Earth Reinforcement Practice, Ochiai, Hayashi & Otani (eds) © 1992 Balkema, Rotterdam. ISBN 90 5410 093 1

Seismic analysis of reinforced slopes – A review

D.M.White
Landau Associates, Inc., Edmonds, Wash. & University of Washington, Seattle, Wash., USA

R.D.Holtz
University of Washington, Seattle, Wash., USA

ABSTRACT: The paper is a review of current methods for the analysis of geosynthetic reinforced earth slopes which are subjected to earthquake shaking. After a brief look at unreinforced slope stability, the available analytical methods and design procedures for static design of geosynthetic reinforced slopes are compared and contrasted. The state-of-the-art and common geotechnical practice in seismic slope stability, primarily pseudostatic in nature, is reviewed, and the two published papers, one analytical and one experimental, on the seismic response of geosynthetic reinforced slopes are summarized. Research is definitely needed to enable geotechnical engineers to design and construct geosynthetic reinforced steep slopes with confidence in seismically active regions.

INTRODUCTION

Over the past decade, construction of steepened slopes using geosynthetic reinforcement has become relatively commonplace. Such construction has had rather widespread acceptance in the industrial and public works sectors, particularly in highway construction. However, use of geosynthetic reinforced slopes in and around residential and commercial construction has been limited, despite the potential for large savings in earthwork and land acquisition costs, increased safety factors, and a more efficient use of land. These potential benefits are particularly great in areas which are seismically active.

Many Western U. S. and other Pacific Rim metropolitan areas experiencing rapid growth in recent years lie in seismically active areas. Often in these areas, topography is also relatively steep, and in order to create level building areas, high steep slopes often result. In many jurisdictions in the U.S. which use the Uniform Building Code (ICBO, 1991) or similar model codes, the lack of seismic design methods with a proven technical basis and wide professional acceptance has the effect of limiting the use of steep slopes reinforced with geosynthetics. Steeper slopes would tend to bring down high land costs (both of which result in increasingly unaffordable housing). In our experience, for example, many west coast U.S. land developers are unable to achieve even relatively restrictive low densities due to a combination of adverse topography and the inability to construct slopes at grades steeper than the current practical limit in soils of 2 horizontal: 1 vertical. Research supporting the use of steeper reinforced slopes is not sufficient to overcome building code restrictions. The hesitancy of code review agencies to adopt new technology is somewhat understandable; the consequences of a slope failure are potentially more serious in residential and commercial construction, because of the potential loss of human life and the (North American) public's desire for a risk free environment.

1 *Unreinforced Slope Stability*

The analysis of the stability of earth slopes has traditionally been one of the primary concerns of the geotechnical engineer. As society developed the engineered infrastructure (water supply, sewage, surface transportation, etc.) that allowed it to move out of river valleys, it has increasingly constructed on higher ground.

This process created a need to understand the behavior of the slopes forming the higher ground so that construction could proceed with confidence. Many methods of analyzing slope stability have been developed through the years, including those of Fellenius (1927), Bishop (1955), Morgenstern and Price (1965), and Janbu (1973), among others. To some extent, all these procedures are currently used in geotechnical practice, although a preference is seen toward the various methods of slices. Each method assumes that a condition of limiting equilibrium exists at the moment of incipient failure and compares the available strength of the soil to the stresses imposed by the geometry of the slope; modifications to strength account for the presence of water in the soil mass.

No matter which limiting equilibrium analysis method is chosen, given a set of geometric and soil parameters, the results of the analysis are almost invariably expressed as a factor of safety (FOS), which is typically an expression of a ratio of the average shear strength on a critical sliding surface to the average shear stress required for equilibrium. The FOS is usually global in nature, in that one such ratio is used to represent the relative stability of the entire slope under consideration.

Sensitivity analyses regarding the input parameters to limiting equilibrium analyses are easily carried out and are often presented in the form of design or stability charts. It is intuitively understood that a soil with greater cohesion or higher friction angle can be expected to stand higher or at a steeper slope angle than a soil with lower strength values. It is also well known that, in general, flatter slopes have a greater reliability (lower risk of failure) than steeper slopes. Thus the FOS is generally higher for stronger soils and flatter slopes. However, when it becomes necessary to evaluate risk of failure, the acceptability of a particular FOS is based on comparison to an arbitrary standard considering the loading conditions and consequences of failure, among other items. Because FOS does not scale linearly, it is difficult at best to evaluate whether the potential for failure of a slope is greater when, for example, its static FOS is 1.5 or its seismic FOS is 1.1.

Finite element models of slopes have also been constructed in two and three dimensions, although the computational and input data requirements necessary to gain significant advantage over limit equilibrium analyses is typically beyond the budget of all but the most critical structures. With such analyses, if the necessary input data is available, both local and global factors of safety may be calculated, and by using a knowledge of the stress-strain behavior of the soil and iterative procedures, the effects of progressive failure can be evaluated. However, the significance of such factors of safety are still subject to the questions raised in the preceding paragraph.

