Simulation of sandy soil degradation due to static liquefaction along with the uncertainty in soil properties

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ABSTRACT For loose saturated sand, when subjected to static loading in undrained condition, the pore water pressure inside the soil tends to increase and the effective stress tends to decrease to zero resulting in the degradation of the soil structure, this phenomenon is called static liquefaction. Although static liquefaction has been studied for decades, it is still necessary to have a better understanding about this kind of soil behavior and its effect on the structure safety. In this research paper, the NorSand model was used to evaluate the static liquefaction of Hostun sand RF. The input parameters of the model were determined based on the experimental data. After that, the triaxial paradigm was built to modelized the triaxial experimental test. And then, the modeling sample was subjected to static loading until reaching the axial strain of 30%. This process gives the clear observation of the degradation of the modeling sample with the variation of deviator stress, pore water pressure in function of deformation development. The results show that under static loading, the deviator stress of the modeling sample reaches the maximum at very small axial strain, after that, the deviator stress decreases to almost 0 corresponding to degradation of soil structure. The modeling sample was liquefied at the end of loading process with zero effective stress condition. The results also present the input parameters for NorSand model which give the suitable fitting between the modeling and experimental results. Thereafter, the effect of relative density uncertainties on the soil degradation was studied. The model predictions show that for fully saturated loose sandy soil, maybe there is a critical value for the relative density, and when the relative density is greater than this value, the degradation on the soil structure will not occur. Finally, NorSand model can provide a theoretical basis for the design of structures with considering the uncertainties on soil parameters.

Keywords Soil structure degradation, Saturated loose sand, Triaxial undrained test, Static liquefaction, NorSand model, Uncertainties, Structure safety

I. INTRODUCTION

As a common construction material in civil engineering (transportation and water conservancy), the mechanical properties of sandy soil are the focus of basic research in engineering and construction, and a hot spot in geotechnical research, the liquefaction of sandy soils is one of the issues of particular concern. The idea of static liquefaction was initially introduced during the evaluation of hydrostatic landslide hazards. In 1975, Castro [1-4] was the first to propose the concept of static liquefaction and conducted an analysis of the conditions that lead to liquefaction. The main reason for its generation is that when a saturated soil is in a situation where it cannot be drained, the pore water pressure inside the soil increases continuously due to the static load, which causes loss of shear strength and reduction of effective stress in the soil, and eventually leads to a phenomenon in which the soil exhibits fluid-like characteristics. This phenomenon can also be considered as the degradation of soil mass, which will have a huge impact on the stability of engineering structures.

In this paper, the finite element simulation method was used to simulate the whole mechanical process to show the degradation of sandy soil during static liquefaction. Through this simulation, the effect of relative density of saturated sandy soil on soil degradation is analyzed. Thereafter, the soil liquefaction potential was discussed. This research also gives the data to model the behavior of Hostun sand RF, a reference material usually used in laboratory testing, using Norsand model; however, not mentioned clearly in literature.

II. MATERIAL

The study material of this paper is Hostun sand RF, and the undrained properties of Hostun sand RF under very looseness are obtained by combining the experimental results in the literature [5], where FIGURE 1 shows the particle shape size of Hostun sand RF under microscope [6], and FIGURE 2 shows the particle distribution of Hostun sand RF, and comparing it with the particle gradation of liquefaction-prone material and non-liquefaction-prone material [7], it can be seen that Hostun sand RF is in between.

FIGURE 1. Hostun sand RF under the microscope [6]

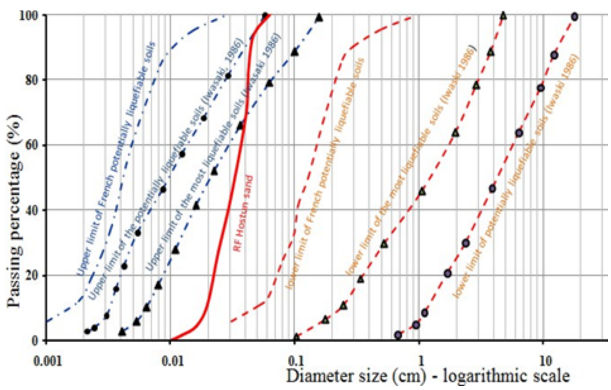

FIGURE 2. Comparison of particle gradation of Hostun sandy soil and liquefaction-prone material, and non-liquefaction-prone material [7]

