GEOSYNTHETIC REINFORCEMENT ABOVE SINKHOLES TO PROTECT LANDFILL LINERS

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ABSTRACT

The two-dimensional finite difference code FLAC is used to model the interaction of a landfill bottom liner supported by geosynthetic-reinforced soil above a sinkhole. The soil is assumed to be a homogeneous, elastic-plastic material. FLAC grids were prepared to represent a range of sinkhole throat (i.e., rock opening) sizes and liner elevations above the sinkhole throat. The sinkhole throat was simulated by removing a portion of the FLAC grid beneath the reinforcing geosynthetic. The model behaves as expected in several respects. The stress and strain in the reinforcing geosynthetic increases with increasing sinkhole-throat width. Also, the strain in the liner decreases as the vertical distance between the liner and sinkhole throat increases. An increase in the number of geosynthetic layers reduces the strain in the liner, especially when the liner is immediately above the geosynthetic reinforcement.

Although the application of FLAC to this problem appears promising, several limitations are apparent when evaluating the results. One primary issue is that the tensile stresses developed in the reinforcing geosynthetic are significantly lower than expected based on the computed tensile strains. It is suggested that either the FLAC encounters a computation difficulty when computing the stress-strain relationship for the reinforcing geosynthetic or the parameters selected for the analysis do not effectively represent the actual behavior of the soil-geosynthetic interface.

Even though the model presented in this paper requires further refinement and improvement, FLAC modeling offers a promising approach for the evaluation of geosynthetic reinforcement above sinkholes where strains within the overlying materials is of concern, such as landfill liners in this case. The flexibility of FLAC is illustrated in this paper in application to static evaluation in homogenous soil. It is anticipated that FLAC models similar to the one presented in this paper can be applied to more complex conditions such as various sinkhole configurations (e.g., circular), layered soils, seepage, and/or seismic motions.

INTRODUCTION

Landfills constructed over karst terrain are exposed to risk associated with sinkholes. Development or enlargement of a sinkhole beneath a landfill can potentially allow the bottom liner to be unsupported, and thus render it susceptible to damage due to high tensile strain. To mitigate this risk, geosynthetics can be used during landfill construction to reinforce the soils above areas of sinkhole activity. Geosynthetic reinforcement is most effective at sites with relatively thin soil overburden, where: 1) the sinkhole throat can be identified and measured during subgrade preparations, and 2) the risk of sinkhole instability is greater as compared to sites with relatively thick soil overburden due to the effects of soil arching (Yang and Drumm, 1999). In this paper, the geosynthetic reinforcement over a sinkhole throat is modeled using the two-dimensional finite difference code FLAC (Itasca Consulting Group, 2000). The model assumes that the sinkhole throat can be identified and measured during landfill subgrade preparation, and that the geosynthetic reinforcement can be constructed over the sinkhole throat.

LITERATURE REVIEW

Early in the evolution of geosynthetics, Giroud (1982) developed tensioned-membrane theory for application to geotextile reinforcement of a geomembrane over a void. Bonaparte and Berg (1987) combined tensioned membrane theory with soil arching (Terzaghi, 1943; Handy, 1985) to estimate the geosynthetic strength requirements for a roadway over karst terrain. Giroud, et al. (1988) prepared simple charts for the combination of tensioned membrane theory and soil arching for design of geosynthetic-reinforced soil. Berg and Collin (1993) presented a variation to Giroud, et al. (1988) by including the contribution of the geomembrane to the stability of the landfill liner. Several published case histories (Paulson and Parker, 1993; Stelmack, et al., 1995; Alexiew, 1997) illustrate the application of the approach originally developed by Giroud and advanced by others to the design of landfills over sinkholes. One assumption common to all of the aforementioned papers is that soil arching develops fully. The applicability of this assumption depends on the amount of soil movement necessary to fully develop soil arching, and its compatibility with the mobilization of tensile resistance in the geosynthetic reinforcement. The model presented in this paper is perhaps more realistic as it achieves compatibility between soil arching and tensile resistance.

Gabr, et al. (1992) modeled a landfill liner over a sinkhole using finite elements and confirmed that the use of geosynthetic reinforcement can reduce the stresses and strains in the liner. The finite element model by Gabr, et al. (1992) assumes that the geosynthetic reinforcement is located immediately below and in contact with the liner. The model presented in this paper has the geosynthetic reinforcement immediately above the rock surface (and sinkhole opening), with the vertical distance between the liner and geosynthetic reinforcement varied to analyze the stress-strain conditions in the liner.

