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Simulation of Quasi-3D Slope Stability in Multi Layered Hill Slopes

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Abstract The hydro-geological properties of a natural hill slope are almost always heterogeneous and anisotropic. The complexities in slope stability analysis resulting from this variation in properties can be handled by dividing the geological formation into many layers, each layer representing a specific type of material. A slip surface may form in such formations at the boundary between two different material types. This is especially true when a material with higher hydraulic conductivity lies over a lower hydraulic conductivity material. In this kind of situation the percolating water flows downhill mostly at the boundary between the layers, eventually creating a slip surface. A method of simulation of quasi-3D factor of safety (FOS) of a multi layered geological formation with slip surfaces along the boundary between layers is proposed. In this method, a finite difference 3D groundwater flow and transport model was used to simulate groundwater fluctuation. Using spreadsheet, the resulting hydraulic heads of each soil column were converted into pore water pressure. The geological formation was divided into a number of sections, each of unit thickness. Using appropriate soil properties, geology of the area, and the resulting pore water pressure, the FOS of each section was calculated by using a 2D slope stability analysis method. The resulting FOS fluctuations for each section were simulated by a 3D graphical simulation package. Thus, a quasi-3D slope stability simulation was achieved by combining 2D analysis methods with a 3D groundwater simulation method. This method can be used to simulate changes in hill slope FOS due to dynamic changes in input and or extraction of water, and in hill slopes with multiple slip surfaces.

Keywords: slope stability, landslide, factor of safety, simulation

Introduction

Countries with steep mountains and heavy rainfalls lose substantial life and property annually due to landslide disasters. In order to properly plan and execute disaster management programs, a better understanding of the mechanisms of landslides and the degree of stability of slopes in the hilly areas is a prerequisite.

There are various two-dimensional (2D) techniques of evaluating slope stability. Most of these techniques were simplified to make them useful for hand calculation. With increasing use of computers, new three dimensional (3D) techniques of slope stability analysis are emerging. However, due to high data requirements and complexity, these methods are not yet popular among practicing geotechnical engineers. A relatively simple approach towards evaluating the overall stability of a slope soil is proposed. This method consists of combining a finite difference 3D analysis technique of groundwater flow with 2D slope stability analysis techniques. The combination results in the ability to estimate and view the fluctuations in factor of safety (FOS) of each section of soil in a slope due to fluctuation in water table, with relative ease. The groundwater flow model is applicable for heterogeneous geological conditions and anisotropic flow conditions. Hence slope stability in complex formations can be simulated as well by combination of the two methods. This paper discusses the details of this method. The ability to visually simulate the fluctuation in FOS of a geological formation is very important when dealing with non-technical decision makers and when interacting with general public for awareness purpose. It is hoped that the application of this method will result in a better understanding of site specific slope stability and landslide mechanism.

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Methodology

A hypothetical geological formation that resembles a cut hill slope with different geological strata and bedding slopes was considered. A representative table of fluctuation in water table resulting from rainfall was created prior to model development. The values in the rainfall-water table fluctuation table were typical of the values observed at a nearby landslide investigation project. A set of hypothetical "observed values" of hydraulic conductivity, based on various types of geological materials, was prepared. The geological formation was divided into discrete numbers of rows, columns and layers. The groundwater regime of the area was "calibrated" to the preset "observed values" of hydraulic conductivity and water table, using MODFLOW (2000), which is a popular finite difference 3D groundwater flow and transport model. MODFLOW is often used to obtain hydraulic head in various geological formations resulting from steady state or transient input scenarios. The "calibrated" model was used to obtain the resulting hydraulic head in each cell for steady state and transient conditions. The different transient conditions were created by changing input values like aerial recharge and pumping rates.

The bottom surface of each layer was considered as a potential slip surface. So each section of the geological formation consisted of a number of sub-cross sections, as shown in Figure 1a. For example, the soil materials in the sub-cross section with the bottom of layer 1 as the potential slip surface consisted of materials from the ground surface to the bottom of layer 1; the soil materials in the sub-cross section with the bottom of layer 2 as the potential slip surface consisted of materials from the ground surface to the bottom of layer 2, and so on. The resulting hydraulic head for each cell of the model was extracted and imported into a spreadsheet program. While writing the resulting hydraulic heads in the spreadsheet the cells were separated so that each set of cells represents a distinct sub-cross section.