Recently, probabilistic-based analyses of slope stability have become more commonplace, at least in terms of research activity. However, their acceptance is not widespread in the practicing engineering community. Few, if any, code review agencies are able to state what constitutes an acceptable risk of failure in geotechnical engineering where material properties are not at all certain. One could argue (with some merit) that slope stability applications are, therefore, suitable for probabilistic-based analyses, but we have more experience and therefore more confidence in the evaluation of a factor of safety than a probability of failure.

2 *Geosynthetic-reinforced Slope Stability*

Due to increasing population density and the related increasing cost of land in metropolitan areas, poor sites which might have been left as unbuildable previously are being developed more frequently today. Roads and foundations have been constructed on softer soils and retaining structures have found greater use in the quest for additional level building ground. During the past twenty years, geotechnical engineers have learned to regularly consider the use of reinforcing materials to overcome the limitations of the soils at such sites. Geosynthetic reinforcement has resulted in even lower cost geotechnical construction.

Design procedures for geosynthetic reinforced earth slopes were presented initially by Murray (1982) with improvements by Leshchinsky and Reinschmidt (1985), Schneider and Holtz (1986), Schmertmann, et al. (1987), Verduin and Holtz (1989), Jewell (1990, 1991), among others. All of these procedures use a limiting equilibrium approach solving for force equilibrium, moment equilibrium or both. Multiple failure modes, including internal and external, are typically checked. Internal stability involves pullout and tensile failure of the reinforcing geosynthetic. A failure surface is assumed, and typical shapes are a circle, log-spiral or a two part wedge. Other surfaces are also possible using the more complex, computer-based analytical methods. Christopher and Leshchinsky (1991) presented a good summary of reinforced slope design methods; they indicated that most methods yield conservative results.

Briefly, the design of geosynthetic reinforced slopes typically considers the following input parameters:

- Geometry of the proposed construction
- Strength of the fill soils
- Arrangement and strength of the geosynthetic material
- Strength of natural soils
- Location of water table (if present)
- Surcharges (if any)
- Seismic loads (if in a seismically active area)

Where possible, steps are taken to specify certain materials or modify the properties of soils (through drainage, compaction, etc.) so as to have a positive influence on the design. However, such specification and modification is not likely to influence the entire mass of the soil under consideration and many of the uncertainties of conventional geotechnical design and construction still prevail.

After establishment of these input parameters to the most reliable extent possible, analyses are conducted to review those internal and external failure mechanisms of concern to the designer. These typically include:

- Tensile failure of the geosynthetic material
- Pullout failure along the geosynthetic/soil interface
- Unreinforced slope stability involving force and/or moment equilibrium of the soil mass considering a hypothetical failure surface of some assumed geometry
- Reinforced slope stability considering tensile forces applied to the soil mass under consideration by geosynthetic materials intersecting the failure surface
- Rigid body stability (sliding, overturning moment and bearing capacity) of the reinforced slope due to loads applied by the surrounding fill and natural soil environment
- Slope stability considering failure surfaces not intersecting the geosynthetic reinforcement

Reinforced slope design charts have been prepared by, e.g., Schmertmann, et al. (1987) and Leshchinsky and Boedeker (1989) to aid in the more complex portions of the above described analyses. Some procedures have been programmed for use with personal computers, e.g., Duncan, et al. (1985), Humphrey and Holtz (1986), and Sharma (1990). Other calculations are straightforward and involve only the comparison of horizontal forces, for example.

In general, the design of geosynthetic reinforced slopes involves consideration of several factors of safety. One FOS is applied to the tensile capacity of the geotextile: however, this FOS is a combination of factors that consider long term durability (biological and chemical), ultraviolet light, degradation, creep, potential construction damage, and overall uncertainty. Another FOS is applied to pullout, but the recommended value is varied according to soil type, and most often arbitrary but conservative minimum embedment lengths beyond the calculated critical failure surface are used. Factors of safety typical of unreinforced soil slopes are applied to other possible failure mechanisms such as sliding, deep seated rotational failures, etc. The significance of each of these factors of safety is a matter of some importance. Typically, it is assumed that an acceptable value for the factor of safety in each circumstance is a value which is used for a similar failure mechanism independently. This assumption often results in extreme conservatism. For instance, it is known that the tensile strength and modulus of many geotextiles increase when confined in soils due to a not fully understood interlocking of the fibres and soil particles (McGown, et al., 1982). It is no wonder, then, that failures of geosynthetic slopes due to tensile failure of the material are unknown.

The limited probabilistic evaluation of geosynthetic reinforced slopes conducted by Cheng and Christopher (1991) indicate that designs with similar factors of safety result in higher reliability (lower probability of failure) in the typical reinforced slope as compared with an unreinforced slope.

