

Slope Stability Modeling of New Orleans Hurricane Protection Levees with Geotextile Reinforcement

Jaideep Chatterjee

Department of Civil and Environmental Engineering
Jackson State University, Jackson, MS, USA (jaideep.chatterjee@jsums.edu)

Farshad Amini

Department of Civil and Environmental Engineering
Jackson State University, Jackson, MS, USA (famini@jsums.edu)

ABSTRACT Due to significant loss of lives and properties in the New Orleans area after Hurricane Katrina, the U.S. Army Corps of Engineers is considering the enlargement of hurricane protection levees to increase the future level of protection against hurricanes. Often, reinforcing the levees with geotextile becomes necessary when adequate factor of safety against slope stability failure cannot be obtained with unreinforced levee. In this paper, the numerical modeling of slope stability of reinforced levees is presented. The enlargement of the New Orleans Airport East-West Runway levee with geotextile reinforcement is chosen for this study.

INTRODUCTION

After Hurricane Katrina made landfall on August 29, 2005 in the New Orleans, Louisiana area and its vicinity, significant damages to the Hurricane Protection System (HPS) in the New Orleans area were observed. Due to the unsatisfactory performance of some of the HPS systems during Hurricane Katrina, the slope stability of these measures subjected to hurricane loading has become an important issue in the geotechnical engineering community. An extensive investigation of the performance of the HPS in the New Orleans area has been undertaken by the New Orleans District of the U.S. Army Corps of Engineers (The Corps). Levees are one of the most common components of the HPS system in the New Orleans area. Currently, enlargement of these levees to increased level of protection against future hurricanes are being considered by the Corps. Both straddle and flood side enlargements are under consideration depending on the suitability and the cost of enlargement and also on the soil conditions. As a result, the stability of the enlarged levees must be assessed when water rises on the flood side of the levee during hurricane. If the levee fails to meet the required factor of safety against slope stability under such condition, some other alternatives to achieve the desired factor of safety must be considered. The use of geotextile reinforcement is one of such viable options. However, proper numerical modeling of levees and the use of proper analysis techniques are of utmost importance to perform a meaningful slope stability analysis, particularly when degrees of soil variability and

presence of geotextile reinforcement become integral parts of the analysis.

Prior to Hurricane Katrina, the Corps had mostly relied upon the Method of Planes (MOP) slope stability analysis to design the hurricane protection levees. MOP was originally developed by the Department of Army, Lower Mississippi Valley Division, in Vicksburg, Mississippi in the 1950's (Stability With Uplift, 2002). MOP is a simplified procedure which satisfies only force equilibrium. MOP became the choice of the Corps because of its simplicity. In most cases, MOP results can be spot checked by hand calculations and it permits quick re-analysis with minor changes in soil properties. As expected, MOP results are generally very conservative (Chatterjee et al. 2009) compared to other rigorous limit equilibrium methods of slope stability analysis satisfying both moment and force equilibriums (eg. Spencer, 1967; Morgenstern & Price, 1965). However, due to the inherent complexity in the numerical modeling of the levees with geotextile reinforcement, more sophisticated approaches towards stability analysis and the use of rigorous analysis techniques has become necessary. The Corps have recently revised their design guidelines for general slope stability analysis of unreinforced levees, which now involves the use of both MOP and Spencer's (1967) method. In addition, optimization (Greco, 1996; Malkawi et al., 2001) of the critical failure surface has become a requirement of the current design procedure. More details on the latest guidelines on design of levees can be found in Hurricane and Strom

Damage Risk Reduction System Design Guideline (HSDRRSDG, 2007).

In this paper, slope stability modeling and analysis of reinforced hurricane protection levee is presented. Proposed enlargement of the New Orleans International Airport East-West Runway Levee is chosen for this study. Rigorous slope stability analyses using both Spencer’s (1967) method and MOP are used in the current design framework to address the stability of proposed reinforced levee enlargement. The degree of the improvement of the stability with the addition of geotextile reinforcement is assessed.

PROBLEM DESCRIPTION

In this study, the proposed enlargement of the New Orleans Airport East-West Runway Levee (North Leg) was selected. The original levee was designed and constructed by the New Orleans Aviation Board in about 1988 to accommodate an extension of the Louis Armstrong International Airport East-West Runway. The existing levee had an average crown elevation of 3.7 m and 1V:3H side slopes. The hydraulic design grade requirement for the year 2057 determined the project grade at El. 4.7 m in 2057. The levee was to have a 3.0 m wide crown, 1V:3H protected side slope and 1V:4H flood side slope. A wave berm was required for the year 2057. The wave berm consisted of a 1V:6H slope from El. 3.7 m to El. 2.6 m. Available surveys indicated that significant settlement had occurred after previous construction at the site. Considering the observed settlement and the minimum sight clearance requirement for the runway, it was estimated that 0.76 m of overbuild to El. 5.5 m would be required to achieve the 2057 design grade. The design hurricane elevation for 2057 was at El. 3.9 m. The problem is shown in Fig 1. The soil stratification numbers used in this analysis are also shown in Fig 1.

