# Simulation and Analysis of Shear Properties of Loess and Concrete Structures Based on the Discrete Element Method

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**Abstract.** To address the issue of shear damage at the interface of loess and concrete structures, we utilized the discrete element method (DEM) to simulate a straight shear test at the interface. By analyzing the distribution of contact force between particles and the evolution law, we were able to determine the shear characteristics of the contact surface and explore the formation of the shear zone.The test results indicate that the established discrete element contact model simulation results are generally consistent with the indoor test results after calibrating the contact model parameters through the test. The simulation of the contact surface test using discrete element analysis shows strain softening during the shear process. The shear stress-shear displacement curve is consistent with the test results. Additionally, the intergranular contact force and number of contacts increase with normal stress. Near the contact surface of the structure, the intergranular contact force gradually increases during the shear process, resulting in a region of relative stress concentration known as the shear zone.The feasibility of establishing a discrete element model of the contact structure was further verified by simulating and analyzing the direct shear test on the contact surface of loess and concrete structure. The model parameters were calibrated to provide a basis for analyzing the soil-structure interaction.

**Keywords:** Contact surface; Straight shear test; Discrete element method; Contact force; Shear zone.

## 1. Introduction

In recent years, the northwest region of China has seen gradual improvements in infrastructure facilities [1]. As a result, engineering problems such as foundation collapse and structural instability have become more frequent in loess areas. The interaction between soil and structure is a common problem in water conservancy and geotechnical engineering. The material properties on either side of the contact interface differ greatly, making the transfer mechanism of shear force inside the interface very complex. As external stress conditions change, the interface may exhibit discontinuous deformation behaviors such as tensioning and slipping, which can compromise the safety of the entire engineering structure [2]. Therefore, researching the mechanical properties of the contact interface between loess and concrete structures is significant for engineering construction.

Currently, research methods for soil-structure interaction are mainly divided into indoor tests and numerical simulations. The mechanical properties of soil-structure contact are greatly influenced by the nature of the soil and the mode of contact with the structure, despite the macroscopic mechanical properties of the contact structure being obtained from indoor tests. Shear zones [3], strain softening [4], shear expansion, and shear shrinkage [5] are observed, and the mode and frequency of shear have a significant effect on the interfacial properties [6, 7]. Because of the limitations of test equipment and monitoring methods, conventional testing processes, such as particle image velocimetry, can only measure the behavior of the soil-structure interface based on local two-dimensional displacement and strain distributions [8]. However, it is very difficult to measure the overall particle migration and fragmentation process. Granular materials, such as soil, have a loose structure that differs significantly from that of concrete structures. The microscopic changes, such as migration, rotation, and fragmentation of soil particles near the contact surface under shear, have a significant effect on the structural strength [9, 10]. Therefore, it is crucial to understand the intrinsic correlation between the macroscopic mechanical properties of granular materials and the state of microscopic particles. The discrete element method (DEM) has unique advantages for simulating particle motion states, such as the effect of particle rotation and shape on material strength [11, 12]. The discrete element method is used to simulate bulk materials by forming independent ball particles and assigning different property parameters, as well as contact cementation properties to them. This approach considers the properties of individual particles from a microscopic point of view and simulates the original macroscopic mechanical properties of the bulk materials. It can reflect the discontinuous behavior and large deformation behavior [13], making it suitable for simulating geotechnical media with a large number of discontinuous structural surfaces. Thus, setting model parameters during the modeling process is crucial for establishing a particle flow model.

This paper presents an analysis of the shear characteristics of the contact surface between loess and concrete structure using the discrete element method. The macroscopic mechanical parameters obtained from the indoor test at the interface of loess and concrete structure are calibrated to the discrete element model parameters to establish the contact model. The particle motion and the size and distribution of the inter-particle contact force are used to explore the formation of the shear zone.

## 2. Discrete Elemental Modeling of the Soil-structure Interface

To establish the discrete element shear model for soil and structure, begin by generating the required shear model using wall. Then, add the particles and contact model with the necessary properties of the two materials in the test. Use the Fish statement to load the specimen box and monitor it. Finally, simulate the shear characteristics of the soil and structure contact model by continuously adjusting the model parameters.

