Stability analysis of a railway embankment on a collapsible-dispersive stratum under transient flow

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ABSTRACT

Collapsible-dispersive soil is one of the most challenging types of problematic soils having the adverse effects of both collapsible and dispersive soils for construction. A natural occurrence of this type of soil was recently encountered along some part of the Chabahar-Zahedan railway line in Southeast of Iran. Indeed, the construction phase was stopped after facing several geotechnical problems along the railway embankment partly constructed such as local and general subsidence, non-uniform settlements of structural elements, etc. Relatively high natural porosity as well as pore water salinity were found responsible for those problems. Therefore, this study aims to conduct a three-phase numerical study to investigate the effect of dispersion potential on the stability of the railway embankment. Results of numerical simulations are compared and discussed for two types of collapsible soil with and without dispersion potential. Results reveal a notable reduction in factor of safety with an increase in pore water salinity. It is postulated that the reduced factor of safety in the saline soil can be attributed to its higher unsaturated hydraulic conductivity compared with that of desalinated the soil.

Keywords: Collapsible; Dispersive; Numerical modeling; Unsaturated soils; Slope stability

1 INTRODUCTION

Collapsible soils are spread all over the world including Asian countries such as China (Ng et al., 2016), and Iran (Sadeghi et al., 2019). Collapsible soils have a metastable structure provided by the stiffening effects of suction at unsaturated states. However, the stabilizing influence of suction may vanish due to a rise in degree of saturation. Therefore, the special microstructure of collapsible soils results in notable differences in several macroscopic features from water retention to shear strength and stiffness degradation curve (Sadeghi, 2016; Ng et al. 2017a & b).

The problems arise from collapsible soils become worse when there is water salinity either from natural or industrial agents, enhancing the dispersion potential. The salt content in a soil can cause piping in geotechnical structures such as earth dams and road embankments. Moreover, salt content affects the geotechnical properties of soils (Shariatmadari et al., 2011). For example, as the salt content increases, the Atterberg limits, compression and swelling indexes decrease, albeit the coefficient of consolidation increases (Ajalloeian et al., 2013).

If the dispersion potential exists in a collapsible soil, challenges for geotechnical design and construction become double. For example, some part of the national Chabahar-Zahedan railway embankment close to the Mokran coastline crosses through this type of soil deposits has faced serious geotechnical problems (Sadeghi et al., 2019). One of the most important factors responsible for these problems is pounding due to the seasonal rainfalls. In fact, the railway line crosses the upper end of the Lipar dike upstream. As rainfall happens, parts of the embankment essentially act as a dike under transient flow. The permeability of soil stratum is low and hence a perched water table forms at shallow depths. Nevertheless, the main water table was reported to locate more than 15 m below ground surface, where the deep tensiometry is inevitable for reliable monitoring of pore water pressure regime in long term (Sadeghi et al., 2018). Therefore, the soil strength dramatically drops causing collapse and local deformations in the embankment. Furthermore, salt seems to play an adverse role in the state of stability.

Accordingly, the main objective of this study is to investigate the influence of soil water salinity on the stability of a railway embankment sitting on a collapsible-dispersive soil stratum. For this purpose, two types of material with natural salinity and without salinity were chosen for the transient flow analyses. The adopted numerical analyses simulate the process of water drawdown as a heavy rainfall incident followed by the dry season, being typical of the climatic conditions in the studied area. The difference between saline and desalinated materials appears in the soil-water retention curves (SWRCs) and hence unsaturated hydraulic conductivities. Differences in SWRCs are accordingly considered by the influence of salt on the liquid limit of test materials. It should also be noted that the embankment is assumed to be constructed with compacted materials, while the foundation of the embankment is assumed to have the natural compaction state. More important, an un-coupled numerical approach was adopted where the soil was considered non-deformable.

