A CASE STUDY OF INVESTIGATION THE INFLUENCE OF SUBSURFACE DRAINAGE ON SLOPE STABILITY

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ABSTRACT

Rainfall is one of the main factors that affect the slope stability. Rainfall infiltration will change the degree of saturation of soil, and further influence the pore water pressure and the permeability coefficient. One landslide occurred in Kurdestan province of Iran in 2009. The main reason of this landslide was assumed to be ground water flow and rainfall infiltration. This paper investigated accuracy of this assumption and predicted the effects of the horizontal drains on the ground water level and stability of case study slope during rainfall using two-dimensional finite element analysis of transient water flow through unsaturated-saturated soil. The slope stability is evaluated by the global safety factor, based on the two-dimensional limit-equilibrium analyses method. The results show that the rainfall is one the main reason of landslide. Also analysis of drains performance show that the horizontal drains can effectively lower the ground water level and consequently increase the slope stability during rainfall.

Keywords: Slope stability, rainfall infiltration, horizontal drains performance, pore-water pressure

INTRODUCTION

Rainfall, especially the heavy rain in summer and the long-term infiltration of melting snow, has been causing many landslides and slope failures (Cai, Ugai et al. 1998). A large number of steep, natural and engineered slopes in tropical and subtropical areas remain stable for a long time and then fail during heavy rainstorms. In many cases these failures cause loss of life and economic losses. Many authors (Fredlund, Brand, Chinniah, Fourie) suggested that conventional methods, based on the assumption of saturated behaviour, for the design and construction of saturated soil slopes cannot be applied successfully for slopes under unsaturated conditions (Tsaparas, et al. 2002).

Slope stability analysis of unsaturated soils requires an extensive and detailed seepage analysis, because slope failures in unsaturated conditions are closely related to heavy rainfall and infiltration (Yeh , et al. 2006). When the degree of saturation of a soil is greater than about 85%, saturated soil mechanics principles can be applied. However, when the degree of saturation is less than 85%, it becomes necessary to apply unsaturated soil mechanics principles. The transfer of theory from saturated soil mechanics to unsaturated soil mechanics and vice versa is possible through the use of stress state variables, which are net normal stress ($\sigma - u_a$) and matric suction ($u_a - u_w$). Where σ is the total stress, u_a is the pore-air pressure and u_w is the pore-water pressure (Bujang, et al. 2006). The mechanism that leads to slope failures is that the negative pore–water pressures start to increase when water starts to infiltrate the unsaturated soil. The loss of negative pore–water pressures decreases the shear strength of the soil below the mobilised shear strength along the potential slip surface.

Usually unsaturated residual soils experience high matric suction during dry periods, which contributes to the shear strength of the residual soil. During prolonged wet periods when there is sufficient infiltration into the slope, the matric suction of the soil decreases, and this in turn results in an increase in the soil water content. As a result, the additional shear strength provided by the matric suction can be reduced enough to trigger a shallow landslide(Fredlund and Rahardjo 1993)

The horizontal drains is an effective measure to lower the ground water level and to increase the slope stability during rainfall, especially for the dangerous slopes and embankments, (Cai, et al. 1998). The main success of a horizontal drain is dependent on how much pore water pressure is reduced on slope (Pathmanathan 2009).

In the present paper, the effects of the horizontal drains on the ground water level are analyzed with a two-dimensional finite element analysis of transient water flow through unsaturated-saturated soils. The slope stability is evaluated with the global safety factor, obtained with the limit-equilibrium analyses method. The pore water pressure is obtained from the above-mentioned analysis of transient water flow through unsaturated-saturated soils.

Mohr Coulomb failure criterion was used to define shear strength parameters for unsaturated soils i.e. c' (apparent cohesion) and φ' (effective angle of friction). The effects of the location, the number of the horizontal drains on the ground water level and the slope stability are numerically analyzed for a typical slope.