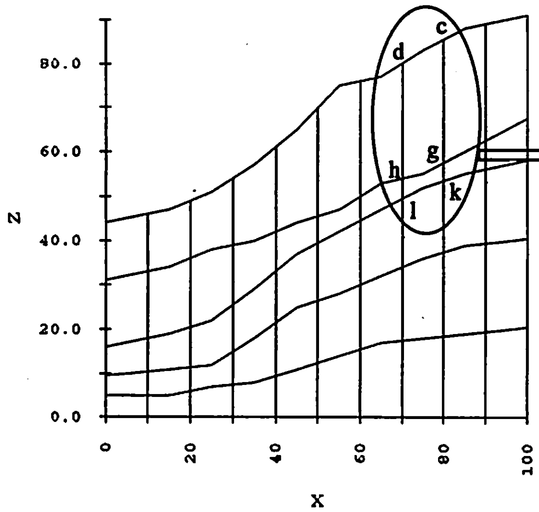

Fig. 1a Cross section through a row

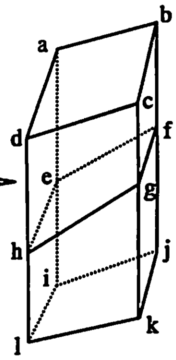

Fig. 1b Soil columns of layers 1 and 2

Figure 1a consists of five sub-sections, one for each layer. The top of all sub-sections is the ground surface and the bottom of each sub-section is the bottom of that layer. In Figure 1b, the surfaces abcd, efgh, and ijkl represent the ground surface, bottom of layer 1 and bottom of layer 2 of one soil column. When calculating the FOS of the soil section containing the soil column abde-efgh lying on layer 1, the surface efgh is considered the slip surface. Similarly, when calculating the FOS of the soil section containing the soil column abcd-ijkl lying on layer 2, the surface ijkl is considered the slip surface, and so on. So the ground surface is the top surface for all the soil columns.

The resulting head value of each cell, which represents the head value of a column of soil of unit thickness, was converted to the pore water pressure (u). For a steady state condition each cell has only one head value. For transient condition each cell has a separate head value for each time step.

Using appropriate representative values of cohesion (c), dry unit weight (γ_s), submerged unit weight (γ_{sw}) and internal angle of friction (ϕ) for the soil, the FOS value of each sub section of the calibrated model were calculated for each scenario, using Janbu's (1957) 2D slope stability analysis technique. Various studies have found that the results from Janbu's method are close to the results of rigorous methods such as Spencer's (1967) method (Fredlund & Krahn 1977, Nash 1987). Generally, a 3D slope stability analysis results in higher, and hence less conservative, FOS value compared to a 2D analysis, due to the boundary effect of the sliding mass. For many cases, the results of a 2D slope stability analysis are considered satisfactory for practical applications.

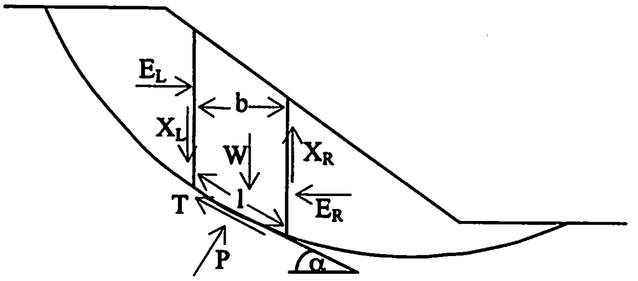

Fig. 2 Forces on a slice

Figure 2 indicates the forces in each soil slice. The width of the slice is *b* and the length of its base along the slip surface is *l*. The W is the total weight of the slice. At the base of the slice the normal stress is σ and shear stress is τ. It is assumed that the Mohr-Coulomb failure condition applies. As per Mohr-Coulomb failure theory, the soil strength $s = c' + (\sigma - u) \tan \phi$. At the time of failure $s = \tau F$, where F is the FOS value.
The normal force $P = \sigma l$ and the shear force $T = \tau\ l$. Hence,

