THREE DIMENSIONAL SLOPE STABILITY

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Abstract: The 1988 slope failure at the Kettleman Hills Waste Repository has forced government agencies to consider and sometimes require three-dimensional (3-D) slope stability analyses. However, 3-D slope stability analysis is in its infancy, and thus 3-D stability methods are not readily available to government agencies or practicing engineers. More importantly, the accuracy of existing 3-D stability methods has not been verified using field case histories. The main objectives of this ongoing research is to determine: (1) the accuracy and applicability of existing three-dimensional slope stability methods using field case histories, (2) the parameters or assumptions that significantly affect the three-dimensional factor of safety, (3) the field situations, if any, where a three-dimensional factor of safety is less than an appropriate two-dimensional factor of safety, (4) the three-dimensional effects on two-dimensional back-calculated shear strength parameters, and (5) to develop a 3-D slope stability method that incorporates beneficial features of existing 3-D methods, predicts field slide surface and slide mass geometries, provides excellent agreement with field case histories, and is suitable for practice.

Key words: Two dimensional, three dimensional, limit equilibrium, slope stability, landslides.

1. Introduction

At present, most slope stability analyses are performed using a two-dimensional (2-D) limit equilibrium method. These methods calculate a factor of safety against failure for a slope assuming plane-strain conditions. Therefore, it is implicitly assumed that the slip surface is infinitely wide, and thus the three-dimensional (3-D) effects are negligible. Clearly, slopes are not infinitely wide and 3-D effects influence the stability of all slopes. There are a number of situations where three-dimensional effects are significant and definitely should be considered. These situations include: (1) slopes that are curved in plan (Baligh and Azzouz, 1975) or form ridges or corners (Giger and Krizek, 1975 and 1976; Hungr et al., 1989), (2) slopes that have asymmetry caused by inclusions such as soil-geosynthetic liner systems, drainage blankets,

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faults, or rock joints, (3) slopes that have shear strength or piezometric conditions that vary in the transverse direction, (4) dams in narrow or curved valleys, and (5) slopes that are surcharged by loads or cut by excavations (Giger and Krizek, 1976).

Previously, it was anticipated that consideration of three-dimensional effects will increase the factor of safety, and thus conventional two-dimensional methods were assumed to be conservative. Therefore, three-dimensional stability analyses were rarely performed in practice. However, Seed et al. (1990) reported that three-dimensional effects can result in a factor of safety that is lower than the two-dimensional factor of safety. This conclusion was based on their investigation of the slope failure in Landfill Unit B-19 at the Kettleman Hills Hazardous Waste Repository. The waste repository consists of a large oval-shaped bowl that was excavated in the ground to a depth of approximately 100 feet. After the failure, Byrne et al. (1992) revealed that sliding occurred along the secondary clay/geomembrane interface in the landfill liner system. They concluded that the slopes surrounding the center of the "bowl" produced three-dimensional driving forces that could not be incorporated into a two-dimensional analysis. Seed et al. (1990) computed a 3-D factor of safety that is less than the 2-D safety factor. As a result, Seed et al. (1990) stated that "possible three-dimensional effects may have a significant impact on the overall stability during placement of waste fill." It should be noted that this conclusion is based on a 3-D factor of safety calculated using a "multiple-block analysis" that was developed by Seed et al. (1990). In this analysis, a number of simplifying assumptions are made and only force equilibrium is satisfied.

Based on the research by Seed et al. (1990), government agencies and private firms have been forced to consider three-dimensional effects in slope stability analyses of natural and man-made slopes. However, three-dimensional slope stability analysis is in its infancy. As a result, existing 3-D slope stability analyses are not readily available to practicing engineers nor have these methods been verified using field case histories. In addition, recommendations for 3-D design factors of safety and the applicability of the methods to field conditions have not been developed. As a result, there is considerable confusion over the importance of 3-D slope stability effects and how to conduct 3-D slope stability analyses.

2. Objectives of Ongoing Research

The main objectives of this ongoing research program are to (1) verify the performance of existing 3-D slope stability methods using field case histories, (2) develop guidelines/recommendations for selecting and using the most appropriate 3-D stability method for problems typically encountered in practice, (3) determine field situations, if any, where a 3-D factor of safety is less than 2-D factors of safety, (4) develop a back-analysis procedure that accounts for 3-D effects, and thus yields back-calculated shear strength parameters that are in better agreement with field strengths, (5) investigate the effects of seismic forces on the 3-D factor of safety, (6) investigate the 3-D geometry of the slide surface and slide mass using field case histories to verify assumptions concerning slide surface and/or slide mass geometry, and (7) develop a 3-D slope stability method that incorporates the important features of existing methods, predicts field geometry of the slide surface and slide mass, and provides excellent agreement with field factors of safety. This research will provide a much needed advance to the State-of-the-Art and the State-of-the-Practice of 3-D slope stability analyses.

