SIMULATION OF MONOTONIC AND CYCLIC TRIAXIAL TESTS ON NATURAL SAND

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Abstract

Extensive experimental research program on element tests have been performed on natural sand from the Vardar river terraces in the city of Skopje. The Skopje sand is planned to be used in longer terms for research at the laboratory for Soil Dynamics at IZIIS-Skopje. Thus, proper, detailed and accurate definition of the parameters of the Skopje sand is the most crucial point in numerical simulation and analysis. The focus of this paper is on numerical simulation of the performed monotonic (drained and undrained) and cyclic triaxial tests on Skopje sand. Preparation of a good set of parameters is basis for further more detailed numerical analysis od 2D shaking table tests and possible simulation of experiments and behavior with different constitutive sand models.

In order to be able to investigate a wider range of behaviour, the series of element tests on the Skopje sand were performed under different relative density (40%, 55% and 75%) and different level of effective stresses (50 kPa, 100kPa, 200kPa and 400kPa). For the triaxial tests**,** the wet tamping method was used for preparation of the samples. The numerical simulation was done by the ANSYS computer program, using the hypoplastic model in three phase soil media. All results were compared with previously performed experimental and numerical investigation on Toyoura sand.

In numerical simulation of the monotonic undrained and drained triaxial tests, it is observed that the numerical simulation leads to correct prediction of evolution of strain and stress. The results show a good agreement between the experimental values and the numerical simulations of the volume change versus axial strain and pore pressure development. Moreover, sufficient consideration of the current state of soil medium is obtained. The small number of model parameters makes the used approach advantageous when compared with other models.

For the cyclic triaxial tests simulation, for the hysteresis loop of stress strain relation for CSR < 0.2, it can be observed that numerical simulation follows the curve of the experimental pore pressure development although there are differences in the middle range of values. The beginning and the mid values of the numerical simulation show a good agreement. However, as the number of cycles increases, the difference between the loops of the numerical and experimental values increases. Thus, based on the performed simulation, a statement can be made that the numerical model can fully satisfactorily simulate the monotonic behavior of the Skopje sand, whereas the cyclic behavior can simulate it until a certain level of pore pressure generation and strain development. Some comments and recommendations are given to investigate the possibility for simulation the large strain behaviour of the sand with other constitutive models.

Keywords: triaxial tests; natural sand; numerical simulation.

1. Introduction

Soils are complex multiphase materials whose stress-strain-strength is characterized by pressure dependency with coupling between volumetric and shear behavior. For example, during drained shearing, dense sands and highly overconsolidated clays tend to dilate, while loose sands and normally consolidated clays tend to contract (when drainage is prevented, undrained shearing is accompanied by shear-induced pore pressures). In general, soils do not have a well-defined region of linear behavior (even at small strain levels) and exhibit unstable strain-softening behavior in some modes of deformation. Anisotropic properties are associated with the structure, depositional environment and subsequent straining of most natural soils. Time dependent behavior (such as variation in response at different strain rates, creep, and relaxation) can be significant for some soils, but it is often difficult to distinguish it from the consolidation effects in the field where soil deformations are accompanied by displacement caused of pore water.

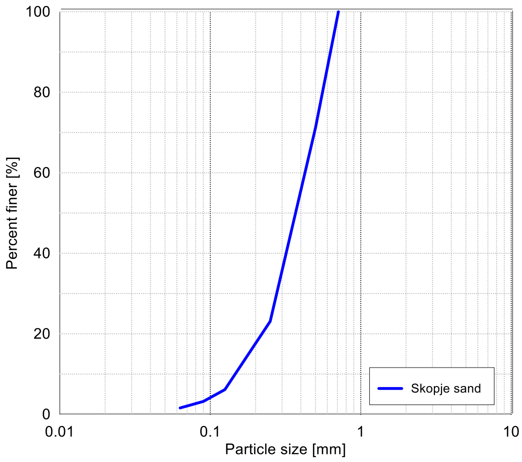
In view of these complexities, it is not possible to think in terms of developing a completely generalized model for all soils. It is important to tailor the modeling of material behavior to the particular problem of interest and the required accuracy of solution.

In this research, simulation of triaxial tests is performed using the hypoplastic constitutive model for the solid state of the porous soil medium. The comprehensive triaxial experimental investigation was previously performed on a natural river sand – the Skopje sand at the Institute of earthquake engineering and engineering seismology – IZIIS, Skopje, Macedonia. The hypoplastic numerical simulation was performed as a basis for further numerical simulation of shaking table tests on laminar box and further calibration and comparison with other constitutive models for sand behavior.