$$T = (1/F)(c'\, l + (P - u\, l) \tan \phi) \tag{1}$$

Balancing the vertical forces, we get, $P \cos \alpha + T \sin \alpha = W - (X_R - X_L)$
But, for the Janbu's Simplified method the interslice force is horizontal, i.e., $X_R = X_L = 0$. So,

$$P = W - (1/F)(c'\, l \sin \alpha - u\, l \tan \phi \sin \alpha) / m_\alpha, \tag{2}$$

where $m_\alpha = \cos \alpha\ (1 + \tan \alpha \tan \phi / F))$
Resolving the forces parallel to base of slice we get,

$$T + (E_R - E_L) \cos \alpha = (W - (X_R - X_L)) \sin \alpha \tag{3}$$

Since $X_R = X_L = 0$, and $T = \tau\ l$,

$$E_R - E_L = W \tan \alpha - (1/F)(c'\, l + (P - u\, l) \tan \phi) \sec \alpha \tag{4}$$

In the absence of surface loading $\Sigma\ (E_R - E_L) = 0$, so
$\Sigma\ (E_R - E_L) = \Sigma W \tan \alpha - (1/F)(c'\, l + (P - u\, l) \tan \phi) \sec \alpha = 0$, and

$$F = [\Sigma(c'\, l + (P - u\, l) \tan \phi) \sec \alpha] / \Sigma W \tan \alpha \tag{5}$$

To obtain the final value of the factor of safely of a section, the F value obtained from equation (5) has to be multiplied by a factor f_0, where f_0 is a function of the ratio of depth of slip surface at the center of the section and the length of the straight line connecting the head and toe of the section.

The final calculated values of FOS of each subsection of the geological formation, for each layer, were exported from the spreadsheet to a 3D simulation package.

The results of the individual 2D analyses can be combined to obtain an 'equivalent' 3D FOS. According to Sherard et al. (1963) 3D FOS (or F_3) can be obtained from the relation

$$F = \frac{\Sigma F_r}{\Sigma F_d} \tag{6}$$

where F_r and F_d represent the total resisting and driving forces for each 2D cross section and the summation is performed for all cross sections. Similarly, Lambe and Whitman (1963) suggested using weighted average of 2D FOS values of each cross section to obtain 3D FOS value; with the cross sectional area as the weighing-factor of each section. Hence, according to Lambe and Whitman,

$$F = \frac{\Sigma F_r A_i}{\Sigma A_i} \tag{7}$$

where F_i and A_i represent the FOS and cross sectional area of the i^{th} cross section. Seed et al. (1990) suggested using the same approach as Lambe and Whitman but the weighing-factor of each section was taken as the weight of each cross section. In this paper, for simplicity, the Sherard et al. method was used to obtain quasi 3D FOS from 2D results.

Results and Discussions

A hypothetical geological formation was considered (Figure 3). For clarity, the formation is shown in wire-frame mode. For simplicity, the area under study was divided into 10 rows, 10 columns, and 5 layers, thus there is a total of 500 cells in the model. Each row represents a section in X-Z direction, hence there are 10 sections. Each section consists of five subsections, since each layer constitutes a subsection. So, there are a total of 50 subsections in X-Z direction. Each layer represents a different soil type consisting of different aquifer properties such as hydraulic conductivity and its heterogeneity and anisotropy in each layer. The thickness and the slope of the bottom of each layer vary from cell to cell. The bottom of the lowest layer (layer number 5) is made flat for no particular reason. To simulate the effect of variations in pumping from wells, several extraction wells were added at various cells. A network of artificial underground horizontal drains was added that draws water from the top three layers.

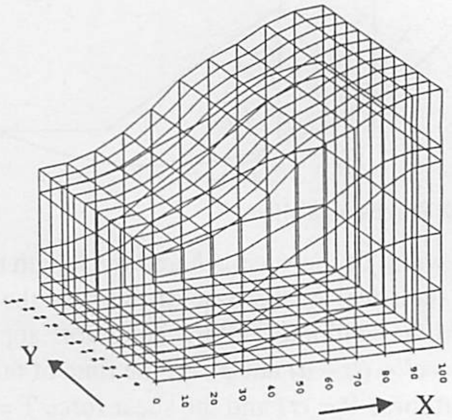

Fig. 3 A 3D representation of hill slope

The artificial underground drains are one of the ways to drain rain water from hill slopes. The hill side is towards the right side of the area and a river runs in the left side of the domain. Considering the river bed at the left side of the model as constant head cells, and the preset "observed values" of hydraulic conductivity at various locations, the geological formation was calibrated for groundwater flow for the steady state condition. Since the focus of this paper is on the use of the calibrated groundwater flow model to obtain the FOS values for each section represented in the model, the details of the calibration process of the groundwater flow model are omitted.

