A New Method of Guyed-Transmission Tower Support

A Thesis

Presented To

The Department of Mechanical Engineering

The Faculty of Engineering

The University of Manitoba

In Partial Fulfillment
of the requirements for the degree
Master of Science in Mechanical Engineering

by

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November, 1990

ISBN 0-315-71904-4

A NEW METHOD OF GUYED-TRANSMISSION TOWER SUPPORT

BY

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A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

Summary

Transmission of hydro-electric power from power station to consumer is carried out by overhead conductors suspended by regularly spaced transmission towers. These towers can be subjected to base vertical displacement, which in the case of guy-wire supported towers can lead to instability due to loss of guy wires, buckling of the tower shaft, or excessive tower top movement.

A new method of guyed tower support is proposed which will accommodate tower base vertical movement. This method is denoted as the weight activated tension stabilizer or WATS. The guy wires are given an initial predetermined sag. The midpoints of each pair of opposing guy wires are joined by tensioner cables which support a central weight and, thereby, impart tension in the guy wires. In operation, if the tower base heaves upward, guy-wire sag diminishes, the weight rides up the tower pole and guy tensions are increased accordingly. If the tower base settles, guy-wire sag increases, the weight rides down the pole and guy tensions are decreased. In the event of wind loading, the weight jams in place and the tower remains laterally stable.

Theoretical and experimental studies indicate that a WATS supported tower can accommodate nearly three times as much base heave as can a conventionally supported tower.

It is recommended that a full size prototype of a WATS tower be constructed for further design evaluation.

Acknowledgments

I would like to thank the many people who contributed comments, criticisms, time and effort to the production of this thesis. Foremost credit is due to the thesis advisor, Dr. J. Shewchuk, for providing the original idea for this thesis and ongoing support in all areas from its start to finish.

I would like to thank Barry Rindall and Andy Staudzs of Manitoba Hydro for valuable information on guyed transmission towers and for helpful comments on the manuscript. I acknowledge useful comments on the thesis by Drs. R. Han and A. Shah. Thanks are also due to Al Lohse for providing assistance in the testing for the scale model and Ron Crampton for providing assistance in the construction of the model. Finally, I am thankful for the financial support from Manitoba Hydro which made this investigation possible.

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1. INTRODUCTION

1.1 Hydro-Electric Transmission Towers in General

Modern society is completely dependent on the use of electricity. Because of this, it is important that the supply of electricity be reasonably priced an reliable. Electricity is transmitted from power station to consumer by means of over-head conductors suspended by transmission towers. It is, therefore, necessary to have a reliable tower system before reliable power is possible.

Transmission towers are either of the steel-angle type or the tubular steel type. These are further divided into free standing or guyed towers. Guyed towers are held in place by firmly mounted symmetrical guy wires, three or four most commonly, connecting the tower at a certain height to the ground. The guy wires are usually coated steel stranded cable. The remainder of this report deals with guyed transmission towers exclusively.

Transmission towers are subjected to wind loads on the conductors and on the tower itself as well as an axial load at the top caused by the weight of the conductors and the guy-wire tension. To keep the tower straight and prevent excessive loading the guy tensions must be maintained at acceptable levels.

1.2 The Problem of Tower Base Vertical Movement

A typical guyed transmission tower consisting of a pole, guy wires, and conductors is shown in Figure 1.1. A common problem with guyed towers in the Canadian north is vertical movement of the tower base which is caused by a combination of soil type and changing conditions of climate. If the conditions are such that the ground heaves the tower base upward, the tower goes into compression, the guy wires are extended, and the guy-wire sag diminishes increasing the wire tension until either the tower fails as a column or the guy-

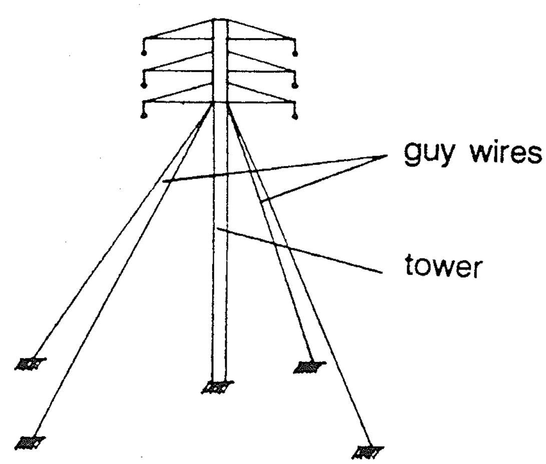


Figure 1.1 Conventional Tower Support Cable Arrangement

wire anchors are broken or pulled out of the ground. On the other hand, if the tower base settles into the ground, the guy wires slacken and the tower could become laterally unstable under wind loading conditions.

Because conventionally supported towers cannot accommodate base vertical movement, it is desirable to design a guy wire support system which will maintain acceptable guy-wire tensions over a range of such movement.

1.3 Proposed Solution to the Problem

The primary objective of this report is to present and describe in detail a new system of guy-wire support comprising of secondary cables and a weight. In this system the guy wires are relatively flexible so that they can tolerate a greater ground heave at the tower base. At the same time, the system provides lateral stability against wind loads.

A secondary objective of this report is to present a conceptual description of two other methods of base displacement accommodation. These are found in Appendix 4.

2. DEVELOPMENT OF THE PROPOSED SOLUTION

2.1 Introduction

This section consists of an overview of the design and operation of the proposed guy-wire support system. As well, it contains a description of theoretical and experimental studies which were undertaken with a view to predicting its performance.

The new method of guy-wire support shall hereafter be referred to as the weight activated tension stabilizer or WATS.

2.2 Overview of WATS Design

2.2.1 Guy-Wire Arrangement

A schematic of the WATS tower support cable arrangement is shown in Figure 2.1

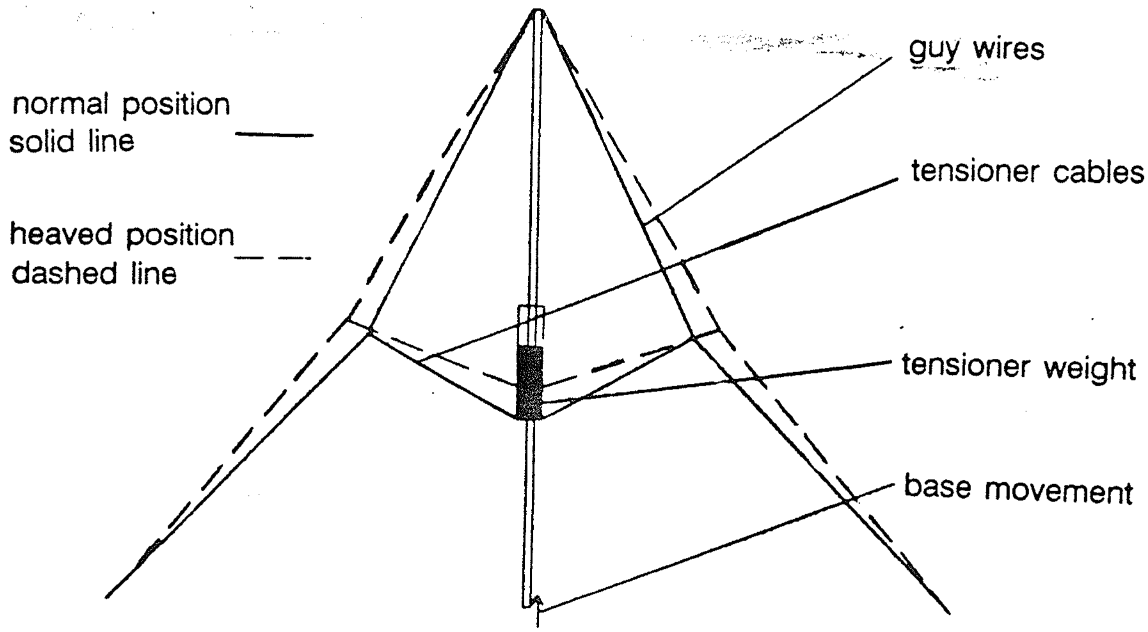


Figure 2.1 WATS Tower Support Cable Arrangement Showing Two Base Positions

Briefly, the WATS arrangement consists of tensioner cables which are attached to the guy wires at mid span and which support a tensioner weight centred at the tower shaft. The purpose of the weight is to maintain tension in the guy wires. The guy wires are set up with an initial sag and their tension is determined by the tensioner cable angle and the amount of suspended weight. Details of the design are given in Appendix A.1.

In the absence of wind loading the guy-wire tensions are all equal. Because under this condition the tensioner cable loads are balanced, the suspended weight is free to move up or down on its guide shaft. If the tower base rises, the guy-wire sag decreases, pulling the tensioner weight up which causes a small increase in guy-wire tension. As will be shown in Section 2.3, the ratio of the change in guy-wire tension to vertical base movement is much lower than it is in a conventionally-supported tower.

2.2.2 Provision for Lateral Stability

One of the requirements of the guy wires is to maintain lateral stability against wind loading. In a conventionally supported tower, this stability is maintained by pre-tensioning the guy wires so that little sag is present. However, because the guy wires in a WATS tower are relatively flexible, it is necessary to arrest this flexibility to prevent wind-induced tower deflection. This arrest is achieved by means of a weight-locking mechanism.

As noted previously, the tensioner weight is free to move up or down as long as no lateral loads are present and the tensioner cable loads are all equal. In the presence of lateral wind loading, the guy-wire tensions are not equal and the resulting unbalance in the tensioner cables will cause the weight to lock against the guide shaft as shown schematically in Figure 2.2. The weight will remain locked in place until the lateral loads disappear. As further illustrated in the same figure, if the weight did not lock in place, that is, if the weight were free to move upward, unacceptable tower top movement would result from lateral wind loading. As noted previously, a more detailed description of WATS is given in Appendix A.1.

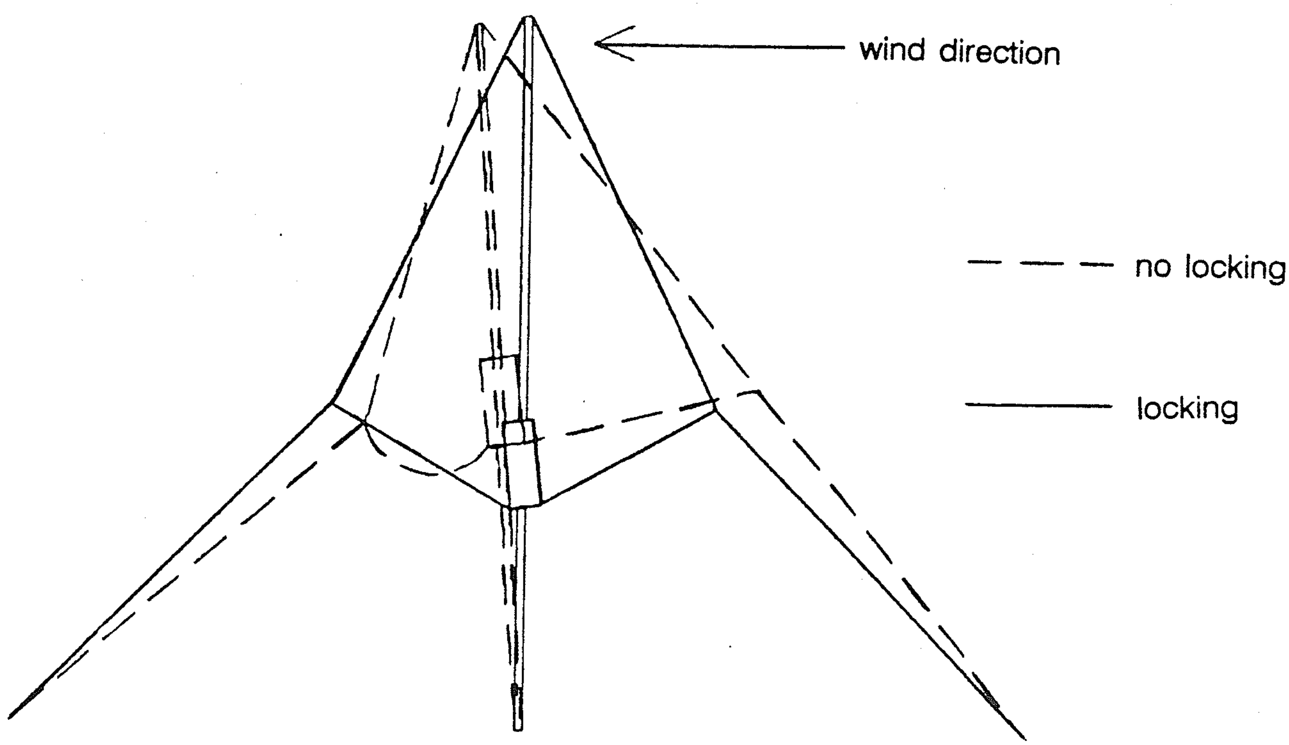


Figure 2.2 The Effect of Lateral Loads on WATS Towers

2.3 Predicted Performance of the Proposed Solution

2.3.1 Mathematical Analysis

A mathematical study was carried out to determine the relationship between axial loading in the tower and vertical base displacement for both the conventional and WATS arrangements.

For the conventional system, raising and lowering of the base is accommodated by deformations in the wires and tower, and to a limited extent by change in the wire geometry through loss of sag. With the WATS system, however, the above noted deformations are small relative to the changes due to sag variation. Hence, in the mathematical analysis of the WATS system, these deformations are neglected. The detailed mathematical analysis is found in Appendix A.2.

The effect of tower base heave was investigated for both the conventional and WATS systems. The effect of base settlement was investigated for the WATS system only because the levels of conventional guy-wire tension under base settlement become not acceptable. As shown in Figure 2.3, the important variables for the conventional tower are the tower height, the initial guy-wire tension, and the chord angle. As shown in the same figure for the WATS tower the variables are: tower height , mid-cable sag s, chord angle $\theta 1$, sag angle $\theta 2$, tensioner cable angle $\theta 3$, and guy-wire angle $\theta 4$.

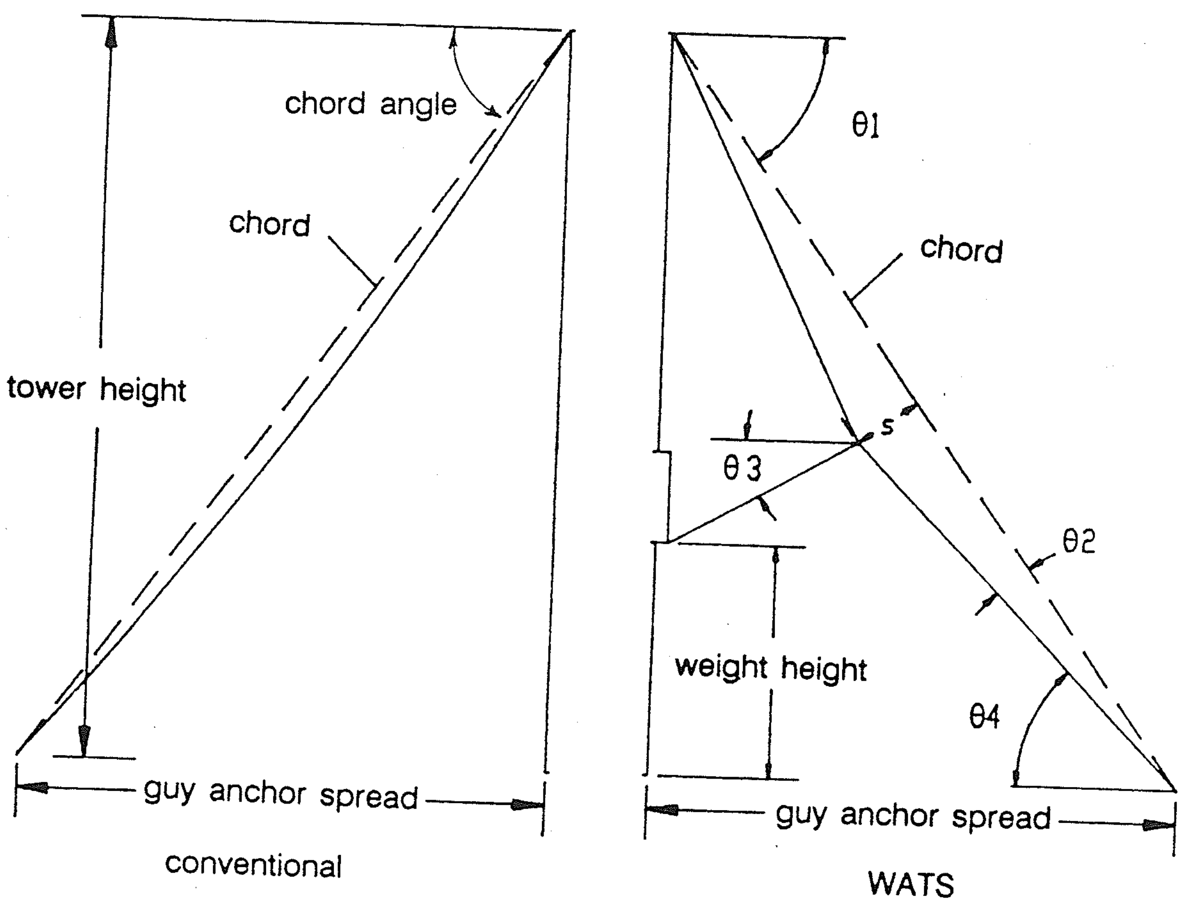


Figure 2.3 Mathematical Variables

The results of the mathematical investigation are given in Figure 2.4 for both the WATS and conventional tower support. Here, tower load vs base displacement is plotted for one set of WATS variables, sag = 60", and tensioner cable angle = 30. This set was chosen because it represents the Neutral position. With this set of variables, a WATS tower will accommodate heave and settlement with equal effectiveness. Also, to allow a clear comparison between WATS and conventional, the initial tower loads are the same. The results presented in Figure 2.4 are discussed in Section 2.4. Also, as stated earlier, the results for other sets of variables are given in Appendix A.3.

