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Probabilistic Analysis of Reinforced Soil Slopes

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Abstract

Geosynthetic reinforcement is being used increasingly to improve the stability and performance of soil slopes and embankments. The current methods of design for such reinforcement are deterministic, based on the same limit equilibrium procedures that are used for design of conventional, unreinforced slopes. Stability is evaluated based on a factor of safety that is typically defined with respect to soil shear strength. The most critical potential failure surface with the minimum factor of safety is found by trial and error. For typical reinforced slope designs, the most critical potential failure surface is located primarily outside of the reinforced zone; thus, the factor of safety essentially reflects the potential for failure in the unreinforced soil. In reality there are two potential modes of failure. One primarily through the reinforced soil mass, the other primarily through the unreinforced soil mass. The conventional factor of safety does not reflect the likelihood of failure by each mechanism. In this paper, we present a design approach for reinforced slopes that is based on structural reliability theory. This approach considers the possible modes of failure and provides a better assessment of the likelihood of failure. It is shown, for example, that the failure mechanism with the highest probability of occurrence may be different from the mechanism associated with the minimum factor of safety. Typical results from the reliability analyses will be presented and compared with results based on the conventional factor of safety-based design procedures for reinforced slopes.

Probabilistic Analysis of Reinforced Soil Slopes

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Abstract

This paper presents an analysis of a geosynthetically reinforced slope that is based on structural reliability theory. This probabilistic analysis is compared to current deterministic analysis methods. Current deterministic methods use limit equilibrium techniques to locate the failure mode with the minimum factor of safety. The analysis presented considers many possible failure modes. It is shown that the failure mode with the highest probability of failure does not necessarily correspond to the failure mode with the minimum factor of safety.

Introduction

Current design methods for geosynthetically reinforced slopes are deterministic, based on the same limit equilibrium procedures that are used for design of conventional, unreinforced slopes. Stability is evaluated based on a minimum factor of safety along a potential failure surface. There are numerous potential failure surfaces in reinforced slopes, some lying within the reinforced zone of the slope and some lying outside of the reinforced zone of the slope. The factor of safety is typically defined with respect to soil shear strength. It is difficult to evaluate the relative reliability of different failure modes using the factor of safety. The conventional factor of safety does not reflect the likelihood of failure of each of the potential failure modes. This paper compares the current deterministic stability analysis method with a probabilistic method using a typical reinforced slope design as an example. The slope analyzed in this paper was derived from guidelines published by the Tensar Corporation and is representative of the current state-of-the-practice for design of reinforced slopes. For a detailed description of the design procedure the reader is referred to the design guidelines (Tensar 1988).

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Deterministic Analysis

Traditional limit equilibrium analysis techniques, adapted for reinforced slopes, were used in the deterministic analysis. The stability method used was Spencer's procedure of slices, including reinforcement forces following the technique developed by Wright and Cuenca (1986). The allowable reinforcement forces were input to the stability computation and the traditional factor of safety was then computed. The factor of safety was defined as the ratio of the available soil shear strength to the applied shear stress. In this case, for cohesionless soil, the factor of safety, F, was

$$F = \frac{\tan\phi}{\tau} \tag{1}$$

where τ is the applied shear stress and ϕ is the angle of internal friction of the soil. The analytical procedure, then, is to search for the potential shear surface that has the minimum factor of safety as defined in Equation 1. The computer program UTEXAS3 (Wright 1991) was used to compute the factor of safety and to aid in the search for the shear surface with the minimum factor of safety. Shear surfaces were restricted to circular arcs. An extensive search was performed to locate the circle with the minimum factor of safety, and included circles lying both within and outside of the reinforced zone of the slope.

Probabilistic Analysis

The probabilistic analysis used the first-order reliability method. The limit state function, g, was defined as

$$g = F - 1 \tag{2}$$

where F is the factor of safety, as defined in Equation 1. Two random variables were considered: the soil shear strength, $\tan\phi$, and the allowable force in the primary reinforcement, R. Both were considered to be normally distributed. The mean value of the shear strength, $\tan\phi$, was taken to be 0.625 (=tan32°) and the mean value of the reinforcement force was taken to be 32 kN/m. A number of different values for the coefficients of variation of these two variable were considered based on an analysis of the expected variabilities (Kitch, 1994).