2 MATERIAL PROPERTIES

2.1 Geotechnical Properties

The dispersive collapsible soil discussed in this study was characterized by Sadeghi et al. (2019). The fraction of sand, silt, and clay in the natural soil is 29%, 37%, and 34%, respectively. The natural soil is classified as clayey loess with moderately dispersive to dispersive characteristics. The specific gravity and the *in-situ* dry density are equal to 2.75 and 1150 kg/m^3, respectively. It is noted that the soil structure is so porous due to the extremely low *in-situ* dry density. Naturally, the soil has salt content, delivering a liquid limit as much as 40. In this study, another material is presumed to be desalinated, representing the material without salt content, and, the liquid limit for this material is assumed to be 60. This assumption was made based on previous studies on the effect of salt on the Atterberg limits. In addition, for the stability analyses, the geotechnical properties for both natural compaction and the standard Proctor compaction are considered. For the materials of the embankment, the standard compaction ratio of 90% of the maximum dry density is adopted (Earth Works for Railway Lines General Technical Specifications Code). The geotechnical properties of test materials are detailed in Table 1.

Table 1. Geotechnical properties of soils at natural state and compacted with the standard Proctor effort.

Material	γ_d (kN/m^3)	*e*	ϕ (°)	*c* (kPa)
Natural state	11.53	1.39	29.8	1.8
Standard Proctor	14.85	0.85	29.1	2.5

2.2 Soil-Water Retention Curve

The *in-situ* test reports revealed that the groundwater table was not observed up to a depth of 15 m. Therefore, employing the principles of unsaturated soil mechanics is inevitable. The most important parameters for solving a transient flow is the soil-water retention curve. In this study, the SWRC is estimated from the basic geotechnical parameters for fine-grained soil including, liquid limit, void ratio and the specific gravity (Aubertin et al., 2003). According to some realistic assumptions made, the foundation of the embankment is always saturated after rainfall incident. Therefore, it is not necessary to consider the unsaturated properties for the materials with the natural compaction. Consequently, the SWRC of the compacted soil is predicted in the presence and absence of salt. Results shown in Figure 1 reveal that saline soil has a less water retention capability in comparison with desalinated soils with the identical soil properties but the salt content.

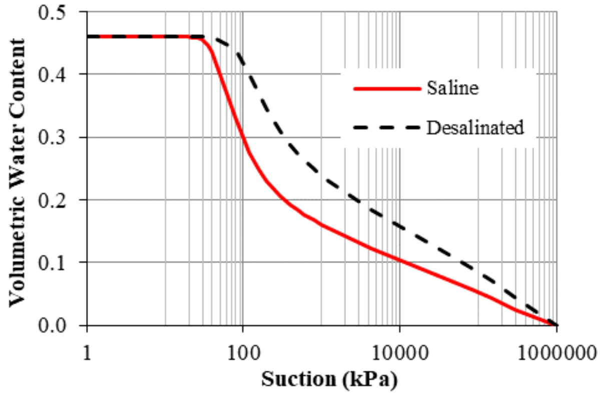

Fig. 1. Soil-water retention curves of saline and desalinated soils with 90% of γ_{dmax} obtained from the standard Proctor procedure.

2.3 Unsaturated Hydraulic Conductivity Functions

The saturated hydraulic conductivity of the material has to be determined for estimating the unsaturated hydraulic conductivity. For this purpose, the saturated hydraulic conductivities are estimated from Mbonimpa et al. (2002). The estimated saturated hydraulic conductivity for the standard and natural compacted soils are 0.2×10^{-9} and 1.3×10^{-9} m/s, respectively.

Figure 2 indicates the hydraulic conductivity functions inferred from the two corresponding SWRCs following the method of Fredlund and Xing (1994). It is necessary to determine the unsaturated hydraulic conductivity for conducting transient analysis. Results confirm the fact that hydraulic conductivity generally declines with suction. More important, the desalinated soil consistently have a higher hydraulic conductivity compared with the saline one at a given suction level.