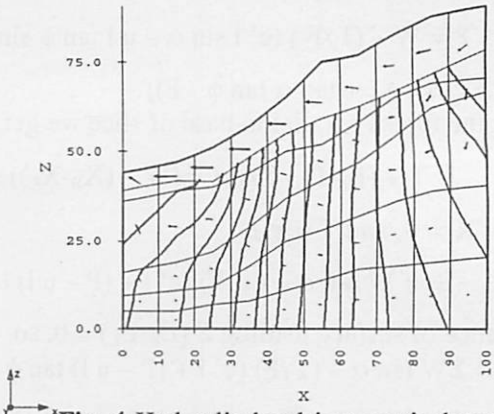

Fig. 4 Hydraulic head in a particular section with flow direction in each cell of the section

For the steady state condition the recharge and the pumping rate were kept constant. Once the model was deemed satisfactorily calibrated for the steady state condition, the model was updated for transient conditions to match the preset "observed values" of fluctuation of water table with the variations in rainfall recharge and pumping of water from different wells. Figure 4 shows an example of a contour of resulting hydraulic head value of a particular section of the area in two dimensions; the arrows in each cell of the section indicate the flow direction in the individual cells, and the length of the arrows indicate the relative rate of flow. Figure 5 is a 3D version of hydraulic head and represents transient hydraulic head for a particular scenario of the hill slope area; the grey area in the hill side represents high head values and the dark color in the valley side represents low head values. As shown in Figure 5, due to the effect of water draining from the horizontal drains, the head at the toe end of layer 3 has lower

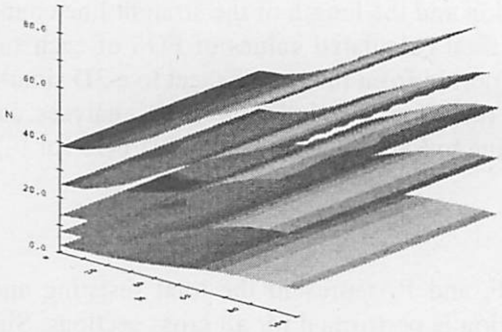

Fig. 5 Example of Hydraulic head distribution in a transient simulation

hydraulic head compared to the surrounding cells. This local drop in hydraulic head reduces the pore water pressure in these cells, and thus increases the FOS value, assuming everything else is constant.

After calibrating the 3D groundwater flow model for a steady state and transient conditions, the resulting hydraulic head values for different scenarios were obtained by changing various input parameters such as the aerial recharge rate, location and slope of artificial horizontal drains and pumping rates from the wells. The resulting head values of all 500 cells for each scenario were converted to pore water pressure.

The FOS of a soil section is basically a function of its cohesion (c), internal angle of friction (ϕ), weight (W), pore water pressure (u), and slope of the slip surface (α). The c, f, and W are soil properties and are generally determined from soil sample analysis at a laboratory. In a natural environment these values are almost always heterogeneous. When calculating the value of W care was taken to break the soil column into the parts that were above and below the water table because the specific weight of soil varies when it is below the water table. The u value depends on the hydraulic head and the density of water. The hydraulic head of each soil column was obtained from the results of MODFLOW; the unit weight of water was taken as 9810 kN/m^3. The α values come from the elevation differences between the lower and upper ends of the base of each column or slice of soil.

The FOS values were calculated for each sub section, assuming the bottom of each layer as the slip surface. The Figures 6a and 6b are examples of the resulting FOS of each subsection in two different sections, in a particular scenario. In Figure 6a, which represents the section in the middle part of the geological formation, the second layer has lowest FOS value. Figure 6b, which is from the edge part of the formation has low FOS value for both the first and the second layer. This kind of variation in FOS value from one subsection to another subsection and from one section to another section results from various factors such as heterogeneity of formation, anisotropy of hydraulic properties of materials, locations of input and output sources such as wells, drains, and rivers, spatial variations in aerial recharge and discharge sources such as precipitation and evapotranspiration and variations in boundary conditions.