Comparison of Analytical Methods

A 70 degree slope (0.36 H : 1 V) 11.6 m (38 feet) high was chosen for analysis (Figure 1). The slope was designed assuming that the foundation and backfill soils were cohesionless with an angle of internal friction of 32 degrees. The nominal factor of safety with respect to soil shear strength chosen for design was 1.3. The slope contained 17 layers of primary reinforcement, each 8.5 m (28 feet) long. The primary reinforcement was SR2 Tensar geogrid with an allowable long-term tensile capacity of 32 kN/m (2200 lb/ft). In the upper portions of the slope, secondary reinforcement was placed between the layers of primary reinforcement. The secondary reinforcement consisted of SS1 Tensar geogrid, 1.5 m (4.9 feet) long, with an allowable long-term tensile capacity of 5.6 kN/m (386 lb/ft).

From the deterministic analysis, the critical circle with the minimum factor of safety

(1.51) was found to be predominately outside the reinforced zone of the slope (Figure 1). For circles contained within the reinforced zone of the slope, the minimum factor of safety was 1.85.

Using the first-order reliability method, the reliability index, β, was computed for different potential failure modes (all circular). It was found that the most probable failure mode was always one of two critical modes: one consisted of a circle lying completely within the reinforced zone of the slope and the second consisted of a circle lying predominately outside the reinforced zone. The locations of these two critical failure modes corresponded essentially to the two circles with the minimum factors of safety shown in Figure 1.

The reliability index for the two critical failure modes was computed for coefficients of variation of the shear strength of 0.1 and 0.2, and coefficients of variation of the allowable reinforcement force ranging from 0.05 to 0.5 (Kitch 1994). In Figure 2 the reliability indexes for these two critical failure modes are compared as a function of the coefficients of variation of shear strength and reinforcement force. It is apparent that either failure mode may be the least reliable (have the lowest reliability index) depending on the magnitude of the coefficients of variation. In contrast, the deterministic analysis indicated that the failure mode passing outside of the reinforced zone of the slope is the most critical.

Conclusion

Both the probabilistic and deterministic analyses show there are potential failure modes within the reinforced zone of the slope and outside of the reinforced zone of the slope. The probabilistic analysis clearly shows that the most likely mode of failure is a function of the uncertainties in the reinforcement force and the soil shear strength. Because the deterministic factor of safety does not contain any information about the effects of the uncertainty of these two variables, it cannot indicate which mode is most likely. The mode with the lowest factor of safety, computed by conventional deterministic methods, may not correspond to the most probable failure mode. Using a probabilistic analysis, the potential for failure in different modes can be made on a rational basis.

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Stephen G. Wright (1991), *UTEXAS3: A Computer Program for Slope Stability Calculations, Users Manual*, Geotechnical Center, Univ. of Texas, Austin TX

Stephen G. Wright and Fernando Cuenca (1986), *Stability Computation Procedures for Earth Slopes Containing Internal Reinforcement*, Research Report 435-1, Center for Transportation Research, Univ. of Texas, Austin TX