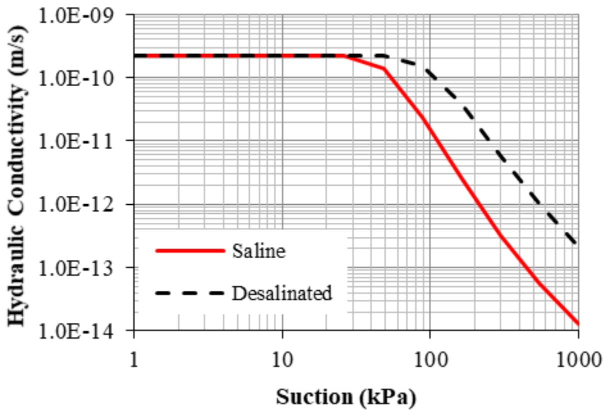

Fig. 2. Unsaturated hydraulic conductivity functions for the two types of soils compacted with the standard Proctor effort.

3 NUMERICAL MODELING

The softwares used in this study are SEEP/W and

SLOPE/W for transient flow analyses and slope stability of the embankment, respectively. The geometry was designed according to the Earth Works for Railway Lines General Technical Specifications code and is shown in Figure 3. According to this code, the minimum allowable width of the embankment for one-way lines is 6 m, and, the allowable slope of the embankment is 1:2.

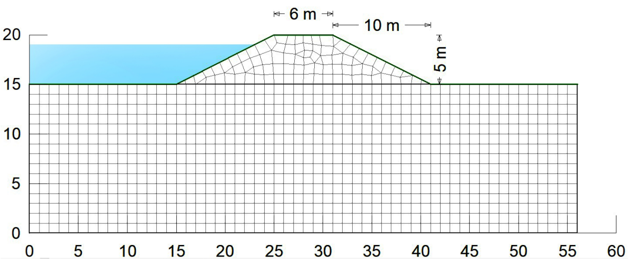

Fig. 3. Geometry and finite element mesh of the model.

3.1 Transient Flow Analysis

In the wet seasons, water level rises and eventually forms a pound at the upstream of the railroad embankment due to the heavy rainfalls and thereafter, the embankment acts like a small earth dam. Following the wet season, the water level in upstream drops down during the hot dry season until any sign of water disappears.

According to this process, a transient flow occurs. This study focuses on the drawdown transient flow of water through the embankment. Therefore, a transient flow analysis is exerted to the finite element model following a steady state analysis, representing the presence of the highest water level at the upstream (Figure 3). In the transient analysis, it is assumed that the water level falls from 4 m above the ground to the ground level in 20 days. The pore water pressure results determined from the transient analysis are used for the slope stability analyses.

3.2 Slope Stability Analysis

According to the Iran national railway code, the total load of the track is assumed to be 52.1 kN/m distributed load, and the service load of 80 kN/m uniform distributed loads are assumed to be mirrored similar to the two point loads with the magnitude of 250 kPa, as depicted in Figure 4. The factor of safety of the embankment is determined at each time step after the transient flow analysis. The shear strength of the materials is determined from the modified Mohr-Columb criterion for the unsaturated soils. In this study, the unsaturated part of the shear strength is calculated from the corresponding SWRCs (Vanapalli et al., 1996). The factor of safety is calculated by the limit equilibrium method following the Spencer method for solving the equilibrium equations (Spencer, 1967).

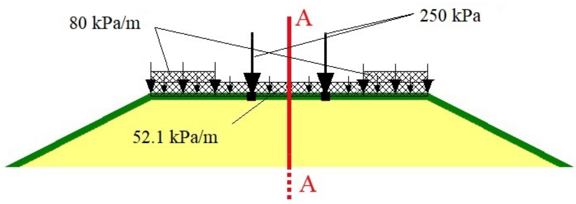

Fig. 4. Working loads applied on the railway embankment.