THEORICAL BACKGROUND AND METHOD OF STUDY

Theory of Water Flow in Saturated and Unsaturated soils

Seepage flows in saturated and unsaturated soils are governed by Darcy's law. One of the major differences between water flows in saturated soils and flows in unsaturated soils is that the coefficient of permeability is not a constant but a function of the degree of saturation or soil suction in an unsaturated soil. The governing equation for water flow through soil can be obtained by introducing Darcy's law into the mass continuity equation. The deformation of the soil skeleton is usually ignored for convenience. Taking the total hydraulic head h as the unknown and when the directions of the coordinate axes are the same as the directions of anisotropy of hydraulic conductivity, the general two-dimensional governing differential equation for water flow through soil is as follows:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(ky\frac{\partial h}{\partial x}\right)=\Upsilon w\frac{\partial \theta w}{\partial \psi}\frac{\partial h}{\partial t} \tag{1}$$

Where, k_x and k_y are the coefficients of permeability in the x-direction and y-direction, respectively; γ_w is the unit weight of water; θ_w is the volumetric water content; ψ is the soil suction; and t is time. According to the equation, a soil-water characteristic curve, which is a relationship between the volumetric water content and the soil suction, as well as a permeability function, must be known for transient seepage analyses,(Zomorodian and Abodollahzadeh 2010).

Shear Strength of Unsaturated Soil

The shear strength of an unsaturated soil may be represented by the extended Mohr-Coulomb envelope in the shear stress τ, net normal stress $(\sigma - u_a)$, and matric suction $(u_a - u_w)$ space .

$$\tau_{ff} = c' + (\sigma_f - u_a)_f \tan \varphi' + (u_a - u_w)_f \tan \varphi^b \tag{2}$$

where τ_{ff} is the shear strength on the failure plane; c is the intercept of the extended Mohr-Coulomb failure envelope on the shear stress axis where the net normal stress and the matric suction at failure are equal to zero; $(\sigma_f - u_a)_f$ is the net normal stress state variable on the failure plane at failure; $(u_a - u_w)_f$ is the matric suction on the failure plane at failure; and φ^b is the angle indicating the rate of increase in shear strength relative to the matric suction.

The existence of the pore-air and pore-water in the unsaturated soils resulting in the formation of surface tension (matric suction) among the soil particles, which pulls together the soil particles and increases the shear strength of the soils. During rainfall, the increasing water content will decrease the matric suction and, hence, reduce the shear strength of the soil. The shear strength for saturated soils may be expressed in mathematical term by letting u_a approaches u_w in Eq. 2, and Eq. 2 is now reduced to the renowned Mohr-Coulomb failure envelope:(Gui and Han 2008)

$$\tau_{ff} = c' + (\sigma_f - u_w)f \tan \varphi' \tag{3}$$

Method of Study and Material Properties

The main purpose of this paper is to study of drain performance in slope stabilization (case study). In this research before study the performance of drains, the influences of ground water flow in slope instability have been studied. Rainfall is one of the main factors that affect the slope stability (Cai, et al. 1998; Gasmo, et al. 2000; Gui and Han 2008) therefore, at first the influence of rainfall infiltration in instability of case study slope was studied, then performance of drains in increase of slopes safety factor, by installation in different location.

The behavior of the slope was examined using a two-stage approach: firstly infiltration and influence of rainfall infiltration in slope instability were analyzed, secondly the performance of drains were analyzed. Rainfall infiltration and change of ground water level were analyzed to obtain the distribution of pore water pressure, then use of this pore water pressure distribution, safety factors of the slope were analyzed. The respective programs used were SEEP/W and SLOPE/W, developed by Geo-Slope International Ltd and Slide5.

The program SEEP/W is a finite element program that analyzes ground water seepage, and excess pore water pressure dissipation problems. The program utilizes two functions to derive a solution for unsaturated flow : (1) hydraulic conductivity function; and (2) soil-water characteristic function (Gasmo, Rahardjo et al. 2000; Gui and Han 2008). The magnitude of the maximum negative pore-water pressure is dependent on the shape of the hydraulic conductivity function, and to a lesser extent, on the rate of infiltration. The capability of the soil to store water under change in pore-water pressure is represented by the soil-water characteristic function.(Gui and Han 2008)

The program SLOPE/W was formulated in terms of moment and force equilibrium factor of safety equations. The program made use of unsaturated shear strength parameters to determine the factor of safety for a slope.