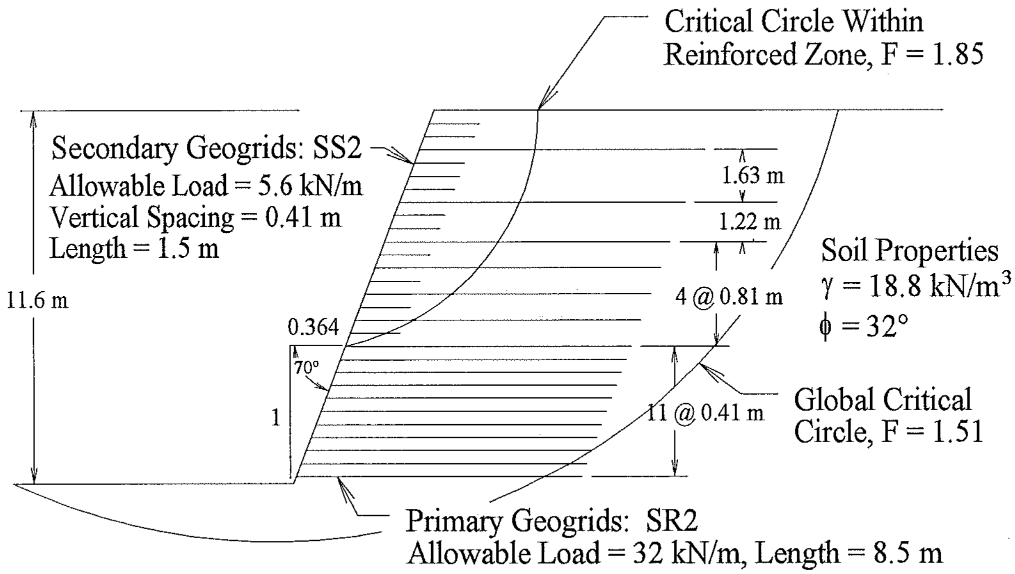

Figure 1: 70 Degree Slope Designed Using Tensar Guidelines, Showing Internal and External Critical Circles.

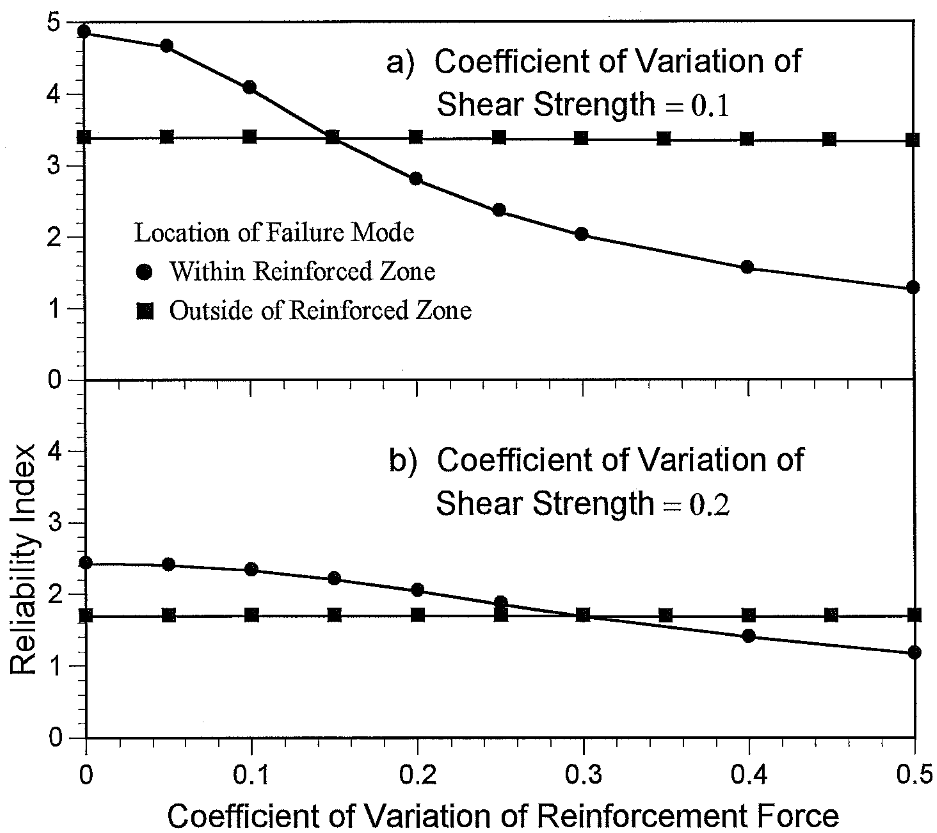

Figure 2: Reliability Index as a Function of Coefficients of Variation.