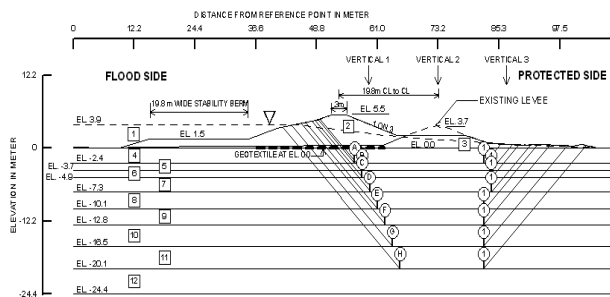


Fig. 1 Problem description and soil stratification

Initial analyses of the viability of a protected side enlargement to a grade (El. 5.5 m) with water at design hurricane level (El. 3.9 m) had indicated that sufficient embedment of the protected side end of the geotextile could not be achieved without degrading the existing levee. Thus, flood side enlargement was selected as a possible alternative. It was found that efficient design could be obtained when the centerline levee was shifted 19.8 m to the north towards the flood side.

SOIL DESIGN PARAMETERS

The foundation soils generally consisted of fill materials underlain, in turn, by organic clays and peat and then high plasticity clays (CH). The design shear strengths and wet densities chosen for the analyses were based on post Katrina laboratory tests performed on samples from undisturbed soil borings and correlations with cone penetration test data. They are shown in Table 1. For each soil stratum, the cohesions at the center of the layer and at the bottom of the layer are shown in Table 1. Samples beneath the crest of the existing levee and beneath the flood side and protected side toes were collected and linear variation of shear strengths and wet densities between the crest and the toes were considered.

TABLE 1 Design shear strengths and wet densities for the soil stratification used in the analysis

SOIL NO.	DESCRIPTION	FRICTION ANGLE IN DEGREES	UNIT WEIGHT KN/m ³	VERTICAL 1		VERTICAL 2		VERTICAL 3	
				COHESION IN KPa	COHESION IN KPa	COHESION IN KPa	COHESION IN KPa	COHESION IN KPa	COHESION IN KPa
1	WATER	0	98	0	0	98	0	0	0
2	FILL	0	181	19.1	19.1	18.1	19.1	18.1	19.1
3	CLAY	0	185	239	239	18.5	35.9	35.9	18.5
4	CLAY	0	185	239	239	114	33.5	33.5	18.5
5	CLAY	0	119	12.0	12.0	114	33.5	33.5	11.9
6	CLAY	0	119	12.0	12.0	182	21.5	21.5	11.9
7	CLAY	0	182	12.0	12.0	14.1	21.5	21.5	18.2
8	CLAY	0	182	139	158	182	19.1	19.1	182
9	CLAY	0	182	177	198	182	19.1	19.1	182
10	CLAY	0	182	222	247	182	21.9	249	182
11	CLAY	0	182	272	298	182	27.5	30.4	182
12	CLAY	0	182	328	359	182	33.7	39.9	182

MODELING METHODOLOGY

The design procedure outlined in this work requires first performing stability analyses using Spencer’s (1967) method of the unreinforced levee. After the critical failure surface and the minimum factor of safety are obtained, if the factor of safety of the unreinforced levee is inadequate, then an additional reinforcement resistance (T) can be added to the analysis to obtain the required factor of safety. It is important to note that the location of geotextile reinforcement can have an effect on the levee stability factor of safety. However, MOP does not consider the location of the geotextile. For this

reason, the location of the geotextile is first finalized using Spencer's (1967) method. The allowable bond stress between the soil and the geotextile is estimated using an empirical equation developed from full scale pullout tests performed by the New Orleans District of the Corps. The following equation is utilized:

$$\tau = 265 + (\gamma h) \tan 19^\circ \quad (1)$$

where, τ is the allowable bond stress, γ is the effective unit weight and h is the depth below ground surface. Limiting the allowable bond stress to some value is also permitted. The tensile force provided by the geotextile is selected as the minimum of either the tensile capacity of the geotextile at 5 % strain or the pullout resistance determined from Eq. (1). The tensile capacity of the geotextile is iteratively changed until the desired factor of safety for the prescribed hurricane loading is obtained. The geotextile location and strength found from the Spencer (1967) analysis is then used in the MOP procedure to check the required factor of safety. The pullout resistance of the geotextile can be calculated using Eq. (1) as done for the Spencer's (1967) method. The tensile force provided by the geotextile is taken as the minimum of the tensile strength calculated using Spencer's (1967) method and the pullout resistance calculated in MOP analysis.