TABLE 1 lists the basic physical properties of Hostun sand obtained from the literatures [8-9]. The specific gravity of this sandy soil is 2.65, its maximum and minimum void ratios are 1.041 and 0.648, respectively, and the friction angle of this material is around 40°. In addition, since the material used in this paper is sandy soil, it is necessary to know the limiting (D_{60}) and effective

(D_{10}) particle sizes of the soil, from this, the uniformity coefficient C_u ($C_u=D_{60}/D_{10}$) can be calculated, and Cu<5, the sandy soil is uniformly and poorly graded.

TABLE 1. Particle size composition and basic physical property index of Hostun sand RF [8-9]

Grain specific weight ρ (g/cm3)	D_{60}(μm)	D_{10}(μm)	e_{max}	e_{min}	Friction angle φ (°)
2.65	400	200	1.041	0.648	40

III. ISOTROPIC TRIAXIAL UNDRAINED TEST OF SATURATED SAND

A. Isotropic triaxial undrained shear strength characteristics of saturated sand

As shown in Figure 3 (a-b) [21], the undrained shear test controls the volume of the soil specimen by preventing drainage during shear, which results in a change in pore water pressure. Negative pore water pressure is generated when the soil tends to expand, while positive pore water pressure is generated when the soil tends to contract. Dense sand produces positive and then negative pore water pressures, and the shear strength increases almost linearly until failure. Very loose sand shrinks during shear, resulting in a decrease in shear strength that may lead to soil degradation. The effective stress path is bent to the left for loose sand and to the right for dense sand, while moderately dense sand shrinks during dilational deformation, making it difficult to attribute the volumetric deformation of sandy soils exclusively to density [11].

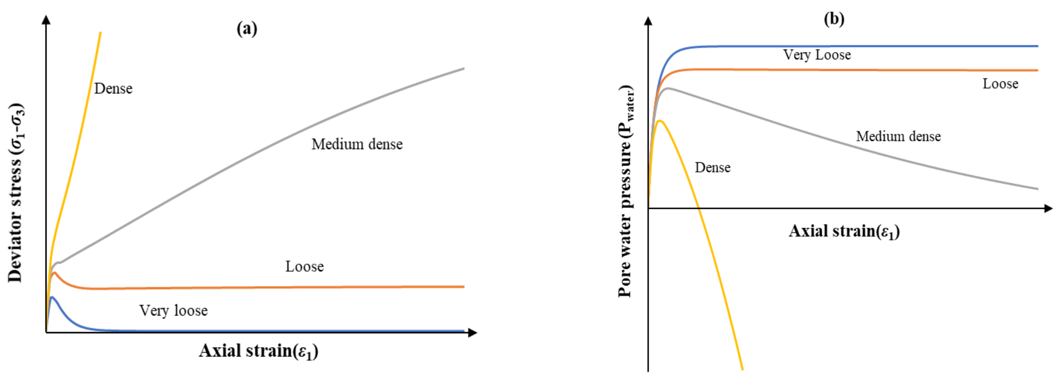

FIGURE 3. Triaxial undrained test of saturated sand [21]:
(a-b) stress-strain curves

B. Isotropic triaxial undrained test of saturated loose Hostun sand RF

The experiment in this paper were taken from the literature [5], which conducted an isotropic triaxial undrained test on Hostun sand RF with the test characteristics shown in TABLE 2. The type of test was an undrained test, the saturation of the specimen was fully saturated, the void ratio before shearing was 1.007, from Table 1 and Equation 1, the relative density before shearing of the saturated sample in this experiment can be calculated as 8.7% (very loose), and the confining stress was controlled at 100 kPa. The size of the sample is a standard triaxial sample with a height of 140mm and a diameter of 70mm.

