Visakhapatnam Chapter

Proceedings of Indian Geotechnical Conference 2020
December 17-19, 2020, Andhra University, Visakhapatnam

Application of Numerical Modelling to Solve Slope StabilityAnd Landslides

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Abstract. In this paper two problems of slope stability and landslides have been solved by numerical techniques. In geotechnical engineering slope stability analysis is a typical problem. The stability of a slope depends upon mainly three parameters c, φ and weight of the soil and the slope fails mainly due to gravity and other instability factors of which pore water pressures within the soil which generates due to the presence of water within the slope. The strength of the soil decreases with increase in pore water pressure. In natural slope when there is no rainfall or in the dry season the slopes are completely dry or partly saturated. In partly saturated portion within the soil mass a negative pore-water pressure zone will exist where the strength of the soil will be more and consequently the factor of safety of the slope will be more in dry season. As to control the landslide we have to determine the F.S. of the slopes of theroad side embankment under various realistic conditions. To determine the F.S. of the slope we have to know the stresses and displacements at different points within the slope. From displacement pattern the failure zone and failure pattern of the slope can be identified. To get the F.S of the slope at different points or along any probable path, it is essential to know the stresses developed within the slope due to its own load and other destabilizing factors. So to get the stresses within the slope and displacements at the points within the slope, the soil has been characterized as Mohr-Coulomb material and modeled the slope as elasto-plastic material and the problem has been solved by FEM. Here in this paper we have solved two problems (1) 'Stability Analysis of slopes by computing stresses and displacements through FEM' and(2) 'Numerical Modeling/Simulation of rainfall induced Landslides'. Finally to get the realistic result for rainfall induced landslides the composite model has been developed.

Key Words: failure zone, saturation, Mohr Coulomb, F.S., displacement

1 Introduction

Here in this paper two problems have been solved by numerical techniques. In geotechnical engineering, slope stability analysis is a very common and basic problem. Slope forming materials are generally soil which is a very complex material. It is not an isotropic and homogeneous material. It is not even a single material; it is a multiphase material with pores. These pores are sometimes totally saturated, but in most of the times it is partially saturated. The strength characteristics of soil depends on its saturation of pores. The strength of soil depends upon mainly two parameters cohesion (c) and angle of internal friction (φ). The stability of a slope depends upon mainly three parameters c, φ and weight of the soil and the slope fails mainly due to gravity and other instability factors of which pore water pressures within the soil which generates due to the presence of water within the slope is the main deciding factor. These pore water pressures are a detrimental factor for the strength of the soil and the strength of the soil is a factor which actually resists the failure of the slope. When there is no rainfall or in the dry season the slopes are completely dry or partly saturated. In presence of less than saturated condition, a negative pore-water pressure zone exists there and which will enhance the strength of the soil and consequently the factor of safety of the slope will be more in dry season. During rainy season, the slopes along the highway of hilly areas for example NH-39, NH-1A become completely saturated and slope fails consequently the highway blocks which resulted to misery of road users, so keep the road open for 365 days in a year, suitable measures to control these landslides is essential. So, 'Stability Analysis of slopes by computing stresses and displacements through FEM' is the first problem and has been discussed.To control the landslide we have to determine the F.S. (factor of safety), and which is equal to the ratio of strength of the soil to the shear stress developed of the slopes of the road side embankment under various realistic conditions. To determine the F.S. of the slope, failure zone and pattern of failure, the stresses and displacements at different points within the slope are required. From displacement pattern the failure zoneand failure pattern of the slope can beidentified. To get the F.S of the slope at different points or along any probable path, it is essential to know the stresses developed within the slope due to its own load and other destabilizing factors. So to get the stresses and displacements within the slope it has been tried to solve the problem by characterizing soil as Mohr-Coulomb material and modeled the slope as elasto-plastic material. The second problem to be discussed is 'Numerical Modeling/Simulation of rainfall induced Landslides'.

Dawson, Roth and Drescher (1999) obtained factor of safety with the shear strength reduction technique and compared to limit analysis solutions for a homogeneous embankment. To obtain the results, they simulated the embankment with FLAC in plane strain, using small-strain mode. The soil was modeled as a linear elastic-perfectly plastic material with Mohr-Coulomb yield condition and an associated flow rule. The boundary conditions they used was that horizontal displacements are fixed for nodes along the left and right boundaries while both horizontal and vertical displacement are fixed along the bottom boundary.