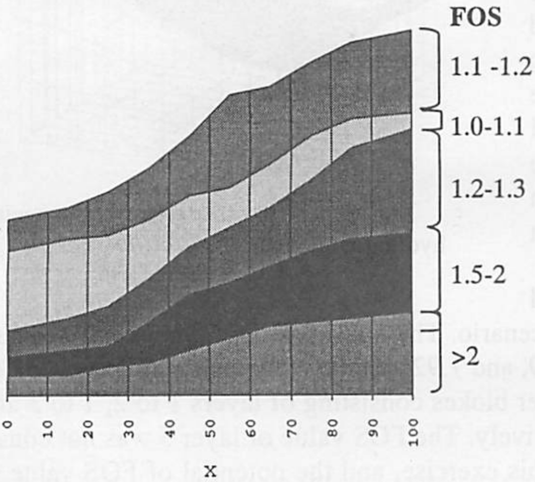

Fig. 6a: FOS value in each subsection in central part of the model domain

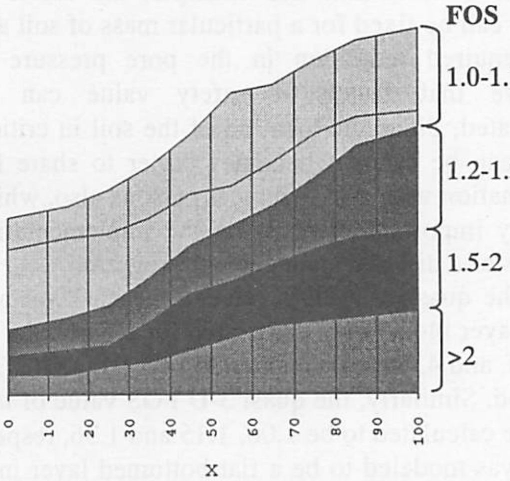

Fig. 6b: FOS value in each subsection in edge part of the model domain

By changing various input parameters the resulting changes in FOS value in each subsection and or layer can be simulated. Similarly, the changes in FOS value in each subsection and or layer with time can be simulated for transient simulation.

The local effects of changes in FOS by interventions can be simulated by plotting specific ranges of FOS values. For example, the effect of artificial drains discharging water, at the upper part of layer 3, and the effect of wells discharging water at the lower part of layer 3 can be seen in Figure 7, which is a plot of area with FOS values less than 1.1. As the excess water is withdrawn, the hydraulic head and the pore water pressure are decreased locally, as indicated by relative absence of shading in layer 3. The reduction in pore water pressure increases FOS value locally. The effects of variations in various other input parameters such as changes in hydraulic conductivity can be simulated in 3D and with respect to time in transient simulations. Freeze (1987) notes that variation in saturated hydraulic conductivity plays an important role in slope stability. One such example of increase in FOS value due to increase in hydraulic conductivity is given in Figure 8, which is a 3D plot of area with FOS value less than 1.1. Due to higher hydraulic conductivity at the central part of the model domain, the water from that part was drained off, which resulted in lower pore water pressure and hence higher FOS value. It should be noted that discrete values of FOS were calculated for each subsection of the model domain, as shown in Figure 6a and 6b. The specific shapes of the area shaded in figures 7 and 8 are due to interpolation of FOS values within the subsection, which is not technically correct but serves to illustrate the concept of the effects of changes in input parameters on FOS values in the vicinity of the changes.

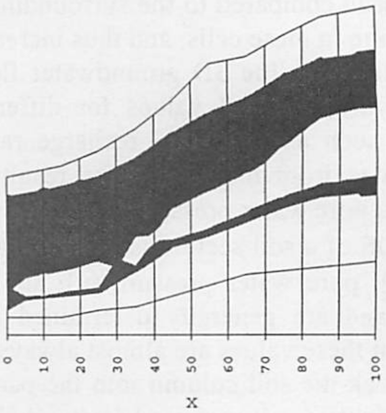

Fig. 7: Local effects of water extraction from drains and wells

The 3D representation of the soil mass in critical state regarding potential of failure, i.e., landslide, can be effectively used to determine the degree of urgency of disaster mitigation action and the mode of action. For example, the factor of safety can be fixed for a particular mass of soil and the required reduction in the pore pressure to achieve that factor of safety value can be calculated. Since the location of the soil in critical state can be seen, it becomes easier to share the information with non-technical persons also, which is very important in planning the implementation phases of a disaster management program.