4 SIMULATION RESULTS

The pore water pressure distribution along section A-A (Figure 4) at the 90th day after initiation of water drawdown is shown in Figure 5. The pore water pressure in the saline soil is consistently higher than the corresponding value for the desalinated soil. According to Figure 1, the retention ability of the saline soil is lower than the desalinated soil, so the unsaturated hydraulic conductivity of the saline soil becomes lower than the desalinated soil, as depicted in Figure 2. Therefore, the excess pore water pressure of the saline soil dissipates slower than the excess pore water pressure of the desalinated soil. This explains the difference between the pore water pressure distribution in both saline and desalinated soil in the 90th day along the embankment. The excess pore water pressure almost dissipates in desalinated soil, while the corresponding value of the saline soil has still a value of about 5 kPa at the bottom of the embankment in 90th day. This, indeed, highlights the role of salt content in governing the water pressure regime.

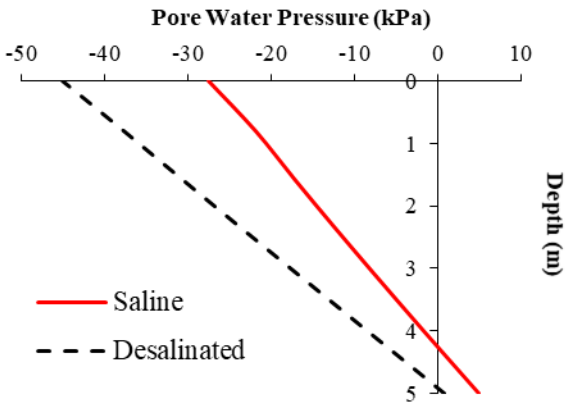

Fig. 5. Distribution of pore water pressure along the embankment centerline (A-A in Fig. 4) after 90 days of dewatering.

The factor of safety of embankment with both saline and desalinated soils is depicted in Figure 6. The factor of safety in the saline embankment is lower than that of desalinated soil due to the difference between pore water pressure distribution and hence the shear strength.

At the beginning of water drawdown, the factor of safety decreases due to the loss of supporting water weight in the equilibrium during the first 10 days. Afterwards, the factor of safety rises because of the generation of suction through the embankment. Results show that the factor of safety of the saline embankment drops below unity and the embankment fails at the 5th day, albeit, the factor of safety of the desalinated embankment never drops below one. According to the results, it can be concluded that the salt content or in other word, the dispersion potential has a major effect on the stability of geotechnical structures. Field observations also confirm this outcome since serious problems such as slope failures, structural damages to the culverts, and subsidence were documented (Sadeghi et al., 2019).

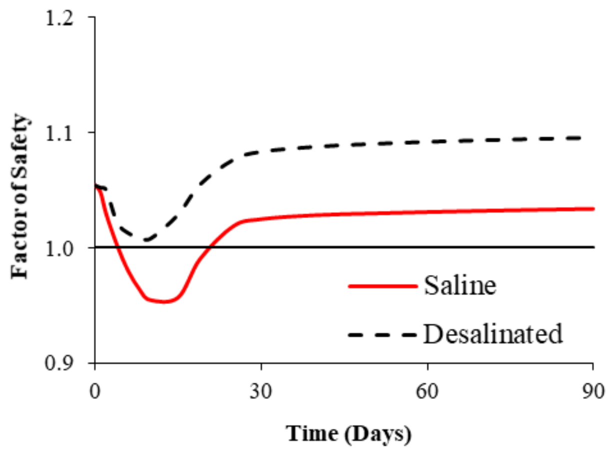

Fig. 6. Factor of safety for the railway embankment being constructed from saline and desalinated soils.

5 CONCLUSIONS

The aim of this study was to investigate the influence of salt content or dispersion potential on the unsaturated flow regime and its impact on the stability of a railway embankment constructed with collapsible-dispersive soils. A reduction in water retention capability of soil with increasing the salt content, resulted in a downward shift in the unsaturated hydraulic conductivity function. This in turn delayed the dissipation of the excess pore water pressure and hence delivered a lower shear strength compared to the case with desalinated soil. Consequently, the factor of safety of the embankment drastically decreased with an increase in salt content. Results revealed that a critical condition where the factor of safety falls below unity could readily occurs due to the notable influence of pore water salinity on flow characteristics and subsequent distribution of water pressure and effective stress.