The determination of factor of safety (FS) against slope stability failure in the presence of geotextile reinforcement is outlined briefly as follows:

Unreinforced Levee

Method of Planes:

MOP is a simplified procedure in which only the horizontal force equilibrium of two wedges and a block, namely, the active wedge, a central or neutral block and a passive wedge, are considered. The driving forces and the resisting forces in each block are obtained from the equilibrium of these blocks by constructing the force diagrams. The buoyant force of water for the submerged soil used in the shear strength calculation is incorporated in the formulation as an uplift force acting normal to the sliding plane. However, for purely cohesive soil, the analysis is based on total stresses and undrained strength, and thus the uplift force is not used. A factor of safety against sliding is computed. Assuming the slope movement occurs from left to

right, the various forces acting on each block are shown in Figure 2

The notations used in the MOP analysis have the following meanings:

- W = weight of water and soil in wedge
- U = total uplift force acting normal to sliding plane
- H = height of the block
- N = normal reaction on sliding plane

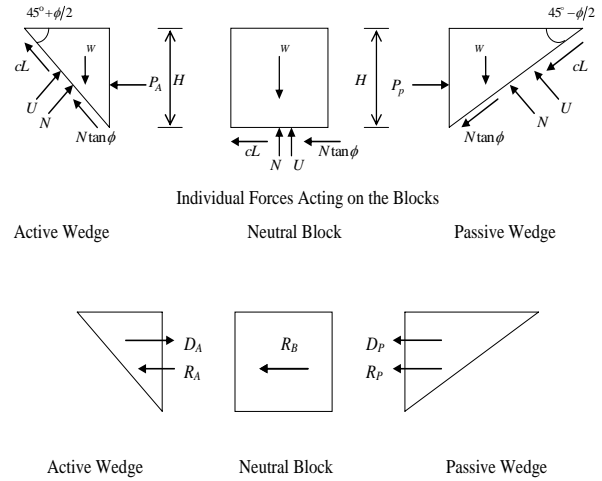


Fig 2. Wedges and forces for MOP analysis

c = cohesion of soil along the length of the sliding plane L

ϕ = angle of internal friction of soil

P_A & P_B are active and passive forces respectively

$$FS = \sum \text{ResistingForce} / \text{DrivingForce} \quad (2)$$

Where

$$\text{Resisting force} = R_A + R_B + R_P \quad (3)$$

$$\text{Driving force} = D_A - D_P \quad (4)$$

Limit /moment equilibrium stability:

$$FS = M_R / M_D = (\tau L) R / W X_S \quad (5)$$

Where:

M_R = soil resistance moment

M_D = driving moment

τ = shear strength of levee and foundation soil

L = arc length of failure plane

W = weight of soil mass

X_S = moment arm of soil mass

R = radius of failure arc

Reinforced Levee

Method of Planes:

The tensile strength of the geotextile (@ 5 % strain) is added to the summation of resisting forces to obtain a factor of safety.

$$FS = \frac{\sum(\text{ResistingForce}+T)}{\text{DrivingForce}} \quad (6)$$

Where, T is the tensile force of the reinforcement (KN/m) and the resisting and driving forces are computed using Eq. (3) and Eq. (4). Here it is assumed that the application of the reinforcement force is independent, which does not affect the soil strength. It is also assumed that the soil strength and the geotextile tensile strength are mobilized simultaneously.

Limit /moment equilibrium stability:

$$FS = \frac{(M_R + \sum T_i y_i)}{M_D} \quad (7)$$

Where T is the allowable geotextile tensile strength and y is the moment arm for geotextile. Here it can be noted that for large deformation situation, this moment arm could become equal to R .

RESULTS

The initial slope stability analysis was performed using Slope/W (2007) computer program and using Spencer's (1967) method. Both circular and non-circular failure surfaces were considered with the optimization routine available in Slope/W (2007). Various search methods were used to determine the critical failure surface, required geotextile strength and the required beginning and ending points of the geotextile. A linear interpolation routine in Slope/W (2007) was utilized to model the spatial variation of soil unit weights and shear strengths along the depth and between the vertices shown in Fig 1. The contribution of the geotextile to the factor of safety was modeled in Slope/W (2007) using the available routine. The allowable bond stress between the soil and the geotextile was specified using Eq. (1). In addition, the allowable bond stress was limited to the soil shear strength. According to HSDRRSDG (2007), the required factor of safety for the design hurricane case (El. 3.9) is 1.5. It was found that the required geotextile strength was 328.4 KN/m in the Spencer (1967) analysis to achieve this factor of safety.

