A numerical study on the effect of salinity on stability of an unsaturated railway embankment under rainfall

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Abstract. Dispersive soils, as one of the main categories of problematic soils, can be found in some parts of the earth, such as the eastern-south of Iran, nearby the Gulf of Oman. One of the most important factors enhancing the dispersive potential is the existence of dissolved salts in the soil water. The main objective of this study is to explore the influence of water salinity on the instability of a railway embankment due to rainfall infiltration. In order to achieve this goal, the embankment resting on a dispersive stratum is numerically modeled and subjected to transient infiltration flow. The effect of dispersion is simplified through variations in the soil-water retention curve with salinity. The measured water retention curves revealed that by omitting the natural salinity in the soil-water, the retention capability of the soil decreases; therefore, the unsaturated hydraulic conductivity of the soil stratum will significantly decline. According to the extensive decrease in the hydraulic conductivity of the desalinated materials, the rainfall cannot infiltrate in the embankment and the rainfall mostly runs off. However, in the saline embankment, the infiltration decreases the soil suction; and consequently, the factor of safety of the railway embankment decreases.

1 Introduction

Problematic soils, such as collapsible, dispersive, and expansive soils, have always been as one of the main concerns of geotechnical engineers, especially when they want to design infrastructures above strata that consist of these types of soils. One of the most dramatic types of problematic soils is dispersive soil. Dispersive soils are found in areas with saline soil water such as the eastern south of Iran, nearby the Gulf of Oman [1]. Contractors in this region have faced lots of problems related to projects in this region. For instance, during the construction of the Chabahar-Zahedan national railway project, excessive deformations in some parts of the embankment were observed. These deformations were categorized in general as local collapse, deep sinkholes, and subsidence. Further studies on this soil indicate that this soil is a special kind of loess that contains a certain amount of dissolved salt. Therefore, the main cause of the dispersive behavior of the soil was revealed to be the dissolved salts in soil-water [2].

Although relatively extensive studies have been conducted in the last decade to clarify the microstructural influence on the behaviour of unsaturated loess [3], much less attention has been paid to the behaviour of dispersive loess within unsaturated context. It is generally known that dispersive potential becomes worse with an increase in water salinity.

In the arid regions of the world, rainfall infiltration plays a paramount role in the instability of the slopes and serviceability problems of geotechnical structures, such as railway and roadway embankments. For example, in

some parts of China, many failures of natural slopes have been frequently reported due to rainfall infiltration [4]. When rainfall infiltrates into the vadose zone, the pores start to fill with water, and the air phase gradually disappears; therefore, the suction in the vadose zone of the stratum will diminish, and the soil structure collapses in many cases. Consequently, the failure of the structure will occur. Thus, rainfall infiltration has to be studied more precisely in unsaturated regions [5].

In this study, stability analyses were conducted for parts of the Chabahar-Zahedan national railway embankment crossing the naturally occurred dispersive loess strata. It is noted that the studied region has suffered from prolonged aridity followed by a relatively intense rainfall during the last winter. It is therefore believed that rainfall infiltration has had a major influence on the instability and deformations of the local infrastructures. The main objective of this study is to investigate the impact of soil salinity on the stability of the railway embankment sitting on the dispersive loess stratum. In order to satisfy this goal, two different materials have applied to the numerical model with two types of salinity, including saline and desalinated soil. Although the influence of some key factors such as net stress on water retention properties of loess was explored in the literature [6], the role of pore water salinity has not been thoroughly examined. To cope with this shortcoming, the influence of pore water salinity is considered through the effect of salt content on the soil-water retention curve (SWRC). In other words, SWRCs of the materials have been measured by the filter paper method for both saline and desalinated materials.

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Furthermore, the rainfall infiltration is exerted to the model through two different patterns based on the meteorological data of the region under investigation.

2 Material properties and methods

In this study, the material properties are divided into three main categories including geotechnical properties, SWRCs, and unsaturated hydraulic conductivity functions.

