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An Investigation of the Dilation Effect of Soil on Liquefaction-Induced Settlement

M. H. Nakhaee, A. Bazrafshan Moghaddam*

Department of Civil Engineering, Shahrood University of Technology, Shahrood, Iran

ABSTRACT: In this paper, the effect of the amount of dilation angle on the settlement of the structure due to the occurrence of liquefaction has been investigated. In this research, the dilation effect related to the density and confining stresses during liquefaction on structural settlement is investigated using OpenSEES. Therefore, a sand layer with different dilation angles and surface load is considered. The numerical model presented in this research calculated the excess pore water pressure based on fully coupled effective stress analysis during seismic loading. Model parameters were selected and verified using the results of VELACS centrifuge tests. The results showed that by increasing the dilation angle, the pore water pressure decreases, and the liquefaction-induced settlements decrease. The decreasing trend of settlement with increasing dilation angle tends to a constant value, so that at high densities with increasing dilation angle, little changes in the settlement were observed. Also, the dilation angle was calculated based on the pre-shear mean effective stresses and compared with the dilation angle caused by the stresses during liquefaction. The comparison shows that for relative densities less than 60%, the dilation angle obtained from pre-shear effective stress is more than the confining stress-based method during liquefaction.

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1. INTRODUCTION

Theoretical and field studies have shown that there are three types of factors that control soil liquefaction, including seismic parameters, ground conditions, and soil parameters, and a total of 22 parameters affecting soil liquefaction have been identified, the most important of which is relative density [1]. In this study, with the change of relative density, the effect of dilation angle on the structural settlement during liquefaction has been investigated. Due to the uncertainty in calculating the dilation angle and the lack of relationships and resources in this field, the effect of the dilation parameter by considering the effect of effective stresses has not been properly considered, which is addressed in this study.

2. THEORY

In the present study, the saturated soil system is modeled based on the two-phase system based on Biot theory for porous media. The soil was modeled using Young's multi-yield model for liquefied soils using OpenSEES software. In this method, simulation based on the cumulative shear strain mechanism due to liquefaction in clean sand is emphasized. Special attention has also been paid to dilation under cyclic loading. Based on what has been accepted in classical plasticity theory, it is assumed that the behavior of materials is linear and isotropic, and nonlinearity and anisotropicity are the results of plasticity. The yield function used in this study is in the form of conical surfaces in a stressful environment, the tip of which is along the hydrostatic axis [2].

2.1. Dilation angle

The dilation angle is calculated based on two relations. The first equation is the one proposed by Schanz & Vermeer [3] in which the maximum stresses that occur in the soil profile during liquefaction occurrence are calculated to obtain the maximum liquefaction-resistant dilation angle. Based on this, the dilation angle is determined according to an inherent property of the soil, namely the porosity ratio, as well as the main principal stresses in the soil, i.e., σ_1 and σ_3. These parameters, as well as relative density, are also the most important factors affecting liquefaction. At an initial value of the ratio of porosity or relative density, ψ decreases with σ_3 increasing. Therefore, the dilation angle is a function of relative density and confining stresses. The shear behavior of sand under drained shear conditions, at constant vertical pressure, is similar to triaxial conditions [3, 4]. The proposed Schanz & Vermeer relation for the dilation angle is as follows [3]:

$$\sin\Psi = \frac{I_R}{6.7 + I_R} \tag{1}$$

*Corresponding author's email: amir.bazrafshan@shahroodut.ac.ir

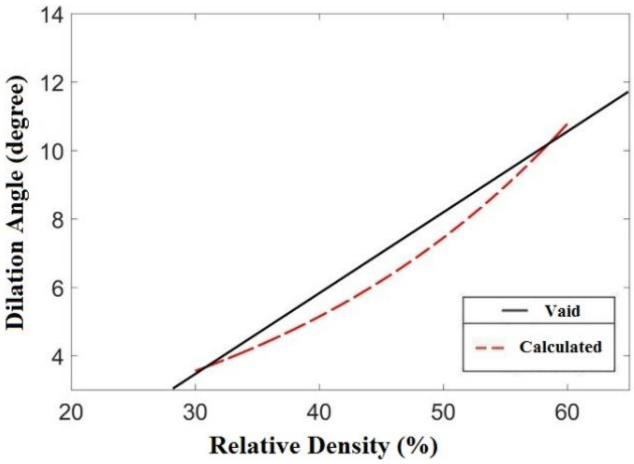

Fig. 1. Dilation angles in different relative densities of the middle soil layer at a depth of two meters below the foundation.

