Numerical study on bearing capacity of a pile group next to a slope in unsaturated soils

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Abstract. The bearing capacity of a pile group mostly depends on parameters of the soil shear strength affected by the soil-water characteristics, especially in unsaturated soils. The soil shear strength is entirely affected by hydraulic stresses in unsaturated soil, such as precipitation and evaporation. Further, the bearing capacity of the pile installed on unsaturated soil depends on hydraulic stresses applied to the soil. Furthermore, slope vicinity may cause a severe decline in the pile bearing capacity. The present study aimed to investigate a pile group in unsaturated soil adjacent to a slope and analyzed the effect of the rainfall on the soil strength parameters. Thus, a numerical study has been performed using a finite difference software, i.e., FLAC2D. Besides, to investigate the model in a real situation, the intensity and duration of rainfall are considered to evaluate changes in hydraulic stresses. Finally, the results show that the rainfall causes a considerable decrease in soil strength parameters in unsaturated soil, leading to the reduction of the pile group bearing capacity and slope stability.

1 Introduction

Climate change, as a primary global concern, brings problems to the environment. Some changes in soil properties could be attributed to climate change, such as global warming, which lowers the water level. On the other hand, in most areas, the evaporation level dominates the precipitation amount which leads to generating more unsaturated and fully-dried soil deposits. These changes directly affect soil material parameters. For instance, the soil strength changes with water table fluctuations, and it influences slope stability. Besides, the variation of shear strength and saturation degree lead to alteration in pile bearing capacity. As a result, it is essential to consider the effect of unsaturated soil on slope stability and bearing capacity of the pile group applied in an unsaturated soil deposit. Moreover, a critical situation occurs when cyclic hydraulic stresses apply to the soil. It means that the repetition of wetting and drying reduces soil strength considerably. Thus, it is vital to consider differences in soil behavior between a fully saturated and dried soil.

Most previous studies investigated unsaturated slope stability induced by rainfall (Cai and Ugai 2004; K. Regmi et al. 2011; TRAN 201; S. Chatra 2017) [1–4]. However, they disregard any structural elements (i.e., pile) for the stability of the slope.

Most studies are performed based on the principles of saturated soil mechanics. However, the soil is mostly unsaturated. Based on the estimations, 60% of the

world's population lives in regions with unsaturated soil. (to a depth of several meters) (Vo and Russell, 2016) [5].

From another point of view, the lateral soil pressure plays a leading role in the evaluation of the bearing capacity of the soil and the slope stability analysis. Considering the lateral soil pressure is a crucial step to avoid slope collapse. In addition, it is vital to estimate confining pressure corresponding to soil stresses applied to the pile. As a parameter for the calculation of lateral pressure, the coefficient of lateral earth pressure (k) in unsaturated soils considerably differs from that in saturated soil (Pirjalili et al. 2016) [6]. As a result, some researchers suggest using unsaturated modes for local rainfall and seepage flows to measure the effect of the saturation degree on soil behaviors. In other words, these transient currents and changes in the level of groundwater should be considered precisely [7, 8].

Introducing parameter c , as a function of soil saturation, Bishop (1959) modified Terzaghi's model for unsaturated soils [9].

In unsaturated soil, matric suction plays an important role in the parameters of soil. However, due to the complexity of involving suction in the constitutive behavior of soil as a parameter affecting shear strength of soil, a few studies investigated the bearing capacity of a single pile or pile group in unsaturated soils [8, 9].

2 Rainfall condition in Iran

Iran is a country with a semi-dry climate. Most of the lands in Iran are covered with unsaturated soils, but in

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some areas, the situation is different. For instance, the northern cities of Iran experience heavy rainfall in rainy seasons while the water table descends in warm seasons. Heavy floods struck Golestan Province on March 23, 2019, which started on March 18, 2019 (Fig.1.). Seventy percent of average annual rainfall hit this province in the first 24 hours. These transient currents change the slope stability and leading to slope failure. Further, the bearing capacity of foundations (both shallow and deep) changes due to the fluctuations of saturation resulting in structures collapse. In the present study, a numerical analysis was done based on the recorded data of rainfall in Golestan.