Griffiths and Lane (1998) solved several examples of finite element slope stability analysis with comparison against other solution methods. Graphical output has obtained to illustrate deformations and mechanisms of failure. They also established that FEM of slope stability analysis is a more powerful alternative to traditional limit equilibrium methods. They used the FE program for two-dimensional plane strain analysis of elastic-perfectly plastic soils with Mohr-Coulomb failure criterion utilizing eight –node quadrilateral elements with four Gauss points. Chen, Lee and Law (2004) had shown that dead –load tests on unsaturated, loosely compacted specimens approximately simulate the field stress path of rainfall induced slope failures. On this basis they concluded that generation of sufficient pore-water pressure is responsible for the initiation of rainfall –induced fill slope failure. They also pointed out that in situ hydrological responses to rainstorms indicate that suction is reduced by infiltration of rain water which provides a triggering factor for initiating slope instability. Tsaparas et. al. (2002) attempted to identify the influence of various hydrological parameters on the stability of an unsaturated soil slope during rainfall. The results of the analysis show that the ratio between the saturated coefficient of permeability with respect to water and the rainfall patterns can significantly influence the seepage pattern within an unsaturated soil slope. Tsaparas et. al. (2003) presented an analysis of the pore-water pressures and seepage conditions within two residual soil samples in Singapore. This analysis was based on field measurements and on numerical modeling using finite element software capable of modeling transient unsaturated flow. Collins and Znidarcic. (2004) studied the potentially unstable soil slopes that are subjected to surface infiltration and explains the various triggering mechanisms that may occur based on individual combinations of the slope geometry, soil strength and infiltration parameters.

2 Stability Analysis of Slopes by Computing Stresses and Displacements Through FEM (Slope Failure Model)

Slope stability analysis has been carried out by modeling the slope forming material (soil) as non-linear elasto-plastic material satisfying Mohr-Coulomb failure criterion and this satisfying process has done by redistributing the stresses which are not satisfying failure criterion through visco-plastic algorithm (Perzyan(1966), Zienkiewicz&Cormeau(1974)). The slope has been modeled by satisfying the soil as elasto-plastic material with Mohr-Coulomb failure criterion and non-associated flow rule. The two dimensional plane strain model has been used to compute the displacements at the initial time. Initiallydisplacements, stresses, strainshave obtained using linear elastic model. These stresses have been used to test the failure function $F_m = \sigma_m \sin\emptyset + \bar{\sigma}\left(\frac{\cos\theta}{\sqrt{3}} - \frac{\sin\theta\sin\emptyset}{3}\right)$,where σ_m , $\bar{\sigma}$ are the stress invariants.The time step for unconditional numerical stability for Mohr-Coulomb failure criterion as given by cormean (1975) has been used. Basically the stresses which are not satisfying failure criterion have been converted to equivalent nodal loads and that will be added to the gravity loads, i.e., the loads which are due to the weight of the soil and the new stiffness equation will be solved to get the displacements and strains, stresses again. These stresses have been be tested by the failure function to remain these within the failure function. Shear stresses were obtained at each Gauss Integration point within the element. Slope Angle =26.57^0, Soil parameters used to calculate stresses,displacements etc., using a program developed at CRRI based on above methodology are shown in Table 1. . F.S. for completely saturated slope =1.2 which is a strength reduction factor for which the numerical instability and drastic increase in displacement occur simultaneously. In a similar way the F.S. for completely dry slope is 1.35. The deformed shapes of slope in dry and saturated condition are showing clearly that in saturated condition the slope has deformed more consequently the F.S. in saturated condition is less than in dry condition. Maximum nodal displacement in dry condition =0.2891816 mm. whereas in saturated condition maximum nodal displacement =0.48397 mm.

Table 1. Properties of Soil

Property	Value
Unit weight (kN/m^3)	20
Shear Parameters	
a. Cohesion (kN/m^2)	1
b. Angle of Internal Friction	20^0
Modulus of Elasticity E (kN/m^2)	1x10^5
Poisson's ratio v	0.3
Matric Suction ψ	0