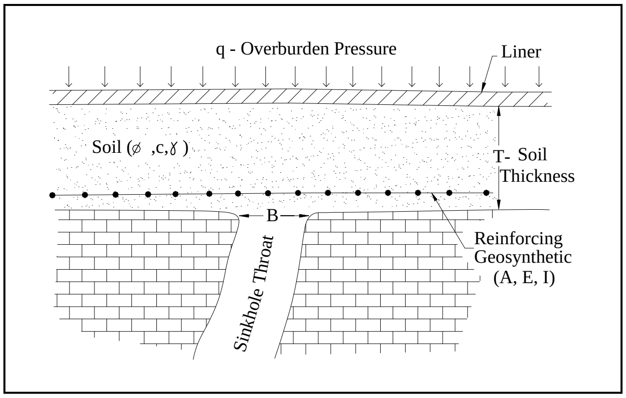

Figure 1: Conceptual Illustration of Sinkhole Model

SINKHOLE MODEL

Geometry

A conceptual illustration of the sinkhole model is shown in Figure 1, where *T* is the fill thickness between the top of the bedrock surface and the bottom liner, and *B* is the width of the sinkhole throat. The sinkhole throat is conservatively assumed to be a trench of infinite length, and therefore, plain-strain conditions are applied. The vertical pressure, *q*, is due to the soil below the critical height. The vertical pressure due to material above the critical height, as determined by numerical analysis, is transferred directly to the rock surface on each side of the sinkhole throat as the result of arching.

Soil properties

The soil behavior is defined by the Mohr-Coulomb plasticity model. The model parameters are defined as follows: ϕ is the friction angle, *c* is the cohesion intercept, γ is unit weight, *K* is the bulk modulus, and *G* is the shear modulus. The friction angle and cohesion intercept define the boundary between elastic and plastic soil behavior. The bulk and shear moduli determine the deformation of the soil at a stress level below yield. For stress levels at or above yield, the soil model behaves perfectly plastic. For simplicity, the soil is modeled as homogeneous with the parameters presented in Table 1.

Geosynthetic properties

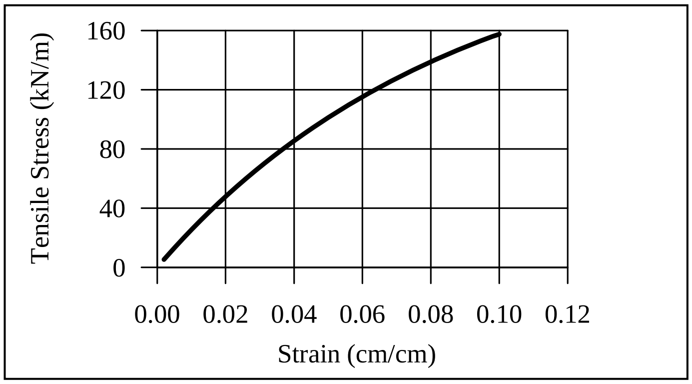

Figure 2: Stress-Strain Curve for Reinforcing Geosynthetic

The reinforcing geosynthetic is modeled as a beam-type structural element with nominal bending and compressive stiffness. The model parameters are defined as follows: *A* is cross-sectional area per unit width, *E* is elastic modulus, and *I* is the moment of inertia. As shown in Figure 2, the tensile stress-strain relationship of geosynthetics are non-linear. To account for this aspect, the FLAC analysis was iterated until compatibility was achieved between the stress and strain in the reinforcing geosynthetic.

Interface properties

A interface element was included in the FLAC grids to represent the contact of the reinforcing geosynthetic with the surrounding soil. The interface allows slip and/or separation along the contact surface. The model parameters, as listed in Table 1, are defined as follows: *kn* is the normal stiffness, *ks* is the shear stiffness, and β is the interface friction angle.