Fig.1. Floods in Aq Qala (Golestan, Iran) overturned the building.

3 Boundary conditions

3.1 Precipitation

In the present study, a numerical analysis was done based on the recorded data of rainfall in Golestan. Precipitation boundary conditions should be satisfied to simulate rainfall infiltration into the soil. All of the rainfall values are assumed to permeate into the soil deposit through the entire surface of the slope, and thus no runoff occurs [1, 10]. The intensity of rainfall is 8.29×10^{-7} m/s and continues for successive five days (overall rainfall of 358 mm).

3.2 Factor of safety calculation

To assess the stability of the slope, the factor of safety (F.S. or FOS) against failure was calculated using the strength reduction technique, which is explained in Potts and Zdravkovic [11]. The variation of the F.S. during the raining time (successive five days) was modeled.

3.3 Bearing capacity of pile group

In the first step, rainfall was applied to the model, pore pressure and rainfall-induced saturation per day were employed in the soil deposit. Then, Based on FLAC2D manual, a negative velocity was applied to the first node of the pile to estimate the bearing capacity of the pile

group. The bearing capacity of the pile group was assessed based on the load-settlement curve. Piles were positioned in a row with a 3-meter space. To check the effect of the pile group location, the piles must be placed eight meters from the slope crest.

3.4 Initial stresses

At the beginning of the analysis, soil stresses were initialized, imposing a unit weight of 18 kN/m^3 . Besides, because of the absence of groundwater, the pore pressure becomes negative and the soil becomes unsaturated; nevertheless, the pore pressure of the shallow depth will become positive over time.

4 Problem definition

4.1 Geometry

The modeled slope was an unsaturated soil deposit with a height of 10 m (Figs. 2 and 3). This issue was considered in plane strain mode and two displacement degrees of freedom were devoted to all zones except the pile elements.

Fig.2. Model geometry (x is the distance of the pile group from the slope).

Fig.3. Model mesh.

4.2 Soil properties and model parameters

The modeled soil properties are summarized in Table 1. Mohr-Coulomb model was considered for partially saturated soils. Based on constitutive laws implemented in FLAC2D, when two-phase flow logic is active, the yield criterion is equivalent to Eq. 1:

$$\tau^{\max} = \sigma^b \tan \phi + c \quad (1)$$

Table 1. Mechanical Properties of Soil.

Parameters	Value
Young modulus (E) [MPa]	100
Poisson's ratio (ν)	0.3
Unit weight (γ), [kN/m ³]	18
Effective cohesion (c), [kPa]	20
Effective friction angle, (ϕ) [Deg]	18
Dilatancy angle, (ψ)	0

Where $\tau_{\max}$ is the soil shear strength, σ^b is the Bishop effective stress, C is cohesion, and ϕ is friction angle. Also, the Bishop effective stress is defined as:

$$\sigma^b = \sigma - (S_w P_w + S_a P_a) \quad (2)$$

Where σ is the total stress, S_w is water saturation, S_a is air saturation ($S_a = 1 - S_w$), and P_w and P_a are water and air pressures, respectively. After substitution of Eq. 2 into the Eq. 1, and some simplifications, the yield criterion may be expressed as shown in Eq. 3:

$$\tau^{\max} = (\sigma - P_a) \tan \phi + S_w (P_a - P_w) \tan \phi + C \quad (3)$$

Further, the van-Genuchten (1980) model of the soil-water characteristic curve (SWCC) was used for the hydraulic behavior. Furthermore, the permeability of the soil, as a function of saturation, varies from its highest value (k_{sat}) to its lowest value (k_{dry}). Hydraulic properties are listed in Table 2.

Table 2. Hydraulic characteristics of soil.