TABLE 2. **Characteristics of isotropic triaxial undrained tests on Hostun RF sand**

	Test type	Saturation	Confining stress	The void ratio before shearing	The relative density before shearing
Experimental test [2]	Undrained	Fully saturated	100 kPa	1.007	8.7%

The experimental results are shown in FIGURE 4, where FIGURE 4(a) shows the relationship curve between the deviator stress and the axial strain, which shows that the shear strength of the soil reaches the peak when the strain is very small, and then decreases sharply (close to 0) as the strain increases, and then remains stable. This test has a very obvious strain softening phenomenon with similar characteristics to the very loose sandy soil in Fig. 3(a). In geotechnical engineering this phenomenon is called static liquefaction, which can be explained using FIGURE 4(b). Due to the undrained condition, the pore water pressure in the soil increases rapidly, which leads to a decrease in the effective stress in the soil, even close to 0, the structure of soil degrades and develops characteristics similar to that of liquid.

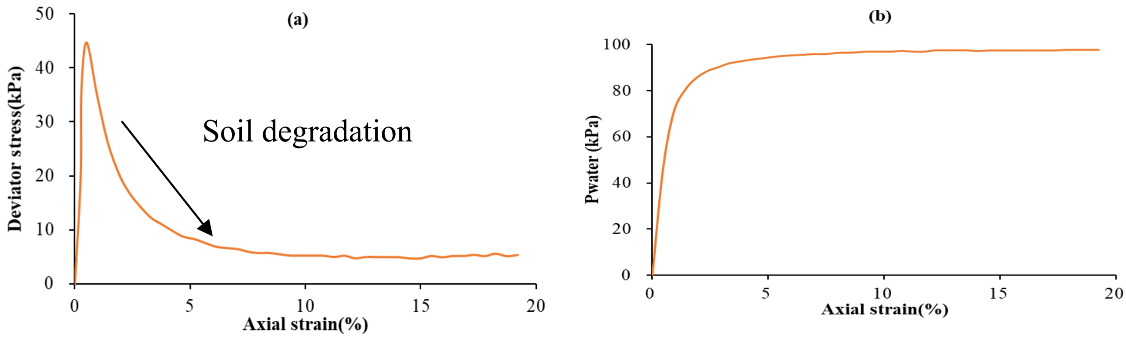

FIGURE 4. **Experimental relation curve between measured excess pore water pressure, deviatoric stress with axial strain of fully saturated Hostun sand RF [11]**
(a) Deviator stress-strain curve and (b) Pore water pressure-strain curve

To consider the probabilistic notion of void ratio measurement in experimental tests presenting in figure 5(a) [7], the lines corresponding to the interval of void ratio distribution are shown in figure 5(b). The lines with their equations can be used in calculating the probabilistic of soil degradation potential.

(a) **(b)**

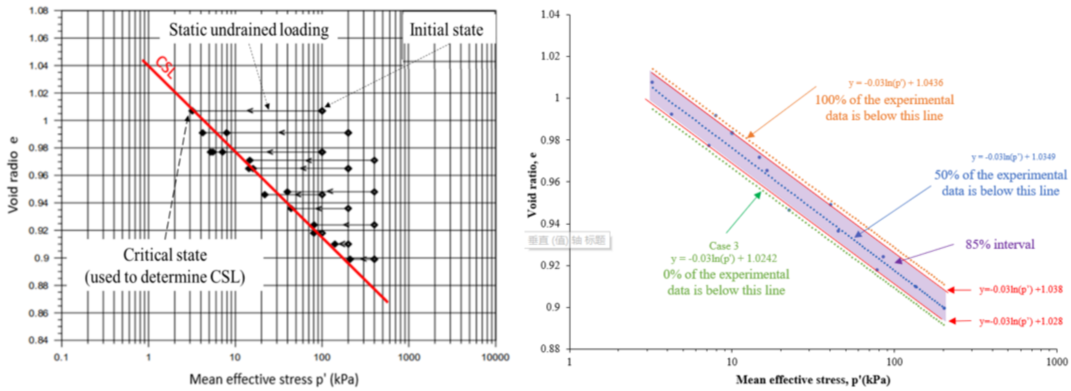

FIGURE 5. Probabilistic notion of void ratio measurement in experimental tests

IV NUMERICAL SIMULATION

A. Norsand model

The characteristics of soil are affected by many factors, such as the change of confining pressure and void ratio, the strength and deformation of soil will be greatly changed. Although these characteristics can be obtained through experimental methods, it is extremely labor-intensive, material and time consuming. Therefore, a useful constitutive model can predict the strength changes and deformation characteristics of soils quickly, cheaply and with sufficient accuracy.