Table 1: Summary of Sinkhole Model Parameters

Soil Parameters		Reinforcing Geosynthetic Parameters		Interface Parameters	
ϕ	25 deg.	A	.007 m^2/m (0.0233 ft^2/ft) per layer	kn	157,000 kPa/m (1000 ksf/ft)
c	0	E	see Figure 2	ks	314 kPa/m (2 ksf/ft)
γ	19.5 kN/m^3 (121 pcf)	I	0	β	17 deg.
K	6700 kPa (140 ksf)	-	-	-	-
G	3070 kPa (64.2 ksf)	-	-	-	-

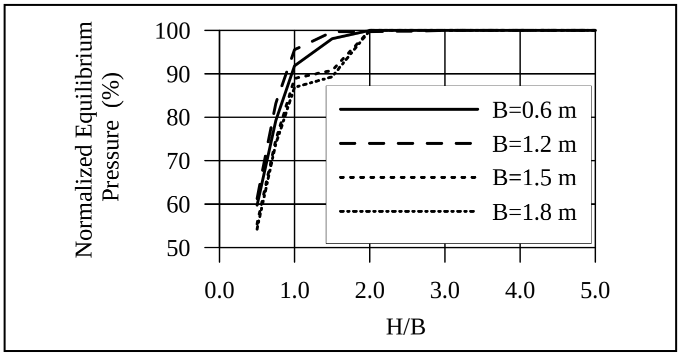

Figure 3: Determination of the Critical Height

FLAC ANALYSIS AND RESULTS

Determination of the critical height

The initial step in the FLAC analysis was to determine the *critical height*. The critical height is the distance above the rock surface beyond which the surcharge load is transferred directly to the rock surface on each side of the sinkhole throat as a result of arching. To determine the critical height, FLAC grids with different heights were subjected to gravitational forces. To avoid the effects of the model boundary constraints, the width of the FLAC grids were at least five times the sinkhole throat width. This is consistent with numerical models prepared by others (DeBoarst and Vermeer, 1984). Once each of these grids achieved equilibrium, an opening or trapdoor was then created in the bottom. As the soil moved downward into the trapdoor, the principal stresses rotated and the vertical stresses immediately above the trapdoor dramatically reduced.