REFERENCES

Ajalloeian, R., Mansouri, H. and Sadeghpour, A.H. (2013). Effect of saline water on geotechnical properties of fine-grained soil, *Electronic Journal of Geotechnical Engineering*,18: 1419–34.

Aubertin, M., Mbonimpa, M., Bussiere, B. nad Chapuis R.P. (2003). A model to predict the water retention curve from basic geotechnical properties, *Canadian Geotechnical Journal*, 40: 1104–1122.

Fredlund D.G., Xing A. and Huang S. (1994). Predicting the permeability function for unsaturated soils using the soil-water characteristic curve, *Canadian Geotechnical Journal*, 31(4): 533-546.

Leong, E.C. and Abuel-Naga H. (2018). Contribution of osmotic suction to shear strength of unsaturated high plasticity silty soil, *Geomechanics for Energy and the Environment*, 15: 65-73.

Management and Planning Organization Office of Deputy for Technical Affairs, Technical Criteria and Specification Bureau, (2004). Earth works for Railway Lines; General Technical Specifications; No: 279.

Mbonimpa, M., Aubertin, M., Chapuis, R.P. and Bussiére, B. (2002). Practical pedotransfer functions for estimating the saturated hydraulic conductivity, *Geotechnical Geological Engineering*, 20(3): 235–259.

Ng, C.W.W., Baghbanrezvan, S., Sadeghi, H., Zhou, C. and Jafarzadeh, F. (2017). Effect of specimen preparation techniques on dynamic properties of unsaturated fine-grained soil at high suctions. *Canadian Geotechnical Journal*, 54(9), 1310-1319. https://doi.org/10.1139/cgj-2016-0531

Ng, C.W.W., Sadeghi, H., Hossen, S.B., Chiu, C.F., Alonso E.E. and Baghbanrezvan S. (2016). Water retention and volumetric characteristics of intact and re-compacted loess, *Canadian Geotechnical Journal*, 53(8): 1258-1269. https://doi.org/10.1139/cgj-2015-0364

Ng, C.W.W., Sadeghi, H. and Jafarzadeh, F. (2017b). Compression and shear strength characteristics of compacted loess at high suctions. *Canadian Geotechnical Journal*, 54(5), 690-699. https://doi.org/10.1139/cgj-2016-0347

Sadeghi, H. (2016). A Micro-Structural Study on Hydro Mechanical Behavior of Loess. PhD thesis. Hong Kong University of Science and Technology & Sharif University of Technology.

Sadeghi, H., Chiu, C.F., Ng, C.W.W. and Jafarzadeh, F. (2018). A vacuum-refilled tensiometer for deep monitoring of *in-situ* pore water pressure. *Scientia Iranica*. DOI: 10.24200/sci.2018.5052.1063.

Sadeghi H., Kiani M., Sadeghi M. and Jafarzadeh F. (2019). Geotechnical characterization and collapsibility of a natural dispersive loess, *Engineering Geology*, https://doi.org/10.1016/j.enggeo.2019.01.015

Shariatmadari N., Salami M. and Karimpour Fard M. (2011). Effect of Inorganic Salt Solutions on Some Geotechnical Properties of Soil-Bentonite Mixtures as Barriers, *International Journal of Civil Engineering*, 9(2): 104-111.

Spencer, E. (1967). A Method of Analysis of Embankments assuming Parallel Inter-Slice Forces, *Géotechnique*, 17(1): 11-26.

Vanapalli, S.K., Fredlund D.G., Pufahl, D.E. and Clifton, A.W. (1996). Model for the Prediction of Shear Strength with respect to Soil Suction, *Canadian Geotechnical Journal*, 33: 379-392.