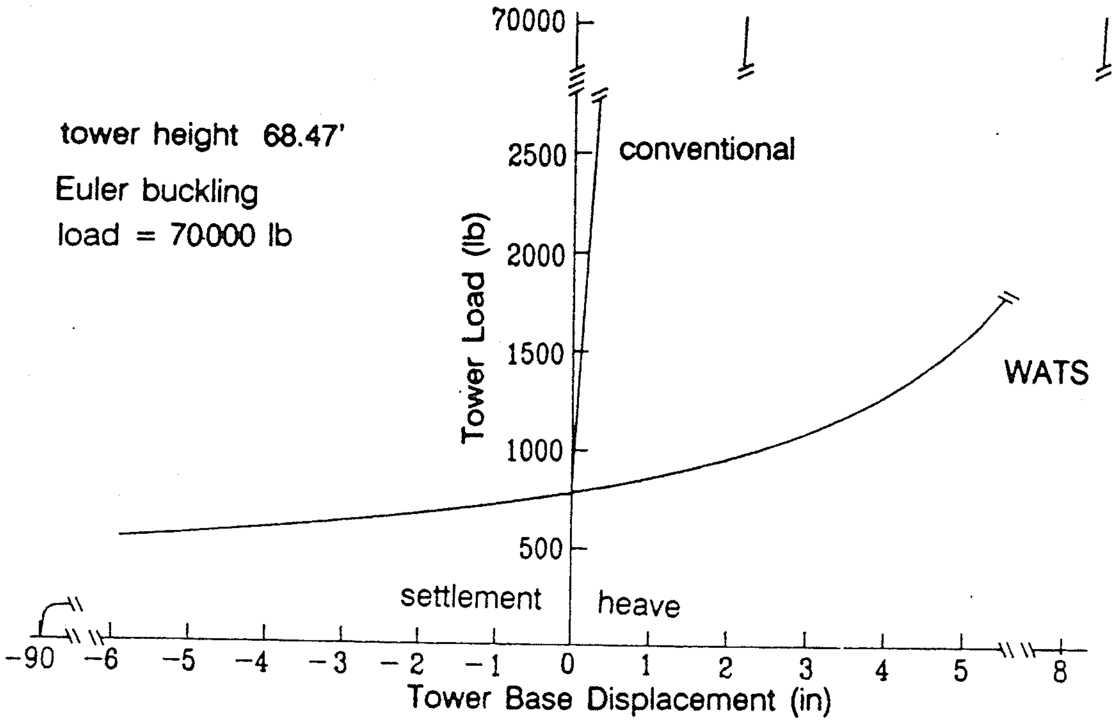


Figure 2.4 Mathematical Analysis Results

2.3.2 Model Experimentation

Physical tests of base displacement and lateral loading were done for both the conventional and WATS systems. These tests were done to complement the mathematical analysis. A schematic of the testing arrangement is shown in Figure 2.5

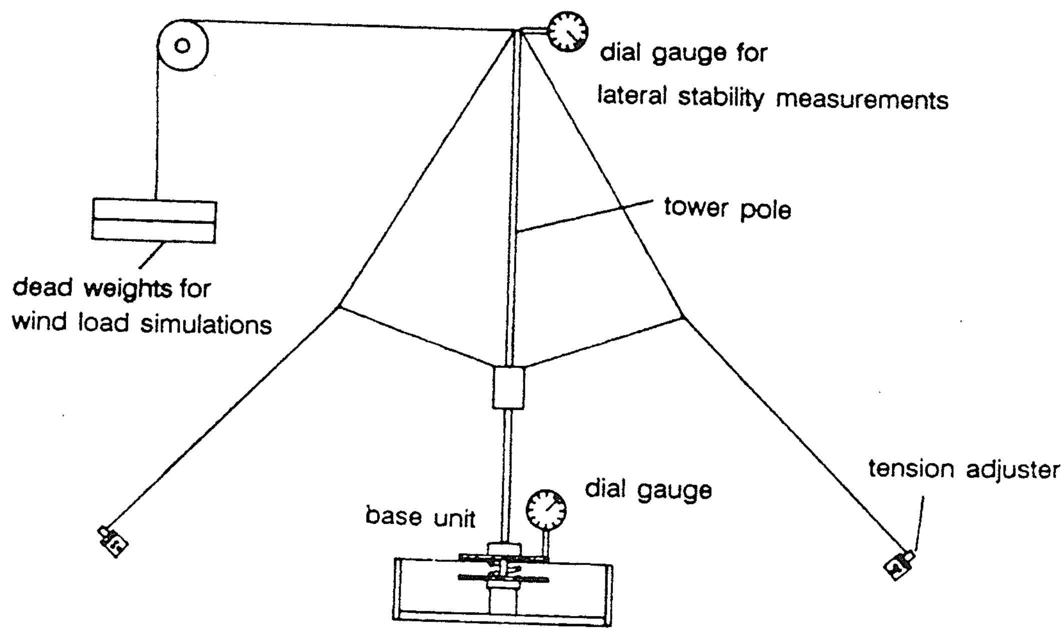


Figure 2.5 Testing Arrangement

Base movement was simulated by raising and lowering the tower shaft as in real life, and the tower load was measured and recorded. Lateral stability was tested by applying known loads representing wind loads to the tower top and measuring the tower top deflection. The experimental investigation is described in greater detail in Appendix A.3.

The results of the experimental model tests for base displacement are shown in Figure 2.6 for both the WATS and conventional systems. The WATS tower load vs base displacement curve is for one set of variables only. Again, this set was chosen because with it tower base heave is accommodated as easily as base settlement. These variables include a sag of 2.4 inches and a tensioner cable angle of 30°. To show the advantages of WATS over conventional the same tower pole of height 32.875" was used starting at the same initial tower load of 4 pounds.

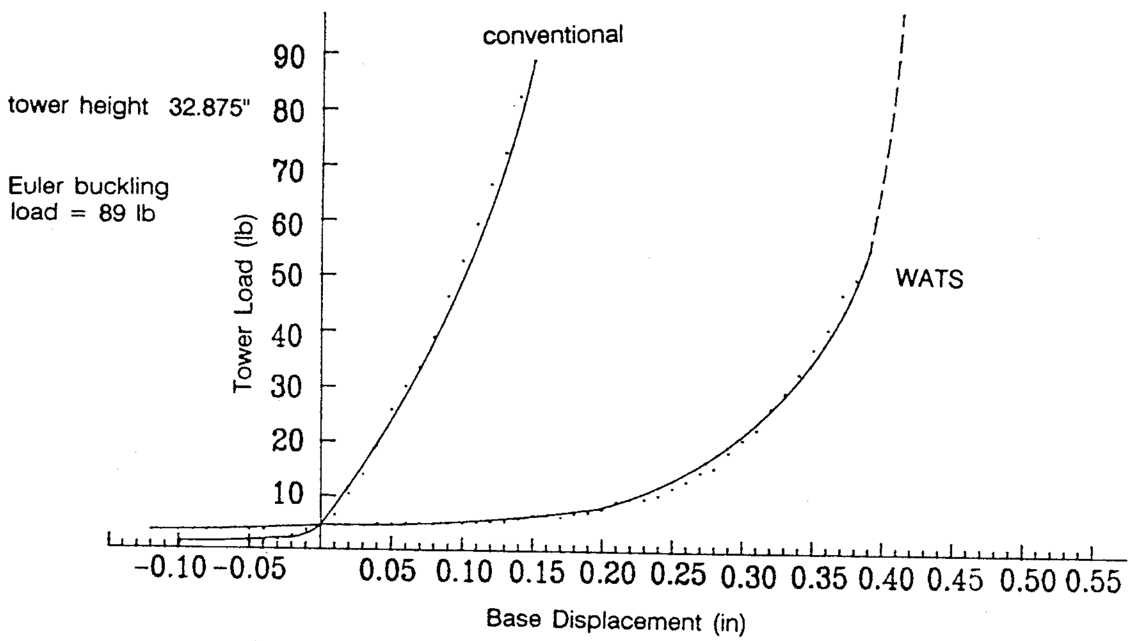


Figure 2.6 Physical Modelling Results

The results of the lateral stability tests for the model tower are given in Figure 2.7 for both WATS and conventional systems experiencing a simulated 100 mph wind. Here, tower top deflection is plotted for three base positions, settled, normal and heaved. WATS variables include an initial sag of 2.4" and a tensioner cable angle of 30.

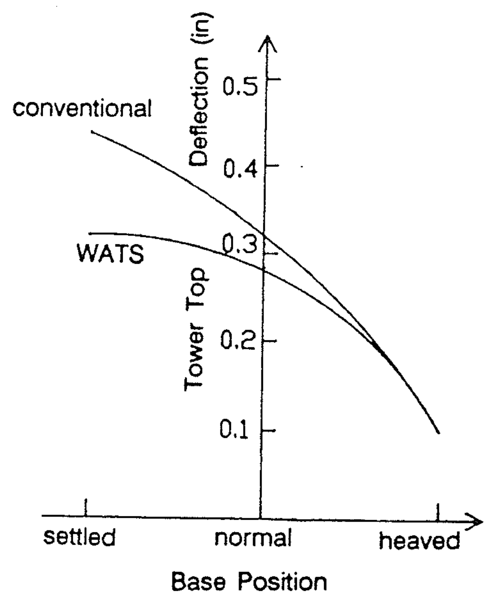


Figure 2.7 Stability Test Results

2.4 Discussion

From the results of the math analysis and physical modelling, it is clear that a WATS supported transmission tower will tolerate more base heave than a conventionally supported tower. This is shown in Figure 2.4, where the math model predicts that a conventionally supported tower will tolerate 2.1 inches of heave while a WATS tower, with initial mid-cable sag of 60" and tensioner cable angle of 30°, will tolerate 8.25" of heave, or 3.9 times as much a conventional tower. It should be noted that at this much heave, the mid-cable sag of a WATS tower with this configuration approaches zero and the tower behaves like a conventional tower.

The above mathematical results are verified through the physical model studies. In Figure 2.6 it is observed that the conventional tower will tolerate 0.15" of heave before buckling, while extrapolating the WATS curve gives a heave of 0.48" before buckling occurs. This represents a ratio of 3.2 over the conventional, which compares favourably with the above mathematical results.

The mathematical results also show that a WATS tower tolerates base settlement whereas a conventional tower does not. In Figure 2.4, the math results show that WATS tower load decreases at a very slow rate under conditions of base settlement curve. This trend was also observed with the physical modelling, as shown in Figure 2.6. Physical model tests show that a WATS tower with the above configuration has a very flat load-settlement. The lower limit of WATS tower settlement occurs when excessive tower top motion is observed, which for this configuration is at about one inch of settlement, or about two feet in real life. The physical model tests also show that conventional tower load decreases rapidly with tower base settlement. After settling 0.07", the measuring device was merely reporting the weight of the model tower and guy wires rather than tower load.

The mathematical results compare favourably with the physical modelling results over a range of base displacement. In Figure 2.7, the experimental and mathematical results are shown for a WATS tower of the above configuration. Here it is observed that the two sets of results are nearly identical until the point at which the WATS tower starts to behave like a conventional tower.

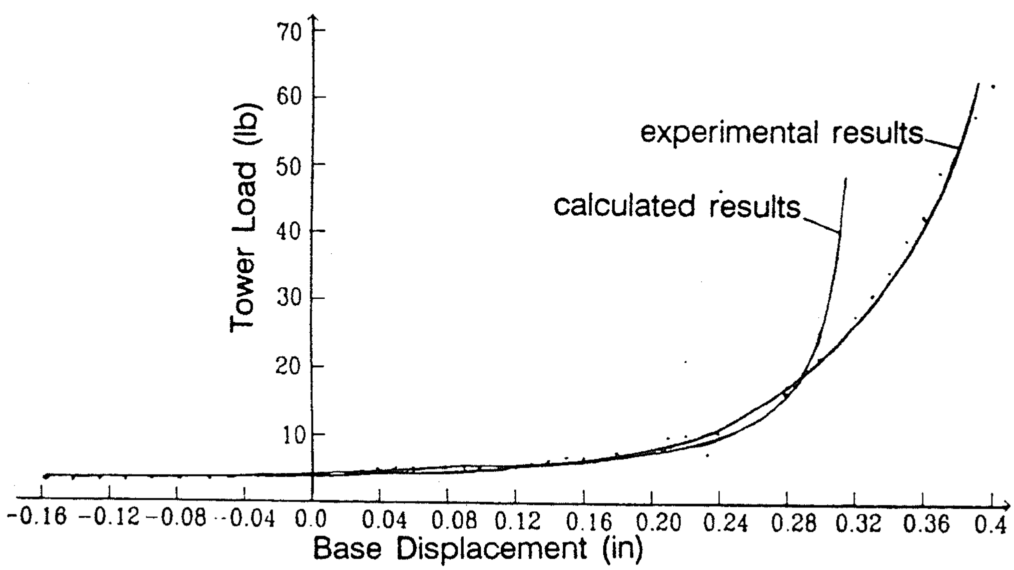


Figure 2.8 Comparison of Experimental and Mathematical Results

The results of the lateral stability tests, summarized in Figure 2.7 show that at normal (no base displacement) conditions, the conventional tower allows less tower top movement than the WATS tower. The WATS tower top moves about 9% more than the other because this tower relies on the jamming mechanism for its lateral stability. A full size tower would not move the same amount in proportion to the model because there is proportionally more slack in the model cable connections than in the full size. What this means is that if a conventional tower top moves 10" in a wind, a WATS tower top will move no more than 11". The cause of this additional movement is due to the jamming action of the tensioner weight. At conditions of high tower load there is little or no difference in tower top movement between the two systems. However, under conditions of tower base settlement a conventional tower becomes laterally unstable and can sway from side to side. On the other hand, with the WATS arrangement the weight locks into place and lateral stability is maintained.

3. CONCLUSIONS

Based on the mathematical analysis and physical modelling of the WATS system of transmission tower support using the chosen set of variables, it is concluded that:

1) A WATS supported tower will withstand about three times more tower base heave than a typical conventionally supported tower.

2) While tower base settlement significantly reduces conventional tower load, WATS tower load is virtually unaffected by this problem.

3) Tower lateral stability at conditions of zero base movement is affected slightly by the WATS arrangement. At conditions of extreme tower load there is little or no difference in lateral stability between the two arrangements, but under conditions of base settlement, the WATS tower is more laterally stable than the conventionally supported tower.

4. RECOMMENDATIONS

Based on the research undertaken in this report, it is recommended:

1) That a full size tower be outfitted with the WATS system of guy-wire support, of the configuration given in Appendix A.1, and situated such that it can be monitored as it undergoes tower base heave.

2) That a full size tower be outfitted with the WATS system, of the configuration given in Appendix A.1, and situated such that it can be monitored as it undergoes settling of the tower base.

5. APPENDICES

APPENDIX A.1 DESIGN AND APPLICATION

A.1. INTRODUCTION

A.1.2. DESIGN

A.1.2.1 Overview of WATS Design

A.1.2.2 Guy Wires

A.1.2.3 Jamming Device

A.1.3. APPLICATION

A.1.3.1 Tubular Steel Tower

A.1.3.2 Steel Lattice Tower

A.1.1 INTRODUCTION

This appendix covers the details of design and application of the weight activated tension stabilizer (WATS) system of guy wire arrangement. Section A.1.2.1 is a complete description of the system and its operation, while details of the design of the guy wires and jamming device are found in A.1.2.2 and A.1.2.3 respectively. Section A.1.3 describes how WATS could be applied to both tubular steel and steel lattice transmission towers.

A.1.2 DESIGN

A.1.2.1 Overview of Design

The WATS system is a guy-wire arrangement which allows tower base vertical displacement to occur without causing tower failure. The system is shown in Figure A.1.1. To allow heave, an initial sag is imparted to the guy wires which decreases if the tower base rises, and increases if the base settles. Guy wire tension is imparted at mid-cable span through tensioner cables suspending a weight. The weight is free to travel up and down the tower shaft but jams into place in the event of side loading, maintaining lateral stability. This jamming action is shown in Figure A.1.2. The weight, in the form of a pipe for tubular steel towers, or a framework for steel lattice towers; is guided by the shaft of the tower itself. In the event of a wind, there would be a tendency for the guy wires to become unequally tensioned. This causes the compensating weight to

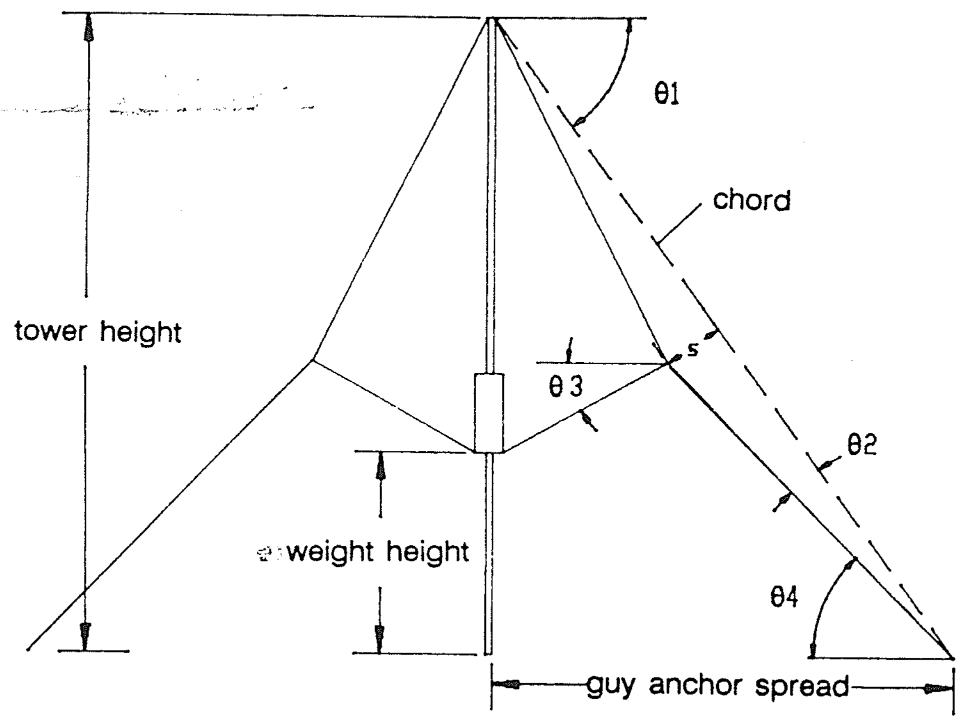


Figure A.1.1 The WATS System

tip to one side and jam, preventing any further movement of the weight until equal tensions are restored. If the weight did not jam, the tensioner cable would pull the weight up. This would cause the sag on the windward guys to decrease to zero and the tower would tip to the opposite side. Because of this jamming,

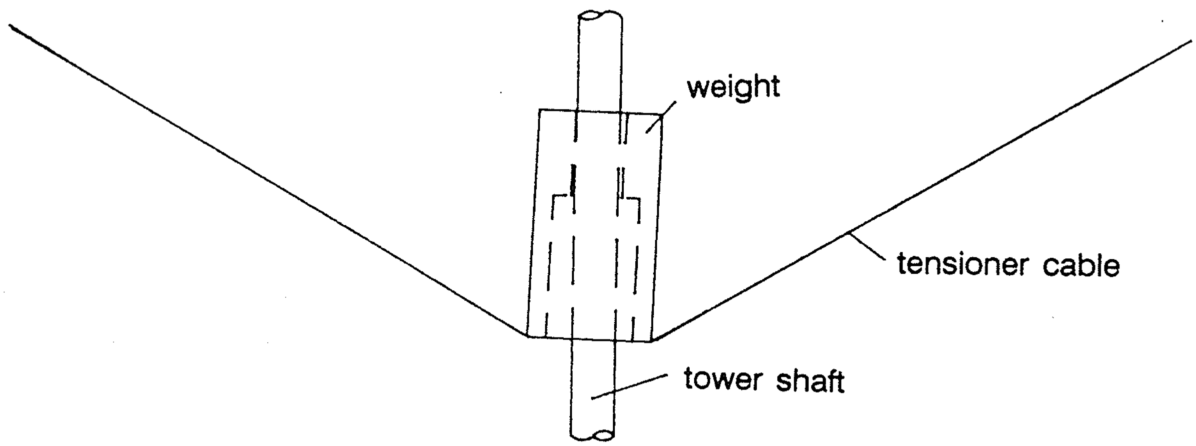


Figure A.1.2 Jamming Action

relatively light guy wire tensions could be used. With no lateral loads present, it is not necessary for a tower supported in this manner to have high initial guy-wire tensions.