Slide is a 2D limit equilibrium slope stability program for evaluating the safety factor or probability of failure, of circular or non-circular failure surfaces in soil or rock slopes. *Slide* analyzes the stability of slip surfaces using vertical slice limit equilibrium methods. *Slide* also includes finite element groundwater seepage analysis built right into the program. This program used in this research to verification the safety factors results from SLOPE/W.

This study has been carried out on a slope is lied at gas transportation line of Kamyaran-Marivan (23+500 KM), near the Zivieh storage dam in Kurdestan province of Iran. The location of the slope is shown in Fig. 1.

This region have mountainous cool climate, because of lie in Zagros range of mountains.

(a) Photography of landslide

(b) The wide of landslide

Fig. 1 Locations and a view of Zivieh landslide

The soil profile of the case study slope is shown in Fig. 2. The slope stands at an angle of approximately 30º.Ground investigation was conducted after the land-slide to determine the subsurface conditions of the study area. Laboratory testing on samples derivative from variant bores show, soil of slope consist of clayey gravel with a saturated permeability, ks, of 5×10^{-5} m/s lied on bedrock layer with a saturated permeability, ks, of 3×10^{-12} m/s.

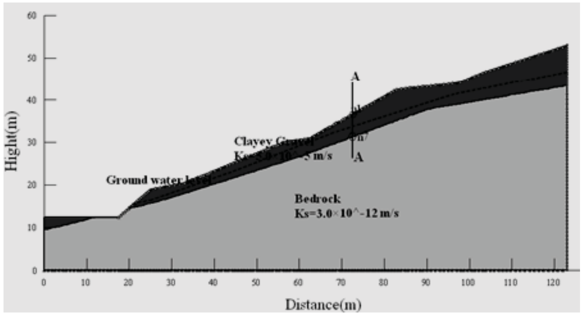

Fig. 2 Profile of case study slope.

The effective shear strength parameters $(c',φ')$ for the saturated soils involved were obtained from the Consolidation Isotropic Undrained (CIU) triaxial tests on undisturbed samples taken from the failed sites and summarized in Table1.

Table 1 Summary of the soil parameters used for the slope stability analysis

Layer	*γ=unit weight (kN/m³)*	*c′=apparent cohesion(kPa)*	*φ= angle of friction*
surface	20.9	4	32
bedrock	25.5	300	35

Soil-Water Characteristic Function

One of the required input parameters of SEEP/W for a transient analysis is the soil-water characteristic function (SWCC). The SWCC curve represents the volumetric water content of a soil at various matrix suction values. Matric suction can be defined as a negative pore-water pressure referenced to the pore-air pressure. As matric suction increases, the volumetric water content of the soil decreases. This affects the movement of water through the soil because there are less water filled spaces available for water flow. As matric suction increases, the permeability of the soil decreases. The permeability of a soil at various matric suction values is represented by the permeability function. Since it can sometimes be difficult or time-consuming to obtain the SWCC, it may be possible to estimate the

SWCC using either a closed-form solution that requires user-specified curve-fitting parameters, or to use a predictive method that uses a measured grain-size distribution curve. SEEP/W has four methods available to develop the volumetric water content function, two are predictive methods based on grain-size, and two are closed-form equations based on known curve fit parameters (Geo-Slope 2004). This study used the Fredlund and Xing (Fredlund and Xing 1994) closed form equation for estimating the SWCC.

