Amirkabir Journal of Civil Engineering

Amirkabir J. Civil Eng., 54(11) (2023) 863-866
DOI: 10.22060/ceej.2022.20556.7462

Evaluation of the effect of micro-parameters on the macroscopic properties of cemented granular soils

N. Mahbubi Motlagh, A. R. Mahboubi Ardakani *, A. Noorzad

Civil Engineering Department, Shahid Beheshti University, Tehran, Iran

ABSTRACT: One of the bonded contact models that is used to simulate the cemented bonds formed between soil particles in a cemented sample in the discrete element method is the "flat joint" model. There are numerous micro-parameters required to define this contact model between particles in the modeling and the effects of each of these parameters on the material response are not clear. In this research, after performing large-scale static and dynamic triaxial tests on cemented gravel in the laboratory, they were simulated as a granular assembly in which the flat joint contact model exists at all grain-grain contacts. Then, a sensitivity analysis was conducted to determine the effect of each micro-parameter on the macroscopic response of cemented samples and to specify the most impressive micro-parameters in order to simplify the calibration process. A regression analysis of the numerical results was performed to quantify the relationships between the micro-parameters and the mechanical properties of the sample. The results show that the maximum and residual shear strength of a sample are mainly dependent on the flat joint cohesion and stiffness ratio. The effects of elastic modulus and stiffness ratio on the initial tangential modulus and shear modulus are significant. The Poisson ratio is affected by the flat join cohesion and stiffness ratio. The damping ratio depends more on the elastic modulus. These results can be used as a guide for modeling the behavior of brittle materials in the discrete element method. A comparison between numerical and experimental test results of cemented granular specimens revealed that the model was able to capture the softening behavior of these materials with good accuracy.

Review History:

Received: Sep. 14, 2021
Revised: Apr. 23, 2022
Accepted: Jul. 10, 2022
Available Online: Jul. 30, 2022

Keywords:

Discrete element method simulation
Flat joint bonded contact model
Cemented granular material
Sensitivity analysis
Regression analysis

1- Introduction

A cemented soil is a soil whose particles undergo cemented bonding as a result of natural or artificial processes. However, the data was derived from a series of experimental tests based on macroscopic measurements, meaning the soil's micro-scale behavior could not be investigated. Hence, numerical methods that enable the micro-scale analysis of materials' behavior can be adopted to simulate the behavior of cemented soils. The discrete element method (DEM) is a powerful numerical method for investigating the behavior of cemented granular soils. The application of the DEM to represent the behavior of cemented granular soils depends heavily on the bonded contact model. One of these models is flat joint contact. A flat-joint contact simulates the behavior of an interface between two notional surfaces, each of which is connected rigidly to a piece of a body. The interface is discretized into elements. Each element is either bonded or un-bonded, and the breakage of each bonded element contributes to partial damage to the interface.

The basic micro-parameters of the flat jointed materials include particle (particle density, ratio of maximum to minimum particle radius, elastic modulus, normal to shear stiffness ratio, and friction coefficient) and bond model parameters (number of elements, elastic modulus, normal to shear stiffness ratio, friction coefficient, bond radius coefficient, tensile strength, cohesion, and friction angle or internal friction coefficient). The sensitivity of a contact model is analyzed with a variance analysis at a significant level of 5%.

In this research, large-scale static and cyclic triaxial tests were performed on cemented sand samples (2% cement) in drained conditions. Then, the DEM model was calibrated with the obtained experimental results. To study the effect of the model micro-parameters on the behavior of the sample, the sensitivity analysis of macro-parameters, such as maximum and residual shear strengths, initial tangential modulus, Poisson's ratio, shear modulus and damping ratio, to microscopic factors (elastic modulus of particles and bond (E_c), ratio of normal to shear stiffness of contact and bond (K), coefficient of friction (μ), bond cohesion (C), bond tensile strength (σ_c) and bond friction angle (φ)) was done. The micro-scale factors affecting the macroscopic response of cement materials were determined and the quantitative relationships between them were expressed using regression