2.1. Geotechnical properties

The main geotechnical properties of the natural soil were studied and reported by Sadeghi et al. [7]. The studied soil was classified as clayey loess and it has moderately dispersive to dispersive characteristics. The fraction analysis of the soil revealed the sand, silt, and clay fractions to be 29%, 37%, and 34%, respectively. The *in-situ* dry density and the specific gravity are equal to 1153 kg/m³ and 2.756, respectively. However, in this study, materials are considered in the standard compacted state based on the Earthworks for Railway Lines General Technical Specifications Code [8]. In other words, both stratum and the embankment are modeled in the compacted state with the dry density of 14.58 kg/m³. The void ratio of the standard compacted soils is 0.85. In order to study the effect of natural salinity, the natural saline material is washed and its salinity is removed and the desalinated material is produced. In addition, in this step of the study, the impact of salinity on the mechanical properties of the materials is ignored [9]. The friction angle and cohesion of the compacted material are measured as 29.1° and 7 kPa, respectively.

2.2 SWRCs

The aridity of the studied region brings about analyses to be viewed in the unsaturated perspective due to the fact that the groundwater table is found up to a depth of 18 m. In such conditions, high suction values in the order of mega Pascal can be easily developed in surface layers and also reported in semi-arid regions of loess plateau of China [10]. The implication is that full-range SWRCs and hydraulic conductivity functions are required for numerical analysis. The first and most important parameter for transient seepage analysis through unsaturated media is SWRC. In this study, the SWRCs of the materials are measured by the filter paper method and their best fits are calculated through the Eq. 1 [11].

$$\theta(\psi) = \left\{ \left[\theta_{sat} - S_1 \log(\psi) - \theta_r \right] \frac{a}{\psi^b + a} + \theta_r \right\} \times C(\psi) \quad (1)$$

where ψ is the soil suction, $\theta(\psi)$ is the volumetric water content corresponding to ψ , θ_{sat} is the saturated volumetric water content, θ_r is the residual volumetric water content, S_1 , a and b are fitting parameters, and $C(\psi)$ is defining in the Eq. (4). The values of these

parameters used in the best fits of saline and desalinated filter paper results are summarized in Table 1.

Table 1. Values of the best fits curves for both materials.

	θ_{sat}	θ_r	S_1	a	b	C_r
Sal	0.55	0.18	0.00	5e+07	2.54	1391.04
Des	0.51	0.17	0.00	98.23	0.97	69.59

The measured SWRCs of the saline and desalinated materials are depicted in Fig. 1. According to this figure, the SWRC of the saline materials is laid above the curve of the desalinated material. Thus the retention capability of the saline material is higher than the desalinated one. Also, the difference between the saline and desalinated SWRCs is due to the osmotic potential of the saline materials. In other words, because the total suction of the materials is measured, the osmotic suction appeared in the total suction of saline materials.

Following the objective set to study the effect of rainfall infiltration in the instability of the railway embankment and the fact that the degree of saturation of the embankment is rising in the analysis, the soil-water retention curves are measured in the wetting branch.

Fig. 1. SWRCs of the saline and desalinated materials (Sal: Saline, Des: Desalinated, BF: Best Fit, FP: Filter Paper).

2.3 Unsaturated hydraulic conductivity functions

The unsaturated hydraulic conductivities of the materials are estimated based on the measured SWRCs and saturated hydraulic conductivities [12].