2. Experimental program

2.1 Skopje sand

Skopje sand is representative natural sand from the river terraces of the Vardar River, which flows through Skopje city. The shape of the sand particles is subangular and homogeneous as it can be seen from the grain size distribution in Figure 1. From the detailed silicate analysis, it is obtained that the sand mostly consists of silica oxides [1]. The physical properties of Skopje sand are given in Table 1.



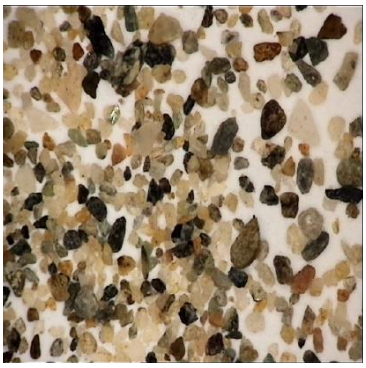


Fig. 1 – Particle size distribution (left) and particle shape (right) of Skopje sand

Table 1 – Physical properties of Skopje sand

e_{min} (Mimimum void ratio)	e_{max} (Maximum void ratio)	Gs [kN/m^3] (Specific gravity)	D_{50} [mm] (Median particle size diameter)	Cu (Uniformity coefficient)	Cc (Coefficient of curvature)
0.95	0.51	2.615	0.26	1.8	0.8

2.2 Triaxial testing program

In order to be able to investigate a wider range of behaviour, the monotonic (drained and undrained) series of element tests on the Skopje sand were performed under different relative density (40%, 55% and 75%) and different level of effective stresses (50 kPa, 100kPa, 200kPa and 400kPa). As a preparation method wet tamping was used [2]. The cyclic triaxial tests were performed for 100 kPa effective stress and frequency of 0.5 Hz according to the ASTM standard [3]. Review of the performed tests is given in Table 2. All tests were performed on the dynamic triaxial system at the laboratory for Soil Dynamics and Geotechnical Engineering in IZIIS Skopje, Macedonia. More detailed explanation can be found in Bojadjieva (2015), [4].

Table 2 – Performed triaxial tests of Skopje sand

Dynamic triaxial tests - symmary							
No. test	Type of test	type fo control	Relative density	Effective stress	CSR	preparation method	other specific informations
1	cyclic	load control	40%	100	0.1	wet tamping	frequency 0.5Hz
2					0.15		
3					0.2		
4					0.25		
5					0.3		
6					0.5		
7			55%		0.1		
8					0.2		
9					0.3		
10					0.5		
11			75%		0.2		
12					0.25		
13					0.3		
14					0.5		
15	monotonic compression drained	strain control	40%	50	/	wet tamping	loading rate 0.2mm/min
16				100			
17				200			
18				400			
19			55%	50			
20				100			
21				200			
22				400			
23			75%	50			
24				100			
25				200			
26				400			
27	monotonic compression undrained	strain control	40%	50	/	wet tamping	loading rate 0.2mm/min
28				100			
29				200			
30				400			
31			55%	50			
32				100			
33				200			
34				400			
35			75%	50			
36				100			
37				200			
38				400			

3. Numerical simulation

Numerical simulation was performed for the triaxial monotonic and cyclic tests. The numerical simulation was done by the ANSYS computer program, using the hypoplastic model. The numerical analysis was closely correlated with the previously done research in the Department of Geotechnics by Edip (Edip, 2013 & Edip et al.,(2018)), [5], [6]. Edip incorporated the hypoplastic model in three-phase soil media and performed simulation of triaxial tests on the Toyora sand. The simulation of the experiments on the Skopje sand is, in a certain way, a continuation of the previously done research.

3.1 Parameters for hypoplastic model of Skopje sand

Hypoplastic equations provide a simplified description of loose and dense unbounded granular materials. In the theory of hypoplasticity, the stress-strain relation is established by means of an incremental nonlinear relation without any recourse to yield or boundary surfaces. This nonlinearity is reflected by the relation between the incremental stress and the incremental strain.