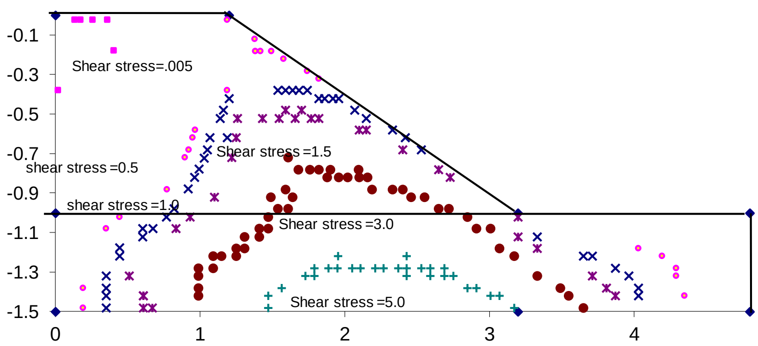

Fig.1. Shear stress contours for completely dry slope

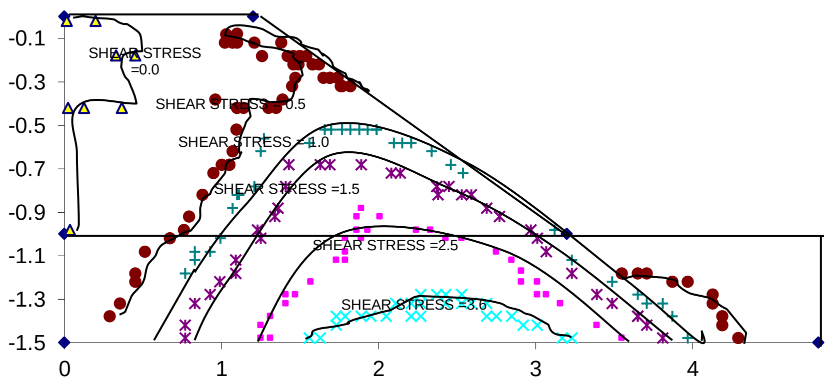

Fig.2. Shear stress contours for completely saturated slope

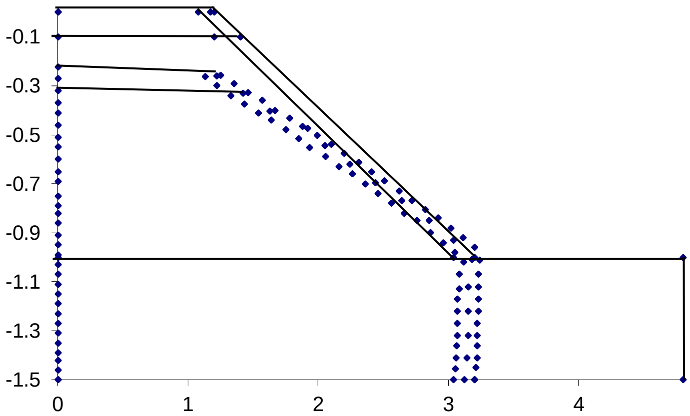

Fig. 3. Displacement behavior of slope in completely dry condition.

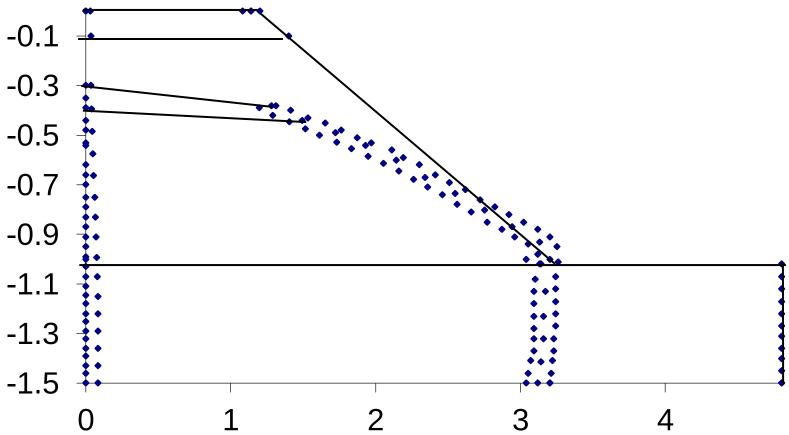

Fig.4. Deformed shape of completely saturated slope

Figures 1 to 4 are showing plotting of these data as shown in the figure and it is showing the failure pattern of the slope with foundation layer in dry and saturated condition. So it is possible by this figure to identify weak zone.

3 Numerical Modeling/Simulation of Rainfall Induced Landslides

The problem of solving rainfall induced landslides has been divided into two parts, (1) computation of suction (negative pore water pressure)/pore pressure and (2) derivation of slope failure model by simulating the soil as elastic plastic material with non-associated flow rule.Mohr Coulomb failure criterion has been tested in this slope failure model by reducing the soil parameters by some factor starting from lower value and advancing to higher values, and during this process of testing, stresses have been modified according to suction/pore pressure developed due to rainfall.

