LIMIT STATES AND RELIABILITY-BASED DESIGN METHODS APPLIED TO THE BUOYANCY ASSESSMENT OF THE SHOAL LAKE AQUEDUCT

by

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ABSTRACT

An actual design example was used to demonstrate how limit states design methods and engineering judgement can be applied to solve a non-codified engineering problem. The work was focussed on the assessment of potential buoyancy during shutdowns of the eighty-three year old Shoal Lake Aqueduct that is the sole source of potable water for Winnipeg, Manitoba. Four separate buoyancy analyses of the Shoal Lake Aqueduct were completed. Three of the analyses were conducted using limit states and reliability-based design methods. For comparative reasons a fourth analysis was completed using a traditional working stress design (WSD) method. A buoyancy model was developed and used in these analyses. The first buoyancy analysis was completed using partial safety factors developed for the Ontario Highway Bridge Design Code. Because these partial safety factors were developed for use with the design code a second analysis was completed using project-specific partial safety factors. These partial safety factors were determined using Second Moment reliability techniques and measured data for the uncertainties in the buoyancy model. A third buoyancy analysis was completed using Monte Carlo simulation techniques. A fourth buoyancy analysis was completed using WSD methods to demonstrate the potential variability in the level of safety. Engineering judgement was required to develop the buoyancy model, to interpret the data obtained for each of the parameters and to provide meaningful design values for those parameters which could not be measured.

The results of the buoyancy analyses completed using limit states design and reliability-based methods were similar. Because the partial safety factors from the Ontario Highway Bridge Design Code were not based on the measured variability of different parameters, the potential for deviation from a target level of safety is significant. The target level of safety provided using project-specific partial safety factors and Monte Carlo simulation is more reliable because the results reflect the measured variability of the parameters. The target level of safety using WSD methods is not directly quantifiable. The results of this thesis show that the selection of a single factor of safety has a very significant influence on the target level of safety, that is it does not give uniform reliability.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ADD	average daily demand
BR1	Branch 1 Aqueduct
BR2	Branch 2 Aqueduct
CHBDC	Canadian Highway Bridge Design Code
GFS	global factor of safety
GWWD	Greater Winnipeg Water District
LF	load factor
LRFD	load and resistance factor design
LSD	limit states design
MLD	millions of litres per day
NBCC	National Building Code of Canada
OHBDC	Ontario Highway Bridge Design Code
PDF	probability density function
P_f	probability of failure
P-S	project-specific
PSF	partial safety factor
RBD	reliability-based design
RF	resistance factor
RR	resisting ratio
SLA	Shoal Lake Aqueduct
SLA_CARP	Shoal Lake Aqueduct Condition Assessment and Rehabilitation Program
SLS	Serviceability Limit State
ULS	Ultimate Limit State
WSD	working stress design

1.0 INTRODUCTION

In the mid-1970's, limit states design (LSD) methods were introduced to Canadian structural engineers as an alternative to working stress design (WSD) methods. (A list of abbreviations used in this thesis is given on page xi following the Table of Contents.) Since this time, LSD methods have become the general state of practice for structural design, with their objective being to provide a more quantifiable and consistent level of safety. In contrast, geotechnical engineers have been slow to adopt LSD methods to replace WSD methods. The slow progress within the geotechnical community can be attributed, at least in part, to the years of experience and level of comfort using WSD and the high degree of uncertainty associated with many geotechnical parameters.

Limit states are defined as conditions under which a structure or its component members no longer perform their intended functions (Becker, 1996a). The use of LSD methods is facilitated with the use of design codes. The objective of design codes is to ensure a minimum level of technical quality and a minimum or specified level of safety. The level of safety or reliability of a system can be defined in terms of the probability of failure. In general, this is achieved through the use of multiple load and resistance factors, specified design values for material properties and specified load combinations. The purpose of load and resistance factors, or partial safety factors (PSF), is to account for uncertainties, for example, in the measurement of material properties, uncertainties in analytical models, and uncertainties in loads that the structure is required to sustain. The PSFs can be determined directly using probabilistic or reliability methods which make use of large databases of measured values, or they can be determined by direct calibration with WSD methods.

In contrast, WSD only uses one global factor of safety (GFS) to account for all uncertainties. This GFS is almost entirely based on engineering judgement and experience and it would be extremely difficult to estimate a level of safety (or a probability of failure) for any value of the GFS.

1.1 STATEMENT OF PROBLEMS

There are two general problems. First, LSD methods are not compatible with WSD methods. Two, many classes of engineering problems are not covered by design codes based on LSD, particularly engineering problems in the general area known as geotechnical engineering.

The first problem is best explained by example. Assume a geotechnical engineer, using WSD, provides foundation recommendations for a spread footing to a structural engineer who will design a structure using LSD methods. The foundation recommendations are based on Terzaghi's bearing capacity equation, which is a strength equation. In traditional geotechnical practice, the ultimate bearing capacity calculated from this equation is reduced using a GFS ranging from 2.5 to 3. These relatively large GFSs are selected to provide not only a safety margin against catastrophic failure, but also, in a notional way, to restrict bearing pressures and limit settlements. In this example, the single GFS provides protection against exceeding both an Ultimate Limit State (ULS) and a Serviceability Limit State (SLS). The resulting “allowable bearing capacity', is the value provided to the structural engineer. Difficulties can develop when a structural engineer tries to evaluate ULSs using a value that is intended to limit settlements, which is considered to be an SLS. Obviously the two systems are not compatible and there is much potential for confusion and human error. In addition, the level of safety associated with the foundation recommendations may not be comparable with the level of safety for the structure itself. The problem arises because LSD methods provide separate evaluations of ULSs and SLSs, which are related to strength and deformation, respectively. In contrast, GFS methods combine these quite separate states through a single ‘confidence’ factor that is purely empirical.