In the work of Wu [7], based on the incrementally nonlinear tensorial functions, a hypoplastic model is presented as an alternative approach to the prevailing elasto-plastic models in describing the mechanical behavior of granular materials. The corner stones pertinent to elasto-plasticity such as yield surface, plastic potential, decomposition of the deformation into elastic and plastic parts, hardening and flow rule are abandoned to be used in formulating the constitutive model. A constitutive model with a simple mathematical formulation and with only eight material constants is achieved. Hypoplastic constitutive models, as given in the works of (Gudehus, 1996) and (P. A. von Wolffersdorff, 1996), [8], [9] describe the evolution of the effective stress tensor as a non-linear tensorial function of the current void ratio, stress state and rate of deformation.

In order to obtain the material constants needed for the hypoplastic material model, the following procedure has to be followed, as given by Numeius & Herle, [10]:

• The critical friction angle ϕ_c can be determined from undrained triaxial tests or from cone pluviation tests. In the cone pluviation test, ϕ_c is the inclination of the cone;

• The granular hardness h_s and the exponent n describe the decrease of the void ratios e_i, e_c, e_d and initial void ratio with the increase of the mean pressure. The constants may be obtained from tests with a proportional compression, i.e. a compression with a linear path of deformation starting from the stress-free state. For this purpose, odometric compression tests are suitable. Ideally, the initial void ratio of the tests should be chosen in the range $e_{c0} < e_0 < e_{i0}$. However, $e_0 = e_{max}$ is thought to be a satisfactory initial state.

• According to Herle, the void ratios for asymptotic states at p = 0 can be estimated from $e_{i0} \approx 1.15\ e_{max}$, $e_{c0} \approx e_{max}$ and $e_{d0} \approx e_{min}$.

• The constant α controls the influence of density on the peak friction angle.

The obtained hypoplastic parameters for the Skopje sand can be summarized in Table 3.

Table 3 Hypoplastic parameters for Skopje sand

Material	φ_c [°]	h_s [MPa]	n	e_{d0}	e_{c0}	e_{i0}	a	b
Skopje sand	31	2000	0.27	0.51	0.95	1.093	0.2	1.2

3.2 Monotonic triaxial tests

The average stress strain curve comparison and volume change versus axial strain curve between the experimental and numerical values for drained conditions is given in Fig. 2. In the undrained case, the stress strain, the pore pressure development are given in Figure 3. Regarding the results, it should be mentioned that the figures clearly demonstrate the influence of the confining pressure on the stress development in the samples. As can be seen from the presented results, the numerical model with hypoplastic material modeling of the solid phase is capable of simulation of the effects from confining pressures in a successful way. The results show a good agreement between the experimental values and the numerical simulations of the volume change versus axial strain and pore pressure development.