Hydraulic Conductivity Function

Other input of SEEP/W require for analyze of water flow in unsaturated slope, is hydraulic conductivity function. It is clear that the ability of water to flow through a soil profile depends on how much water is present in the soil, which is represented by volumetric water content function. Actually measuring the hydraulic conductivity function is a time-consuming and expensive procedure, but the function can be readily developed using one of several predictive methods that utilize either a grain-size distribution curve or a measured volumetric water content function and the saturated hydraulic conductivity. SEEP/W has built-in predictive method that can be used to estimate hydraulic conductivity function once the volumetric water content function and Ksat value have been specified,(Geo-Slope 2004).

Rainfall Data

Rainfall analysis was based on data collected at the rainfall station located some 10 km away from the study area. The daily rainfall intensity, from October 23 to November 19, 2009 is presented in Fig. 3. Hence, the rainfall pattern and intensity at the study area could be postulated.

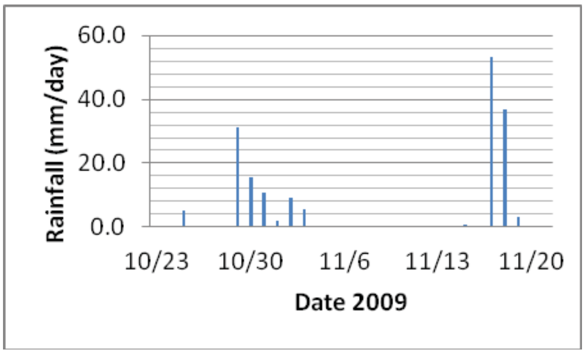

Fig. 3 Daily rainfall between October and November of 2009

MODELING AND ANALYSIS

The analysis undertaken includes transient seepage analysis to determine pore-water pressures during rainfall duration and stability analysis of the slope. Both analyses were conducted in automatic coupled mode.

Seepage Analyzes

By using the 26-day rainfall data (Fig. 3) as input, we could then obtain the transient flow or more specifically the pore-water pressure changes over time for slope over a period of 26 days.

The contour of the pore-water pressure on day 1and 26 of slope are presented in Fig. 4. It can be seen that on day1 negative pore-water pressure is equal to 30kPa but the contour of the pore-water pressure on day-26 showed that the suction reduced to 20kPa.

The pore-water pressure profiles over time for section A-A in Fig. 2 of Slope is presented in Fig. 5. N1 is in ground surface and N7 lie in boundary of soil and bedrock. Fig. 5 shows that as take away from N1 and approach to N7, the negative pore-water pressure reduced and become to positive pore-water pressure. Also at every seven node in section A-A, the infiltration of rainfall and ground water table increase and the negative pore–water pressures start to decrease ,with along the time of rainfall duration. As shown in Fig. 5,at day-9 to day-21 from rain duration, the pore-water pressure does not change, that’s why no rainfall occurred at that time interval.

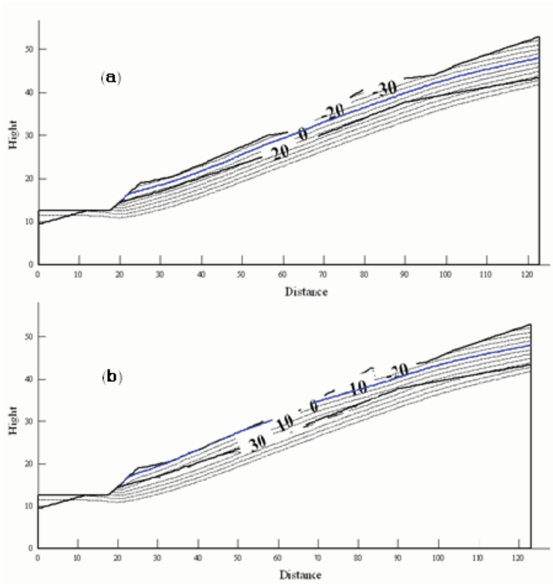

Fig. 4 Contour of pore-water pressures (kPa) for slopes: (a) day 1, and (b) day 26