As well as upward movement, the tensioner weight allows the tower base to settle, keeping the guy wires taut and maintaining lateral stability as long as the tensioner weight is suspended off the ground.

A.1.2.2 Guy Wires

As previously noted, tower base vertical movement is accommodated by giving the guy wires an initial sag, and tension is imparted by tensioner cables. The tensioner cables are attached to the guys at mid-span because it is this point that has the greatest influence on guy tension [4], equal to upper and lower portions of the wire. It is desirable to have an initial geometry which allows the tower base to rise as well as settle, while maintaining acceptable guy-wire tensions and lateral stability.

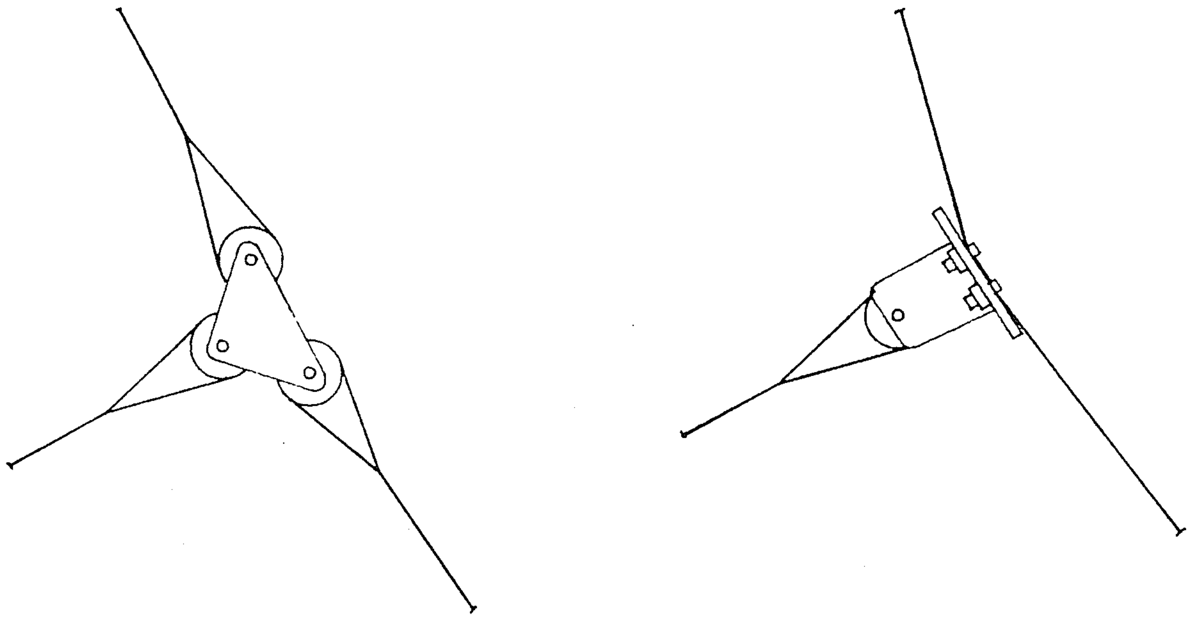
Referring to Figure A.1.1, for a tower whose guy wires attach at a height h, and a guy anchor spread of w, the distance from tower to guy anchor (chord) is

$$\text{chord} = \sqrt{w^2 + h^2} \tag{1}$$

If the initial sag is s, then the distance from guy anchor to tensioner cable (half guy cable length) is

$$\sqrt{s^2 + (\text{chord}/2)^2} \tag{2}$$

The point of connection of the tensioner cable to the guy wire could either be with a three way connector as shown in Figure A1.3a, or with a slip connection, Figure A1.3b. With the three way connector, upper and lower parts of the guy wire are separate. This could be used for new or replacement installations. With the slip connection, the guy wire is continuous. This would allow the WATS arrangement to be used on existing installations.



a) 3-Way Connector b) Slip Connector

Figure A.1.3 Wire Connectors

Lateral loading of guyed hydro towers caused by wind, is shown schematically in Figure A.1.4. As noted previously, under wind loads, the guys on the windward side of the tower experience an increase in tension while those on the other side slacken.

A typical transmission tower system supports n conductors of diameter d spanning a distance L between towers. To find the drag force on the

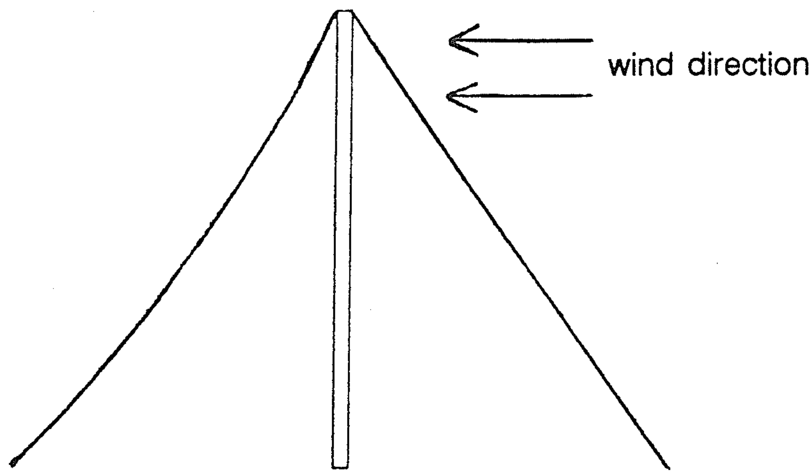


Figure A.1.4 Lateral Loading of a Guyed Tower

conductors, first find the associated Reynolds number, given by

$$Re = \frac{\rho V l}{\mu}, \tag{3}$$

where ρ = air density, V = wind velocity, l is a characteristic length such as conductor diameter, and μ= air absolute viscosity. For Re less than 200,000 the drag coefficient for the conductors is given by [2]

$$C_D = 1.0 + 10(Re)^{-0.67} \tag{4}$$

The drag force is then

$$D = 1/2 \rho V^2 A C_D \tag{5}$$

where A is the frontal area of the conductors equal to

L X d X (no. of conductors).

If an arrangement of 6 conductors of diameter d = 0.02184 m, spanning L = 350 m is subjected to a 44.7 m/s wind (100 mph), with an air density of 1.09 kg/m^3 and a viscosity of $1.95\text{X}10^{-5}$ Ns/m, then

$$Re = \frac{(1.09)(44.7)(0.02184)}{(1.95\times10^{-5})} = 54,569.8$$

$$C_D = 1.0 + 10(54569.8)^{-0.67} = 1.0067.$$

The drag force on each tower caused by this 44.7 m/s wind loading on the conductors is

$$D = 0.5(1.09)(44.7)^2(350)(0.02184)(1.0067) \times 6 = 50,278.6 \text{ N}$$

or D = 11,303 lb.

A force diagram showing one guy wire being tensioned by the lateral wind force, is shown in Figure A.1.5 for the WATS arrangement. One guy wire

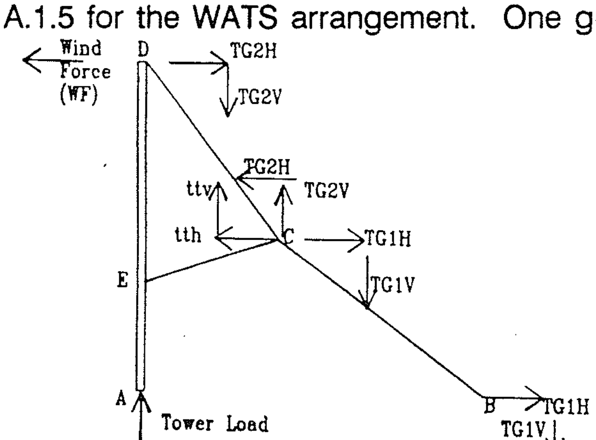


Figure A.1.5 Force Diagram of WATS Tower under Lateral Loading is shown because the opposite guy wire tension essentially goes to zero and does not contribute to the tower load. Taking moments about the point A, we get

$$\Sigma M_A = 0 = (WF)(\overline{AD}) + (TG1V)(\overline{AB})$$

$$TG1V = -(WF)(\overline{AD}/\overline{AB}).$$

The lower guy-wire tension is then

$$TG1 = TG1V/\sin\theta 4 = -\left[(WF)(\overline{AD}/\overline{AB})\right]/\sin\theta 4 \qquad (6)$$

Summation of horizontal forces at point D gives

$$TG2H + WF = 0 \quad \text{or} \quad TG2H = -WF$$

and

$$TG2 = TG2H/\cos(\theta 1 + \theta 2) = -WF/\cos(\theta 1 + \theta 2) \qquad (7)$$

Summation of horizontal forces at point C gives

$$TG1\cos\theta 4 - TG2\cos(\theta 1 + \theta 2) - tt\cos\theta 3 = 0$$

The tensioner tension tt is then given by

$$tt = [TG1\cos\theta 4 - TG2\cos(\theta 1 + \theta 2)]/\cos\theta 3$$

or $$tt = \{-[(WF)(\overline{AD}/\overline{AB})]/\tan\theta 4 + WF\}/\cos\theta 3$$

which reduces to

$$tt = \frac{WF}{\cos\theta 3}\left[1 - \frac{\overline{AD}/\overline{AB}}{\tan\theta 4}\right]. \qquad (8)$$

Tower load is given by adding all vertical forces at point A

$$\text{Tower Load} = TG2V - tt\sin\theta 3$$

or Tower Load = $(-WF)\tan(\theta 1+\theta 2) - (WF)\tan\theta 3[1-(\overline{AD}/\overline{AB})/\tan\theta 4]$

which reduces to

$$\text{Tower Load} = -WF\{\tan(\theta 1+\theta 2) + \tan\theta 3[1-(\overline{AD}/\overline{AB})/\tan\theta 4] \qquad (9)$$

As an example, consider a WATS tower under the influence of the 11303 lb lateral load, with $\overline{AD}/\overline{AB}$ = 1.4056, $\theta 1$=55, $\theta 2$=6.6, $\theta 3$=45, $\theta 4$=48.4.

TG1 = -[(-11303)(1.4056)]/sin(48.4) = 21,245 lb

TG2 = -[(-11303)/cos(61.6)] = 23,764 lb

tt = [-11303/cos(45)][1-(1.4056/tan48.4)] = 3963 lb

Tower Load = 11303{tan61.6 + tan45[1-(1.4056/tan48.4)]}=18102 lb

As noted previously, the weight is free to travel vertically along the tower shaft but locks in place when lateral loads are applied to the tower. For circular tower shafts, the weight is in the form of a collar as shown in Figure A.1.6, and the dimensions of the central hole are such that very little lateral motion is required before jamming takes place. For a tower shaft of diameter d, and a weight with contact length l and a hole diameter D, the clearance is D - d. The weight is able to tip through an angle α as shown in Figure A.1.7. The angle α is defined as

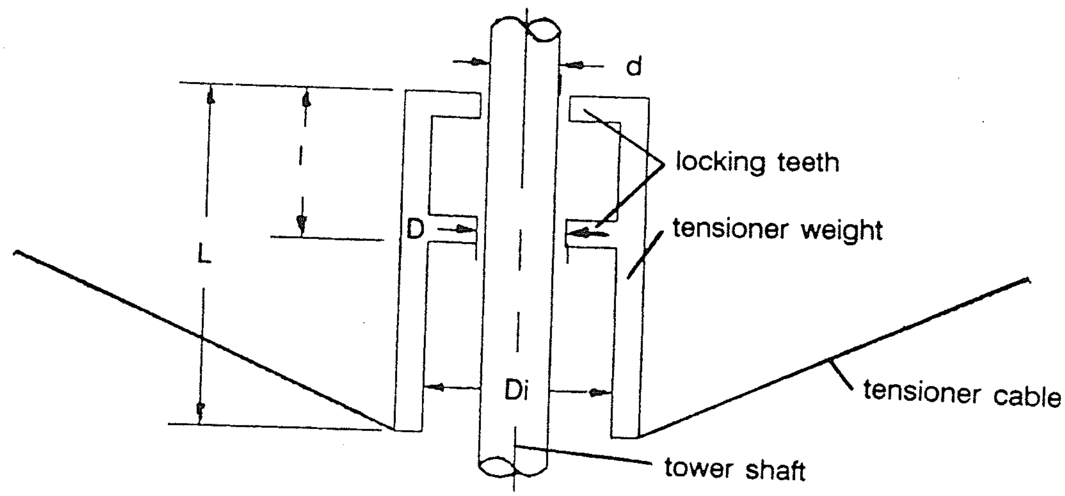


Figure A.1.6 Jamming Device

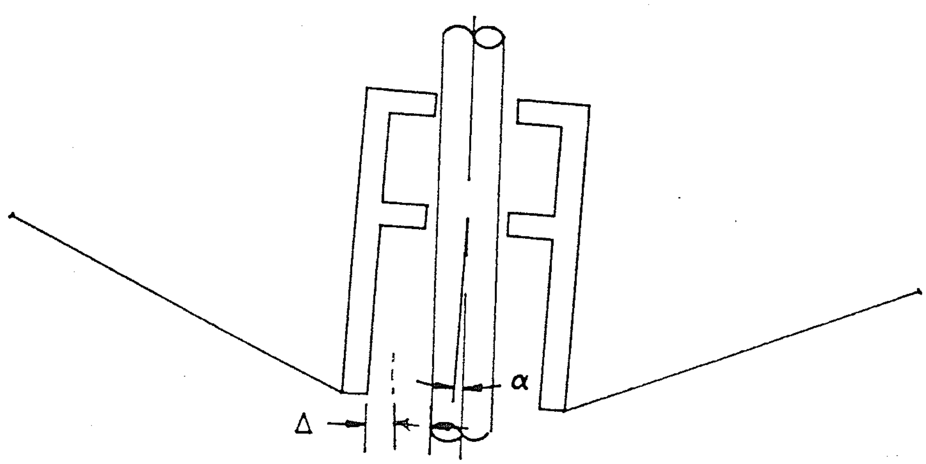


Figure A.1.7 Tipping Angle

$$\tan\alpha = (D-d)/l \quad \text{or} \quad \alpha = \mathrm{Tan}^{-1}[(D-d)/l]. \tag{10}$$

For jamming to occur it is necessary to have L > l, and the amount of lateral movement Δ is given by

$$\Delta = L\sin\alpha. \tag{11}$$

The dimension Di of such a weight would have to be large enough that jamming can occur before the rim of the weight comes into contact with the guide shaft.

For the weight shown in Figure A.1.6, the dimension Di would have to be such that

$$Di/2 - d/2 > L\sin\alpha,$$

or
$$Di > 2L\sin\alpha + d \qquad (12)$$

As an example, consider a weight with a hole diameter D = 13.25" and a contact length of 10" riding a pole 12.75" in diameter. If the desired weight is 150 pounds and is made of steel (density = 0.284lb per cubic inch), [1] then the volume must be

$$\text{Volume} = 150/0.284 = 530 \text{ cu. in.}$$

If the total length of the weight is 16", the tipping angle would be

$$\alpha = \mathrm{Tan}^{-1}[(D-d)/L] = \mathrm{Tan}^{-1}[(13.25-12.75)/16] = 1.79^{\circ}$$

and the dimension Di would have to be at least

$$Di = 2(16)\sin(1.79) + 12.75 = 13.75".$$

Neglecting the weight of the locking teeth, this weight would be 0.7" thick.

A.1.3 APPLICATION

A.1.3.1 Tubular Steel Tower

Tubular steel towers usually have one central, round shaft supporting a frame which carries the conductors and guy-wire attachments. Because of its central location, the shaft is well suited as a guide shaft for the compensating weight of the WATS arrangement. For these towers, the weight would be made of two halves with the central hole 0.5" larger in diameter than the tower shaft. This is shown schematically in Figure A.1.8.

When lateral loads are present, the force at the bottom of the weight would be the horizontal component of tensioner cable tension, or tth.

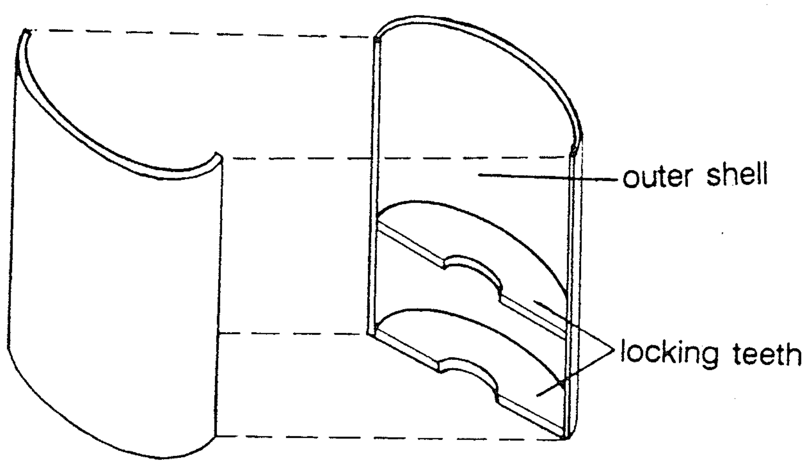


Figure A.1.8 Tensioner Weight

This causes a bending moment as shown in Figure A.1.9

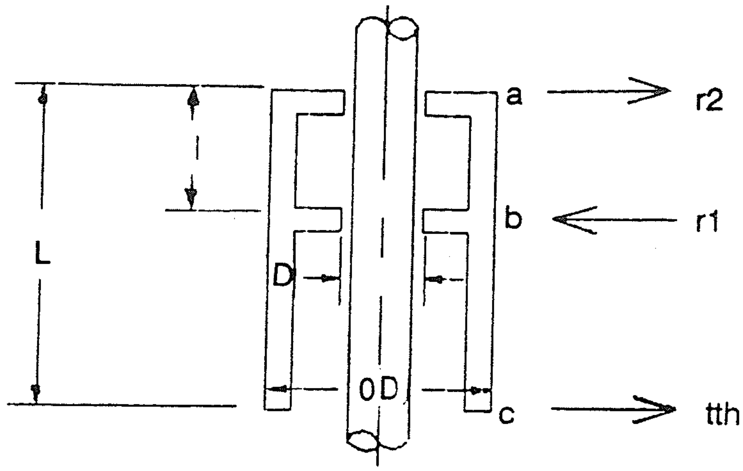


Figure A.1.9 Bending of Tensioner Weight

Taking moments about b and solving for r2 gives

$$r2 = tth\left(\frac{L-l}{l}\right) \tag{13}$$

while summing forces gives

$$r1 = tth\left[1 + \left(\frac{L-l}{l}\right)\right] \tag{14}$$

The maximum bending moment occurs at b and is equal to

$$M_{MAX} = tth(L-l) \tag{15}$$

The moment of inertia of the weight, with D and Di as the outer and inner diameters respectively, is given by

$$I = \pi/64(Do^4-Di^4). \tag{16}$$

The maximum bending stress at b is given by [3]

$$\sigma_{MAX} = \left[M_{MAX}(Do/2)\right]/I \tag{17}$$

For an example, consider a weight with L = 16", l = 10", weighing 150 lb with

Di = 14.35", and D = 15.75", and the horizontal component of tensioner tension = 3900 lb.

$$M_{max} = (3900)\ (16\text{-}10) = 23{,}400 \text{ in-lb}$$

$$I = 939.1 \text{ in}^4$$

$$\text{max} = \frac{(23400)\ (7.875)}{939.1} = 196.2 \text{ psi}$$

A.1.3.2 Steel Lattice Tower

With guy-wire supported steel lattice towers the central column is made up of steel angles with a square cross section. Because of this, the weight must also be of square cross section, riding on guide vanes fitted to the four corners of the tower as shown in Figure A.1.10. A schematic of the tower and weight is shown in Figure A.1.11.