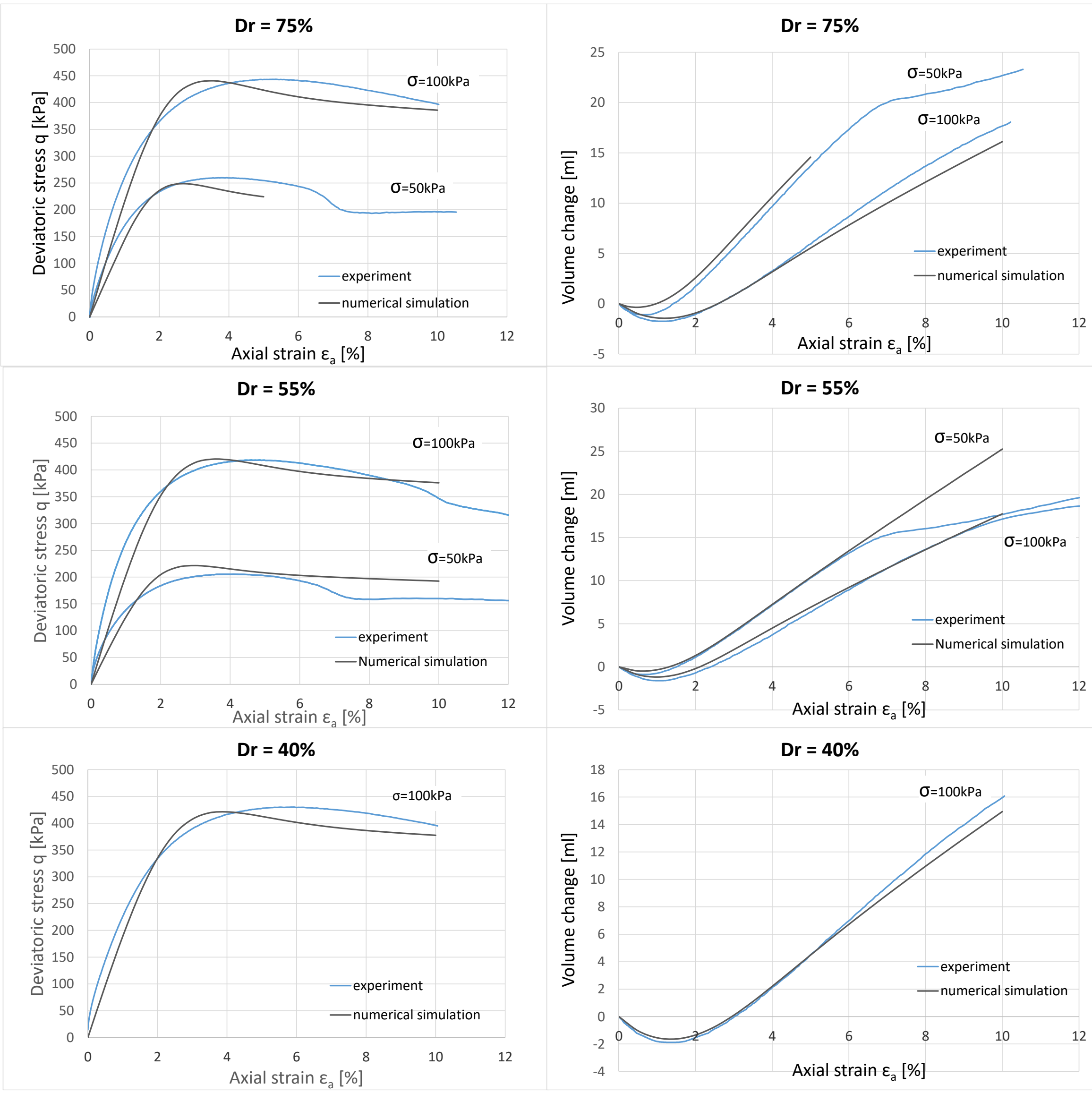


Fig. 2 Simulation of drained monotonic triaxial test on Skopje sand

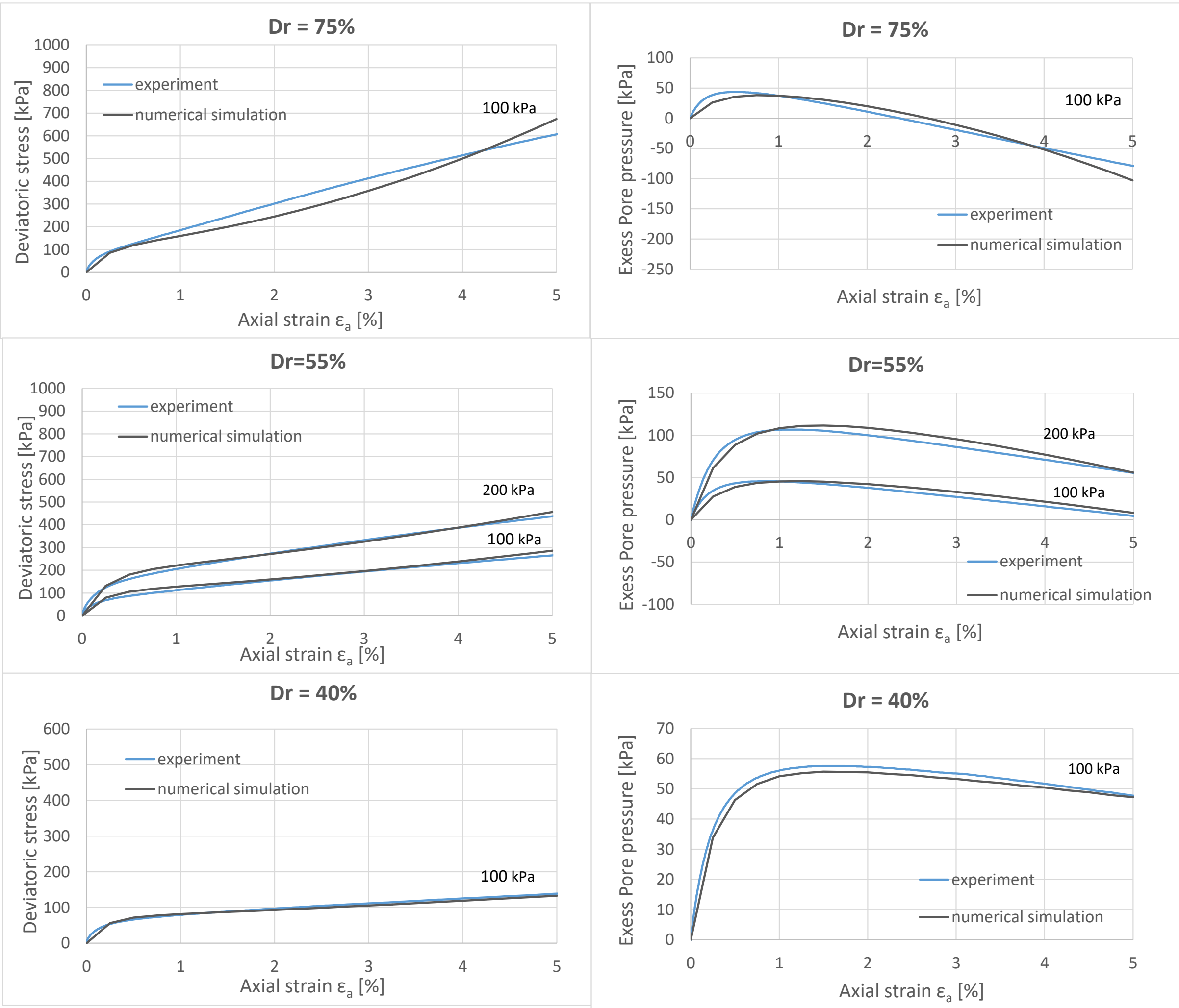


Fig. 3 Simulation of undrained monotonic triaxial test on Skopje sand

3.3 Cyclic triaxial tests

Several cyclic triaxial experiments with different sinusoidal excitation were simulated. For a sample with Dr=40% and cyclic stress ration of 0.25 comparison of experiments with performed numerical simulation is presented in Figure 4.

The development of pore pressure compared to the number of cycles and the applied cyclic loading for the experiment and numerical simulation are given in Figure 4 (left). The comparison of recorded hysteresis loops of stress strain relation for CSR=0.25 (Dr=40%) are shown in Figure 4 (right), starting from the first cycle up to the third cycle. For the first cycles the numerical values of pore pressure development show a satisfying agreement with the experimental ones. The development of pore pressure continues until the point of initiation of liquefaction. At that particular point, the line begins to vibrate showing that the soil specimen has lost its capacity of resisting the applied load. The numerical simulation, on the other hand, although with differences in values, follows the state of increment until the point of liquefaction where the analysis is finished.

From the results it can be observed that the numerical simulation follows the curve of the experimental pore pressure development at the first cycles, whereas for larger deformation the model cannot simulate the stress strain curve and no failure is obtained in the numerical simulation. As can be seen from the results, the initial and the mid values of the numerical simulation show a good agreement with each other. However, as the number of cycles increases, the difference between the loops of the numerical and experimental values increases. This is mainly due to the fact that the soil sample begins to liquefy in such a way that the strain levels of the soil sample increase suddenly, which is not possible to simulate numerically with the hypoplastic model since this particular model considers small deformation only. Further upgrade of the constitutive models for application in large deformation is necessary.

