0167-1987(01)00194-5)

Rempel, C. B., Hutton, S. N., and Jurke, C. J. (2014). Clubroot and the importance of canola in Canada. *Canadian Journal of Plant Pathology*, 36(supl), 19–26.

- <https://doi.org/doi.org/10.1080/07060661.2013.864336>
- Saljnikov, E., Mueller, L., Lavrishchev, A., and Eulenstein, F. (2022). *Advances in Understanding Soil Degradation Innovations in Landscape Research*. <https://link.springer.com/bookseries/16118>
- Schjønning, P., Lamandé, M., Keller, T., and Labouriau, R. (2020). Subsoil shear strength – Measurements and prediction models based on readily available soil properties. *Soil and Tillage Research*, 200(March). <https://doi.org/10.1016/j.still.2020.104638>
- Singh, R., and Ghildyal, B. P. (1977). Influence of soil edaphic factors and their critical limits on seedling emergence of corn (*Zea mays* L.). *Plant and Soil*, 47(1), 125–136. <https://doi.org/10.1007/BF00010374>
- Sivarajan, S., Maharlooei, M., Bajwa, S. G., and Nowatzki, J. (2018). Impact of soil compaction due to wheel traffic on corn and soybean growth, development and yield. *Soil and Tillage Research*, 175, 234–243. <https://doi.org/doi.org/10.1016/j.still.2017.09.001>
- Vance, W. H., Bell, R. W., and Johansen, C. (2024). Physical Conditions That Limit Chickpea Root Growth and Emergence in Heavy-Textured Soil. *Seeds*, 3(1), 26–39. <https://doi.org/10.3390/seeds3010003>
- Yan, M., Yang, D., He, Y., Ma, Y., Zhang, X., Wang, Q., and Gao, J. (2024). Alfalfa Responses to Intensive Soil Compaction: Effects on Plant and Root Growth, Phytohormones and Internal Gene Expression. *Plants*, 13(7). <https://doi.org/10.3390/plants13070953>
- Yang, C., Wu, J., Li, P., Wang, Y., and Yang, N. (2023). Evaluation of Soil-Water Characteristic Curves for Different Textural Soils Using Fractal Analysis. *Water (Switzerland)*, 15(4). <https://doi.org/10.3390/w15040772>
- Zhang, S., Zhang, X., Liu, Z., Sun, Y., Liu, W., Dai, L., and Fu, S. (2014). Spatial

heterogeneity of soil organic matter and soil total nitrogen in a Mollisol watershed of Northeast China. *Environmental Earth Sciences*, 72(1), 275–288.  
<https://doi.org/10.1007/s12665-014-3081-4>

Zuo, Q., Kuai, J., Zhao, L., Hu, Z., Wu, J., and Zhou, G. (2017). The effect of sowing depth and soil compaction on the growth and yield of rapeseed in rice straw returning field. *Field Crops Research*, 203, 47–54. <https://doi.org/10.1016/j.fcr.2016.12.016>

## Chapter 6

---

### General conclusions and recommendations

#### 6.1. General conclusions

Soil properties are critical factors influencing both soil stability and crop productivity. This research utilised laboratory tests, field experiments, and Discrete Element Methods (DEM) to study soil and crop responses to normal and shear loading of varying agricultural soils in the Canadian Prairies. The laboratory investigations demonstrated that soil surface shear properties are strongly influenced by applied normal stresses, texture, and moisture conditions. Increasing normal stresses enhanced soil shear strength, adhesion, and frictional resistance. Soil shear strength increased with an average percentage change of 539% among all the four soils tested. Higher clay content and moisture improved aggregate cohesion and reduced susceptibility to detachment in the context of soil erosion. Compression and shear experiments further revealed that normal stresses elevated soil bulk density, with axial strain recording average percentage change of 32% for the same four soils. Although these changes enhanced structural stability and resistance to erosion, they also increased soil mechanical impedance, limiting root penetration and restricting water movement within the soil matrix. These findings indicate that compaction provides short-term stability benefits but introduces long-term constraints for crop establishment.

The field-based assessments confirmed the significant impact of compaction on soil penetration resistance and plant development. Cone index measurements showed that compaction increased soil resistance to penetration, with variations influenced by soil texture and penetrometer geometry. The canola growth studies highlighted that excessive compaction suppressed plant establishment, reduced height, and lowered biomass accumulation. This

resulted in a reduced emergence rate at high compaction levels with a minimum rate of about 65%. These findings demonstrate that while compaction may improve soil stability against erosive forces, it undermines the soil characteristics required for optimal crop productivity.