### 2.1 Modeling Contact Structures with Discrete Elements

The shear box specimen is a rectangular enclosure measuring 150mm × 300mm (height × width) designed for horizontal shear loading. The top and bottom are walls for vertical loading, and the interior is filled with discrete meta-particles representing different materials in the form of balls, creating a model as depicted in Fig. 1. The contact structure model of loess and concrete was formed, in which the loess part formed a ball with particle density of 1885kg/m3, particle radius of 0.5~1mm obeying random distribution and porosity of 0.12 to simulate the loess with dry density of 1.69g/cm3 and water content of 12.9%; the concrete part formed a ball with particle density of 2384kg/m3, particle radius of 0.5~2mm obeying uniform distribution and porosity of 0.2 to simulate the concrete with water-to-cement ratio of 0.317. A linear contact model was chosen as the fine-grained ontological model between the particles, and the contact surface shear model was established, and the initial state was equilibrated by the Cycle command.

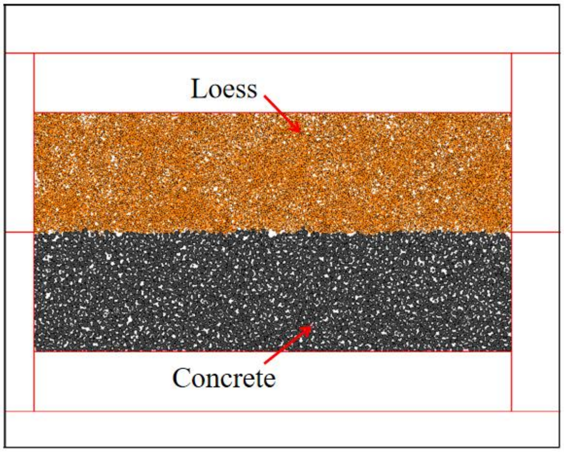


Fig. 1 Shear model of loess and concrete structure

### 2.2 Numerical Simulation Scheme

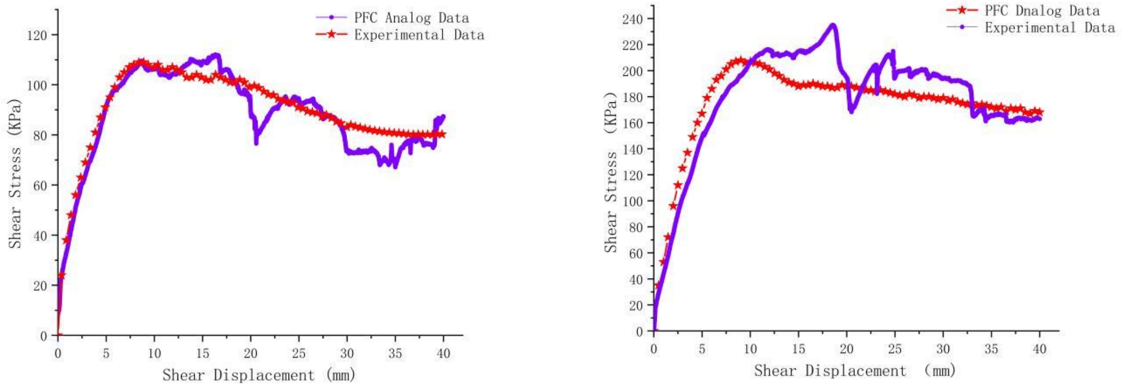
The stress-strain curve obtained from the contact surface straight shear test with a normal stress of 100 kPa was used as the basis for parameter calibration. The numerical model parameters were calibrated through numerous trial calculations and repeated adjustments of the particle fine-view parameters. This resulted in stress-strain curves of the numerical simulation test and the indoor straight shear test that were roughly coincident, as shown in Fig. 2. The fine-view mechanical parameters of the contact model obtained after calibration are presented in Table 1. After calibration, we performed shear simulations at normal pressures of 100 kPa, 200 kPa, 300 kPa, and 400 kPa to analyze the effect of normal stress on the shear damage mode.