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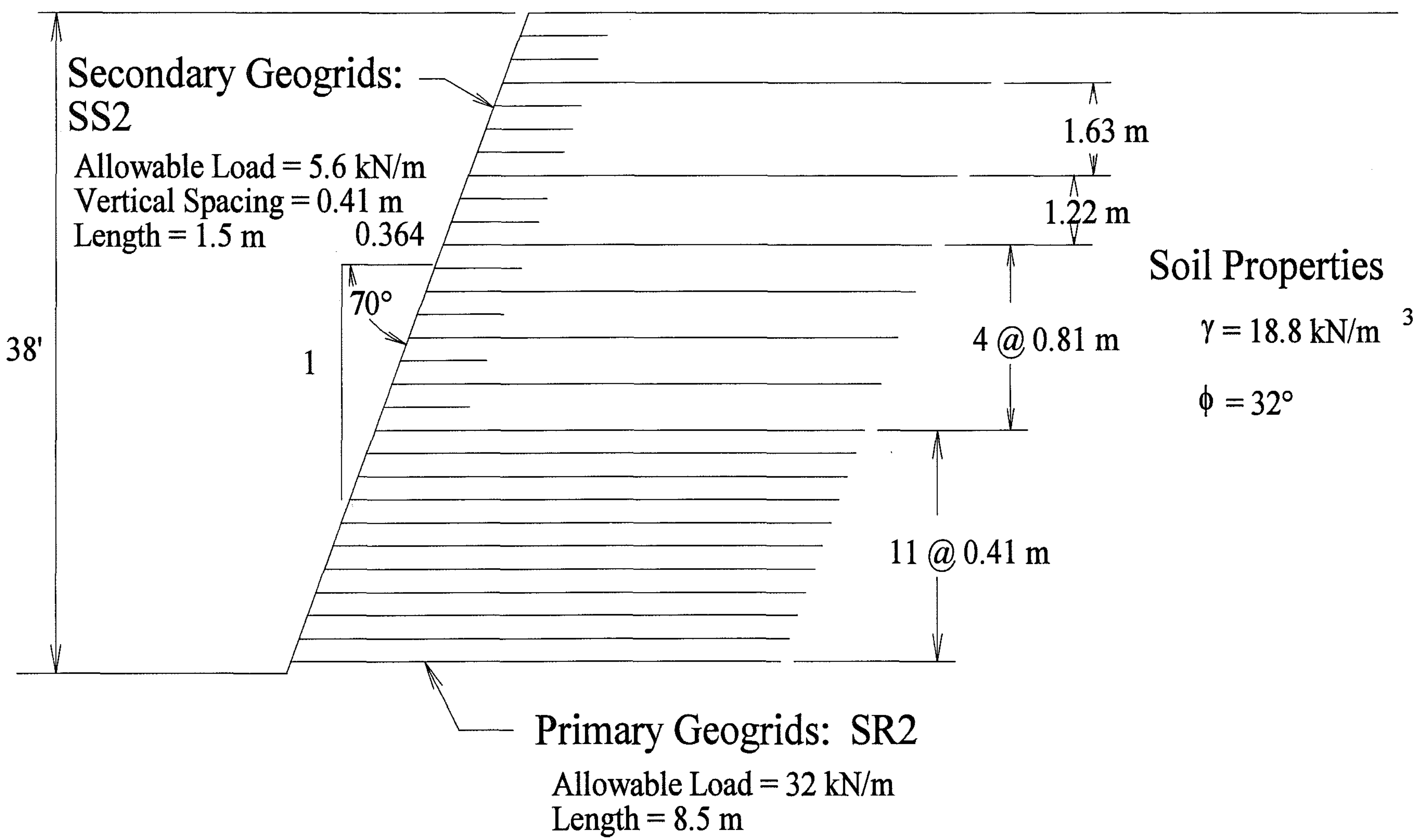
Overview

- **Problem Chosen for Analysis**
- **Deterministic Analysis Method**
- **Probabilistic Analysis Method**
- **Comparison of Deterministic and Probabilistic Methods**
- **Conclusions**

