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Technical Note

A Canadian Perspective of Limit State Design in Geotechnical Engineering

by

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Introduction

The design of any civil engineering structure is to address the two criteria of 1) Ultimate safety and 2) Serviceability. Firstly, the structure should have a reasonable margin of safety against a total collapse or failure under the worst combination of loads during the life of a structure. Secondly, the structure should serve its function during the time without excessive deformations or disruption to the materials. The complete collapse of the structure due to failure of surrounding soil caused by overturning, sliding, bearing capacity, seepage, uplift and piping etc. is generally called Ultimate Limit State. Excessive total and differential settlement of the structure leading to cracking, loss of its function and vibration are covered under Serviceability Limit State.

The uncertainties in geotechnical engineering could be two fold. Firstly, the ambiguities regarding the various types of loads and load effects on the structure, the determination of soil properties including methods of sampling, testing and interpretation of their results can be categorised as objective uncertainties. Secondly, the method of analysis, types of construction, expertise in judgement and other human errors comprise the subjective uncertainties. The objective uncertainties are taken care of by providing a reasonable factor(s) of safety, either total or partial in the design of the structure whereas the subjective uncertainties are taken care of by providing adequate quality control and resorting to alternate design methods. It may be remarked that the total and partial safety factors are interrelated and both

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these approaches aim at providing a reasonable margin of safety against total and functional failure of the structure (Meyerhof, 1984).

Historical Developments

Krey (1926) first introduced the concept of overall safety factors, now called the total safety factors which were adopted in Europe, North America, Japan etc. He suggested a value of 1.5 for the stability of slopes, retaining walls and 2-3 for the bearing capacity of foundations. Later Terzaghi and Peck (1948) have suggested a list of values of total safety factors which are presented in Table 1 and are adopted by the Canadian Foundation Engineering Manual, hereafter referred to as CFEM, in 1978 and are retained as such still today in its latest publication of 1992. Taylor (1948) suggested partial safety factors on cohesion and friction angle Tan in the slope stability analyses. Later on Brinch Hansen (1953, 1956) gave a list of detailed partial safety

factors on loads (dead load, soil weight, live load, environmental loads, etc.), shear strength of soil (C, Tan) for slope stability analyses, earth pressure computations, foundations and on ultimate pile loads from load tests as well as dynamic formulae. These partial safety factors have been modified based on semi-probabilistic theories based on the variabilities in loads, soil strength and design procedures.

Immediate settlement computations are based on the theory of elasticity whereas ultimate settlements are arrived at from the theory of consolidation.

TABLE 1
Total Safety Factors Adopted by the Canadian Foundation Engineering Manual (1992)

Failure Type	Item	Safety Factor
Shearing	Earthworks	1.3 - 1.5
	Earth-retaining Structures, Excavations	1.5 - 2.0
	Foundations	2.0 - 3.0
Seepage	Uplift, Heave	1.5 - 2.0
	Exit gradient, Piping	2.0 - 3.0

Non linear stress strain behaviour of soil is considered in modern developments in the interaction. These estimates are then compared with the tolerable limits of settlements for different types of structures in different parts of the world.

Ultimate Limit State

The various safety factors in ultimate limit state design are influenced by the reliability of the information on loads and load effects due to dead, live, environment loads (wind, wave, snow and earthquake), soil properties (method of sampling, testing, interpretation), pore pressure, progressive failure quantification, design method, soil profile, quality control, construction technique, consequence of failure, service life of the structure, economy etc. (Meyerhof, 1993). It was also suggested that a more consistent and uniform range of safety margin for different structures, under widely differing load combinations (dead, live and environmental etc.) can be obtained by using partial safety factors, which has become the basis for the Ontario Highway Bridge Design Code (1983) and the National Building Code of Canada (1985).