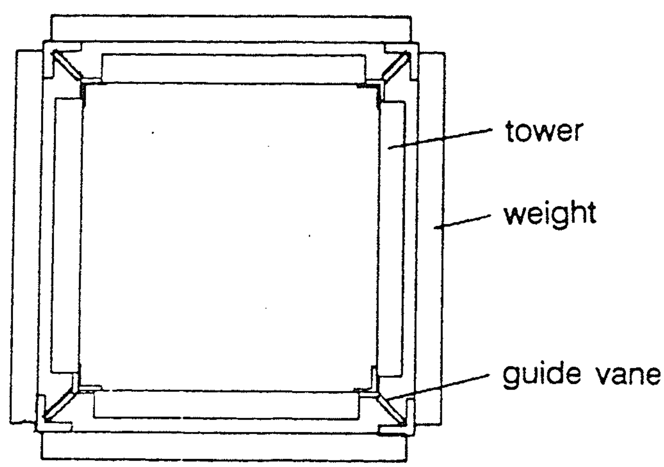


Figure A.1.10 Cross Sectional View of Tower and Weight

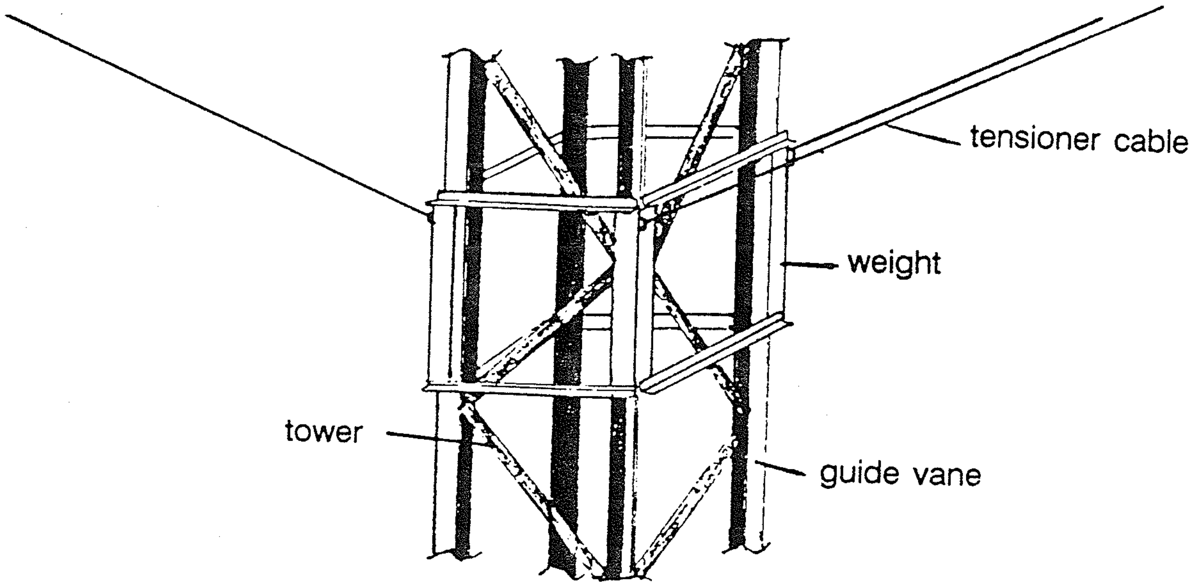


Figure A.1.11 Tower and Weight Schematic

The weight consists of four corner angles upon which the tensioner cables would attach, held together by four smaller angles at the top and bottom. For additional weight, steel plates could be bolted to the lower four sides of the assembly.

For example, consider a tower with a 4' square cross section. To provide clearance, the guide vanes protrude such that the cross-section of the weight is 4.5' square. The desired weight is 200 lb. With the tensioner cable tension as in Section 3.1, 3900 lb, the force in the two facing connecting angles is 1950 lb each. Using 2 X 2 X 0.25 steel for the connecting angles, the stress in the facing angles is only 2078 psi. The weight per foot of these angles is 3.19 lb/ft, so their weight is 115 lb. Using 2.5 X 2.5 X 0.25 steel angles for the corners, weighing 4.1 lb/ft, the length of each would be 5 feet. To provide jamming, the weight would be of the configuration shown in Figure A.1.12.

The guide vanes would be 7 feet long and would be situated along the tower such that the weight is guided over the full range of tower base heave and settlement. This would depend on tower height and guy anchor spread which differs from tower to tower, as well as the initial WATS configuration.

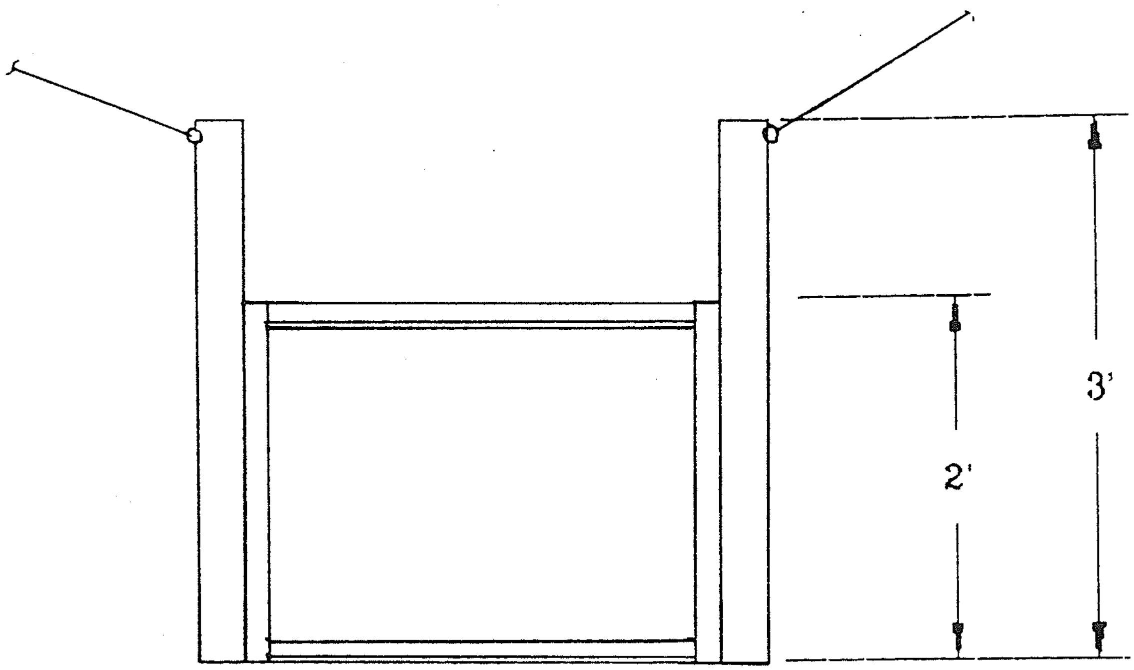


Figure A.1.12 Steel Lattice Weight Schematic

APPENDIX A.2 MATHEMATICAL ANALYSIS OF GUYED TRANSMISSION TOWERS

A.2.1. INTRODUCTION

This appendix covers the mathematical modeling of the weight activated tension stabilizer (WATS) system of guy-wire arrangement as well as of the conventional arrangement. Section A.2.2 is a mathematical study of the tower base heave limit of a conventional tower. Section A.2.3 is a complete description of the mathematical modeling of WATS, with a parametric study of four configurations to be found in Section A.2.3.3.

A.2.2 MATHEMATICAL ANALYSIS OF CONVENTIONAL TOWER BASE HEAVE LIMIT

The purpose of this section is to demonstrate analytically the amount of tower base heave allowed before tower load - due to excessive guy wire tensions - reaches its critical load. This is done taking into consideration the elasticity of the pole structure and guy wires as well as the fact that the guy-wire profile is a catenary. As the tower base rises, the pole goes into compression, the guy wires are tensioned even further, and the mid-cable sag of the catenary decreases. A schematic of a typical guy-wire supported transmission tower is shown in Figure A.2.1.

Important variables to consider are: the tower height, h; the distance from the tower base to the guy anchor (guy anchor spread)l; cable dip z, from which cable sag is obtained; the angle of guy-wire inclination, θ; the cable tension T; the horizontal component of cable tension H; the amount of base vertical movement δ; the modulus of elasticity of the tower pole E; the moment of inertia of the pole I; and the diameter of the pole d.

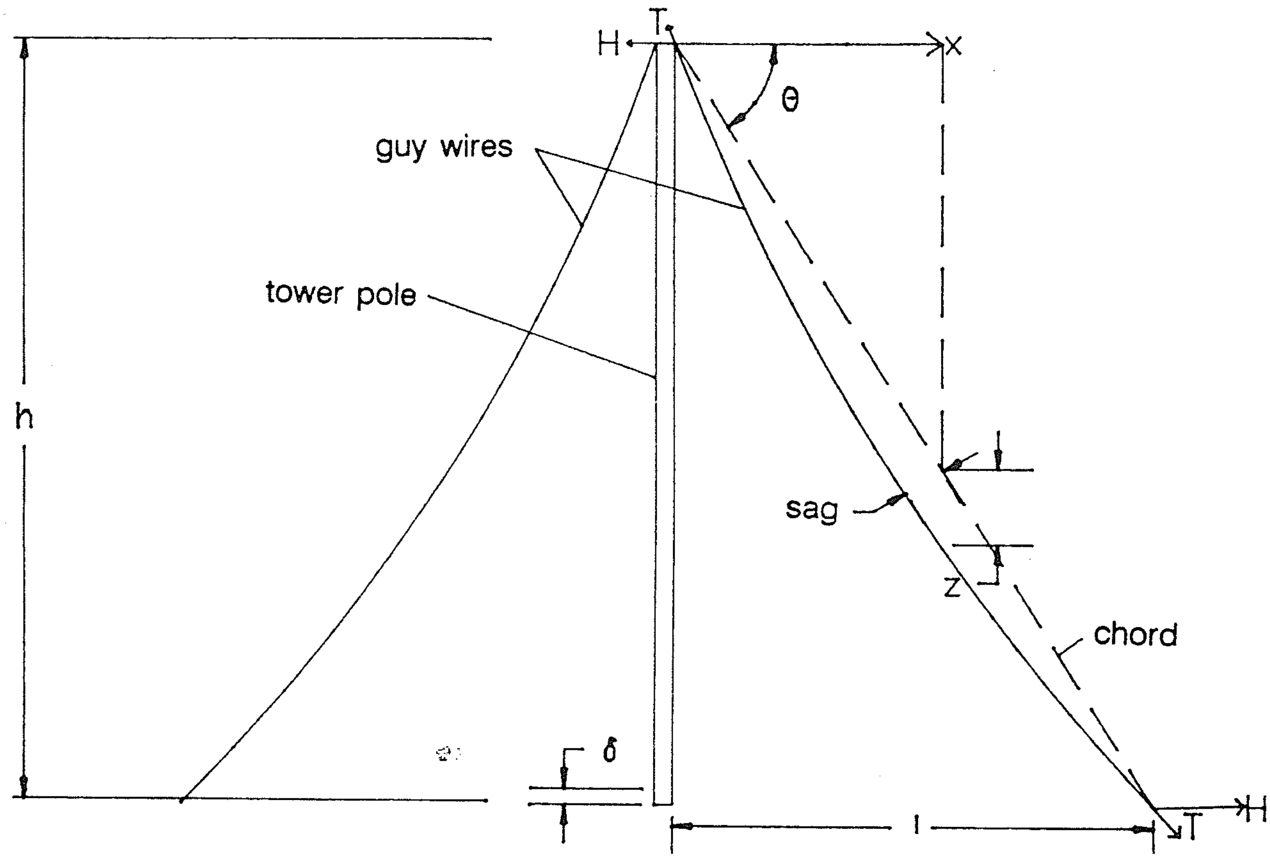


Figure A.2.1 Typical Guy-Wire Supported Tower and Pertinent Variables

In order to determine the amount of base heave allowed, it is necessary to:

- determine the critical column load of the tower pole
- determine the guy wire length
- determine tower pole compression at the critical load
- determine guy-wire extension at the critical load
- relate the above deformations to get the total base heave.

The quantity z in Figure A.2.1 measures the dip of the wire profile below the chord. Equilibrium is satisfied by [4]:

$$H\frac{d^2z}{dx^2} = -mg\left\{1 + (\tan\theta + \frac{dz}{dx})^2\right\} \tag{1}$$

If dz/dx is considered sufficiently small (as it is in the case of a taut guy wire) to ignore its square, the equation reduces to

$$\frac{d^2\bar{z}}{d\bar{x}^2} + \varepsilon\frac{d\bar{z}}{d\bar{x}} = -1 \tag{2}$$

where $\bar{z} = z/(mgl^2/H\cos\theta)$, $\bar{x} = x/l$, and $\varepsilon = mgl\sin\theta/H$. The parameter ε is small because for the cable to lie close to the

chord, mgl must be a small fraction of H. Substituting:

$$\bar{z} = \bar{z}_o + \varepsilon\bar{z}_1 + \ldots, \tag{3}$$

and collecting like terms, we obtain

$$\frac{d^2\bar{z}_o}{d\bar{x}^2} = -1 \qquad \text{and} \qquad \frac{d^2\bar{z}_1}{d\bar{x}} = -\frac{d\bar{z}_o}{d\bar{x}} \tag{4}$$

whose solutions are required to satisfy zero displacement at the cable end points. These solutions are:

$$\bar{z}_o = \bar{x}(1-\bar{x})/2 \tag{5a}$$

and $$\bar{z}_1 = \bar{x}(1-\bar{x})\left\{1 + \varepsilon/6(1-2\bar{x})\right\} . \tag{5b}$$

giving

$$\bar{z} = \frac{1}{2}\,\bar{x}(1-\bar{x})\left\{1 + \varepsilon/6(1-2\bar{x})\right\} \tag{6}$$

To determine the mid-cable sag, x = l/2, and $\bar{x}$ = 0.5, yielding

$$\bar{z} = \frac{1}{2}(1/2)(1 - 1/2)\{1 + \varepsilon/6[1 - 2(1/2)]\}$$

and $$\bar{z} = \frac{1}{8} . \tag{7}$$

Since $\bar{z} = z/(mgl^2/H\cos\theta)$,

$$z = (mgl^2)/(8H\cos\theta), \tag{8}$$

where mg is the force of gravity on the guy wires per unit length of wire.

The Euler buckling load of a tower shaft such as that of Figure A.2.1 is designated as P_{crit} and is given by [3]

$$P_{crit} = \frac{\pi^2 EI}{h^2} \tag{9}$$

Compression of the tower shaft, δ tower, is given by

$$\delta_{tower} = \frac{(P)(h)}{(A)(E)} \tag{10}$$

where A is the cross-sectional area of the tower shaft. Guy wire extension, δwire, is given by

$$\delta_{wire} = \frac{(T)(L)}{(a)(E)} \tag{11}$$

where a is the cross-sectional area of the wire and L is the wire length. The total allowable amount of tower base heave is then

$$\delta = \delta(\text{wire straighening})/(\text{no. wires}) + \delta_{wire}\sin\theta/(\text{no. wires}) + \delta_{tower} \qquad (12)$$

Consider now a conventionally supported hydro tower, made of tubular steel, $E = 30X10^6$, $h = 68.5'$, $Do = 12.75''$, $Di = 12.25''$, $I = 191.8 \text{ in}^4$, $A = 9.817 \text{ in}^2$, supported by four guy wires anchored at $l = 48.7'$ under 225 lb tension, with cross-sectional area $a = 0.0792 \text{ in}^2$, and $mg = 0.27$ lb/ft. This yields $\theta = 55$ and $H = 130$ lb.

The critical column load for this tower, according to (9), is

$$P_{crit} = \frac{\pi^2(30X10^6)(191.8)}{(68.5)(12)} = 70{,}000 \text{ lbs}$$

Using (8) for this tower we get

$$z = \frac{(0.27)(48.7)^2}{8(130)\cos(55)} = 1.073 \text{ ft} = 12.875''$$

For this z, sag is

$$\text{sag} = z\cos\theta = 7.385''.$$

Since the cable sag is proportional to the square of l, a good estimate of the cable length is given by assuming the cables are straight between mid-point and supports. The chord is given by

$$\text{chord} = \sqrt{l^2 + h^2} \qquad (13)$$

or $$\text{chord} = \sqrt{(68.5)^2 + (48.7)^2} = 84.047' = 1008.564''$$

From this, the guy cable length is found to be

$$\text{cable length} = 2\sqrt{\left[\frac{\text{chord}}{2}\right]^2 + (\text{sag})^2} = 84.056'$$

Tower load at the starting position is

$$\text{Tower Load} = 4T\sin\theta = 737.2\ \text{lb}$$

Using (10), the initial compression of the tower shaft is given by

$$\delta_{tower,i} = \frac{(737.2)(68.5)(12)}{(9.817)(30\text{X}10^6)} = 0.00205''$$

Similarly, guy-wire extension is given by (11) as

$$\delta_{wire,i} = \frac{(225)(84.056)(12)}{(0.0792)(30\text{X}10^6)} = 0.0955''.$$

As the tower base rises, the tower height increases, while the guy anchor spread l remains the same. Because of this, the angle also changes. But since the amount of heave δ is very small in comparison to tower height h, assume a raised θ of 55. From above, P_{crit} = 70000 lb, and the guy-wire tension would then be

$$T_{rise} = \frac{P}{4\sin\theta} = \frac{70000}{4\sin 55^\circ} = 21,363.6\ \text{lb}$$

The number 4 is in the denominator because there are four guy wires which cause tower load to become P_{crit}. At this tension,

$$H = T\cos\theta = 12,253\ \text{lb}$$

and using equation (8),

$$z = \frac{(0.27)(48.7)^2}{8(12253)(\cos 55^\circ)} = 0.0114''$$

So then mid-cable sag is 0.0054". Using the above guy-wire length calculated at initial conditions and the sag of the raised tower, we find the raised chord length as

$$\text{raised chord} = 2\sqrt{(42.028)^2-(0.00654)^2} = 84.056'$$

This corresponds to a tower height given by

$$h_{raised} = \sqrt{(\text{raised chord})^2 - l^2} \tag{14}$$

or

$$h_{raised} = 68.511'$$

The total amount of base heave allowed due to wire straightening is then

$$\delta_{st} = (h_{raised} - h) = 0.011' = 0.132''$$

Using (10), the compression of the tower shaft is found to be:

$$\delta_{tower,r} = \frac{(70000)(68.5)(12)}{(9.817)\ (30X10^6)} = 0.1954''.$$

Using (11), guy wire extension is given by:

$$\delta_{wire} = \frac{(21363.6)(84.056)(12)}{(0.0792)\ (30X10^6)} = 9.07''$$

Using (12), with δ due to wire straightening $=\delta st$ = 0.132"; δwire = δwire,r-δwire,i= 10.704", and δtower= δtower,r-δtower,i=0.2329", the total amount of base heave allowed is

$$\delta = \frac{(0.132)}{4} + \frac{(8.975)(\sin 55\ )}{4} + 0.1934 = 2.1''$$

A.2.3 WATS GUY-WIRE ARRANGEMENT

A.2.3.1 Support Cable Geometry

The pertinent variables of WATS are shown in Figure A.2.2. These are, the chord angle $\theta 1$, sag angle $\theta 2$, tensioner cable angle $\theta 3$, guy wire angle $\theta 4$, weight height, guy-anchor spread, guy-wire length, the chord, tower height, and mid-cable sag. The chord is defined in equation (13).