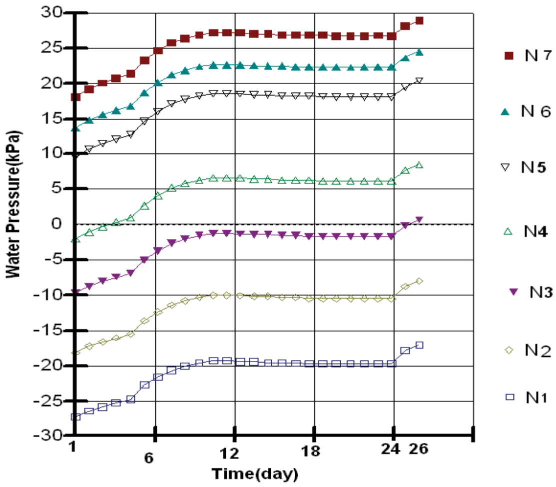

Fig. 5 Pore-water pressure profiles at section A-A of Slope.

Slope Stability Analysis

The pore–water pressures that were determined in the seepage analysis by Seep/W were used as input data for the slope stability analysis. The other requirement input data of SLOPE/W and Slide is soil shear strength parameters. The results of slope safety factor analysis via SLOPE/W and Slide programs show in Fig. 6. As shown in Fig. 6 the results of two programs are equal, therefore the results are acceptable. At day-1 safety factor of slope is 1.32, then reduces to 1.13 at October 30, due to 79 mm of rain and remains constant until November 16, where the intense raining began. The factor of safety of Slope then reduces to 0.873 on November 18, at which point the slope failed. The slip surface with the minimum safety factor is shown in Fig. 7, it is similar to site reconnaissance.

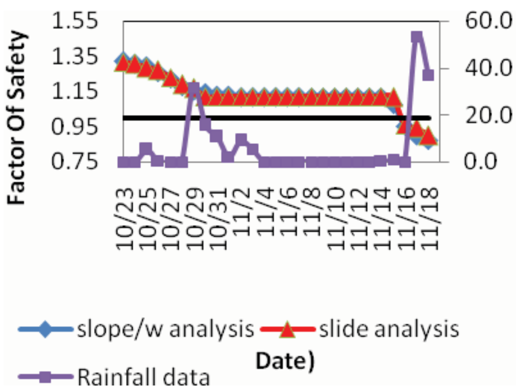

Fig. 6 Factor of safety vs time.

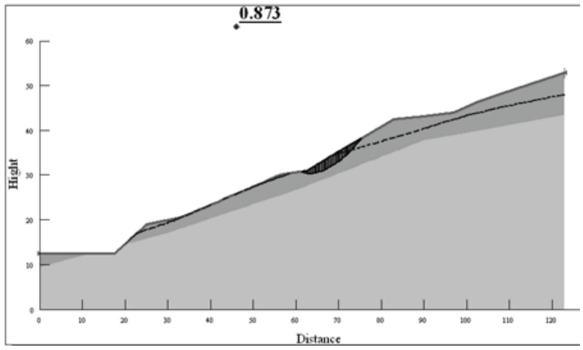

Fig. 7 Slip surface at November 18.

Analysis of Drain Performance

The case study was performed to investigate the significance of drain location within a slope. The seepage analysis was performed using the finite element seepage software Seep/W (Geo-Slope 2004) and the stability analysis was performed using the limit equilibrium slope stability software Slope/W(Geo-Slope 2004) .

The horizontal drainage location and finite element mesh configuration are shown in Fig. 8. Several scenarios were analyzed based on different drainage configurations. Six evenly spaced drain locations were considered as shown in Fig. 8 . The first scenario involved the slope configuration without drainage. The next six scenarios involved the slope configuration with each drain on its own and the next six scenarios incorporated combining two and three drains. Drain properties used in this model were as follows: γ of 20.9 kN/m^3, an effective cohesion c' of 0 kPa and an effective angle of internal friction φ' of 40° with a saturated permeability, ks, of 5×10^{-3} m/s.

Steady-state conditions were established for all different drainage scenarios. The steady-state water table was developed below the drained zones so that each initial condition was identical. In other words, the drainage configurations had no influence on the initial conditions. Subsequently, the rainfall rate function that shown in Fig. 3 was applied to the slope and the transient process was calculated. Data from each time step were saved over the course of the transient analysis.