Table 1. Contact model fine-scale mechanical parameters

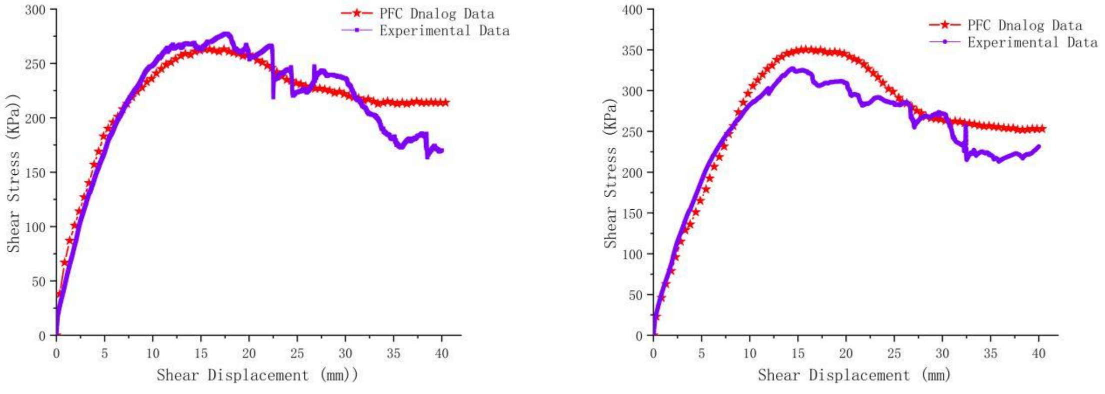
| | $E_C$/MPa | $K_{ratio}$ | $f_{ric}$ | cb_tens/kPa | cb_shears/kPa | dp_nratio | dp_sratio |
|---|---|---|---|---|---|---|---|
| Loess | 38 | 1 | 0.25 | 30 | 36 | 0.2 | 0.2 |
| Concrete | 61 | 1 | 0.5 | 50 | 58 | 0.2 | 0.2 |

## 3. Analysis and Discussion of Results

### 3.1 Contact Surface Shear Properties



(a) 100KPa (b) 200KPa



(c) 300KPa (d) 400KPa

Fig. 2 Comparison between straight shear test results and numerical simulation results

Fig. 2 displays the curves that illustrate the relationship between shear stress and shear displacement of the loess-concrete contact model under different normal stresses (100 kPa, 200 kPa, 300 kPa, 400 kPa) in comparison to the test results. As shown in the figure, the test results are generally consistent with the simulation results, the simulation results can reflect the macroscopic mechanical properties of the straight shear test. Taking the shear characteristic curve when the normal stress is 100KPa as an example, it can be seen from Fig. 2 that the initial shear stress increases rapidly with the increase of shear displacement, and with the increase of normal stress, the peak strength is also the larger, and there is a hysteresis, The later contact structure is gradually destroyed, and the shear stress decreases slowly with the increase of shear displacement until the steady state, the stage of residual strength, is reached. Overall, the shear stress-shear displacement curves of the loess-concrete contact surface are of the hyperbolic type with strain softening.

## 3.2 Analysis of inter-particle contact forces

The distribution of the intergranular contact force of particles under normal stress is shown in Fig. 3, where the intergranular contact force is significantly higher in the loess region than in the concrete region, and the contact force inside the soil body near the contact surface is significantly higher. Quantitative analysis of the maximum value of intergranular contact force and the number of contacts after shear is shown in Fig. 4, where the maximum value of intergranular contact force as well as the number of particle contacts after shear increase with increasing normal stress. Fig. 5 cloud diagram of contact force distribution in the shear process, the unevenly distributed intergranular contact force in the bulk material in the shear process is gradually distributed along the tendency, and there are obvious contact force larger parts near the shear surface, and the larger values of intergranular contact force are all gradually transferred to the vicinity of the contact interface, that is, there is the phenomenon of stress concentration to resist a larger shear force. Due to the relatively weak bonding force between soil particles, the soil body within the larger intergranular contact force region gradually in the interface near a certain thickness of the soil body within the formation, with the shear, the gradual development and formation of shear zone, so that the contact structure fracture surface tends to be formed in the contact surface near the soil body within the formation.