Numerical simulations using the DEM successfully reproduced soil responses observed in both the laboratory and field conditions. The DEM models accurately replicated the shear strength and the penetration resistance across soil types and compaction levels, validating their reliability as predictive tools. It further provided valuable insights into micro-mechanical processes such as force-chain distribution during penetration, which are not easily measured in physical experiments. The strong agreement between the simulations and the experiments establishes DEM as a powerful framework for predicting soil responses under mechanical loading and for supporting sustainable soil and crop management strategies.

The study provides a comprehensive understanding of soil compaction as a multi-scale process linking mechanical and biological systems. Surface and internal shear analyses reveal the mechanisms of soil particle bonding and load transfer under stress, establishing the foundation for understanding structural integrity. Penetration resistance measurements translate these mechanical changes into quantifiable indicators of soil strength and root impedance, bridging laboratory results with field-scale performance. Finally, the observed canola response connects these mechanical properties to biological outcomes, revealing how variations in shear strength and penetration resistance directly affect crop emergence, growth, and productivity. Together, these complementary perspectives advance the understanding of how soil compaction evolves from particle-scale deformation to field-scale agronomic effects, providing a mechanistic framework for developing sustainable soil management and crop production strategies in the Canadian Prairies.

## 6.2. General recommendations

The findings of this research emphasize the importance of balanced soil management practices that mitigate the adverse effects of compaction while maintaining sufficient soil stability. Laboratory and field experiments demonstrated that excessive mechanical stress reduces pore continuity, increases bulk density, and limits water infiltration, ultimately affecting root development and crop growth. Agricultural operations should therefore limit machinery traffic during periods of high soil moisture, when soils are most susceptible to structural degradation. Implementing controlled traffic systems and optimized tillage practices can minimize unnecessary compaction, preserve soil structure, and sustain favourable conditions for root penetration and water movement. Additionally, incorporating cover crops enhances soil aggregation, improves cohesion, and reduces the risk of erosion. For canola production, careful management of soil compaction is essential. While slight compaction may improve seed–soil contact, moderate and excessive compaction restricts emergence, negatively affecting yield.

The Discrete Element Method (DEM) proved to be an effective tool for simulating soil behaviour under mechanical loading, capturing interactions at the particle scale that influence bulk soil response. Future research should focus on calibrating DEM for a wider range of soil types and management practices while incorporating dynamic processes such as root–soil interactions and variable climatic conditions. Long-term field validation would enhance model robustness and establish DEM as a reliable decision-support tool for sustainable soil management.

### 6.3. Contributions to knowledge

This research makes important contributions to the understanding of soil compaction and its effects on agricultural soils and crop performance:

#### 1. Integration of soil and crop responses

The study establishes a comprehensive framework connecting surface shear, internal shear, penetration resistance (CI), and canola response under varying compaction levels. By linking laboratory, field, and Discrete Element Method (DEM) simulation results, the research provides a perspective that bridges micro-mechanical soil behaviour with field-scale agronomic outcomes.

#### 2. Quantification of soil mechanical behaviour under compaction

The laboratory investigations quantified how normal stress, soil texture, and moisture influence soil shear strength, adhesion, cohesion and friction resistance. The findings revealed a substantial increase in shear strength (average 539%) and bulk density (average 32% axial strain) under compaction, demonstrating both the stabilizing benefits and potential limitations for root growth and water movement.

#### 3. Advancement of predictive modelling using DEM

DEM simulations were successfully calibrated and validated against experimental results, accurately reproducing soil shear strength and penetration resistance across soil types and compaction levels. This demonstrates the utility of DEM as a predictive tool for soil behaviour, providing insights into micro-scale force-chain distributions that cannot be easily measured in the field.

#### 4. Linking mechanical properties to crop performance

The study explicitly connected mechanical soil properties to canola establishment and growth. Field results showed that excessive compaction increased penetration resistance, reduced emergence rates, and limited crop biomass.

## 5. Guidance for soil and crop management strategies

By integrating mechanical and biological perspectives, this research provides evidence-based recommendations for managing compaction in the Canadian Prairies. The framework can inform decisions on tillage, crop selection, and compaction mitigation strategies, balancing soil stability with optimal crop performance.