$$k_w = k_s \frac{\sum_{i=j}^N \frac{\Theta(e^y) - \Theta(\psi)}{e^{y_i}} \Theta'(e^{y_i})}{\sum_{i=1}^N \frac{\Theta(e^y) - \Theta_s}{e^{y_i}} \Theta'(e^{y_i})} \quad (2)$$

where k_w is the calculated conductivity for a specified water content or negative pore-water pressure (m/s), k_s is the measured saturated conductivity (m/s), θ_s is the volumetric water content, e is the Euler's number 2.71828, y is a dummy variable of integration representing the logarithm of negative pore-water pressure, i is the interval between the range of j to N , j is the least negative pore-water pressure to be described by the final function, N is the maximum negative pore-water pressure to be described by the final function, ψ is the suction corresponding to the j^{th} interval, and Θ' is the first derivative of the equation (3).

$$\Theta = C(\psi) \frac{\Theta_s}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^n \right] \right\}^m} \quad (3)$$

where a is approximately the air-entry value of the soil, n is a parameter that controls the slope at the inflection point in the volumetric water content function, m is a parameter that is related to the residual water content, and $C(\psi)$ a correcting function defined as

$$C(\psi) = 1 - \frac{\ln \left(1 + \frac{\psi}{C_r} \right)}{\ln \left(1 + \frac{10^6}{C_r} \right)} \quad (4)$$

where C_r is a constant related to the matric suction corresponding to the residual water content.

The saturated hydraulic conductivities are measured by the falling head test method for the fine-grained materials [13]. The measured values for the saline and desalinated materials are 1.14×10^{-8} and 0.81×10^{-8} m/s, respectively.

The predicted unsaturated hydraulic conductivity functions of the materials are depicted in Fig. 2. According to this figure, in the suction range higher than 1 kPa, the desalinated soil has lower hydraulic conductivity than the saline one.

Fig. 2. Unsaturated hydraulic conductivity functions of the four materials.

2.4 Rainfall infiltration patterns

As it is mentioned previously, the site under investigation is located in one of the arid regions of Iran, as depicted in Fig. 3. Consequently, the rate of water infiltration is relatively low. Fig. 3 illustrates the average long-term precipitation of all provinces of Iran. According to the reported meteorological data of Chabahar station, the maximum effective amount of the rainfall is 87.20 mm [14].

For the purpose of illustrating the effect of the rainfall infiltration on the slope instability of the embankment, two rainfall patterns, including two different intensities with two different durations, are adopted in this study. The details of selected rainfall patterns are summarized in Table 2.

Fig 3. Long-term precipitation zoning of Iran in 2018.

Table 2. Details of two rainfall infiltration patterns.

	Intensity (mm/day)	Duration (days)	Total amount of rainfall (mm) [14]
Low Intensity	8.72	10	87.20
High Intensity	43.60	2	

3 Numerical modeling

The numerical analyses have been performed through SEEP/W and SLOPE/W software for simulating precipitation and examining the factor of safety of the embankment, respectively. The numerical model, with its finite element mesh is plotted in Fig. 4. The model is divided into two main regions including the railway embankment with a height of 5 m, the width of 6 m, and the slope of 1:2 (1 vertical: 2 horizontal), and the stratum with the height of 20 m, and width of 56 m.

Fig. 4. Geometry and the finite element mesh of the numerical model.

Fig 5. Contours of pore water pressure distribution for different conditions; (a) Saline soils under high-intensity infiltration, (b) Saline soil under low-intensity infiltration, (c) Desalinated soil under high-intensity infiltration, and (d) Desalinated soil under low-intensity infiltration.

3.1. Transient flow analyses

For the initial hydraulic condition of the transient flow analyses, the groundwater table is placed at a depth of 18 m, and the soil suction above the water table is hydrostatically distributed toward the ground level. The groundwater table as an initial condition for the distribution of soil suction in the profile of the model is just a simplification due to the lack of measurements and other scenarios for variations in suction with depth like inverse profile to high suctions could also happen [15]. The more rigorous methodology is to run a field monitoring of pore water pressure regime up to such relatively deep layers based on advanced tensiometry [16].

After the specification of initial soil suction distribution, transient analyses are applied to the model by adjusting the specific flux on the top of the model. In each transient analysis, the pore water pressure distribution is determined by simulating the rainfall infiltration in two different patterns and used in the consequent slope stability analyses.