The numerical values of these partial safety factors adopted in the United States of America and Europe together with those incorporated in the latest edition of the CFEM are presented in Table 2. The safety factors given in brackets in Table 2 apply to dead loads and water pressures when their effect is beneficial, and for dead loads resisting instability by sliding, overturning, or uplift. When both live and environmental loads act together, a load combination factor of 0.7 is suggested to both loads, but the total *effect must not be smaller than that for full,* live or environmental load acting alone. The various loads and load effects are to be multiplied by the partial safety factors whereas the soil strength values have to be divided by the suggested safety factors.

It is necessary to mention that the partial safety factors are selected to give an overall safety margin as given by the total safety factors, good practice and experience. The conventional total safety factor in the case of bearing capacity of foundations is 3 which is split into a partial safety factor of 1.5 for live loads often referred to as load factor and a partial safety factor of 2 on the soil resistance. Even the most recent partial safety factors adopted in Eurocode 1992 were obtained by calibrating against the total safety factors.

TABLE 2
Partial Safety Factorss

Item			Denmark (DS 415) 1965	Eurocode 1992	Canada (CFEM) 1992	USA (ANSI A58) 1980
Loads	Dead loads		1.0	1.0 (0.95)	1.25 (0.85)	1.2 - 1.4 (0.9)
	Live loads		1.5	1.3 (0)	1.5 (0)	0.5 - 1.6 (0)
	Environmental loads		1.5	1.3 - 1.5 (0)	1.5 (0)	1.3 - 1.6 (0)
	Water pressure		1.0	1.0 (1.0)	1.25 (0.85)	
Shear Strength	Friction (tan ϕ)		1.2 - 1.25	1.2 - 1.25	1.25	Resistance factor of 1.2 -1.5 on ultimate resistance using unfactores strengths
	Cohesion (c)	slopes, earth pressures	1.5	1.5 - 1.8	1.54	
	Cohesion (c)	spread foundations	1.75	1.5 - 1.8	2.0	
		piles	2.0	Special rules	2.0	

Serviceability Limit State

The allowable total and differential settlements in a structure depend upon the type of superstructure (frame building, load bearing walls, flexibility of structure, etc.) so that harmful cracking does not result during the service life of the structure. Large structures are designed to accommodate certain allowable movements without effecting the function of the structure. Most of the failures are due to excessive total and/or differential settlements which result in the functional failure of the structure even though total collapse of the structure does not occur. As such the Serviceability consideration in the limit state design is of utmost importance. For common type of structures the rotation limits are given in Table 3. which are recommended by the CFEM (1992). The Serviceability limit are checked by adopting a partial safety factor of unity on all loads, and load effects. However, when both live and environmental loads act together, a load combination factor of 0.7 is suggested as stated under ultimate limit state above.

A factor of unity is suggested on the strength and compressibility properties of the soils. However, in view of the uncertainty and great variability in in-situ soil structure stiffness and the complexity in evaluating certain soil properties such as the subgrade modulus, a performance factor of 0.7 is suggested in the CFEM (1992). In other words this performance factor results in a partial safety factor of 1/0.7 approximately equal to 1.4 on the characteristic values of deformation and compressibility properties of the soils.

TABLE 3
Tentative Safe Rotation Limits

Relative (δ/L)* Ratio	Type of Structures
1/150	Statically determinate structures with flexible cladding, retaining walls.
1/250	Open steel and concrete frames, offshore platforms, steel storage tanks, high rigid structures.
1/500	Panel walls of frame buildings and bridge abutments
1/1000	Sagging of unreinforced load bearing walls.
1/2000	Hogging of unreinforced load bearing walls.

* δ is the differential settlement in span L.

Conclusions

Safety factors are incorporated in the geotechnical design of structures to provide adequate safety against total collapse and functional failure of the structure. The conventional designs using total safety factors as incorporated in the various design codes have proved to be safe. However these total safety factors are subdivided into partial safety factors which are currently used all over the world for loads, load effects and soil resistance based on the reliability of information. It is important to note that the total safety factors are the basis in arriving at the partial safety factors.

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