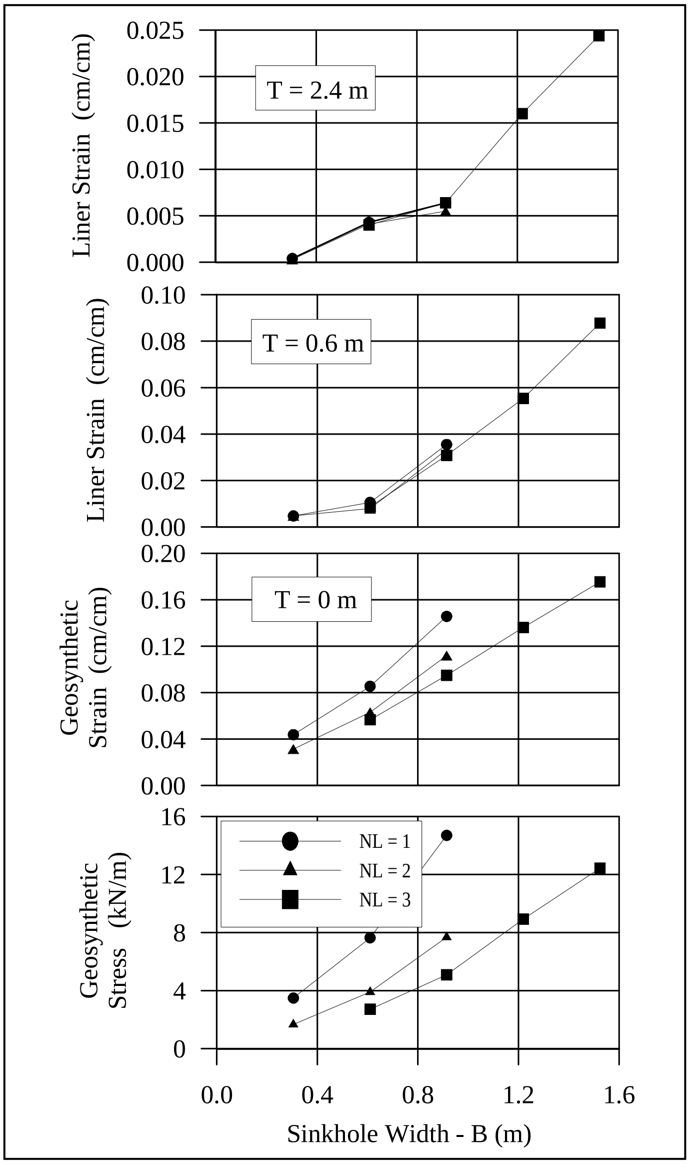

Figure 4: Summary of FLAC results

The minimum upward pressure (labeled hereafter as the *equilibrium pressure*) necessary to resist the downward movement of the soil through the trapdoor was determined using an iterative process. By incrementally increasing the grid height, the equilibrium pressure approached a constant value. The soil height where the equilibrium pressure became constant with increasing grid height is the critical height. Figure 3 is a plot of the normalized equilibrium pressure versus the ratio of soil height-to-trapdoor width (i.e., *H/B*), and indicates that the critical height occurs at a soil height-to-trapdoor width ratio of approximately 2. In Figure 3, the equilibrium pressure at different values of *H/B* is normalized to the equilibrium pressure at the critical height (i.e., *H/B*=2).

Evaluation of geosynthetic-reinforced sinkhole

Using the model parameters presented in Table 1, FLAC grids were prepared to represent a range of conditions. The sinkhole width was varied between 0.3 m and 1.5 m. As many as 3 layers (NL) of geosynthetic reinforcement were included in the FLAC grids. The distance from the rock surface to the liner was varied from zero (i.e., the liner is directly above the reinforcing geosynthetic) to 2.4 m. Reinforcement provided by the liner was conservatively ignored in this analysis; however, it would be quite easy to include such resistance.

For each FLAC grid, a sinkhole throat was simulated by removing a portion of the FLAC grid beneath the geosynthetic. Then FLAC solved for the forces within the grid, including the tensile stress developed within the geosynthetic reinforcement, in accordance with static equilibrium. Once an acceptable level of static equilibrium was achieved, the stress and strain conditions in the geosynthetic reinforcement and the strain condition in the liner were extracted from the FLAC output.

The results of the FLAC sinkhole model are graphically summarized in Figure 4. In general, the FLAC sinkhole modeled behave as expected in several respects. First, the stress and strain in the reinforcing geosynthetic increased with increasing sinkhole throat width (*B*). Second, the strain in the liner decreased as its distance (*T*) to the rock surface increased. And third, additional layers of reinforcing geosynthetic reduced the strain in the liner, especially when the liner is immediately above the geosynthetic.

For ease in evaluating the results, the liner was also modeled as a beam-type element; however, the properties were selected so that the behavior of the FLAC grids was not influenced by the presence of the liner.

Evaluation of the FLAC results also indicates that there are several limitations to the model presented in this paper. A primary limitation is evident by the observation that the tensile stresses developed in the reinforcing geosynthetic are significantly lower than expected based on the computed tensile strains. As a consequence, the use of multiple reinforcing layers has significantly less influence than expected. The reason(s) for this limitation was not apparent from the analysis performed for this paper. However, the authors believe that either FLAC encounters a computation difficulty when computing the stress-strain relationship in the geosynthetic reinforcement or the parameters selected for the analysis do not effectively represent the actual behavior of the soil-reinforcing geosynthetic interface. Further evaluation is necessary to identify to cause of this limitation and to improve the FLAC models so that the stress-strain behavior of the geosynthetic reinforcement is effectively represented.

CONCLUSIONS

FLAC modeling offers a promising approach for the evaluation of geosynthetic reinforcement of soil above sinkholes where strains within the overlying materials is of concern, such as landfill liners in this case. FLAC solves for static equilibrium, which inherently achieves compatibility between (1) development of soil arching, and (2) mobilization of tensile resistance in the reinforcing geosynthetic. The flexibility of this approach is illustrated by its application to a range of sinkhole sizes, layers of reinforcing geosynthetic, and liner elevations with respect to the sinkhole throat. In this paper, the soil is assumed to be a homogeneous, elastic-plastic material. It is anticipated that FLAC models similar to the one presented in this paper can be applied to more complex conditions such as various sinkhole configurations (e.g., circular), layered soils, seepage, and/or seismic motions. The analysis results include stresses and strains in the reinforcing geosynthetic and strains in the liner that may be compared to survivability criteria established during design. During design, the computed liner strains can be compared to laboratory determined stress-strain criteria established for the liner to determine if the resultant strain is within tolerable limits (i.e., typically within a strain of 5% to 10%).

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Janet Carwile for preparation of the final manuscript and Kelvin Engram for preparation of the illustrations.

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