Problem Chosen for Analysis

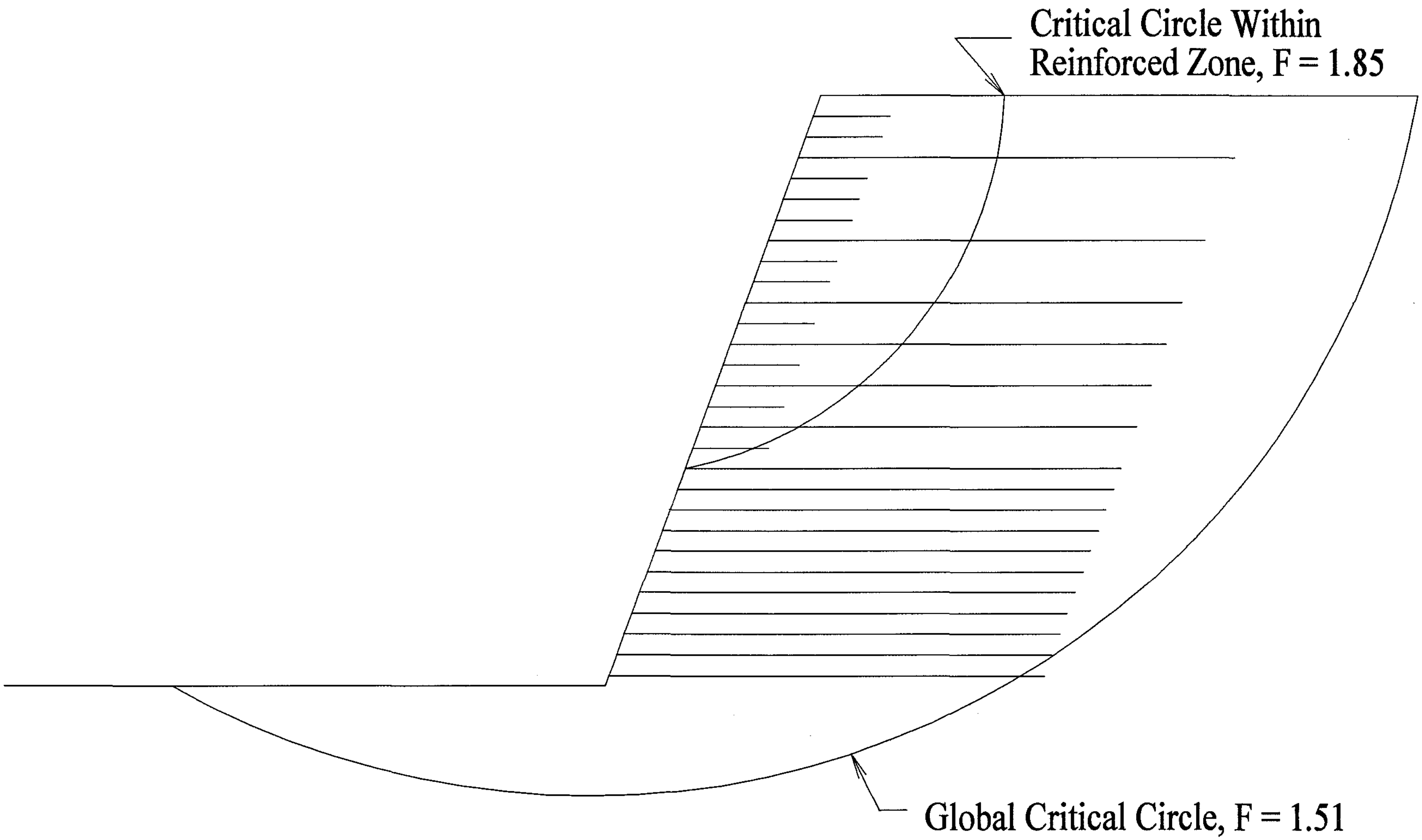
- **Standard Design Procedures Used as Published by Tensar®**
- **Allowable Reinforcement Forces Specified by Manufacturer**
- **Nominal Factor of Safety Based on Soil Shear Strength was 1.3**


Secondary Geogrids:
SS2
Allowable Load = 5.6 kN/m
Vertical Spacing = 0.41 m
Length = 1.5 m
0.364
70°
1
38'
1.63 m
1.22 m
4 @ 0.81 m
11 @ 0.41 m
Soil Properties
γ = 18.8 kN/m3
ϕ = 32°
Primary Geogrids: SR2
Allowable Load = 32 kN/m
Length = 8.5 m

Deterministic Analysis Methods

- **Traditional Limit Equilibrium Methods Used**
- **Reinforcement Forces Incorporated as Know Forces**
- **Assume Circular Arc Shear Surfaces**
- **Search Performed to Find Shear Surface With Minimum Factor of Safety Based on Shear Strength**

$$F = \frac{\tan \phi}{\tau}$$


Critical Circle Within
Reinforced Zone, F = 1.85
Global Critical Circle, F = 1.51