3.2. Slope stability analyses

After each transient flow analysis, a slope stability analysis was carried out to investigate the variation in the factor of safety of the embankment for each rainfall pattern. The factor of safety is calculated with the limit equilibrium method, and the equilibrium equations are solved through the Spencer method [17]. The shear strength of the materials is determined from the modified Mohr-Coulomb criterion for the unsaturated soils [18]:

$$\tau = c' + \sigma_n \tan \phi' + (u_a - u_w) \tan \phi^b \quad (5)$$

where τ is the unsaturated shear strength, c' is the effective cohesion, σ_n is the net stress, ϕ' is the effective friction angle, u_a is the pore-air pressure, u_w is the pore-water pressure, and ϕ^b is an angle defining the increase in strength due to the negative pore-water pressure. The value of ϕ^b for the materials is assumed to be 14.6° . In addition, the unsaturated unit weight of the materials is calculated in each step according to the SWRCs of the materials. Moreover, the total train and track loads are assumed to be 170 kPa, according to the allowable subgrade bearing pressure of the embankment [19].

4 Results

4.1. Pore water pressure distributions

Pore pressure distribution at the symmetry axis of the model for two saline and desalinated materials during the two high and low-intensity infiltrations is depicted in Fig. 5, at 6 time-steps. All four sub-figures show the distribution at time steps of zero, 2, 5, 10, 28, and 90 days. The zero-day represents the initial condition; therefore, in all of them, the initial pore water pressure distribution is hydrostatic. Fig. 5(a) illustrates the pore water pressure distribution of the saline materials during the high-intensity rainfall. According to this specific distribution, the pore water pressure dramatically increases during the first two days of the infiltration.

Consequently, soil suction completely diminishes. Additionally, the wetting front infiltrates gradually through the whole 90 days of the analysis, and it gives rise to a trivial increase in the groundwater table level. Fig. 5(b) indicates the results of the saline soil model under the low-intensity precipitation. According to this specific distribution, the pore water pressure gradually increases during the infiltration and consequently, soil suction decreases and reaches the zero amount after 5 days. After the infiltration, the soil suction again increases in the profile. Meanwhile, the wetting front infiltrates gradually through the whole 90 days of the analysis, and it brings about an increase in the groundwater table level. The comparison of both high and low intensity infiltration concludes that intensity could have a contribution at the groundwater level in the sense that the groundwater rises more if the duration is longer. Figs. 5(c) and (d) show the pore water pressure distribution for desalinated materials under high and low-intensity precipitations, respectively. As shown in these two figures, rainfall cannot infiltrate in the desalinated embankment and the soil suction just diminishes in the first few meters of the embankment. In other words, in such conditions the major part of the rainfall runs off the embankment and does not infiltrate in the deeper layers. The observed difference between the rate of the infiltration in two saline and desalinated embankments is due to the significant difference between the unsaturated hydraulic conductivities of the materials (Fig. 2). The higher the unsaturated hydraulic conductivity, the higher the rate of the infiltration; thus, the higher the rate of drop in suction. As a result, if the salinity of the soil decreases, the unsaturated hydraulic conductivity of the soil will reduce in accordance with less retention capability of desalinated soil. Therefore, water cannot infiltrate in the soil stratum, and the soil suction will not significantly decrease.