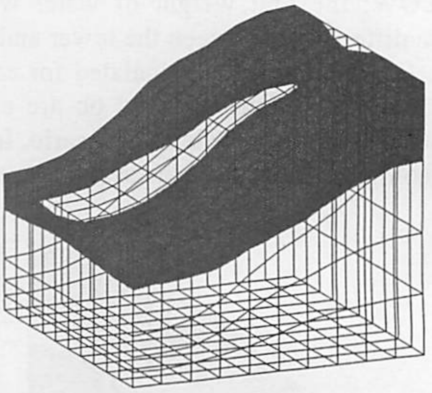

Fig. 8: Local effects of heterogeneity in hydraulic conductivity

The quasi 3-D FOS values of each layer and each layer block were calculated for a particular scenario. The quasi 3-D FOS value of layer numbers 1, 2, 3, and 4, were calculated to be 1.01, 1.04, 1.29, and 1.92, respectively, using Sherard et al. (1963) method. Similarly, the quasi 3-D FOS value of layer blokes consisting of layers 1 to 2, 1 to 3 and 1 to 4 were calculated to be 1.06, 1.15 and 1.36, respectively. The FOS value of layer 5 was not considered as it was modeled to be a flat bottomed layer in this exercise, and the potential of FOS value of this layer going below 1 is practically zero.

This approach combines the versatility of 3D groundwater flow and transportation software with the simplicity of 2D slope stability analysis techniques, thereby providing the facility to visualize the fluctuation in factor of safety value of a hill slope depending on the fluctuations in various input parameters such as groundwater recharge and withdrawal or recharge from wells or drains. Similarly, the effects of heterogeneity and vertical and horizontal anisotropy in geological parameters such as hydraulic conductivity on the factor of safety value can be accounted for. The effects of heterogeneity in various soil properties such as the cohesion and angle of internal friction can also be represented. Hence, the model can be made as complex as the data are available.

Since 2D equilibrium methods are used for slope stability analysis, all the assumptions associated with the 2D slope stability method used are inherent in this method. Furthermore, the inter-column shear stresses between two columns in adjacent sections are not accounted for because, again, the method of slope stability analysis employed is a two dimensional method. Therefore, it is a good practice to apply this method only after testing its applicability at a particular landslide site.

The concept of obtaining 3D FOS by using 2D methods has been proposed by various researchers (Lambe and Whitman, 1969, Seed et al. 1990). The approach often used is to combine the 2D results from several cross sections and obtain a 3D FOS value by weighted average method. Recently, Loehr et al. (2004) proposed a resistant weighted procedure, which is a modified form of the weighted average approach. The method described in this paper can be easily adapted to use weighted average method.

Conclusions

A method to visualize the factor of safety value of a hill slope in three dimensions is proposed. The proposed method uses flexibility and robustness of an existing finite difference three-dimensional software developed for obtaining hydraulic head of a geological formation to calculate FOS values.

Once a geological formation is calibrated for groundwater flow regime, then fluctuations in the FOS value of the formation with time due to fluctuations in various input values can be calculated and visualized by combining the results with a simulation-software. The visualization is important, and can be critical, for information sharing between geotechnical engineers and non-technical persons, and hence can be an effective medium for planning and implementation of disaster mitigation measures.

The boundary between each layer was considered to be a potential slip surface. Hence care should be taken to modify this method when applying to real world situation. However, with correct adjustments, this method can be applied to simulate factor of safety fluctuation in complex geological formations with time dependent variations in various input parameters.

The combination of a 3D groundwater flow model with 2D slope stability analysis methods results in the versatility of the 3D model with the simplicity of a spreadsheet. Hence, this method has the potential to be used by practicing geotechnical engineers.

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