The NorSand model, first proposed by Mike Jefferies [12], is a critical state model for sands and is capable of accurately capturing soil behavior from static liquefaction of very loose sands to swelling of very dense sands. The NorSand model is primarily used to simulate the large deformation behavior of sands, up to failure, and is particularly suitable for analyzing the static liquefaction behavior of soils [13-14]. In addition, the soil parameters of the NorSand model are independent of void ratio and confining stress, which means that the parameter values remain constant for each type of soil. And the NorSand model requires relatively few soil parameters, which can be estimated by laboratory experiments or in situ tests, as shown in TABLE 3, the soil parameters required for the NorSand model and the values of each parameter for the Hostun sand RF are listed.

Although the NorSand model has been widely used to simulate the liquefaction behavior of sand, there are still some limitations when using the model to simulate the liquefaction phenomenon in sand. The main limitation is that the model is based on homogeneous and isotropic sand, so there may be errors when simulating non-homogeneous or anisotropic sand. In addition, the model assumes that the sand is in a fully saturated state and does not consider the influence of fine particle content on liquefaction behavior, so there may also be errors in predicting the results when simulating sand with fine particles or partial saturation. However, in this study, these limitations can be ignored because the experimental material used is the Hostun sand RF, which does not contain any fine particle content, and the saturation state is fully saturated, so the error caused by these limitations can be negligible.

TABLE 3. Soil parameters of NorSand model [15]

Description	Parameters	Values
Critical state locus	'Altitude' of CSL: Γ	1.00
	Slope of CSL: λ_e	0.03
Dilation limit	Material parameter : χ_{tc}	4
Strength parameter	Critical friction ratio : M_{tc}	1.4
	Material parameter : N	0.35
Plastic hardening	Hardening parameter : H_o	100
	Hardening parameter : H_Ψ	0
Elasticity	Reference value of the shear modulus at the reference pressure: G_{ref}	15000
	Exponent of the power-law elasticity: n_G	0.5
	Poisson's ratio : ν	0.2

B. Modeling of isotropic triaxial undrained test of saturated loose Hostun sand RF

In this study, the finite element method is used to simulate the undrained shear test of saturated sandy soil using PLAXIS 2D software. The size of the specimen is shown in FIGURE 6(a) as a standard triaxial specimen with a height of 140 mm and a diameter of 70 mm, with two symmetrical axes and the top of the specimen simulating shear by applying pressure to the specimen through the attachment of a top-cap.

The model size does not have an effect on the simulation results because the soil sample is set as a weightless material during the simulation [17-18]. Therefore, the axisymmetric model in PLAXIS 2D was chosen for the simulation, a quarter of the sample is taken along the two symmetry axes of the sample for the simulation as shown in FIGURE 6 (b), where FIGURE 6(b) shows the implementation in the software simulation. Its deformation boundary conditions are similar to those of laboratory tests. In this calculation, a medium mesh was chosen. The deformation along the symmetrical axes is normally fixed, and only smooth movement along the symmetrical axis is allowed, while the deformation perpendicular to the symmetrical axis is free, the applied distributed load simulates the deviator stress and confining stress respectively.

In addition, because this test is an undrained test, all boundaries are impermeable, that is, there is no water flow, so after the pressure is applied, excess pore water pressure will be generated inside the sample.