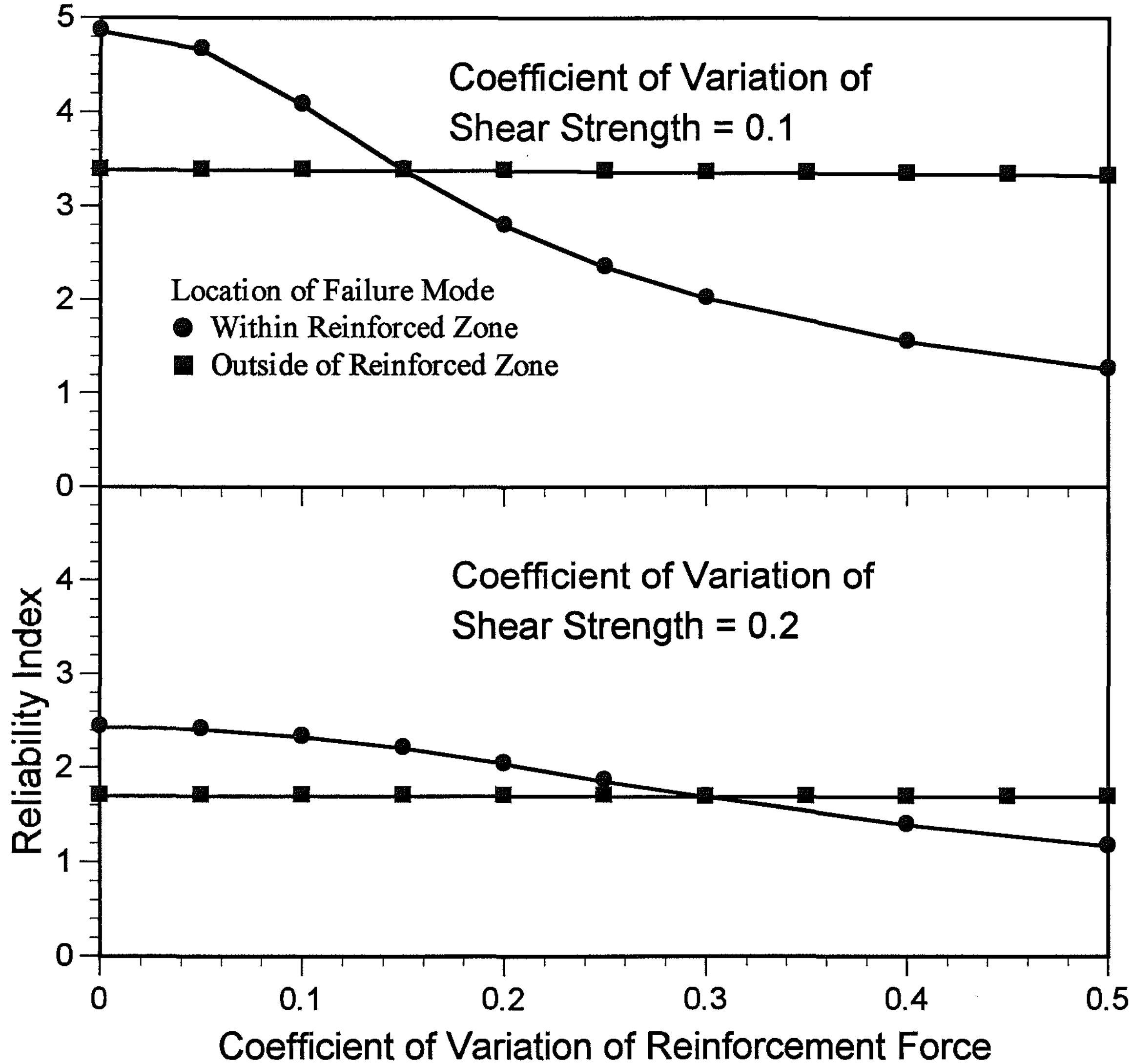
Probabilistic Analysis Method

- **Limit State Function, *g*, Defined as**

$$g = F -$$

- **Normally Distributed Random Variables**
  Soil Shear Strength
  Reinforcement Force

- **First-Order Reliability Method Used**


5
4
3
2
1
0
Coefficient of Variation of
Shear Strength = 0.1
Location of Failure Mode
Within Reinforced Zone
Outside of Reinforced Zone
4
3
2
1
0
Coefficient of Variation of
Shear Strength = 0.2
Reliability Index
0
0.1
0.2
0.3
0.4
0.5
Coefficient of Variation of Reinforcement Force

Conclusion

- **Potential Failure Modes Exist Both Within and Outside of The Reinforced Zone of the Slope**
- **The Factor of Safety Cannot Identify the Most Probable Failure Mode**
- **The Probabilistic Analysis Clearly Shows the Most Probable Mode is a Function of Uncertainties in Both Shear Strength and Reinforcement Force**
- **Probabilistic Analysis Can Compare Different Failure Modes on a Rational Basis**