*Corresponding author's email: a_mahboubi@sbu.ac.ir

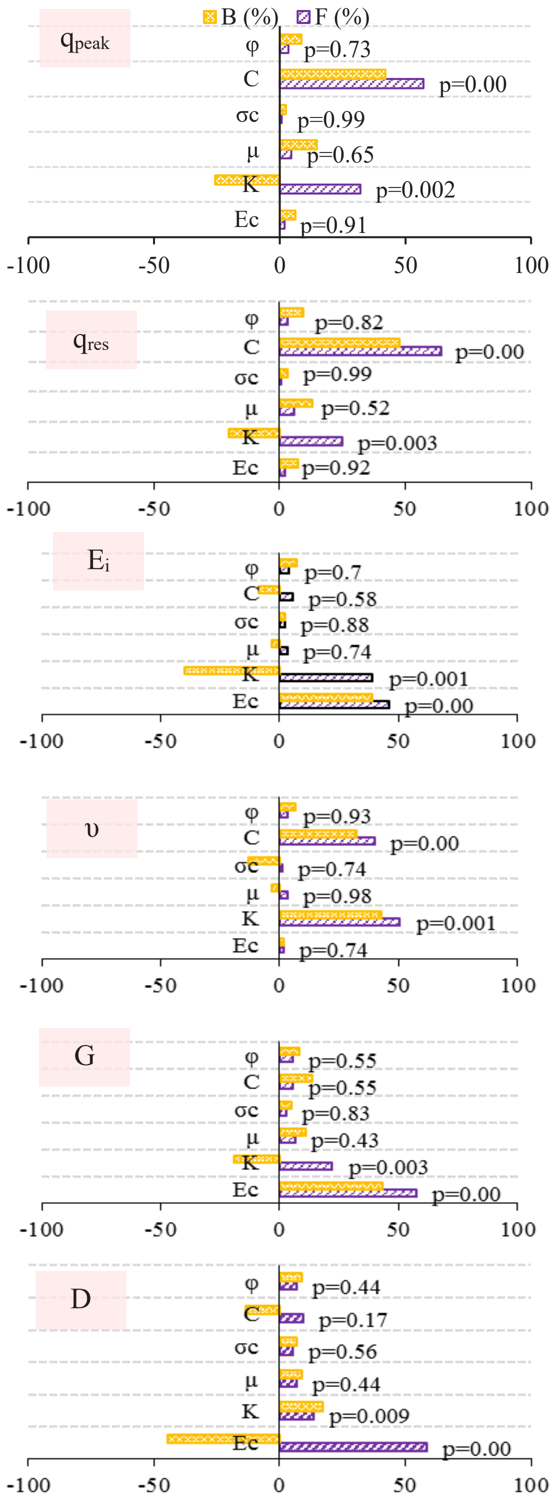

Fig. 1. Analysis of variance results for macro-parameters

analysis.

2- Methodology

In this study, well-graded gravelly soil with sand stabilized with 2% cement was used.

The static and cyclic triaxial tests in consolidated drained conditions in the laboratory were carried out on cylindrical samples with a diameter of 150 mm and a height of 300 mm at a porosity ratio of 0.42 and a confining pressure of 300 kPa. Experimental tests have been carried out according to Table 1.

In PFC^{3D} software [1], the specimens were generated as sets of dry spherical particles assembled in a cylindrical mold with a diameter of 150 mm and a height of 300 mm with flexible lateral boundaries and a void ratio of 0.42. The cemented materials were defined as a collection of granular materials to which the flat joint bonded contact model was assigned for all particle-particle contact. A linear contact model was applied to any new particle-particle contacts that might have formed during the triaxial test. Flexible walls were used as the boundaries for the cylindrical mold. The specimen's top and lower planes were non-frictional rigid planes.

The orthogonal experimental design method was used to calibrate the mentioned micro-parameters [2, 3].

3- Results and Discussion

To determine the sensitivity of peak and residual shear strengths, initial tangential modulus, Poisson's ratio, shear modulus and damping ratio to E_c, K, μ, $\boldsymbol{\sigma}_c$, C and, φ, variance analysis at a significant level of 5% on the response of the model was done. The F and p values of the mentioned parameters are given in "Figure 1" for the assumed variables. B shows the influence of the independent variable on the dependent variable (the relative contribution of each factor in predicting the dependent variable), which is also specified in this figure. After the sensitivity analysis, regression analysis was used to quantify the relationships between the dependent variables and the effective independent variables, and the obtained relationships (relationships 1 to 6) are summarized in Table 2.

The calibrated micro-parameters for DEM simulations are listed in Table 3.