Parameter	Value
Van Genuchten (α) [m ⁻¹]	1.06
Van Genuchten (α) [m ⁻¹]	9433
Van Genuchten (a)	0.28
Porosity	0.47
Hydraulic conductivity (k_{sat}), [cm/s]	1.51×10^{-4}
Initial degree of saturation	0.6
Initial pore pressure [kPa]	-30.2

4.3 Soil-Water Retention Curve (SWRC)

The soil-water retention curve of the silty sand is obtained by Eq. (4). Capillary pressure, P_c , decreases with an increase in saturation, and it is represented in FLAC by an empirical law of the van Genuchten form:

$$P_c = P_0 \left(s_e^{\frac{-1}{a}} - 1 \right)^{1-a} \quad (4)$$

Where $p_c = p_a - p_w$, p_a and p_w are pore air and water pressures, respectively. P_0 and a , are parameters which should be determined experimentally. The Soil-Water retention curve is depicted as Fig.4.

Fig.4. Soil- water retention curve calculated from Van Genuchten model.

4.4 Pile properties

Piles are modeled as two-dimensional elements with 3 degrees of freedom (two displacements and one rotation) at each end node. Piles interact with the FLAC grid via shear and normal coupling springs. The properties of the pile group are shown in Table 3.

Table 3. Mechanical properties of pile group.

Parameters	Value
Young modulus (E), [GPa]	25
Normal stiffness (K), [MN/m/m]	1.87×10^2
Pile perimeter [m]	3.14

5 Rainfall and slope stability analysis

In the present study, numerical analyses were done to evaluate the factor of safety of slope under specific rainfall (rainfall intensity = 8.29×10^{-7} m/s). Fig 5 displays the gradual changes of F.S. considering the pile group location.

Fig.5. Variation of slope stability in successive five days rainfall.

6 Pile group bearing capacity

The bearing capacity did not remain constant like the stability of the slope and it is affected by rainfall and location of the pile group. Fig.6 displays the variation of the bearing capacity of the pile group versus the time elapsed for the pile group distancing from the slope.

Fig.6. Variation of bearing capacity of the pile group in successive five days rainfall considering the pile location.

7 Optimum distance for installing pile group

As shown in Figs. 5 and 6, when the pile group moves away from the slope's crest, the bearing capacity of the pile group increases; however, F.S. of slope decreases. Besides, Fig. 7 schemes the variations of slope stability and bearing capacity concerning the distance of the pile in successive five days rainfall. In this case, optimum distance from the slope can be estimated.

8 Evaporation effects

To simulate evaporation in unsaturated soil, it was assumed that rainfall have occurred in the past. Then, soil saturation, S_r , changes with the time-lapse. In the first step, S_r was 0.9 and then decreased to 0.2 as time passes. The fluctuation of saturation degrees leads to changing in suction through the entire soil structure. Figs. 8 and 9 show the variations of the bearing capacity and F.S. versus saturation degree and corresponding matric suction, respectively. As mentioned above, the

F.S. and bearing capacity increase as the soil dries because in the soil drying path, the matric suction increases and strengthens soil shear. It is worth noting that each point of saturation represents the specific value of suction in the soil. This value can be extracted from the soil–water retention curve, as depicted in Fig. 4.

Fig.7. Variation of slope stability and bearing capacity regarding the location of the pile group in successive five days rainfall.

Fig.8. Variation of slope stability and bearing capacity considering the saturation of soil.

Fig.9. Variations of slope stability and bearing capacity considering the matric suction of soil.

9 Conclusion

Due to the global climate change and having more dried soil than before, the unsaturated state of the soil is vital in slope stability modeling. Besides, it has already been approved that soil variables are different in the unsaturated mode which affects the calculation of the pile bearing capacity. Moreover, the cycle of wetting and drying impacts on soil properties. This numerical study was performed to address these crucial issues. Based on data obtained from this numerical investigation, it is observed that the safety of the slope stability and bearing capacity of the pile group increase as matric suction increases. Further, in an investigation of pile locations and slope, it was concluded that pile group location affects its bearing capacity and slope stability. Results show that bearing capacity has been modified more commonly than changes in pore pressure caused by rainfall due to the position of the pile group installation. (more than 5 percent). To find the optimum place for installing piles on an unsaturated soil deposit, all of these issues must be considered.

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