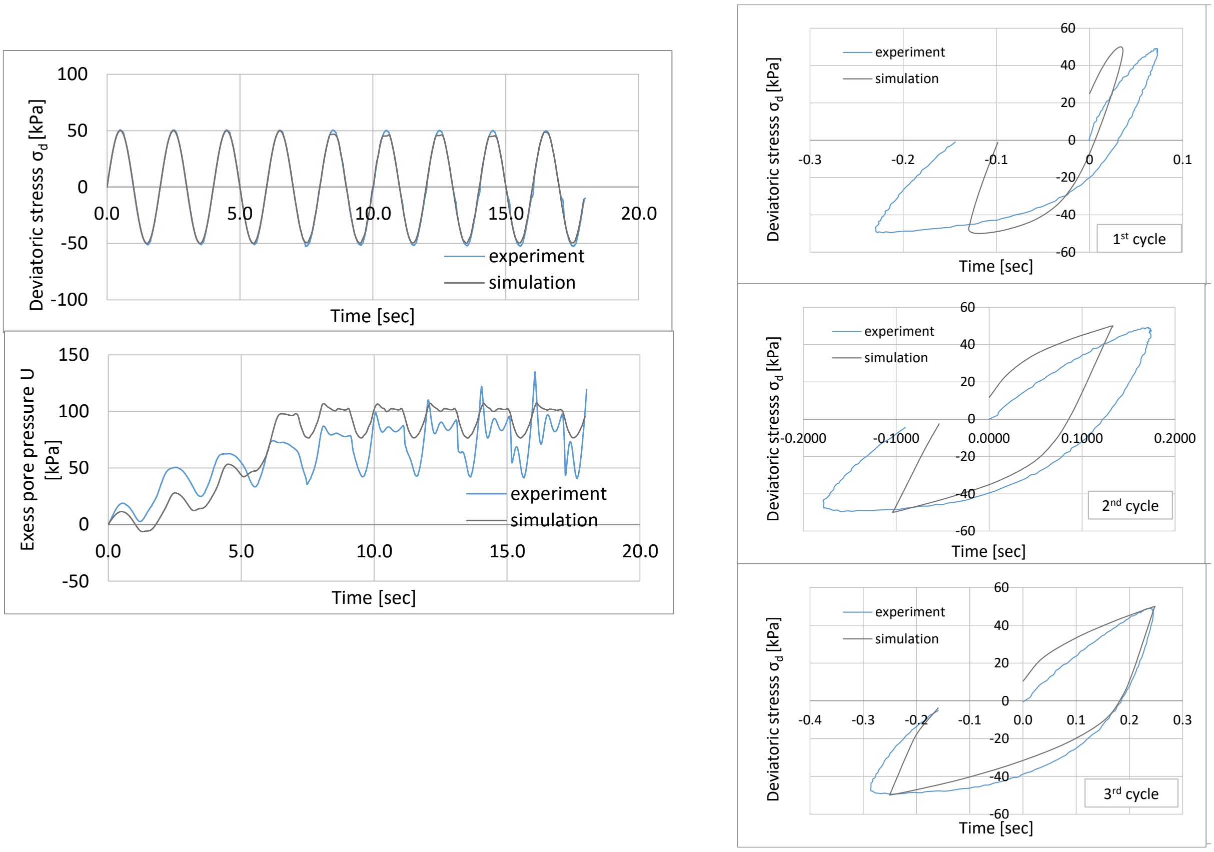


Fig. 4 Cyclic loading and pore pressure development comprasion of cyclic triaxial test and numerical simulation (left), Stress strain comparison per cycle of the test with the numerical simulation (right),

(CSR =0.25, Dr=40%)

4. Conclusion and recommendations for further studies

Numerical simulation of the triaxial monotonic and cyclic tests was performed. The numerical simulation was done by the ANSYS computer program, using the hypoplastic model. Efforts were made and good results were achieved to define the hypoplastic parameters for the Skopje sand. This is of a great importance and significance because it represents continuation of the work done by Edip, 2013 in the IZIIS' Department of Geotechnics and also provides a good basis for further research and use of the defined parameters of the newly investigated sand. From the numerical analysis the following conclusions can be made:

- In numerical simulation of the triaxial tests, it is observed that the numerical simulation leads to correct prediction of evolution of strain and stress. Moreover, sufficient consideration of the current state of soil medium is obtained. The small number of model parameters makes the used approach advantageous when compared with other models.

- For the Hysteresis loop of stress strain relation for CSR < 0.2, it can be observed that numerical simulation follows the curve of the experimental pore pressure development although there are differences in the middle range of values.
- The beginning and the mid values of the numerical simulation show a good agreement. However, as the number of cycles increases, the difference between the loops of the numerical and experimental values increases. This is mainly due to the fact that the soil sample begins to liquefy such that the strain levels of the soil sample increase suddenly, which is not possible to simulate correctly with this soil model.

Thus, based on the performed simulation, a statement can be made that the numerical model can fully satisfactorily simulate the monotonic behavior of the Skopje sand, whereas the cyclic behavior can simulate it until a certain level of pore pressure generation and strain development. For large strains and liquefaction occurrence, some improvement an additional investigation of the model is necessary.

The performed simulations are starting program for further simulation of shaking table tests on Skopje sand performed in IZIIS, Skopje, Macedonia. Calibration and comparison with other numerical models are also set up as further investigation program.

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