It can be seen that the numerical model has been able to present the brittle behavior of cemented samples. The volumetric strain-axial strain diagram obtained from the two methods shows a good compatibility with each other. The maximum dynamic shear strength and shear strain of the samples are very close to each other.

4- Conclusions

In this research, static and cyclic triaxial tests on cemented samples were conducted in the laboratory, and then they were simulated by PFC3D software (version 6). The most effective micro-parameters for maximum and residual shear strengths, initial tangential modulus, Poisson's ratio, shear modulus, and damping ratio of the simulated samples were determined by the sensitivity analysis method. It was found that the maximum and residual shear strengths are mainly dependent on the cohesion and stiffness ratio. The effect of elastic modulus and stiffness ratio on the initial tangential modulus and shear modulus is significant. The Poisson's ratio is influenced by the stiffness ratio and cohesion. The damping ratio depends on the elastic modulus. After sensitivity analysis, regression analysis was used to

Table 1. Experimental tests schedule

Test	Sample	Void ratio	Confining pressure	Description
Static triaxial test	Cemented rounded particles	0.42	300 kPa	Drained, strain controlled
Cyclic triaxial test				Drained, stress controlled, 1 step sinusoidal loading-unloading, and includes 40 cycles

Table 2. Quantify relationships for the macro-parameters

$q_{peak}[\text{kPa}]=0.011E_c[\text{MPa}]+1275\mu-444K+10.75\sigma_c[\text{MPa}]$ $+36.375C[\text{MPa}]+30\varphi[\text{deg.}]-3110.077$	(1)
$q_{res}[\text{kPa}]=0.006E_c[\text{MPa}]+555\mu-177.5K+6.5\sigma_c[\text{MPa}]$ $+20.825C[\text{MPa}]+16\varphi[\text{deg.}]-1726.231$	(2)
$E_i[\text{MPa}]=0.044E_c[\text{MPa}]-177.5\mu-444K+5.5\sigma_c[\text{MPa}]$ $-5C[\text{MPa}]+15\varphi[\text{deg.}]+217.865$	(3)
$\upsilon=5\times10^{-7}E_c[\text{MPa}]-5\times10^{-2}\mu+0.125K-9\times10^{-3}\sigma_c[\text{MPa}]$ $+5\times10^{-3}C[\text{MPa}]+4\times10^{-3}\varphi[\text{deg.}]-0.42$	(4)
$G[\text{GPa}]=4\times10^{-3}E_c[\text{MPa}]+55\mu-19.5K+1.25\sigma_c[\text{MPa}]$ $+0.7C[\text{MPa}]+1.7\varphi[\text{deg.}]-198.154$	(5)
$D[\%]=3\mu+1.15K+0.113\sigma_c[\text{MPa}]-4.5\times10^{-2}C[\text{MPa}]$ (۱) $+0.12\varphi[\text{deg.}]+20.454$	(6)

Table 3. Calibrated model parameters

Parameters	Unit	Value
ρ	kg/m^3	2650
N_r	–	1
N_a	–	3
λ	–	0.3
g_0	mm	0
g	mm	1.78
φ_B	–	1
E_c	GPa	45
k	–	2
μ	–	0.6
σ_c	MPa	8
C	MPa	100
φ	º	25

quantify the relationships between dependent variables and effective independent variables. Using the driven relations in predicting the macro-parameters of the cemented sample can be useful.

References

[1] Itasca Consulting group Inc. Particle Flow Code in Three Dimensions (PFC3D) (2018) Version 6.00. Minneapolis, USA.

[2] H. Wu, B. Dai, G. Zhao, Y. Chen, Y. Tian, A novel method of calibrating micro-scale parameters of PFC model and experimental validation, Applied Sciences, 10(9) (2020) 1-20.

[3] S. Yu, M. Jia, J. Zhou, C. Zhao, L. Li, Micro-Mechanism of spherical gypsum particle breakage under ball–plane contact condition, Applied Sciences, 9(22) (2019) 1-16.

HOW TO CITE THIS ARTICLE

N. Mahbubi Motlagh, A. R. Mahboubi Ardakani, A. Noorzad, Evaluation of the effect of micro-parameters on the macroscopic properties of cemented granular soils, Amirkabir J. Civil Eng., 54(11) (2023) 863-866.

DOI: 10.22060/ceej.2022.20556.7462