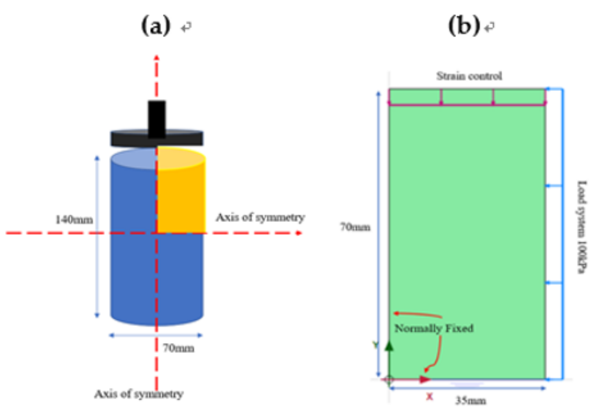

FIGURE 6. Simulation of undrained triaxial test

(a) The size of the specimen, (b) Numerical simulation

C. Comparison of experimental and numerical simulation results

After the modeling was completed, the results were compared with the experimental results, as shown in FIGURE 7(a), it can be seen that with the increase of axial strain, both the simulated and experimental results its overall trend is consistent, from the very beginning of the rapid increase in shear strength to the peak followed by a rapid decline close to 0, from the obvious strain softening of the simulation results, one can see that the NorSand model is able to simulate the degradation (liquefaction phenomenon) of sandy soil well. As far as the accuracy of the simulation is concerned, it can be seen that the peak shear strength of the simulated and experimental results is about 0.5% of the axial strain, where the peak strength of the simulated results (45.7 kPa) is very close to that of the experimental results (44.7 kPa), and the maximum difference of the shear strength in the range of 2%-8% of the axial strain is about 2 kPa.

From FIGURE 7(b), it can be seen that the general trend of the simulated and experimental results is also basically the same, with the increase of axial strain, the pore water pressure increases rapidly from 0 to the maximum value, and then remains stable, this change of pore water pressure is the main reason for soil structure degradation. The difference between the simulated (98.1 kPa) and experimental (97.8 kPa) maximum pore water pressure values is not significant, in the range of 0-8% axial strain, the maximum difference of pore water pressure between numerical simulation and experimental test is 4 kPa.

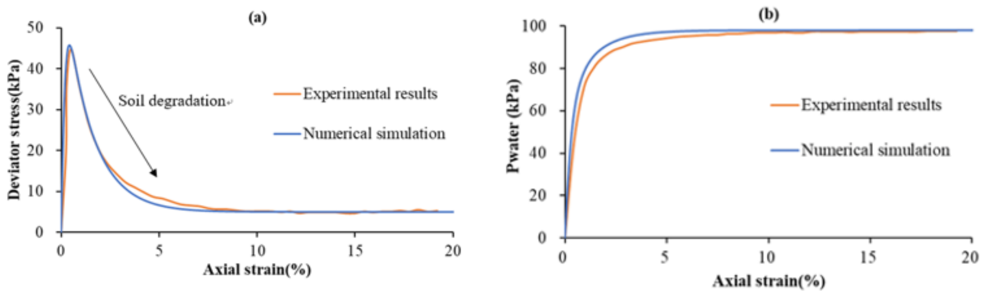

FIGURE 7. Comparison between numerical simulation and experimental results: (a)Deviator stress-strain curves and (b) Pore water pressure-strain curves

D. Sensitivity analysis to relative density

It is known that the undrained shear strength of sand is influenced by factors such as relative density, effective confining stress and saturation, and the mechanical behavior of sand can vary under different conditions. The degradation of soil structure is closely related to its shear strength, in order to unilaterally study the uncertainties of relative density on the degradation of sandy soil, only change the relative density of sand under the control of other factors, use the NorSand model to simulate and predict the mechanical behavior of saturated Hostun sand RF from very loose (D_r =5%) to loose (D_r =30%).

As shown in FIGURE 8 (a), it is a stress-strain curves with relative density from 5% to 30%. It can be seen that with the increase of relative density, the peak strength of sand also increases continuously, this is because with the increase of relative density, the soil become more and more dense, and the ability to resist shear will become stronger and stronger. However, the axial strain corresponding to the peak strength has little change (<1%), which shows that the relative density of soil has little effect on the axial strain when the soil reaches the peak strength. In addition, after the peak strength appears, the stress-strain curves will show a downward trend, and the downward range continue to decrease with the increase of the relative density until the strength reach the minimum value. After reaching the minimum stress, with the increase of axial strain, when the relative density is less than or equal to 25%, the stress-strain curves begin to stabilize, and when the relative density is 30%, the shear strength increase slowly with the increase of axial strain.