The second problem, and the focus of this thesis, is that many classes of engineering problems are simply not covered by current design codes based on LSD. This is particularly true for existing infrastructure and geotechnical engineering problems. In these cases, engineers may feel that WSD methods are more attractive due to their relative simplicity. The level of safety provided by WSD would be unknown. Engineers might therefore prefer to use a Limit States approach. However, if no design code has been prepared, it may indicate there is a lack of data that can be used to derive PSFs for many of the parameters used in geotechnical design.

1.2 LIMIT STATES DESIGN IN GEOTECHNICAL ENGINEERING

In 1980, an agreement was reached to draft a geotechnical design code for use across Europe (Ovesen, 1981). Some countries, such as Denmark, had been using design codes with prescribed PSFs for quite a few years. This generated quite a bit of interest from European engineers using WSD methods. Many questions were raised about the pitfalls that might be encountered using prescribed PSFs or attempting to account for the variability of geologic uncertainties using statistics and probability theory. Many felt that the use of LSD and prescribed PSFs would remove the engineer from the design process and there would be no room for engineering experience or judgement. From about 1981 to the early 1990's, there seems to be a distinct gap in published literature on the use of LSD in geotechnical engineering. Since that time a considerable amount of work has been completed and published in conference proceedings (International Limit States Design Symposium, 1993; Uncertainty in the Geologic Environment, 1996) and engineering journals such as the Canadian Geotechnical Journal and the ASCE Journal of Geotechnical Engineering. In addition, three Canadian limit states design codes now require the use of LSD for the geotechnical component of design. These codes include the Ontario Highway Bridge Design Code (OHBDC; Ministry of Transportation of Ontario, 1991), the National Building Code of Canada (NBCC; National Research Council of Canada,1995) and the Canadian Highway Bridge Design Code (CHBDC; Canadian Standards Association, 2000). Limit States Design procedures will be introduced in the next edition of the Canadian Foundation Engineering Manual published by the Canadian Geotechnical Society. The new edition is expected in 2003-2004.

The use of LSD methods by Canadian geotechnical engineers has been initiated through the design codes mentioned above. However, many of the problems faced by geotechnical engineers do not have design codes to guide the engineer. How can engineers apply LSD methods to non-codified problems? Can engineers use prescribed PSFs from other codes? What risk would be associated with this? Do engineers need to use PSFs or can reliability theory be used to help evaluate the level of safety? How much understanding of probability and reliability theory is required? Can engineering judgement be used in conjunction with LSD methods?

These issues are addressed in this thesis by way of an actual design example, which involved assessment of possible buoyancy of the Shoal Lake Aqueduct in eastern Manitoba. The eighty-three year old Shoal Lake Aqueduct is the sole water supply for Winnipeg, Manitoba. It was constructed between 1915 and 1919 and has been in almost continuous use since that time. Only in recent years has the aqueduct been shutdown to facilitate much needed maintenance repairs. During these shutdowns, there is a possibility that the aqueduct could become buoyant in areas where the aqueduct is submerged and the backfill material is mainly comprised of light-weight organic soils. No design code exists to evaluate the potential for buoyancy of a structure like the aqueduct. One of the biggest advantages the engineer has is that the aqueduct has already been constructed. This permits direct measurement for many of the parameters or uncertainties involved in assessing buoyancy potential. Direct measurement was necessary because there is no database available that can be used to determine appropriate design parameters or PSFs that can be used in design.

This LSD example is a case study of a unique and rare engineering problem involving a very critical component of civil engineering infrastructure. There is no design code directly applicable to buoyancy assessment and there is minimal engineering experience. The amount of field information that was required to solve this problem is not ordinarily available to students and therefore the work in this thesis represents a unique opportunity to show how LSD methods can be applied outside of design codes. This work is not simply the application of probabilistic and reliability methods. It involves a significant component of engineering judgement to develop the buoyancy model and to interpret the data used in the model.

HYPOTHESIS:

A combination of limit states design (including reliability-based design methods) and good engineering judgement can provide technically sound, economic solutions to many classes of engineering problems, particularly problems involving remediation of existing infrastructure.

1.3 OBJECTIVES

The objectives to be met in this thesis include the following.

1. To show that LSD methods can be successfully applied to non-codified engineering problems.
2. To show why PSFs from non-related design codes may not be applicable.
3. To show how project-specific PSFs can be developed.
4. To show how reliability-based design methods can be used as an alternative to the PSF method and to check the results of designs completed with project-specific PSFs.
5. To demonstrate the inherent uncertainty in using WSD methods.
6. To demonstrate the importance of engineering judgement in design.

1.4 ORGANIZATION OF THESIS

Following this introduction, Chapter 2 presents a general overview of LSD. The chapter begins by outlining the various uncertainties and required level of safety that need to be identified before design begins. For comparative purposes, a brief discussion on WSD has been included. The section on LSD provides a definition and history of LSD, an overview of the various LSD methods that can be used in design and a discussion of the concerns raised by engineers regarding the use of LSD methods in geotechnical engineering. A general approach to applying LSD methods to non-codified engineering problems is included at the end of the chapter.

Chapter 3 provides an overall summary of the Shoal Lake Aqueduct. The chapter highlights the engineering challenges faced in the early 1900's by the engineers during the design and construction of the aqueduct. The operating history of the aqueduct has been included to show how the operating requirements have changed over the years and how these relate to buoyancy potential of the aqueduct. The chapter concludes by introducing the Shoal Lake Aqueduct Condition Assessment and Rehabilitation Program that was initiated by the City of Winnipeg, Water and Waste Department in the early 1990's.