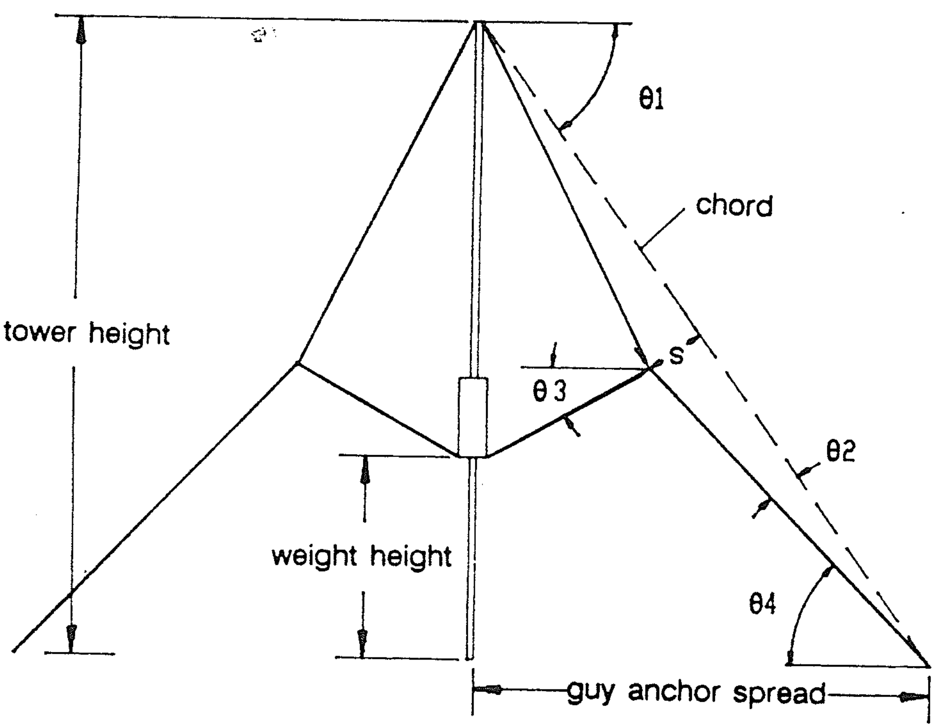


Figure A.2.2. WATS Variables

The first component of WATS is the mid-cable sag. Given an initial sag of s, the guy-wire length is defined as

$$\text{g.w.l.} = 2\sqrt{(\text{sag})^2 + (\text{chord}/2)^2}\ .$$

Using this approach, the guys are treated as two force members whose catenary is neglected. This approach was taken because the sag due to the catenary is very small compared to the initial input sag. Different values of initial sag cause different amounts of heave allowed before the guy wires become straight.

The second component of WATS is the tensioner cable angle. This angle determines how much force from the suspended weight is transmitted to the guy wires. Smaller values of $\theta 3$ cause higher tensioner cable tensions and hence higher guy-wire tensions. Large values of $\theta 3$ could cause problems with the tensioner weight coming to rest on the ground under conditions of base settlement.

The mid-cable height (m.c.h.) is given by

$$\text{m.c.h.} = \left(\frac{\text{g.w.l.}}{2}\right)\sin\theta 4, \tag{15}$$

and the mid-cable spread (m.c.s.) is given by

$$\text{m.c.s.} = \text{guy anchor spread} - \left[\frac{\text{g.w.l.}}{2}\cos\theta 4\right] \tag{16}$$

The tensioner-cable length (t.c.l.) is then given by:

$$t.c.l. = m.c.s./\cos\theta 3 \tag{17}$$

and the weight height (wh) is

$$w.h. = m.c.h.-(t.c.l.)\sin\theta 3 \tag{18}$$

A.2.3.2 Tension Requirements

For any given WATS support cable geometry, guy-wire tensions can be varied accordingly by increasing or decreasing the mass of the tensioner weight. The tensioner cable tension, tt, is given by

$$tt = (wt/\sin\theta 3)/n.o.w. \tag{19}$$

where wt is the force of gravity acting on the suspended weight and n.o.w. is the number of guy wires involved. A force diagram of the tensioner cable and guy-wire system is shown in Figure A.2.3. The upper guy-wire tension is denoted by TG2, and the lower tension is TG1.

Using the sign convention of Figure A.2.3, equilibrium of forces in the x-direction gives:

$$\sum F_x = 0 = TG1\cos\theta 4 - tt\cos\theta 3 - TG2\cos(\theta 1+\theta 2). \tag{20}$$

Equilibrium in the y-direction gives:

$$\sum F_y = 0 = TG2\sin(\theta 1+\theta 2) - tt\sin\theta 3 - TG1\sin\theta 4. \tag{21}$$

Equations (20) and (21) contain two unknowns, TG1 and TG2, therefore it must be possible to solve for these two quantities. Rearranging these two equations, we get

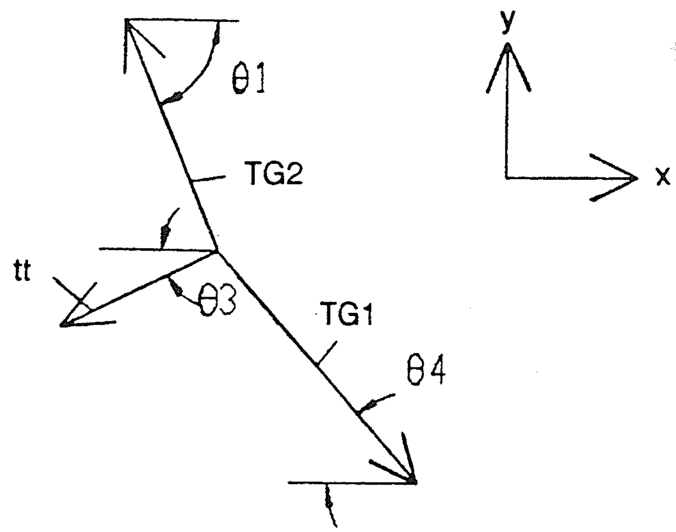


Figure A.2.3 Cable Force Diagram

$$tt\cos\theta 3 = TG1\cos\theta 4 - TG2\cos(\theta 1+\theta 2) \tag{22}$$

$$tt\sin\theta 3 = -TG1\sin\theta 4 + TG2\sin(\theta 1+\theta 2) \tag{23}$$

Multiplying (22) by sin(1+ 2), and (23) by cos(1+ 2), we get

$$tt\cos\theta 3\sin(\theta 1+\theta 2)=TG1\cos\theta 4\sin(\theta 1+\theta 2)- TG2\cos(\theta 1+\theta 2)\sin(\theta 1+\theta 2) \tag{24}$$

$$tt\sin\theta 3\cos(\theta 1+\theta 2)=-TG1\sin\theta 4\cos(\theta 1+\theta 2)+ TG2\sin(\theta 1+\theta 2)\cos(\theta 1+\theta 2) \tag{25}$$

Adding (24) to (25), we obtain an expression relating tt and TG1,

$$tt\left[\cos\theta 3\sin(\theta 1+\theta 2)+\sin\theta 3\cos(\theta 1+\theta 2)\right]=$$

$$TG1\left[\cos\theta 4\sin(\theta 1+\theta 2)-\sin\theta 4\cos(\theta 1+\theta 2)\right] \qquad (26)$$

To simplify, set $C1 = \cos\theta 3\sin(\theta 1+\theta 2) + \sin\theta 3\cos(\theta 1+\theta 2)$ (27)

and

$$C2 = \cos\theta 4\sin(\theta 1+\theta 2) - \sin\theta 4\cos(\theta 1+\theta 2). \qquad (28)$$

So we have then

$$C1(tt) = C2(TG1)$$

or

$$TG1 = (C1/C2)tt \qquad (29)$$

Substituting into (22), and solving for TG2,

$$TG2 = tt[\sin\theta 3 + (C1/C2)\sin\theta 4]/\sin(\theta 1+\theta 2). \qquad (30)$$

Drawing a free body diagram around the tower only gives Figure A.2.4.

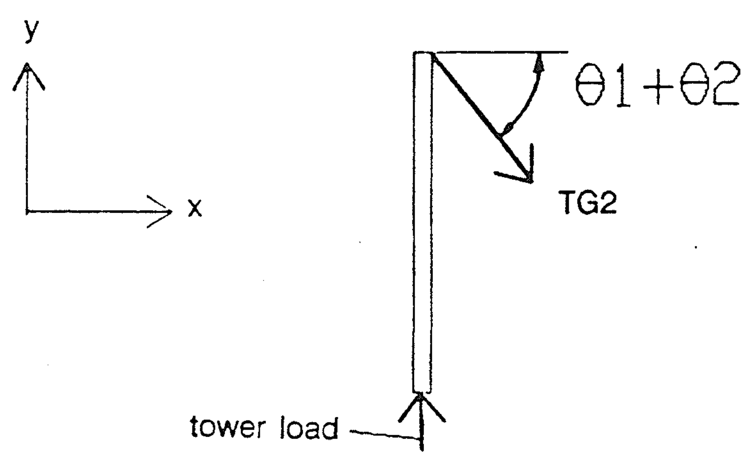


Figure A.2.4 Free body Diagram of Tower

Because of the symmetrical nature of guyed towers, only one guy is shown in Figure A.2.4, equilibrium being maintained by the opposing guys. The tower column load is defined in terms of the upper guy tension and the number of guy wires. Using the sign convention of Figure A.2.4, the tower column load is given by

$$\text{Tower Load} = TG2\sin(\theta 1+\theta 2)(\text{no. of wires}) \qquad (31)$$

A.2.3.3 Mathematical Analysis of WATS

Using the results of Sections A.2.3.1 and A.2.3.2, a mathematical analysis of the WATS arrangement was performed with the aid of a computer program. The analysis was done on a tower of 68.5' height and guy anchor spread of 48.72'. Inputs into the program include: number of guy wires, initial mid-cable sag, initial tensioner cable angle, and the amount of heave and settlement to be investigated. Outputs include all cable tensions and tower load, as well as all geometrical variables given in Figure A.2.3.

The analysis was done with the inputs given in Table A.2.1, over a range of base vertical movement from -6.0 to +6.0 inches.

Tensioner Cable Angle		Mid-Cable Sag	Tensioner Weight	No. Wires
1	30	60"	105.6 lb	4
2	45	60"	154.0 lb	4
3	30	78.75"	140.8 lb	4
4	45	78.75"	206.8 lb	4

Table A.2.1 Input Parameters to WATS Program

The results of the analysis are given in Tables A.2.2 to A.2.5, and a plot of these results is shown in Figure A.2.5. Included in the plot are the results of section 2, the conventional tower heave analysis. The upper and lower extremes (in terms of tower base vertical displacement) are given in Table A.2.6, for each of the four WATS configurations. Using the above analysis, the upper extreme is reached when either the guy wire sag approaches zero, or the tensioner cables become horizontal. The lower extreme is reached when the tensioner weight height becomes zero.

Configuration 1 θ_3= 30 , s = 60" , wt = 105.6 lb					
Base Position	Guy Tension	Tower Load	Base Position	Guy Tension	Tower Load
+5.91"	595.7 lb	1998.6 lb	-0.40"	218.5 lb	760.0 lb
5.51"	528.6 lb	1773.8 lb	-0.79"	211.3 lb	736.0 lb
5.12"	475.8 lb	1601.3 lb	-1.18"	204.5 lb	714.1lb
4.72"	433.9 lb	1464.4 lb	-1.58"	198.5 lb	693.8 lb
4.33"	400.0 lb	1352.7 lb	-1.97"	192.9 lb	674.9 lb
3.94"	371.0 lb	1259.6 lb	-2.36"	187.5 lb	657.2 lb
3.54"	346.2 lb	1180.6 lb	-2.76"	182.1 lb	640.6 lb
3.15"	326.4 lb	1112.8 lb	-3.15"	177.6 lb	625.0 lb
2.76"	308.4 lb	1053.7 lb	-3.54"	172.9 lb	610.3 lb
2.36"	292.5 lb	1001.8 lb	-3.94"	168.6 lb	596.4 lb
1.97"	278.0 lb	955.7.lb	-4.33"	164.7 lb	583.4 lb
1.58"	265.7 lb	914.5 lb	-4.72"	160.9 lb	571.2 lb
1.18"	255.0 lb	877.4 lb	-5.12"	157.6 lb	559.6 lb
0.79"	244.0 lb	844.0 lb	-5.51"	154.0 lb	548.3 lb
0.40"	233.8 lb	813.1 lb		150.7 lb	537.9 lb
0.00"	225.0 lb	785.4 lb			

Table A.2.2 Math Analysis of WATS Configuration 1

Configuration 2 θ_3= 45 , s = 60" , wt = 154 lb					
Position	Guy Tension	Tower Load	Position	Guy Tension	Tower Load
+5.91"	471.6 lb	1615.1 lb	-0.40"	224.8 lb	806.4 lb
5.51"	433.8 lb	1491.6 lb	-0.79"	219.0 lb	786.8 lb
5.12"	403.2 lb	1391.1 lb	-1.18"	213.5 lb	768.6 lb
4.72"	377.7 lb	1307.5 lb	-1.58"	207.7 lb	751.5 lb
4.33"	355.9 lb	1236.4 lb	-1.97"	203.3 lb	735.5 lb
3.94"	337.2 lb	1175.1 lb	-2.36"	199.0 lb	720.5 lb
3.54"	321.1 lb	1121.4 lb	-2.76"	194.5 lb	706.1 lb
3.15"	306.4 lb	1074.2 lb	-3.15"	190.3 lb	692.7 lb
2.76"	293.7 lb	1031.9 lb	-3.54"	186.3 lb	679.9 lb
2.36"	282.6 lb	994.1 lb	-3.94"	182.5 lb	667.7 lb
1.97"	272.0 lb	959.7 lb	-4.33"	179.1 lb	656.1 lb
1.58"	262.1 lb	928.7 lb	-4.72"	175.8 lb	645.0 lb
1.18"	253.4 lb	900.1 lb	-5.12"	172.5 lb	634.5 lb
0.79"	245.4 lb	873.8 lb	-5.51"	169.5 lb	624.3 lb
0.40"	238.1 lb	850.0 lb	-5.91"	166.5 lb	614.9 lb
0.00"	231.2 lb	827.0 lb			

Table A.2.3 Math Analysis of WATS Configuration 2

Configuration 3 θ_3= 30 , s = 78.75" , wt = 140.8 lb					
Position	Guy Tension	Tower Load	Position	Guy Tension	Tower Load
+5.91"	342.2 lb	1250.6 lb	-0.40"	221.9 lb	785.5 lb
5.51"	349.4 lb	1201.0 lb	-0.79"	217.4 lb	770.0 lb
5.12"	336.0 lb	1156.0 lb	-1.18"	212.9 lb	754.2 lb
4.72"	323.1 lb	1115.0 lb	-1.58"	208.4 lb	740.0 lb
4.33"	311.6 lb	1077.0 lb	-1.97"	204.1 lb	725.7 lb
3.94"	300.0 lb	1042.4 lb	-2.36"	200.0 lb	712.6 lb
3.54"	291.1 lb	1010.3 lb	-2.76"	196.3 lb	700.1 lb
3.15"	282.0 lb	980.6 lb	-3.15"	192.4 lb	688.0 lb
2.76"	273.6 lb	952.9 lb	-3.54"	189.1 lb	676.5 lb
2.36"	266.0 lb	927.1 lb	-3.94"	185.7 lb	665.0 lb
1.97"	258.3 lb	903.1 lb	-4.33"	182.5 lb	654.6 lb
1.58"	251.1 lb	880.4.lb	-4.72"	179.4 lb	645.0 lb
1.18"	245.0 lb	859.2 lb	-5.12"	176.3 lb	634.6 lb
0.79"	239.0 lb	839.2 lb	-5.51"	173.5 lb	625.2 lb
0.40"	232.9 lb	820.3 lb	-5.81"	170.7 lb	616.3 lb
0.00"	227.5 lb	802.3 lb			

Table A.2.4 Math Analysis of WATS Configuration 3

Configuration 4 θ_3= 45 , s = 78.75" , wt = 206.8 lb					
Position	Guy Tension	Tower Load	Position	Guy Tension	Tower Load
+5.91"	324.2 lb	1156.7 lb	-0.40"	230.2 lb	847.0 lb
5.51"	315.6 lb	1128.0 lb	-0.79"	226.4 lb	834.5 lb
5.12"	307.3 lb	1101.0 lb	-1.18"	222.7 lb	822.4 lb
4.72"	299.7 lb	1075.8 lb	-1.58"	219.2 lb	810.9 lb
4.33"	292.4 lb	1052.0 lb	-1.97"	216.0 lb	800.0 lb
3.94"	285.5 lb	1030.0 lb	-2.36"	212.3 lb	789.1 lb
3.54"	279.2 lb	1008.6 lb	-2.76"	209.5 lb	778.7 lb
3.15"	273.1 lb	988.6 lb	-3.15"	206.5 lb	768.9 lb
2.76"	267.5 lb	969.6 lb	-3.54"	203.6 lb	759.5 lb
2.36"	261.9 lb	951.6 lb	-3.94"	200.8 lb	750.1 lb
1.97"	256.7 lb	934.3 lb	-4.33"	198.1 lb	741.2 lb
1.58"	251.7 lb	918.1 lb	-4.72"	195.4 lb	732.5 lb
1.18"	247.1 lb	903.6 lb	-5.12"	192.8 lb	724.1 lb
0.79"	242.3 lb	887.8 lb	-5.51"	190.4 lb	716.0 lb
0.40"	238.5 lb	873.6 lb	-5.91"	188.1 lb	708.1 lb
0.00"	233.0 lb	860.0 lb			