(1) Model to Compute Pore-Water Pressure in the soil due to infiltration and the existing ground water level. The governing equation for this purpose is

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}(K(\theta)) - \frac{\partial}{\partial z}\left(K(\theta) \;\; \frac{\partial \psi}{\partial z} \right) \qquad (1)$$

Where θ is volumetric moisture content, K is hydraulic conductivity, ψ is matric suction, z is depth and t is time. This equation has been solved numerically using explicit finite difference scheme.In this formulation it has been assumed that (1): Infiltration is governed by total rainfall duration and soil water changes take place till the end of total rainfall duration. (2): Precipitation supplies water into each column at a rate up to the infiltration capacity. (3): The rate of precipitation is always higher than the infiltration capacity. In the unsaturated zone, K is no longer constant, depends upon the moisture content of the soil. It is necessary to know the soil moisture content (volumetric) and hydraulic conductivity relationship for the specific soil used in the analysis. In order to relate the unsaturated hydraulic conductivity to moisture content, a method was proposed by Millington and Quirk (M-Q) has been used.For this purpose, it is essential to obtain firstly a soil suction -moisture content (volumetric) curve for the soil, and then from this relationship, using Millington-Quirk (M-Q) method, the suction and permeability of the soil at different time after rainfall starts has been obtained by equation (1). To solve the equation (1), at least two boundary conditions are needed at all time intervals. The boundary condition adopted is that ground water table exists at the level of top of two bottom cells. It means that at all time intervals, for every column for bottom two cells,$\theta = \theta_s$, saturated soil volumetric water content.Discretisation of the geometry has shown in fig. 9. Slope Failure Model which mentioned above in**'2'** has been used to get the F.S.

3.1 Numerical calculations and results using this composite model

Here by combining the above two models, it has been tried to compute the F.S. of three selected slopes which are under rainfall saturated condition. For this purpose we have considered three slopes. These slopes have been discretised. The problem of solving rainfall induced landslides has been divided into two parts, (i) Computation of suction (negative pore water pressure)/pore pressure and (ii) Derivation of slope failure model by simulating the soil as elastic-plastic material with non-associated flow rule.

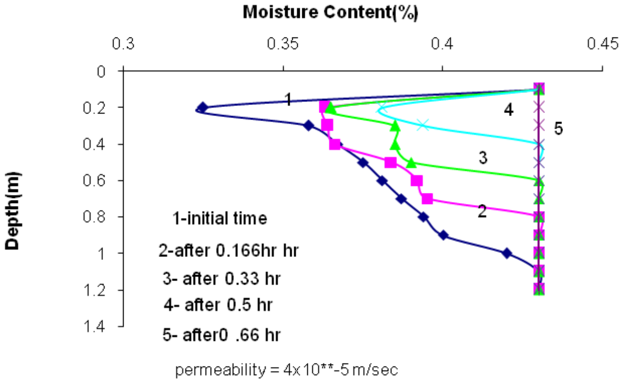

Fig.5. Variation of moisture content with depth with time (permeability = $4x10^{-5}$)

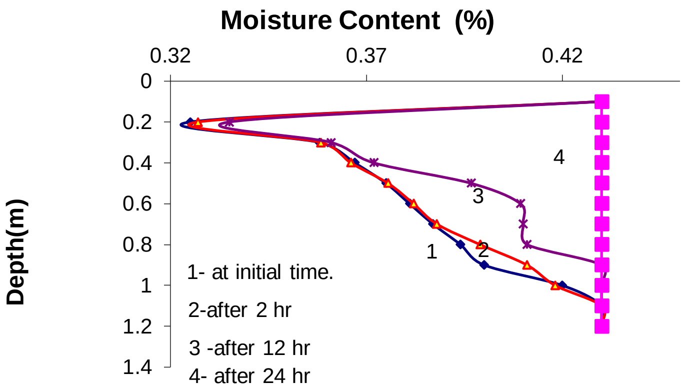

Fig. 6. Variation of moisture content with depth with time (permeability = $2x10^{-7}$)