A factor of safety was calculated for each drainage scenario at every time step by importing the pore–water pressure head files into Slope/W model. The results of the slope stability analyses are shown in Fig. 9(a). The general trend of Fig. 9 (a) shows that the least amount of benefit was derived from the drains located in the upper region of the slope. The most benefit was derived from the drain located at the location 4 of slope. After slope analysis with individual drain, the slope was analysed with combining drainage system of drain 4 and other drains the results are shown in Fig. 9(b). The most benefit was derived from the combining drains located at the location 4 and 3 of slope, a very small additional benefit was obtained by combining drains 4 and3 with other drains in 4 and 3 and 2. This is shown by comparing the factor of safety obtained from the case with two drains as opposed to the case with three drains at location of 4 and 3 and 2.

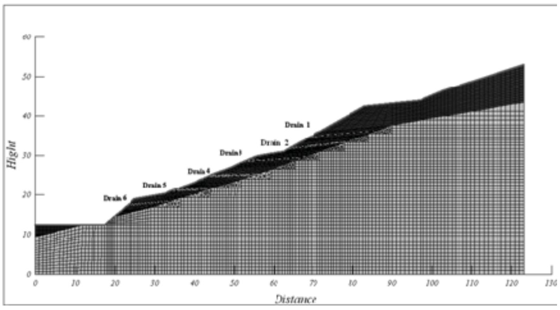

Fig. 8 Finite element model for the parametric study, slope configuration and horizontal drain location

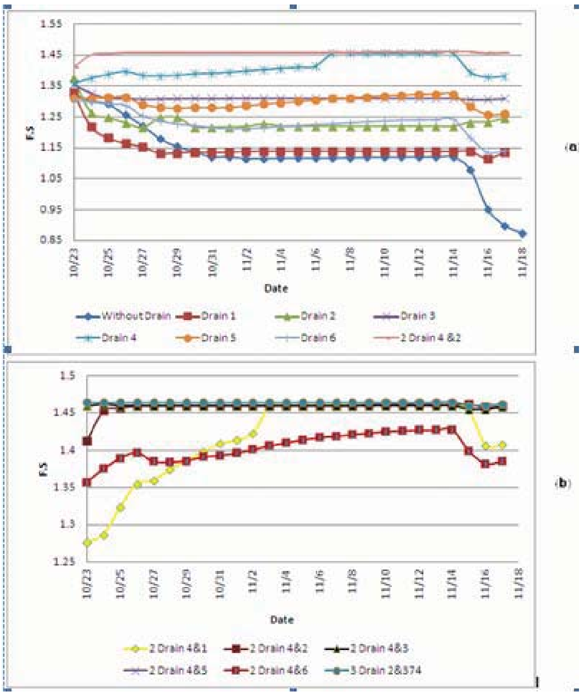

Fig. 9 Theoretical factor of safety with respect to drain position for a constant rainfall rate (a) one drain (b) two and three drain.

CONCLUSIONS

In this research studied effectiveness of horizontal drains in slope stabilization (case study). Since the rainfall infiltration has an important effects on slope stability, at first section, the influence of rainfall infiltration on instability of the case study slope studied, at second section, the effectiveness of drains in slope stability studied, by calculating the safety factor of slope and so, on studied the influence of drain's location in lowering the water table, an increase of the safety factor of slope. From the calculated results, the following conclusions are obtained:

1. Rainfall infiltration cause to increase of water table level, and decrease in safety factor of case study slope.
2. Horizontal drains have important role in increase safety factor of case study slope.
3. Location of the horizontal drains in the slope has an important role in their performance. There are different safety factors for different location of the drains in this case study slope and drain lied in location-4 has given the maximum safety factor for the slope.
4. The slope stability increases with the increase in the number of the horizontal drains, but the rate of the increase in the safety factor of the slopes becomes smaller and smaller, when the number of horizontal drains are extended beyond a critical number.

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