Several other questions arise when considering typical design methods for geosynthetic reinforced slopes. Berg et al. (1989) pointed out that it may be inappropriate to use failure planes typical of unreinforced slopes for limit equilibrium type analyses of a reinforced slope. In addition, when it comes to maintaining internal stability, many design/analysis procedures lead to the unreasonable conclusion that the lengths of reinforcing material are greater for shallow slopes than steep slopes because of the greater depth of the critical sliding surface and the minimum pullout length required beyond it. Jewell (1990, 1991) has developed revised design charts which effectively take care of this anomaly. Although each of the above matters is of concern to the designer, it is important to note that no failures of geosynthetic reinforced steep slopes have occurred. This leads to the logical conclusion that even greater economies with an acceptable level of safety are possible using geosynthetic reinforcement.

3 *Seismic Slope Stability*

As understanding of the influence of seismic motions on the behavior of foundations and slopes increased in the 1960's and 70's, procedures were developed to permit a reasonable analysis of the seismic loading of slopes. Although dynamic analyses using finite element models are used for the design of major earth fill dams, the majority of current geotechnical practice uses an extension of the limit equilibrium analysis to the seismic case. A pseudostatic analysis method similar to the Mononobe-Okabe method used for gravity retaining walls is applied to slopes (Matasovic, 1991; Yourman and Diaz, 1991). In using the method, a representative ground motion is selected for the site, and the seismic load is simulated by the imposition of a horizontal force on the soil which is equal to its mass times a seismic coefficient, k_s, which is an acceleration derived from the representative ground motion. Makdisi and Seed (1978) developed a procedure for evaluating this critical parameter that is still commonly used. The selection of soil strength parameters appropriate to the loading conditions is also critical, and the importance of considering pore pressures and behavior under cyclic loading is well known. Seed (1979) discussed the use and limitations of this method in his Rankine lecture, while also noting its widespread use.

The pseudostatic analysis is often combined with a liquefaction analysis which is separate from the stability analysis. Additionally, an estimate of permanent deformations using the sliding block method proposed by Newmark (1965) or the more complicated Seed-Lee-Idriss method discussed by Seed (1979) may be added to the above analyses to form a complete package for an important earth embankment slope. Procedures presented by Ishihara (1985) which are modifications to the pseudostatic method show promise, but at least in North America, they have not gained widespread use.

Seismic design procedures for geosynthetically-reinforced slopes are very limited. A few authors, e.g., Christopher, et al. (1990), acknowledge seismic conditions and then quickly state that a pseudostatic Monomobe-Okabe type analysis is acceptable. A factor of safety greater than 1.1 should be used in this case. This suggestion apparently has little to no research basis to justify its use. Bonaparte, et al. (1986) examined a few cases analytically using a pseudostatic rigid-body model, and they recommend using an admittedly conservative input acceleration of 85% of peak horizontal ground acceleration and a factor of safety of 1.1 to 1.15.

The only other research on the seismic stability of geosynthetic reinforced embankments was performed by Koga, et al. (1988) who carried out some 14 large scale model tests on a shaking table. The models were reinforced with steel rods, geogrids, and nonwoven geotextiles, and their behavior was compared with identical unreinforced slopes subjected to the same degree of shaking. They found that stiffer reinforcement performed well, provided it was anchored to the backslope. Surficial slope failures were also a problem.

An evaluation of several geogrid reinforced walls and slopes in the San Francisco, California, Bay area after the 1989 Loma Prieta earthquake (M.7.1) indicated that most structures generally performed quite satisfactorily (J. Collin, personal communication, 1992).

4 *Need for Additional Research*

In order to construct steeper earth slopes with confidence in seismically active areas, research addressing the critical aspects of their seismic design is needed. This is especially true for steep geosynthetic reinforced earth slopes, and a number of questions concerning their behavior during seismic events have been discussed above. Although no known failures of geosynthetic-reinforced slopes during earthquakes have occurred, building code officials are hesitant to approve the technology, and this despite design practices which are recognized as being quite conservative. It was the first author's experience while serving on a southern California geotechnical advisory board that this is due in a large part to the lack of published research regarding the seismic stability of steep geosynthetic reinforced slopes.

In presenting their preliminary recommendations for a design method, Bonaparte, et al. (1986) stated that additional experimental and analytic research is necessary to understand the seismic behavior of geosynthetic reinforced steep slopes. Koga et al. (1988) also indicated the need for additional research. Finally, researchers, consultants, and contractors attending a recent workshop on Soil Improvement and Foundation Remediation with Emphasis on Seismic Hazards, sponsored by the U.S. National Science Foundation, concluded that the seismic design of geosynthetic reinforced slopes and walls is among "high priority" research needs (Kramer and Holtz, 1992).

ACKNOWLEDGEMENTS

The first author acknowledges with thanks the generous financial support of the Valle Scholarship Program. Kristin Mingus prepared the manuscript.

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