4.2. Factor of safety

The initial safety factors of the saline and desalinated embankments are revealed to be 2.398 and 2.410, respectively. Although the initial suction distribution is identical in both materials, this slight difference between these two initial factors of safety is due to the different unsaturated unit weight which was calculated based on the SWRCs. Since desalinated materials have the lower capability of water retention, they are dryer than the saline soils at the same suction; in consequence, the unsaturated unit weight of desalinated materials is less than the saline ones and they have the higher initial factor of safety. Variations in the safety factor of the embankment under the different rainfall patterns are indicated in Figs 6 to 9. Variations in the safety factor of both saline and desalinated embankments under the high-intensity precipitation are shown in Fig. 6. According to the results, the safety factor of both saline and desalinated models decreases during the infiltration, but the rate of their decrease is considerably different. The factors of safety of saline and desalinated embankments under the high intensity rainfall reach the

minimum amount of 2.107 and 2.351, respectively. During the whole time of the analysis, the saline embankment has a smaller factor of safety than desalinated ones due to the enhanced rainfall infiltration in the saline model. In addition, the factor of safety of the saline model starts to recover at the end of the rainfall, but desalinated one constantly decreases.

Fig. 7 shows the variations in the safety factor of both saline and desalinated embankments under the low-intensity rainfall. The initial safety factors of both embankments are identical to the previous amounts due to the same initial conditions. Similar to the previous analysis, the safety factor of the desalinated embankment is greater than the saline one under the low rate of raining. The minimum amount of factor of safety of saline and desalinated embankments are equal to 1.692 and 2.345, respectively. After 90 days, the factor of safety of saline embankments reaches 2.106.

Fig. 6. Variations in factor of safety with time under the high-intensity rainfall.

Fig. 7. Variations in factor of safety with time under the low-intensity rainfall

Figs. 8 and 9 compare the factor of safety variations of each embankment under different rainfalls. The factor of safety of saline embankment under both rainfall patterns is depicted in Fig. 8. As shown in this figure, the factor of safety under the low-intensity rainfall is lower than that corresponding to the high-intensity one. As the wetting front can proceed to deeper zones in the low-intensity rainfall, the decrease of the suction is more significant; thus, the factor of safety becomes lower. The factor of safety variation of desalinated embankment under both rainfall patterns is illustrated in Fig. 9. Although the reduction in the factor of safety is not as significant as the saline embankment, the low-intensity condition is still more critical than the high-intensity one

due to the same reason. Moreover, the comparison between the results of Figs. 8 and 9 also suggests that the impact of rainfall intensity on the stability of saline materials is more pronounced than desalinated materials. According to the results of numerical analyses, the desalinated embankment has a relatively higher factor of safety in comparison with that of the saline embankment in all studied conditions. All the differences between the safety factors of saline and desalinated embankments are based on the remarkable differences between the pore water pressure distributions in the models. As discussed earlier, the rainfall infiltrates easier when the salinity of the soil increases; therefore, the factor of safety decreases due to the decrease in the soil suction and shear strength.

Fig. 8. The influence of rainfall intensity on variations in factor of safety with time for the saline embankment.

Fig. 9. The influence of rainfall intensity on variations in factor of safety with time for the desalinated embankment.

4 Conclusion

The salinity has a dramatic influence on dispersion potential and the behavior of dispersive soils. Therefore, its influence on the stability of a railway embankment under different patterns of rainfalls was investigated in this study under transient seepage. Two main types of materials with different salinities including saline and desalinated soils were applied to the numerical model. The measured water retention formulation revealed that by omitting the natural salinity in the soil-water, the retention ability of the soil decreases due to the decline of the osmotic suction; therefore, the unsaturated hydraulic conductivity of the soil stratum will significantly decline. According to the results of transient flow and slope stability analyses during the

rainfall, rainfall can readily infiltrate in the saline embankment and cause a significant decline in the soil suction; consequently, the factor of safety of the embankment declines. On the other hand, in the desalinated materials, since the water cannot infiltrate into the embankment easily, the suction of the soils does not decrease very much; thus, the factor of safety of the desalinated materials declines slightly. Additionally, the study of the rainfall infiltration revealed that the intensity of the rainfall has a more notable impact on the instability of the embankment constructed with saline materials, rather than desalinated ones. However, the lower the intensity of the rainfall, the lower the factor of safety against failure of the railway embankment.

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