Next, using the location and strength of the geotextile found from the Spencer (1967) analysis, stability analysis was conducted for the proposed levee enlargement using MOP. According to HSDRRSDG (2007), the required factor of safety

for the design hurricane loading (water at El. 3.9 m) is 1.3. In MOP, first, the critical active location was established at the bottom of each soil stratum by assuming a critical passive wedge location. Then, with this critical active wedge location, failure surfaces were checked at the bottom of each soil stratum with various locations of passive wedges. The tensile force provided by the geotextile was taken as the minimum of the tensile strength obtained using Spencer (1967) analysis and the pullout resistance obtained using Eq. (1). This tensile force is then manually added to the resisting force computation using Eq. (6). The critical failure surfaces along the bottom of each soil stratum are shown in Fig 1 and the results are tabulated in Table 2. For the MOP analyses, the contribution of the geotextile is only shown for the cases where the unreinforced levee failed to meet the minimum factor of safety requirement of 1.3. The minimum factor of safety in the MOP analysis was 1.54 and the corresponding failure surface was at El. -12.8 m which was in close agreement with the Spencer (1967) analysis. At this elevation, the factor of safety for the unreinforced levee was 1.25, which indicates a 23 % increase in the factor of safety by adding the effect of geotextile reinforcement. Also, the minimum factor of safety of 1.50 using Spencer (1967) analysis was found to be in close agreement with the MOP factor of safety of 1.54. The MOP results are summarized in Table 2.

TABLE 2 Results of MOP analysis

Failure Surface	Summation of Forces KN/m		Factor of Safety (Unreinforced Levee)	Factor of Safety (With Geotextile)
	Resisting	Driving		
A-1	1065.10	445.00	2.39	Not Needed
B-1	966.20	538.90	1.79	Not Needed
C-1	1010.60	629.84	1.60	Not Needed
D-1	1097.30	801.40	1.37	Not Needed
E-1	1224.20	971.05	1.26	1.60
F-1	1410.20	1131.60	1.25	1.54
G-1	1791.10	1336.50	1.34	Not Needed
H-1	2179.20	1486.00	1.47	Not Needed

DISCUSSIONS

A comprehensive slope stability modeling and analysis procedure of the New Orleans Hurricane Protection Levees with geotextile reinforcement was presented in this paper. The proposed procedure utilizes rigorous limit equilibrium based Spencer's (1967) method for the determination of the strength and location of the geotextile. Then, simplified MOP analysis is used to check the adequate factor of safety against failure of the levee embankment during possible hurricane loading. The factors of safety using both procedures appear to be in good agreement. The proposed procedure is capable of handling the complexity of the interaction between the soil and the geotextile. At

the same time, the flexibility and the simplicity of the MOP is retained which permits quick re-analysis of the problem with slight changes in soil properties.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Engineering Research and Development Center (ERDC) of U.S. Army Corps of Engineers, Vicksburg, Mississippi for making available the computer program “Stability with Uplift (2002)” based on Method of Planes for slope stability analysis. Thanks are due to the Department of Civil and Environmental Engineering at the Jackson State University for making available the computer program Slope/W (2007) to successfully perform the present study. The support provided by the Department of Homeland Security (DHS) through Oak Ridge National Laboratory (ORNL) is also gratefully acknowledged. The conclusions in this paper are solely those of the authors and do not necessarily reflect the opinions or policies of DHS or other agencies. Endorsement by DHS is not implied and should not be assumed.

REFERENCES

- Chatterjee, J., Amini, F., and Cooley L.A. (2009) A comparative slope stability analysis of New Orleans I-wall subjected to hurricane loading., *Int. J. Geotech. Eng.*, 3 (3), 459-467.
- Greco, V.R. (1996) Efficient Monte Carlo Technique for locating critical slip surface., *Jl. Geotech. Eng., ASCE*, 122 (7), 517-525.
- HSDRRSDG (2007) Hurricane and Storm Damage Risk Reduction System Design Guidelines., Interim Guide, U.S. Army Corps of Engineers, New Orleans District)
- Malkawi, A.I.H., Hassan, W.F., and Sarma, S.K. (2001) Global search method for locating general slip surface using Monte Carlo Technique., *Jl. Geotech. Geoenv. Eng.* 127(8), 688-698.
- Morgenstern, N.R., and Price, V.E. (1965) The analysis of the stability of general slip surfaces., *Geotechnique*, 15, 79-93.
- Slope/W (2007) Computer Program for slope stability analysis., *Geo Slope International Ltd.*, Calgary, Alberta, Canada.
- Spencer, E. (1967) A method of analysis of embankments assuming parallel interslice forces., *Geotechnique*, 17(1), 11-26.
- Stability With Uplift (2002) Computer Program on Slope Stability Analysis., Version 2.2., *Engineering Research and Development Center*, Vicksburg, Mississippi.