FIGURE 8 (b) shows the relationship curves between pore water pressure and axial strain under different relative density. It can be seen that with the increase of axial strain, the pore water pressure in soil also increases to the maximum value due to undrained conditions, and the maximum value decreases with the increase of relative density. After the pore water pressure reaches the maximum, with the increase of axial strain, when the relative density is less than or equal to 25%, the pore water pressure no longer change and remain stable, while for the sample with the relative density of 30%, there be a slow decay.

Soil degradation is very dangerous for the safety of engineering structures, the pore pressure ratio (R_u) is often used in geotechnical engineering to discern whether liquefaction has occurred [19-20], and R_u is calculated as shown in Equation 2.

$$R_u = \frac{P_{excess}}{\sigma_1'} \tag{2}$$

Where P_{excess} is the excess pore water pressure, and σ_1' is the principal effective stress in the initial state, when $R_u > 0.95$, the calculation point is considered to be liquefied, and in order to prevent this phenomenon, it can be seen that increasing the relative density of soil can effectively prevent soil degradation by combining FIGURE 8 (c). For the very loose saturated sandy soil (D_r <15%) is the most prone to degradation, which is because the pore water pressure at this time is greater than 95kPa, and the effective stress of the soil basically tends to 0 under the premise of the confining stress of 100kPa, this means that according to equation 2, the pore pressure ratio (R_u) is greater than 0.95, so it is considered that liquefaction occurs and the soil structure is degraded. As the relative density increases, the pore water pressure of the sandy soil decreases from very loose to loose (15% < D_r < 35%) and the effective stress increases, the pore pressure ratio (R_u) is smaller than 0.95, thus making it more resistant to degradation.

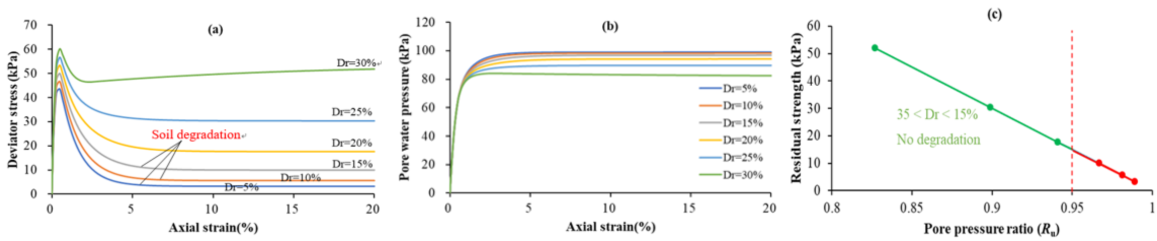

FIGURE 8. Effect of simulated relative density on RF shear strength of saturated Hostun sand (a-b) Stress-Strain curves and (c) Residual strength-Pore pressure ratio curve

V CONCLUSION

This paper investigates and analyzes the undrained properties of saturated sandy soils, then to combine the experimental data in the literature to verify the applicability of the NorSand model, and then, the NorSand model was used to analyze the uncertainties of soil degradation from the perspective of relative density. The conclusions drawn from this study are summarized as below.

1. The NorSand model has limitations in simulating undrained sand behavior, only applicable to uniform, and fully saturated sand. However, the soil in reality can be in unsaturated state with the void ratio distributing around a mean value. And it is necessary to have more study to take into account the effect of saturation degree and the distribution law on the degradation of soil due to the liquefaction.
2. In undrained experiments with saturated sandy soils, bulk variation causes a change in pore water pressure. Shearing dense sand generates negative pore water pressure, increasing soil shear strength, while shearing loose sand generates positive pore water pressure, decreasing soil shear strength.
3. The NorSand model agrees well with experimental data for very loose Hostun sand RF. At small axial strains (<1%), deviatoric stress in the soil reaches a maximum, rapidly decreasing (close to 0) and then stabilizing.
4. Simulation results demonstrate that relative density of saturated sandy soil strongly affects soil degradation due to the liquefaction. As relative density increases, soil resistance increases. The most susceptible to soil degradation is when relative density is below 15%.

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