3. Preliminary Results

Limitations of existing 3-D slope stability methods and the urgency to conduct 3-D stability analyses in practice have resulted in the initial phase of this research focusing on techniques for incorporating 3-D effects in a 2-D stability analysis. The main uncertainty in a 2-D analysis is the selection of the critical 2-D cross section. Preliminary results indicate that the critical 2-D cross section will be parallel to the direction of the resultant of the 3-D driving and resisting forces. Therefore, a simplified method was sought to determine the orientation of the resultant 3-D force, which would facilitate selection of the critical 2-D cross section and reduce the need for a 3-D analysis.

Initial research results indicate that the resultant 3-D force can be evaluated using a vector analysis similar to that presented by Hendron et al. (1980) for the analysis of slopes in jointed rock masses. In this analysis, the geometry of the failure mass and the orientation of individual planes are taken into account to determine the direction of the resultant 3-D force acting on the failure mass. Two-dimensional cross-sections parallel to the resultant 3-D force can be analyzed to determine the critical 2-D cross section and factor of safety. The vector analysis is better suited for practice than a comprehensive three-dimensional analysis, and should facilitate the consideration of three-dimensional effects in two-dimensional stability analyses. Additional research is being conducted to determine the applicability of a vector analysis to a wide range of natural and man-made slope geometries.

Evaluation of field case histories using existing three-dimensional slope stability analyses has shown that the 3-D slope stability software CLARA 2.31, developed by Hungr et al. (1989), provides the best agreement with field factors of safety. However, improvements could be made in the stability program by incorporating a non-linear Mohr-Coulomb failure envelope, a back-calculation routine, and using a stability method that satisfies all conditions of equilibrium (e.g., Spencer's method, 1967). The evaluation of case histories also revealed that the three-dimensional factor of safety is dependent on the direction of sliding of the sliding mass. This is especially true in the case of waste containment facilities because of the complex geometries that are involved in sliding. Sliding along a three-dimensional failure surface will occur in the direction of the resultant three-dimensional force acting on the failure mass, and the critical two-dimensional cross-section will be parallel to the resultant three-dimensional force direction. This fact was used to evaluate the potential for the 3-D factor of safety to be less than the 2-D factor of safety. As a result, another initial phase of the research focused on clarifying whether a 3-D factor of safety can be less than representative 2-D values. Re-evaluation of the Kettleman Hills landfill failure using Janbu's simplified stability method indicates that the three-dimensional factor of safety is greater than the two-dimensional factor of safety when the appropriate direction of sliding is used to determine the two-dimensional cross-section. Therefore, if a 2-D cross section is selected parallel to the direction of sliding, the 2-D factor of safety will be less than the 3-D value, and will be representative of the field stability.

4. Conclusions

The following conclusions are based on the comparison of existing three-dimensional slope stability methods and the following field case histories: (1) Kettleman Hills Waste Repository, (2) Oceanside Manor landslide, (3) San Luis Dam slide, and (4) Ririe Dam.

1. The microcomputer program CLARA 2.31 provides an accurate estimate of the three-dimensional factor of safety for the types of slope stability case histories (circular slip surfaces) considered to date. The program utilizes an extension of Janbu's simplified or Bishop's modified stability method to three-dimensions. However, improvements could be made in the program by incorporating a non-linear Mohr-Coulomb failure envelope, a back-calculation routine, and by satisfying all conditions of equilibrium.

2. The three-dimensional factor of safety is dependent on the direction of sliding of the failure mass.

3. The three-dimensional factor of safety increases as the concavity of the slope curvature increases.

4. The three-dimensional factor of safety is greater than the two-dimensional factor of safety for the field case histories considered to date.

5. A vector analysis can be used to identify the 3-D direction of sliding, and thus the orientation of the critical two-dimensional cross section. This allows three-dimensional effects to be incorporated into 2-D stability analyses. The proposed vector analysis is better suited for practice than a comprehensive 3-D analysis.

6. The most important aspect of any slope stability analysis is the determination of the mobilized shear strength parameters.

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