Table A.2.5 Math Analysis of WATS Configuration 4

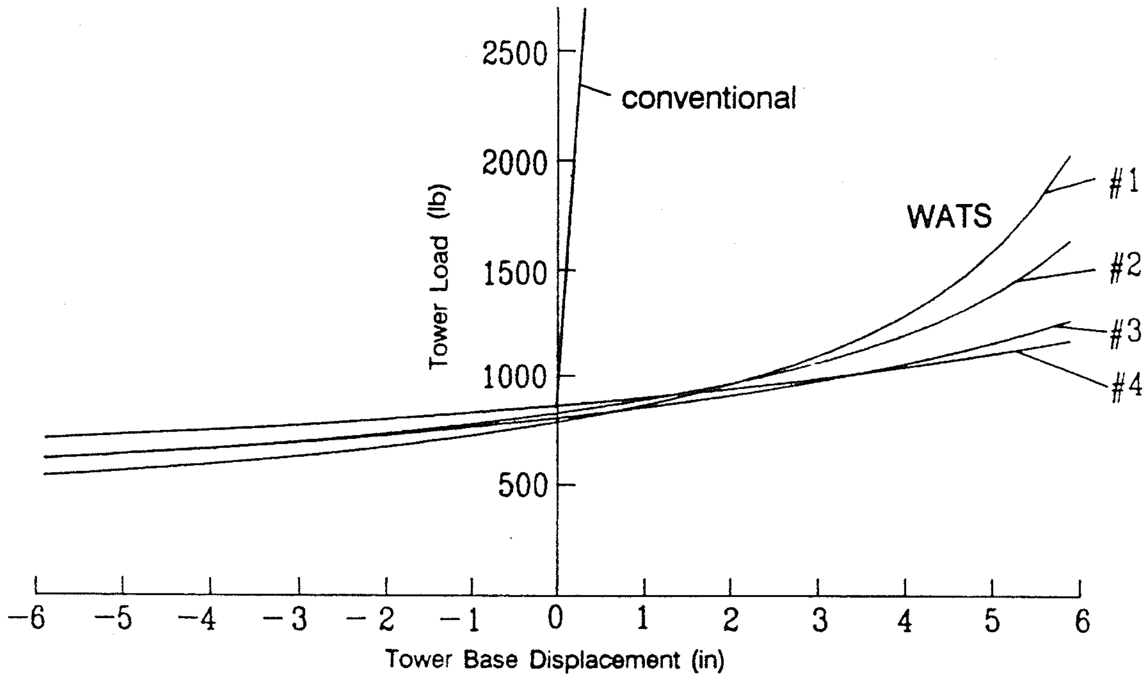


Figure A.2.5 Calculated WATS Base Displacement Curves

Base Position	Weight Ht.	Tensioner ten.	Guy ten.	sag	Tower Load
Config. 1 Upper +8.25" Lower -89.0"	31.2' 0.46"	931.7 lb 34.6 lb	14457 lb 42 lb	1.16' 16.28'	46467 lb 187.5 lb
Config. 2 Upper +8.7" Lower -46.75"	19.0' 0.565"	79.1 lb 49.3 lb	7708 lb 77 lb	0.22' 12.4'	25270 lb 329 lb
Config. 3 Upper+11.95" Lower -98.1"	32.4' 0.08"	1344 lb 43.1 lb	8000 lb 48 lb	2.95' 17.5'	26449 lb 222 lb
Config. 4 Upper+14.85" Lower -55.5"	22.2' 0.24"	120 lb 63.3 lb	4500 lb 88 lb	0.562' 14'	14909 lb 386.3 lb

Table A.2.6 Upper and Lower Extremes of WATS

APPENDIX A.3 MODEL TESTING OF GUYED TOWERS

A.3.1. INTRODUCTION

A.3.2. MODELING THEORY

A.3.3. MODEL DESCRIPTION

A.3.3.1 Introduction

A.3.3.2 Model Components

A.3.3.3 Testing Procedure

A.3.4. EXPERIMENTAL RESULTS

A.3.4.1 Base Heave

A.3.4.2 Base Settlement

A.3.4.3 Lateral Stability

A.3.4.4 Errors

A.3.1 INTRODUCTION

This appendix covers the modeling and testing procedures for both the conventional and WATS (weight activated tension stabilizer) guy wire supported transmission towers. Included are all of the experimental data as well as a description of the WATS model apparatus. The objective of these tests is to study the effects of tower base vertical movement (heave or settlement) as well as lateral stability for both systems, thereby generating load vs base displacement curves to aid in the comparison. It was decided to do physical modeling to complement the analytical work and also to visually demonstrate the operation of WATS. By actually seeing the system in operation it is hoped that any obvious short-comings will become quite clear, which might not be seen otherwise.

A.3.2 MODELING THEORY

The first, most obvious requirement of model testing is that the model look exactly like the full scale or prototype version. This is known as geometric similarity. Every model length dimension is related to the corresponding prototype length dimension by a constant scale factor, S, which in this case S = 25. Because of this, prototype areas are S x S times model areas and prototype volumes are S x S x S times model volumes. This means that in order to have the same stress in the model as in the prototype, the forces involved must be reduced by 1/(S x S) = 1/625 times.

A.3.3 MODEL DESCRIPTION

A.3.3.1 Introduction

In order to simulate real life conditions as much as possible, nominal dimensions of an actual transmission tower (as supplied by Manitoba Hydro) were used as a guideline. These consisted of a simple pole structure 20.8707m (68.473ft) high, supported at the top by four radial guy wires as shown in Figure A.3.1. The guy wires are spread 14.8503m (48.721ft) from the tower base. Because of the symmetrical nature of these towers and to further simplify matters, it was decided to work in two dimensions only, using two opposite guy wires.

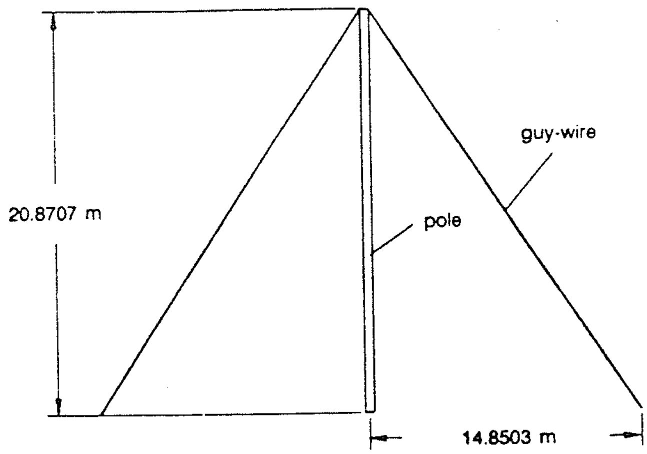


Figure A.3.1. Tower Arrangement in Two Dimensions

Since the main purpose of the model testing was to demonstrate the advantages of the WATS system over the conventional means of tower support, and because there is such a wide variety of transmission towers in existence, a hypothetical aluminum pole was used rather than an exact scaled down replica of a real life tower pole. The aluminum pole has the following dimensions and specifications:

Length..0.835m

Diameter...9.535mm

Radius of Gyration,(D/4),k............2.3813mm

Slenderness Ratio,(L/k).......................350.66

Material..................................6061 Aluminum

Cross Section.......................................Solid

The same pole was used to test both the WATS and conventional guy wire arrangements.

The buckling load of such a column, pinned at both ends, according to Euler is given by [3]:

$$P_{buckling} = \frac{\pi^2 EA}{(Le^2/k)}$$

where in this case Young's Modulus E = 69×10^9 Pa; area = πr^2 = $7.13 \times 10^{-5} m^2$; for a pinned-pinned column Le = L= 0.835m; and Le/k = 350.66. This gives

$$P_{buckling} = 395 \text{ N}, \ (89 \text{ lb})$$

Using the model, the amount of tower base heave which can be accommodated can be found on both systems, before the above buckling load is reached.

Stability is to be measured simulating conditions of 40 mph, 80 mph, and 100 mph wind loads. The real life towers support six conductors, 21.84mm in diameter, spanning 350 m. This represents a total frontal area of A = 45.864 m^2. Reynolds number is given by

$$Re = \frac{\rho V l}{\mu}$$

where ρ = air density, V = air velocity, l = characteristic length (such as diameter) and μ = absolute viscosity. For a 40 mph wind, V = 17.88m/s, ρ= 1.09kg/m^3 , l = 0.02184m,

$\mu = .95\text{x}10^{-5}\ \text{Ns/m}^2$, and Re = 21,828. For Re < 200,000, the drag coefficient for a cylinder is given by [2]

$$C_D = 1.0 + 10(Re)^{-0.67}$$

For a 40 mph wind, C_D = 1.012, for 80 mph, C_D = 1.008, and for 100 mph, C_D = 1.007. Drag D is given by

$$D = 1/2\rho V^2 A C_D,$$

and for 40 mph wind blowing perpendicular across the conductors, the drag load is 8.08kN. Similarly, an 80 mph wind gives a drag load of 32.2kN, and a 100 mph wind gives a drag load of 50.3kN. For the model, these loads are reduced 25x25 times, giving loads of 12.928N (2.9lb), 51.52N (11.51b), and 80.48N (18.11b).

These loads are applied to the tower top, and since the tower pole frontal area is very small in comparison to the conductors, the wind force on it is neglected.

A.3.3.2 Model Components

The testing arrangement is shown in Figure A.3.2. Tower base heave is measured using a Mercer dial gauge, accurate to within 0.001". Tower column load is obtained by measuring the compression of a spring in the tower base unit. The tower base unit, as shown in Figure A.3.3, consists of a 5/8" bolt, a compressing washer, a compression spring, a bearing, and a tower cradle. Tower base heave is simulated by turning the compressing washer counter clockwise, thus compressing the spring against the tower cradle and also displacing the tower top up a certain amount, as recorded on the dial gauge. Compression of the spring is measured between the lower surface of the compressing washer and the top surface of the flange on the tower cradle. To give as accurate a reading as possible, the measuring surfaces on the tower cradle and the compressing washer were machined true on the engine lathe.

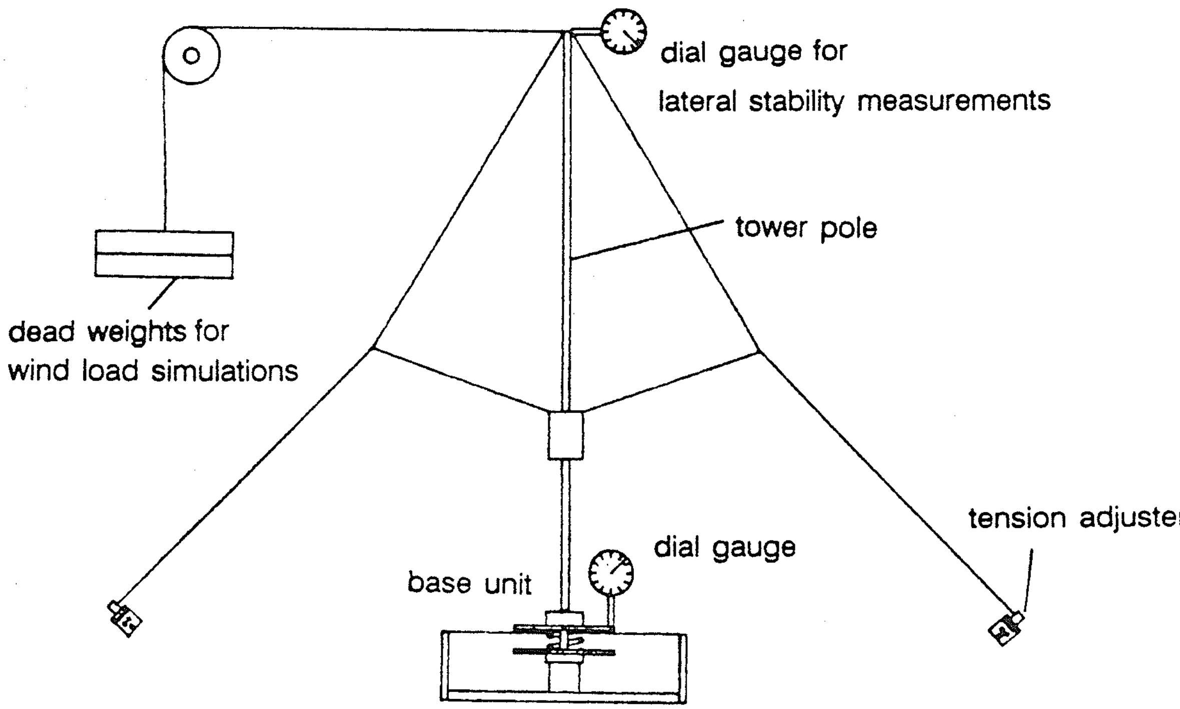


Figure A.3.2 Testing Arrangement

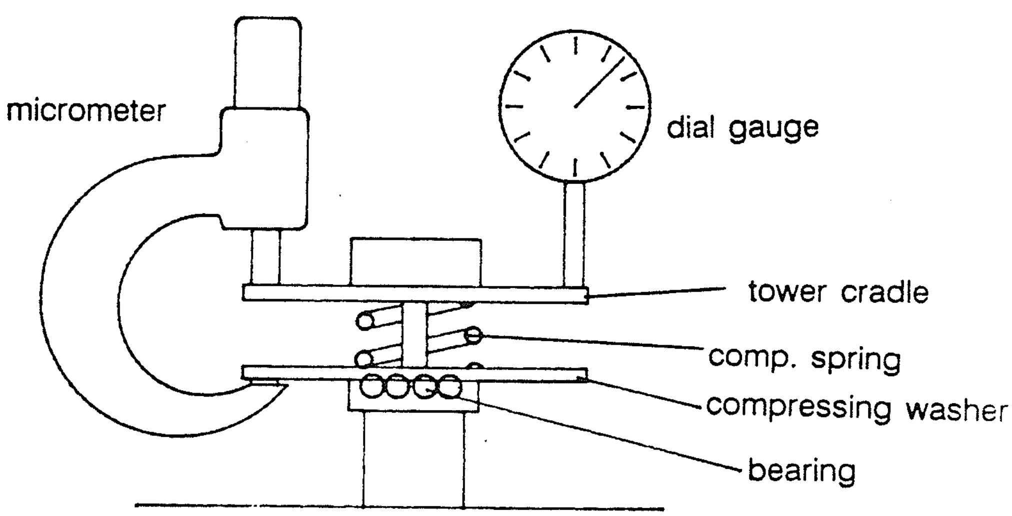


Figure A.3.3 Tower Base Unit

Two compression springs were used, one for light loads, and another for heavy loads. These were calibrated using dead weights and measuring the compression from a known load. The result of this is the calibration curves given in Figures A.3.4 and A.3.5 for light and heavy loads respectively. The useful range of the base unit is 0 to 100 pounds. Beyond 100 pounds, the spring has reached its solid height and is no longer useful. Since the aluminum pole buckles at about 89 pounds, the heavy spring is more than adequate for this application. If buckling of a steel pole were desired, then a heavier spring(s) could be used. To prevent uncoiling of the spring, a bearing is located under the spring, in the form of 14 balls of 3/16" diameter in a race. This also provides for ease of operation.

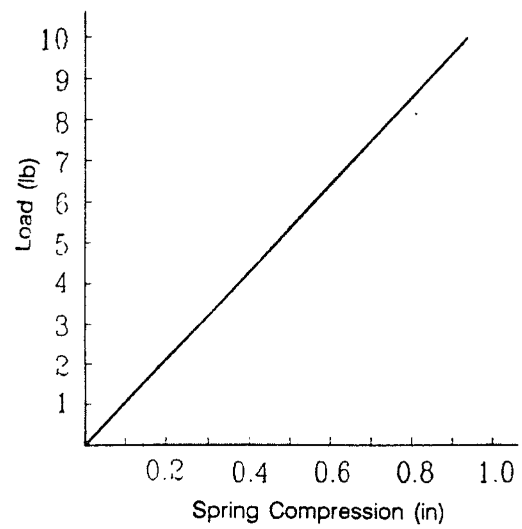


Figure A.3.4 Load Cell Calibration Chart Light Loads

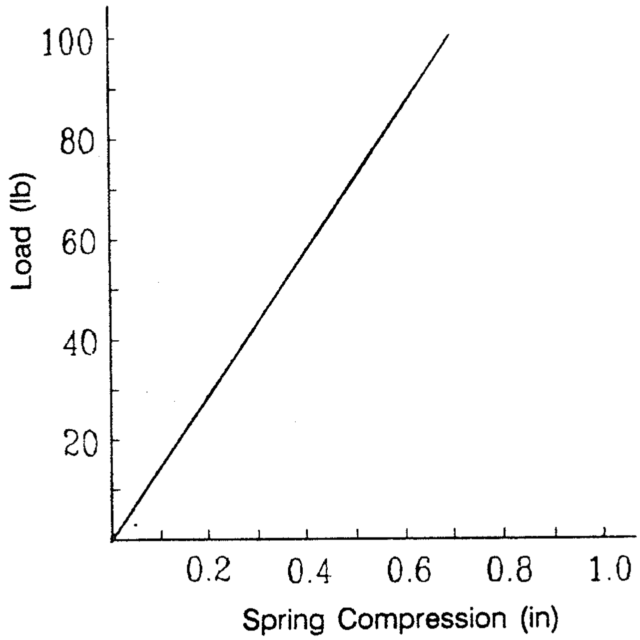


Figure A.3.5 Load Cell Calibration Chart, Heavy Loads

The tower used is a pinned-pinned column, which means that there is no transmission of moment through the tower supports at the top or bottom. To provide this at the base, the tower cradle has a rounded out socket machined at the center, and the bottom of the pole is machined round as shown in Figure A.3.6. This allows for swivelling in all directions. The tower top is fitted with a cap which not only provides swivelling, but also provides for the attachment of the guy wires, as shown in Figure A.3.7.

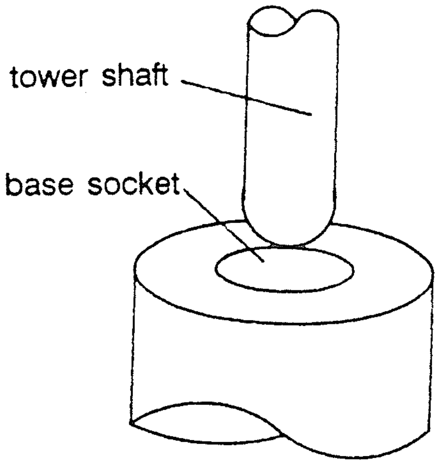


Figure A.3.6 Base Socket

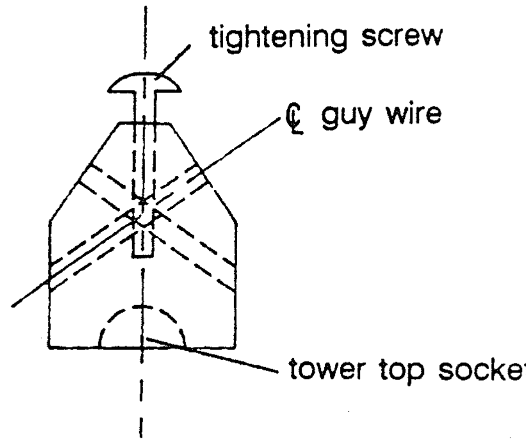


Figure A.3.7 Tower Top Cap

The guy wires used for both the WATS and conventional systems are 3/16" diameter steel stranded throttle cables, weighing 0.00773 kg/m, (0.00518 lb/ft). Tension is provided to the guy wires by two base guitar tuning machine heads with 0.55" shafts mounted on 3/16" angle irons. The tower base unit is mounted on a 9.5" length of 3.5"x3.5"x0.25" steel angle. To prevent collapse in the unsupported direction, the pole is supported at 3/4 height by a loose fitting slotted angle iron. This support in no way prevents buckling to occur. All of the above components are mounted on a 48"x41" slab of 3/4" fir plywood using bolts. For demonstration purposes, the background is white and the board stands upright under its own support.

A.3.3.3 Testing Procedure

Model testing begins by setting up the desired configuration and loading to a known starting point, or pre-load. For the conventional set up, the pre-load is set according to scale and the WATS set up is the same in order to make a direct comparison between the two. At this point it should be remembered that in actual fact, a lower initial tension can be used with the WATS, (and therefore more base heave can be accommodated), about 1/4 to 1/6 that of the conventional arrangement. Using the scaling factor of 25 gives initial pre-loads of about 4.0 lb.