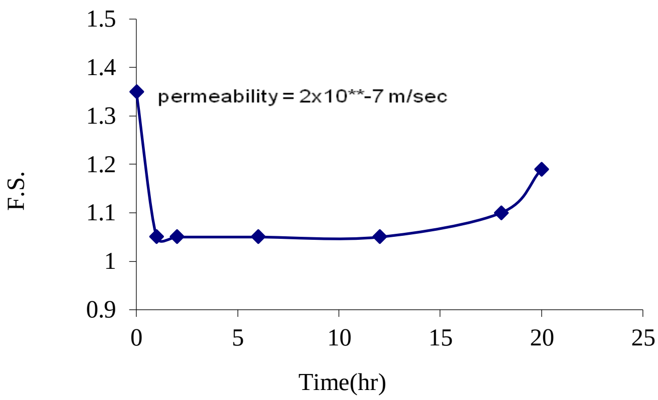

Fig.7. Variation of F.S. with time (permeability =$2x10^{-7}$)

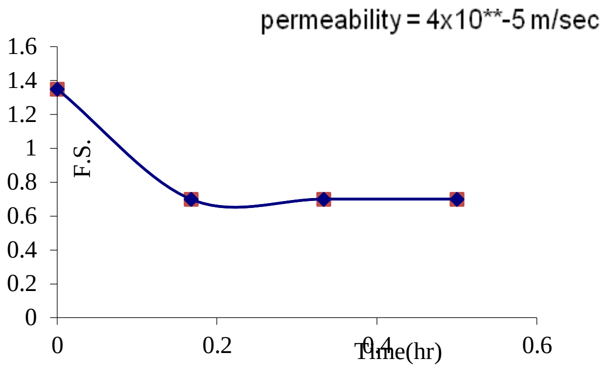

Fig. 8. Variation of F.S. with time (permeability =4x10-5)

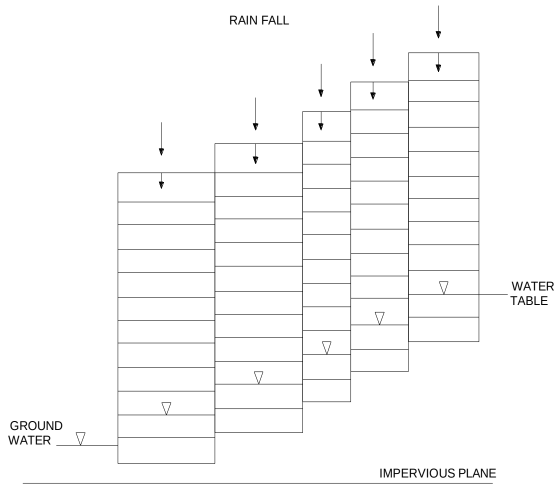

Fig. 9. One dimensional rainfall model

This derivation of slope-failure model has shown in earlier section. During the process of testing, in the slope failure model stresses have been modified according to suction/pore pressure developed due to rainfall as per the equation (1) which has been solved numerically by finite difference method. Results obtained from this composite model have been plotted as shown in fig. 5 to fig. 8 in above. The soil parameters for this slope (26.57 degree) are $\Phi = 20^0$, c = 1.0 kN/m^2, γ_d = 20kN/m^3, E= 1.0x 10^{5}kN/m^2, ν = 0.3. The saturated permeability for the soil= 2x10^{-7} m/sec and the saturated moisture content = 0.43. The portion of soil depth above ground water level has been divided into ten equal parts and the moisture content and suction values obtained from soil water characteristic curve taken as 0.43, 0.4, 0.375,0.35,0.325,0.3,0.275,0.25,0.225,0.2 and 0.1,0.4,0.6,0.9,1.4,2.0,3.0,4.0,6.1,10.0

respectively, for all the three slopes at the initial stage, say at the starting of rainfall. There is a change in soil parameters of the second slope (32^0) and third slope (34^0) has the same soil parameters. The curves have been plotted for 26.57^0 slope for two different values of permeability and they are showing the change in moisture content with depth (shown in fig 5 and fig. 6) and the change in F.S. with time(shown in fig 7 and fig. 8) .

4 Conclusions

The ultimate aim of these two projects is to develop a composite model to predict the landslide due to rainfall and other natural disasters for example earthquake so that there will be no breakdown in day to day life of citizen and there will be no loss of property and human life. As soil geometry, soil properties, soil profiles are varied in nature, so the predicting rainfall induced landslides will be also varied from site to site and to study the slope failure, the depth of soil layer, its permeability, its variation in moisture content with rainfall, the variation in pore water pressures (positive and negative) are essential. All these parameters which are essential for this model to be measured through instrumentation with time during rainfall, as all these parameters are changing with time during rainfall. On the basis of these data this model will determine the failure zone and numeric value of F.S. with time which is not possible using conventional method.

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