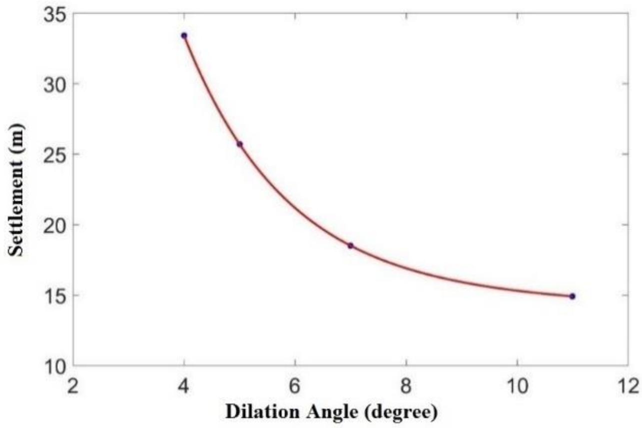

Fig. 2. Changes in the settlement in terms of dilation angle based on Eq. (2).

The second relation has been proposed by Cinicioglu and Abadkon [5] which is a newer relation and based on the average effective stress of the soil sample before shear and its relative density. The above researchers showed that the dilation angle has a direct and linear relationship with the soil effective stress before shear, which is as follows:

$$\tan \psi = \alpha_{\psi} (\frac{P_i'}{P_a}) + m_{\psi} I_D \quad (2)$$

3. MODELING

The soil used is saturated sandy soil with different relative densities. The parameters suggested by the OpenSEES Guide are not a function of soil compaction and are mostly based on the recommendations of Mazzoni *et al*. [6]. Therefore, to obtain density-dependent parameters, the research of Chen *et al*. [7] has been used. PDMY material model has been used for sand. The behavior of these materials is elastoplastic, which is used to simulate soil responses such as expansion and contraction under loading. In rapid dynamic loading, the stress-strain path is elastoplastic. Plasticity is based on the principle of multi-yield and with non-associative law to reproduce the effect of dilation. Yield surfaces are expressed according to the Drucker-Prager criterion. The model includes a profile with a height of 30 meters and a width of 100 meters. First, a dense layer with a thickness of one meter is considered on the ground surface to prevent the occurrence of liquefaction and therefore liquefaction occurs at depth. Then the liquefied soil layer with different relative densities with a thickness of 2 m is considered. The soil profile was affected by the 1995 Kobe earthquake with a maximum acceleration of 0.36 g. The only drainage from the soil surface is allowed. Lateral boundaries are absorbent and can move laterally. First, the model with the middle layer with a density of 30% is modeled and analyzed, then in other densities of 40, 50, and 60% to study the effect of these changes in relative density and dilation on the settlement of structure and also excess pore water pressure and soil liquefaction. The rigid foundation is located in the middle of the model with a width of 10 meters and a linear load of 200 kN/m. The value of this load is selected according to the article by Vaid *et al*. [4]. The model includes 714 elements and 774 nodes. The elements used for the soil are Quadup type and the lateral boundaries of the Lysmer-Kuhlemeyer adsorbent have been used to prevent the interference of the return waves of the earthquake [8]. Foundation is modeled in two dimensions using the Beam-on-Nonlinear-Winkler-Foundation (BNWF).

4. RESULTS AND DISCUSSION

Fig. 1 compares the diagram of changes in the angle of expansion versus density with the diagram of Wade *et al*. It was observed that the results of this numerical analysis are close to the graph obtained from the experiments of Wade *et al*. It should be noted that the dilation angle obtained in this study, unlike the method of Wade *et al*., Depends on the density and all-round stresses and the difference between the two graphs is due to this.

Examining Fig. 2, it can be seen that at dilation angles of less than 7 degrees (relative densities less than 50%), the settlement has increased significantly and the slope of the settlement-dilation angle curve has become much steeper.

5. CONCLUSION

In this paper, the effect of the magnitude of dilation angle on the settlement of the structures due to the occurrence of liquefaction was investigated. The results of this study showed that with an increase of the dilation angle of the soil, settlement decreases but the decreasing trend of settlement is not linear and asymptotes towards a constant value. However, at high dilation angles, increasing the dilation angle led to slight changes in the settlement. Also, the dilation angles obtained during liquefaction showed that the increase in the dilation angle occurred with the reduction of the excess pore water pressure and cyclic stresses, and as a result, the foundation settlement decreased. Since the angle of soil friction is a function of soil density, it follows a similar pattern to changes in density concerning settlement and the angle of dilation. Also, the dilation angle was calculated based on the mean effective stresses before the occurrence of liquefaction and was compared with the state during the occurrence of liquefaction. The results showed that for relative densities less than 60%, the dilation angle calculated based on the effective stresses before shear is greater than that of during liquefaction. Also, as the dilation angle increases, the rate and amount of settlement decrease.

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