Once the pre-load or starting conditions have been set, the heave test proceeds by increasing the base heave 0.01" at a time and measuring the amount of spring compression with a micrometer. This is done until either the tower buckles or the base unit runs out of upward travel. Usually by this time a definite trend is observed. The settlement test is carried out in the same way except that the compression spring is now decompressed by lowering the tower base 0.01" at a time. Stability tests are carried out by applying lateral loads at the tower top. This is done with the tower base at the starting position, at 0.12" of settlement, and when the tower load is at 75 pounds.

Testing conditions for the WATS arrangement, referring to Figure A.3.8 were as given in Table A.3.1. A great many combinations of sag, table angle and weight are possible, but this group was chosen because they showed the most promise from an analytical viewpoint.

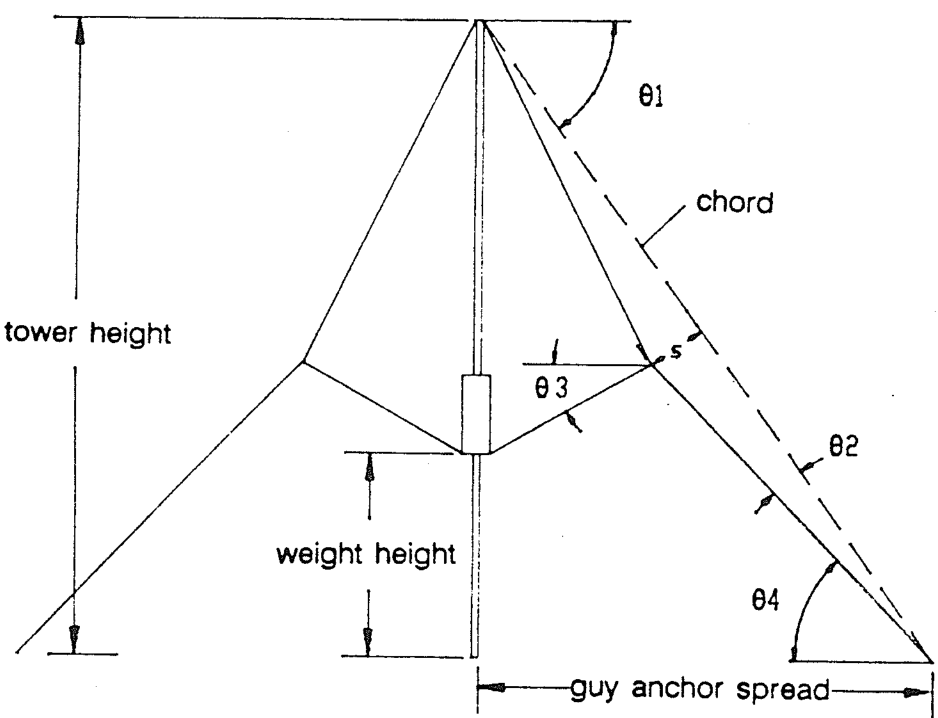


Figure A.3.8 WATS Geometric Parameters

Initial Sag	Tensioner Cable Angle	Weight
2.4"	30	0.506 lb
2.4"	45	0.506 lb
3.15"	30	0.506 lb
3.15"	45	0.506 lb

Table A.3.1 WATS Testing Conditions

A.3.4 EXPERIMENTAL RESULTS

A.3.4.1 Base Heave

Experimental results for the conventional arrangement tests are given in Table A.3.2. Results for the WATS tests are given in Tables A.3.3 to A.3.6. A graph of the results is shown in Figure A.3.9.

Pre-Load = 4.7 lb			
Heave	Load	Heave (in)	Load
0.01"	6.75 lb	0.10"	54.82 lb
0.02"	10.78 lb	0.11"	61.80 lb
0.03"	14.59 lb	0.12"	69.33 lb
0.04"	20.00 lb	0.13"	75.29 lb
0.05"	26.93 lb	0.14"	85.80 lb
0.06"	31.29 lb	0.15"	92.55 lb
0.07"	34.98 lb	0.16"	93.33 lb
0.08"	40.55 lb	0.17"	93.41 lb
0.09"	48.24 lb		

Table A.3.2 Conventional Tower Heave Data

Pre-Load = 4.7 lb θ_3= 30 Weight = 0.506 lb s= 2.4					
Heave	Load	Heave	Load	Heave	Load
0.01"	4.70 lb	0.15"	6.90 lb	0.29"	19.20 lb
0.02"	4.70 lb	0.16"	6.90 lb	0.30"	21.55 lb
0.03"	4.70 lb	0.17"	6.58 lb	0.31"	23.51 lb
0.04"	5.02 lb	0.18"	7.29 lb	0.32"	27.59 lb
0.05"	5.10 lb	0.19"	7.60 lb	0.33"	30.49 lb
0.06"	5.21 lb	0.20"	8.15 lb	0.34"	34.01 lb
0.07"	5.21 lb	0.21"	9.80 lb	0.35"	38.79 lb
0.08"	5.10 lb	0.22"	10.11 lb	0.36"	42.32 lb
0.09"	5.21 lb	0.23"	10.20 lb	0.37"	48.82 lb
0.10"	5.21 lb	0.24"	10.97 lb	0.38"	51.72 lb
0.11"	5.49 lb	0.25"	12.30 lb	0.39"	57.21 lb
0.12"	5.56 lb	0.26"	13.71 lb	0.40"	61.91 lb
0.13"	5.96 lb	0.27"	15.28 lb		
0.14"	6.27 lb	0.28"	16.26 lb		

Table A.3.3 WATS Tower Heave Data, θ_3= 30, s = 2.4"

Pre-Load = 4.14 lb θ_3= 45 Weight = 0.506 lb s= 2.4"					
Heave	Load	Heave	Load	Heave	Load
0.01"	4.52 lb	0.16"	5.12 lb	0.31"	13.28 lb
0.02"	4.70 lb	0.17"	5.70 lb	0.32"	15.08 lb
0.03"	5.08 lb	0.18"	6.13 lb	0.33"	18.13 lb
0.04"	4.61 lb	0.19"	5.47 lb	0.34"	20.78 lb
0.05"	3.70 lb	0.20"	6.02 lb	0.35"	22.00 lb
0.06"	2.93 lb	0.21"	5.48 lb	0.36"	28.44 lb
0.07"	4.04 lb	0.22"	5.94 lb	0.37"	32.03 lb
0.08"	4.08 lb	0.23"	6.20 lb	0.38"	37.50 lb
0.09"	4.60 lb	0.24"	7.04 lb	0.39"	36.33 lb
0.10"	4.37 lb	0.25"	7.79 lb	0.40"	45.16 lb
0.11"	4.38 lb	0.26"	8.13 lb	0.41"	48.67 lb
0.12"	4.53 lb	0.27"	8.92 lb	0.42"	51.09 lb
0.13"	4.49 lb	0.28"	8.93 lb	0.43"	62.50 lb
0.14"	4.60 lb	0.29"	9.06 lb	0.44"	70.78 lb
0.15"	4.77 lb	0.30"	10.04 lb	0.45"	75.39 lb

Table A.3.4 WATS Tower Heave Data, θ_3= 45 , s = 2.4"

Pre-Load = 4.7 lb θ_3= 30 Weight = 0.506 lb s= 3.15"					
Heave	Load	Heave	Load	Heave	Load
0.01"	4.06 lb	0.18"	4.88 lb	0.35"	7.81 lb
0.02"	3.73 lb	0.19"	4.90 lb	0.36"	7.81 lb
0.03"	4.37 lb	0.20"	5.16 lb	0.37"	8.28 lb
0.04"	4.06 lb	0.21"	4.90 lb	0.38"	8.91 lb
0.05"	3.52 lb	0.22"	4.53 lb	0.39"	10.00 lb
0.06"	3.73 lb	0.23"	4.80 lb	0.40"	10.07 lb
0.07"	4.14 lb	0.24"	4.79 lb	0.41"	11.09 lb
0.08"	4.49 lb	0.25"	6.09 lb	0.42"	11.64 lb
0.09"	4.61 lb	0.26"	6.11 lb	0.43"	12.50 lb
0.10"	4.59 lb	0.27"	6.12 lb	0.44"	13.98 lb
0.11"	4.59 lb	0.28"	6.33 lb	0.45"	15.23 lb
0.12"	4.69 lb	0.29"	6.12 lb	0.46"	16.17 lb
0.13"	4.67 lb	0.30"	6.25 lb	0.47"	17.97 lb
0.14"	4.61 lb	0.31"	6.40 lb	0.48"	21.88 lb
0.15"	4.61 lb	0.32"	7.03 lb	0.49"	24.22 lb
0.16"	4.77 lb	0.33"	7.42 lb	0.50"	28.59 lb
0.17"	4.80 lb	0.34"	7.66 lb		

Table A.3.5 WATS Tower Heave Data, θ_3= 30, s = 3.15"

Pre-Load = 2.4 lb θ_3= 45 Weight = 0.506 lb s= 3.15"					
Heave	Load	Heave	Load	Heave	Load
0.01"	2.40 lb	0.20"	3.65 lb	0.39"	4.85 lb
0.02"	2.40 lb	0.21"	3.65 lb	0.40"	4.85 lb
0.03"	2.40 lb	0.22"	3.65 lb	0.41"	4.85 lb
0.04"	2.40 lb	0.23"	3.65 lb	0.42"	4.85 lb
0.05"	2.40 lb	0.24"	3.65 lb	0.43"	5.10 lb
0.06"	2.40 lb	0.25"	3.65 lb	0.44"	5.49 lb
0.07"	2.40 lb	0.26"	3.65 lb	0.45"	5.79 lb
0.08"	2.40 lb	0.27"	3.88 lb	0.46"	6.00 lb
0.09"	2.40 lb	0.28"	4.20 lb	0.47"	6.00 lb
0.10"	3.14 lb	0.29"	4.20 lb	0.48"	6.12 lb
0.11"	3.22 lb	0.30"	4.20 lb	0.49"	6.12 lb
0.12"	3.61 lb	0.31"	4.20 lb	0.50"	6.67 lb
0.13"	3.61 lb	0.32"	4.20 lb	0.51"	6.67 lb
0.14"	3.61 lb	0.33"	4.20 lb	0.52"	7.14 lb
0.15"	3.61 lb	0.34"	4.20 lb	0.53"	7.45 lb
0.16"	3.61 lb	0.35"	4.78 lb	0.54"	7.45 lb
0.17"	3.61 lb	0.36"	4.78 lb	0.55"	7.84 lb
0.18"	3.61 lb	0.37"	4.85 lb		
0.19"	3.65 lb	0.38"	4.85 lb		

Table A.3.6 WATS Tower Heave Data, θ_3= 45 , s = 3.15"

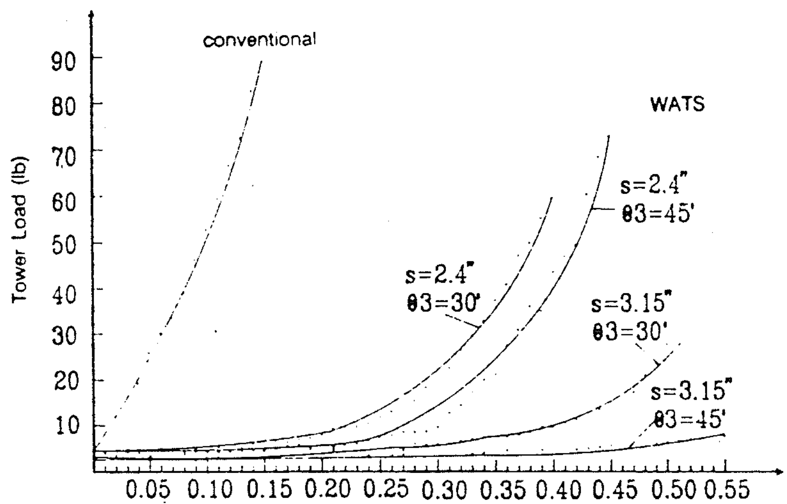


Figure A.3.9 Graph of Base Heave Experimental Results

From the graph of Figure A.3.9 it is obvious that there is a significant difference between the two methods of guy wire support. The conventionally supported tower shows a linear increase in tower load with base heave until the onset of buckling at about 90 pounds. The WATS tower load curve shows that the load is essentially constant over a range of base heave (about 0.2" for 2.4" sag, 0.4" for 3.15" sag), then increases at about the same slope to buckling as the conventional tower. This occurs because of the sag which is imparted to the guy wires initially. As the sag is increased, the tower is able to tolerate more base heave. The disadvantage with this is that the tensioner weight sits closer to the ground initially, and tower settlement would cause the weight to rest on the ground thus de-tensioning the guys. Greater vertical movement of the tensioner weight is involved with the larger sags also.

It is evident that larger tensioner cable angles for a given sag will also give the tower more tolerance for base heave. That is more heave is required to cause the tensioner cables to become horizontal for the larger angles. Once the tensioners are horizontal, the guy tensions tend to increase very rapidly. The disadvantages with larger tensioner angles are that more weight is required to maintain a given tension and the weight sits close to the ground limiting the amount of tower base settlement tolerable.

The WATS tower (with sag = 2.4", θ3 = 45), will accommodate 0.50" of base heave, while the conventional tower will tolerate only 0.15" before buckling occurs. In full size, this translates to 12.5" and 3.75" respectively, giving the WATS tower a three to one advantage in base heave accommodation. Extrapolating the curve of Figure A.3.9, such that the pre-load of the WATS tower is one sixth the conventional the WATS will tolerate 0.52" or about 317% more heave than the conventional.

A.3.4.2 Base Settlement

Tests were carried out to analyze the effects of base settlement using a conventionally supported tower and a WATS tower (sag = 2.4", θ3 = 30). Data from these tests is given in Tables A.3.7 and A.3.8. The pre-load for both tests was 4.0 pounds. A graph of the results is shown in Figure A.3.10.

Conventional Tower, Pre-Load = 4.0 lb			
Settlement	Load	Settlement	Load
0.01"	3.00 lb	0.07"	1.05 lb
0.12"	2.60 lb	0.08"	1.00 lb
0.13"	1.85 lb	0.09"	0.99 lb
0.14"	1.50 lb	0.10"	0.90 lb
0.05"	1.40 lb	0.11"	0.88 lb
0.06"	1.20 lb	0.12"	0.81 lb

Table A.3.7 Conventional Tower Settlement Data

WATS Tower, Pre-Load = 4.0 lb, sag = 2.4" , $\theta 3$= 30			
Settlement	Load	Settlement	Load
0.01"	3.66 lb	0.07"	3.58 lb
0.12"	3.62 lb	0.08"	3.46 lb
0.13"	3.62 lb	0.09"	3.42 lb
0.14"	3.62 lb	0.10"	3.42 lb
0.05"	3.60 lb	0.11"	3.42 lb
0.06"	3.58 lb	0.12"	3.42 lb

Table A.3.8 WATS Tower Settlement Data

Comparing the two guy-wire support methods for tower base settlement using Figure A.3.10, there is a sharp difference in tower load behavior. The

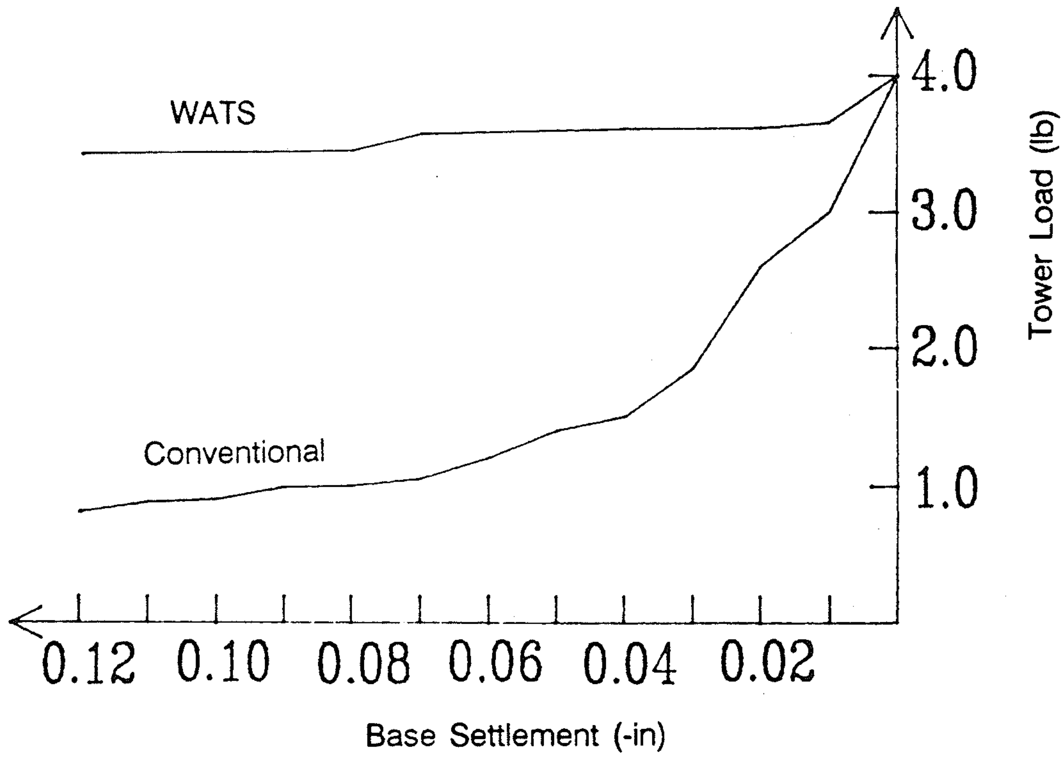


Figure A.3.10 Graph of Base Settlement Experimental Results

conventional tower shows an exponential decay of tower load from the pre-load down to 0.66 pounds, which represents the weight of the model tower shaft together with all of the mounting hardware. The WATS tower shows an initial drop in tower load, and then declines at a very slow rate (slope of graph = -1.75 lb/in). This decline would continue until the tensioner weight runs out of downward travel and contacts the ground.

A.3.4.3 Lateral Stability

Lateral stability was tested by applying loads of 2.9 lb, 11.5 lb, and 18.1 lb at the tower top. These loads were applied to both conventional and WATS tower models at initial conditions (4.0 lb pre-load), at a tower load of 75 pounds, at 0.12" of base settlement. The results of these tests are given in Tables A.3.9 and A.3.10.

Tower Base Condition	Lateral Load	Tower Top Deflection
0.12" settlement	2.9 lb	0.194"
0.12" settlement	11.5 lb	0.321"
0.12" settlement	18.1 lb	0.436"
4.0 lb tower load	2.9 lb	0.066"
4.0 lb tower load	11.5 lb	0.185"
4.0 lb tower load	18.1 lb	0.283"
75 lb tower load	2.9 lb	0.010"
75 lb tower load	11.5 lb	0.080"
75 lb tower load	18.1 lb	0.100"

Table A.3.9 Conventional Tower Stability Data

Tower Base Condition	Lateral Load	Tower Top Deflection
0.12" settlement	2.9 lb	0.082"
0.12" settlement	11.5 lb	0.240"
0.12" settlement	18.1 lb	0.319"
4.0 lb tower load	2.9 lb	0.063"
4.0 lb tower load	11.5 lb	0.232"
4.0 lb tower load	18.1 lb	0.311"
75 lb tower load	2.9 lb	0.010"
75 lb tower load	11.5 lb	0.065"
75 lb tower load	18.1 lb	0.100"

Table A.3.10 WATS Tower Stability Data, s = 2.4" $\theta 3 = 30$

At initial conditions, the conventionally supported tower shows less tower top displacement under the given lateral loads than the WATS tower. With the WATS system, there must be a small amount of lateral movement in order to lock up the weight. In real life, proportionally less movement would occur than shown with the model, because the clearance between the weight and the tower on the model are larger than to scale.

Under conditions of high tower load, both systems allow essentially the same amount of tower top deflection. With 0.12" of tower base settlement however, the WATS tower deflection was not much different than it was at initial conditions, while the conventional tower showed a dramatic change in deflection, as high as 3 times as much.

A.3.4.4 Errors

Experimental errors in the tests are mainly associated with the measurement of tower load, or more specifically, the measurement of spring compression. Even though the measuring device surfaces were carefully machined, a certain amount of run-out exists on the compressing washer. This run-out amounts to about +/- 0.005" to +/- 0.010", which represents +/-2.5 pounds of tower load. A further amount of movement is caused by the fact that the compressing washer turns on bolt threads. This amounts to about +/- 0.01", which represents a further error of +/- 2.5 pounds. However, the thread error disappears as more load is applied.

A further source of error is the method of attachment of the model guy wires. It was found that the wire tends to follow a curved bend, rather than a straight bend at the guy-wire attachment points. This would give slightly greater than expected base heave. This problem was corrected at the tower top by mounting the wires at approximately the incoming angle as shown previously. At the guy anchor points, the wire is clamped in a hole drilled into the tuning heads and the bend is made as sharp as possible. The error in measurements resulting from these types of mounts is estimated to be +/- 0.002" for every 0.1" measured, and would be the least noticeable when higher loadings are involved.

APPENDIX A.4 ADDITIONAL METHODS OF GUYED-TOWER SUPPORT

A.4.1. INTRODUCTION

A.4.2. THE METHOD OF SPRING-LOADED TENSIONER CABLES

A.4.3. THE METHOD OF SPRING SUPPORTED GUY-WIRE ATTACHMENTS

A.4.1 INTRODUCTION

This appendix briefly describes the configuration and operation of two additional methods of guyed tower support. Section A.4.2 is a description of the method of spring-loaded tensioner cables, wherein the guy wires are given an initial sag and are tensioned at their mid-point by springed tensioner cables which are attached to the tower top at some point. Section A.4.3 is a very brief description of the method of spring-loaded guy-wire attachments on the tower, wherein the accommodation of tower base heave is through the compression of a spring at the point of guy-wire attachment.

A.4.2 THE METHOD OF SPRING-LOADED TENSIONER CABLES

This method of guy wire arrangement, like the WATS method, relies on the sag of the guy wires for tower base vertical displacement. Tension is imparted to the guy wires through tensioner cables as with WATS, however, these cables are fixed to the tower and when the mid-cable sag changes, the length of the tensioners changes by stretching or relaxing a spring in tension. A schematic of this arrangement is shown in Figure A.4.1.

In order to tolerate heave as well as settlement, the springs would initially be stretched an amount which would give the desired tension in the guy wires. If the tower base rises, the mid-cable sag decreases, increasing the length of the tensioner spring which causes an increase in the guy-wire tension. If the tower base settles, the sag increases and the length of the tensioner spring decreases causing a decrease in guy-wire tension. It is necessary then to use a spring which is still in tension over the range of guy-wire sag displacement.

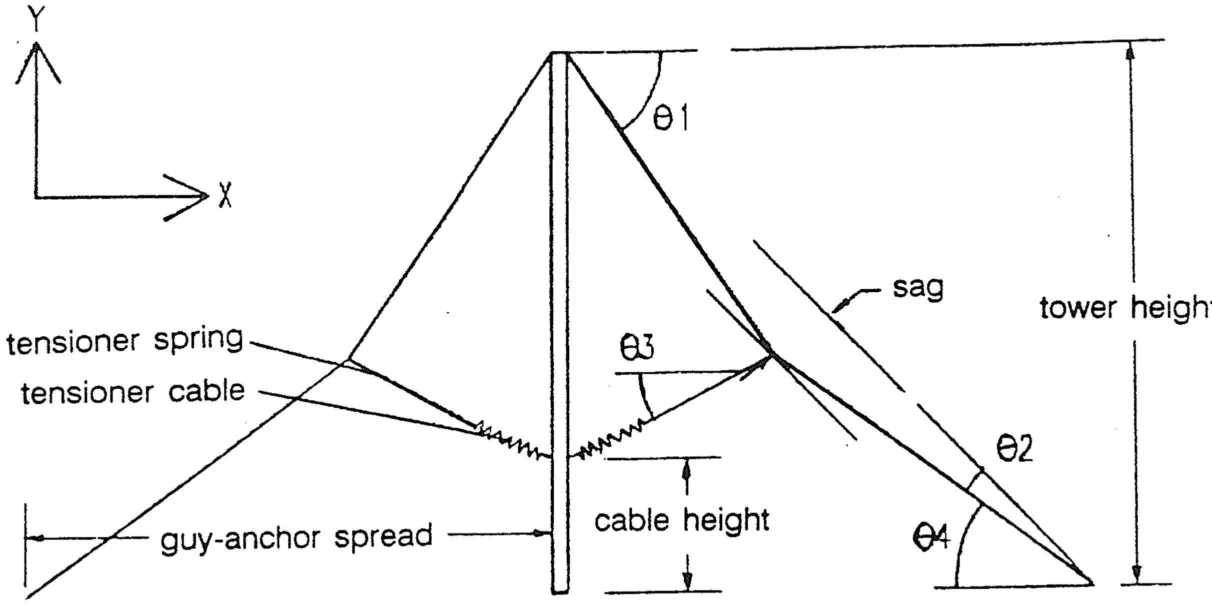


Figure A.4.1 The Method of Spring-Loaded Tensioner Cables

The variables of this method, as shown in Figure A.4.1 are the tensioner cable height, the tensioner spring constant k, the mid-cable sag, the chord angle $\theta 1$, the sag angle $\theta 2$, the tensioner angle $\theta 3$, and the guy-wire angle $\theta 4$.

The chord is simply

$$\text{chord} = \sqrt{(\text{tower height})^2 + (\text{guy-anchor spread})^2} \qquad (1)$$

from which the guy-wire length is

$$\text{gwl} = 2\sqrt{(\text{sag})^2 + (\text{chord})^2}. \qquad (2)$$

The x and y coordinates of the guy-wire midpoint are

$$x = \text{guy-anchor spread} - [(gwl/2)\cos\theta 4], \tag{3}$$

$$y = \left(\frac{gwl}{2}\right)\sin\theta 4 \tag{4}$$

Treating the upper and lower guy wires (G2 and G1) as two force members, equilibrium of forces in the x-direction and y-direction gives

$$\Sigma F_x = 0 = TG1\cos\theta 4 - tt\cos\theta 3 - TG2\cos(\theta 1+\theta 2) \tag{5}$$

$$\Sigma F_x = 0 = TG2\sin(\theta 1+\theta 2) - tt\sin\theta 3 - TG1\sin\theta 4 \tag{6}$$

Solving (5) and (6) with

$$C1 = \cos\theta 3\sin(\theta 1+\theta 2) + \sin\theta 3\cos(\theta 1+\theta 2) \tag{7}$$

$$C2 = \cos\theta 4\sin(\theta 1+\theta 2) - \sin\theta 4\cos(\theta 1+\theta 2) \tag{8}$$

yields

$$TG1 = (C1/C2)tt \tag{9}$$

$$TG2 = tt[\sin\theta 3 + (C1/C2)\sin\theta 4]/\sin(\theta 1+\theta 2) \tag{10}$$

The tower load is caused by the action of the upper guy wires (TG2), or

$$\text{Tower Load} = TG2\sin(\theta 1+\theta 2)(\text{no. of wires}) \tag{11}$$

To analyze this method mathematically, a computer program was written. The analysis was done over a range of +/-6 inches of base displacement for mid-cable sags of 60" and 78.75", with spring constant of 2.855 lb/in, and for tensioner attachment heights of 0.0 and 6.56 feet. The results of this analysis are for a tower of height 68.5' and guy anchor spread 48.7', and are given in

Tables A.4.1 to A.4.4 with a plot of the results shown in Figure A.4.2.

Base Displacement	Tower Load	Base Displacement	Tower Load
+5.91"	3008 lb	-0.40"	727 lb
5.51"	2667 lb	-0.79"	670 lb
5.12"	2389 lb	-1.18"	617 lb
4.72"	2156 lb	-1.58"	566 lb
4.33"	1957 lb	-1.97"	519 lb
3.94"	1784 lb	-2.36"	474 lb
3.54"	1633 lb	-2.76"	432 lb
3.15"	1499 lb	-3.15"	391 lb
2.76"	1379 lb	-3.54"	353 lb
2.36"	1271 lb	-3.94"	316 lb
1.97"	1172 lb	-4.33"	282 lb
1.58"	1083 lb	-4.72"	248 lb
1.18"	1000 lb	-5.12"	217 lb
0.79"	924 lb	-5.51"	186 lb
0.40"	854 lb	-5.91"	157 lb
	788 lb		

Table A.4.1 Mathematical Data for k = 2.855 lb/in,

sag = 60", height of tensioner cables = 0.0

Base Displacement	Tower Load	Base Displacement	Tower Load
+5.91"	3138 lb	-0.40"	724 lb
5.51"	2778 lb	-0.79"	663 lb
5.12"	2483 lb	-1.18"	606 lb
4.72"	2236 lb	-1.58"	553 lb
4.33"	2026 lb	-1.97"	502 lb
3.94"	1843 lb	-2.36"	455 lb
3.54"	1683 lb	-2.76"	410 lb
3.15"	1541 lb	-3.15"	367 lb
2.76"	1414 lb	-3.54"	326 lb
2.36"	1300 lb	-3.94"	288 lb
1.97"	1195 lb	-4.33"	251 lb
1.58"	1100 lb	-4.72"	215 lb
1.18"	1013 lb	-5.12"	182 lb
0.79"	932 lb	-5.51"	149 lb
0.40"	858 lb	-5.91"	118 lb
	788 lb		

Table A.4.2 Mathematical Data for k = 2.855 lb/in,
sag = 60" , height of tensioner cables = 6.56'

Base Displacement	Tower Load	Base Displacement	Tower Load
+5.91"	1560 lb	-0.40"	770 lb
5.51"	1487 lb	-0.79"	737 lb
5.12"	1421 lb	-1.18"	705 lb
4.72"	1358 lb	-1.58"	675 lb
4.33"	1298 lb	-1.97"	646 lb
3.94"	1241 lb	-2.36"	617 lb
3.54"	1187 lb	-2.76"	590 lb
3.15"	1136 lb	-3.15"	563 lb
2.76"	1088 lb	-3.54"	537 lb
2.36"	1042 lb	-3.94"	513 lb
1.97"	998 lb	-4.33"	488 lb
1.58"	956 lb	-4.72"	465 lb
1.18"	915 lb	-5.12"	442 lb
0.79"	877 lb	-5.51"	420 lb
0.40"	840 lb	-5.91"	399 lb
0.00"	804 lb		

Table A.4.3 Mathematical Data for k = 2.855 lb/in,
sag = 78.75" , height of tensioner cables = 0.0

Base Displacement	Tower Load	Base Displacement	Tower Load
+5.91"	1610 lb	-0.40"	768 lb
5.51"	1534 lb	-0.79"	733 lb
5.12"	1462 lb	-1.18"	699 lb
4.72"	1394 lb	-1.58"	666 lb
4.33"	1331 lb	-1.97"	635 lb
3.94"	1270 lb	-2.36"	605 lb
3.54"	1213 lb	-2.76"	575 lb
3.15"	1159 lb	-3.15"	547 lb
2.76"	1107 lb	-3.54"	519 lb
2.36"	1058 lb	-3.94"	493 lb
1.97"	1011 lb	-4.33"	467 lb
1.58"	966 lb	-4.72"	442 lb
1.18"	923 lb	-5.12"	418 lb
0.79"	882 lb	-5.51"	394 lb
0.40"	842 lb	-5.91"	371 lb
	804 lb		

Table A.4.4 Mathematical Data for k = 2.855 lb/in, sag = 78.75", height of tensioner cables = 6.56'

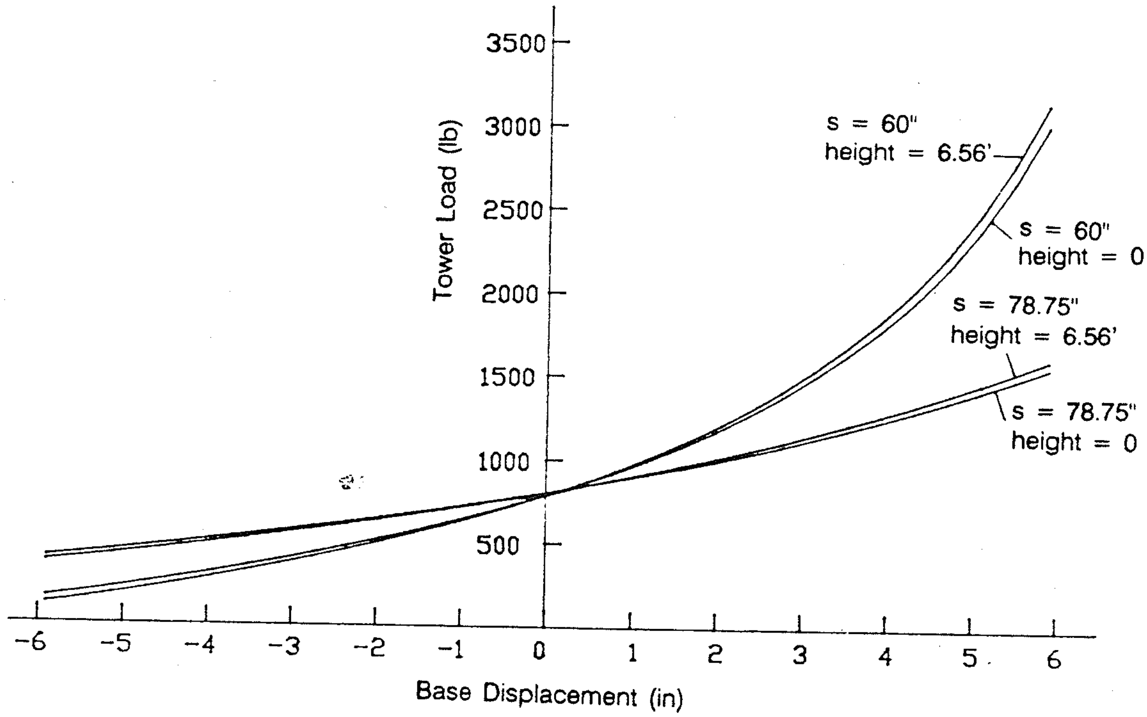


Figure A.4.2 Plot of Tower Load vs Base Displacement

A.4.3. THE METHOD OF SPRING-SUPPORTED GUY-WIRE ATTACHMENTS

With this method, tower base heave is accommodated by compression of a spring located at the point of guy-wire attachment, rather than by diminishing mid-cable sag as previously has been the case. A schematic of this arrangement is shown in Figure A.4.3.

In operation the compression spring would be under some pre-load, which would impart tension to the guy-wires. If the tower base rises, the spring would compress further and the guy-wire tensions would increase, and conversely if the tower base settles, the spring decompresses and guy tensions would decrease. The guy attachment is guided by a shaft such that it locks in place when lateral loads are applied, as shown in Figure A.4.4.

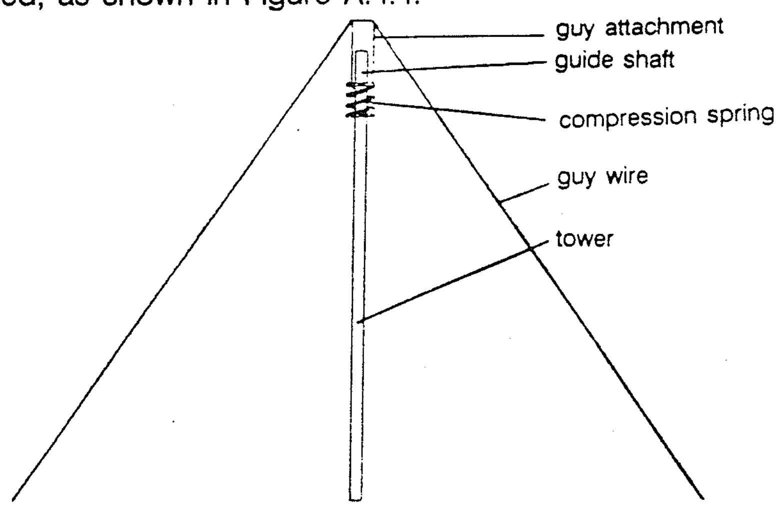


Figure A.4.3 Method of Spring Supported Guy-Wire Attachments

If six inches of heave is desirable, then the spring must compress at least six inches before solid height is obtained, at which point the tower behaves the same as a conventional tower. For an initial downward component of guy tension of 200 lb as the starting point, then a spring of k = 500 lb/in would be compressed 1.6 inches initially. If this tower is of the dimensions of that of Section A.4.2, this represents a guy tension of 245 lb and a tower load of 800 lb. A base heave of six inches results in a tower load of 6 x 500 = 3000 pounds, and a guy tension of 615 pounds.

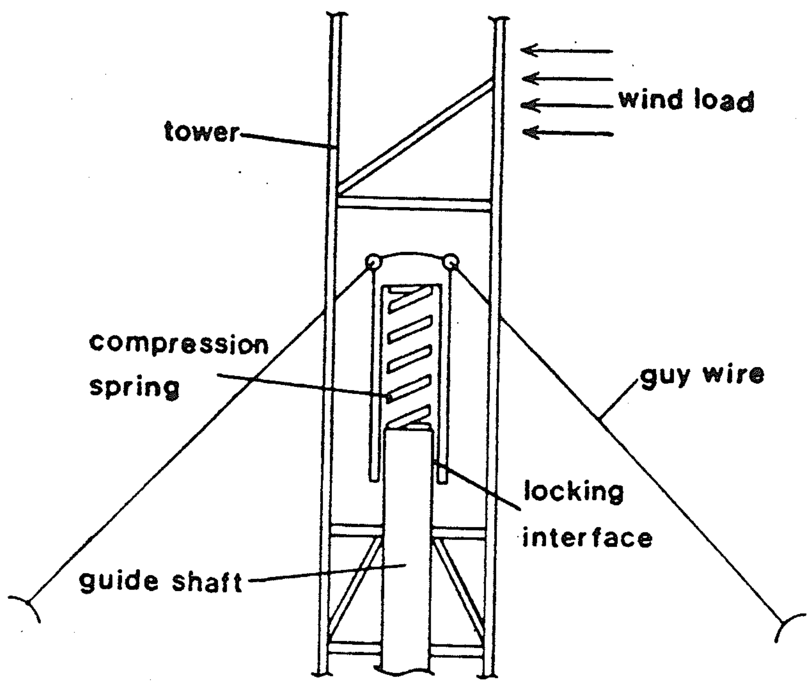


Figure A.4.4 Details of Spring- Compensator

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