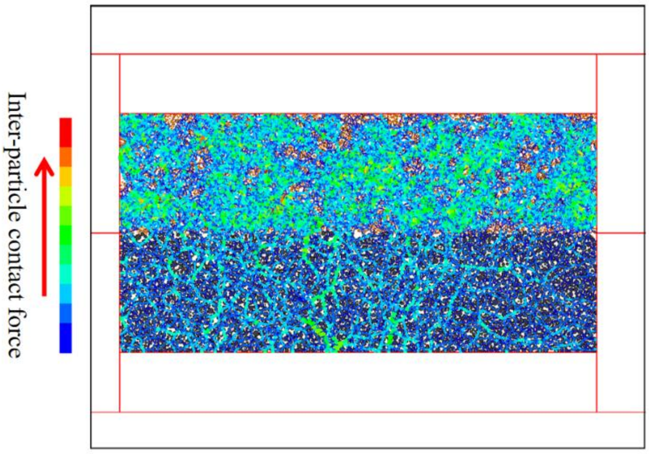


Fig. 3 Cloud view of the contact force distribution between grains of the contact model under normal stress

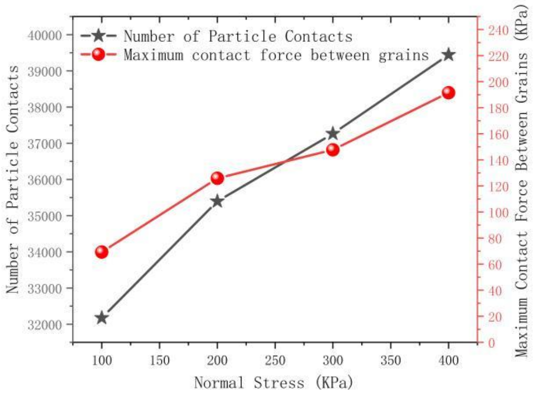


Fig. 4 Number of particle contacts and maximum intergranular contact force versus normal stress curve

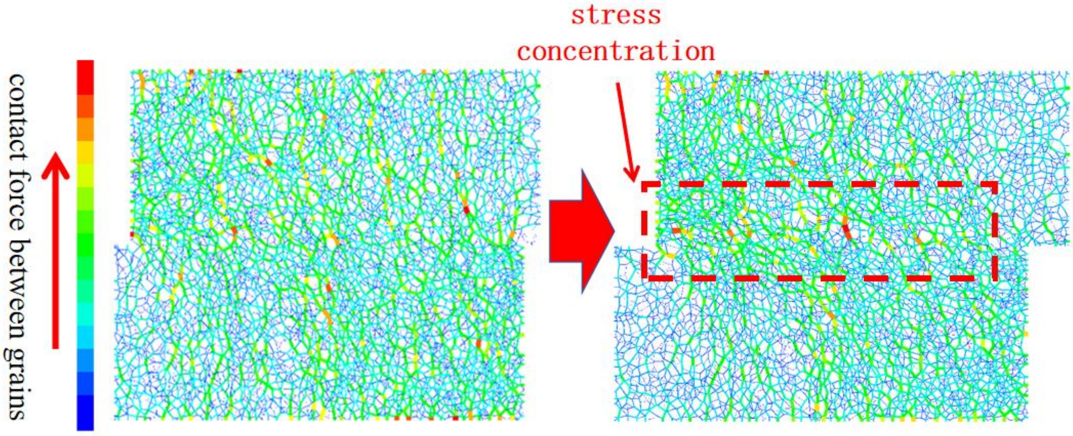


Fig. 5 Cloud diagram of contact force distribution during shear process

## 4. Summary

In this paper, based on the discrete element method to establish the contact surface direct shear test model corresponding to the indoor direct shear test, to study the effect of normal stress on the interface between loess and concrete structure, and to further study its shear characteristics through its fine particle distribution, the following conclusions are obtained:

A contact surface direct shear test model corresponding to the indoor test was established to determine the values of the fine-scale parameters, and the simulation results were highly consistent with the indoor test results, indicating that the proposed model can more accurately respond to the soil-concrete interaction.

The shear strength of the contact surface of the loess-concrete structure increases with increasing normal stress, and there is a hysteresis in the appearance of the peak strength with increasing normal stress.

The mechanism of shear zone formation is studied through the evolution process of contact force distribution between particles in the shear process.

## References

[1] Jinsheng Jia. A Technical Review of Hydro-Project Development in China. Engineering. 2016, 2: 302-312.

[2] Rongsen Zhu, Wan-li Xie, Qiqi Liu, et al. Shear behavior of sliding zone soil of loess landslides via ring shear tests in the South Jingyang Plateau. Bulletin of Engineering Geology and the Environment. 2022, 81: 244.

[3] Zhongping Yang, Haoyu Liu, Jin Li, et al. Study on shear mechanical properties and deformation characteristics of shear zone of soil-rock mixture-bedrock interface. Chinese Journal of Rock Mechanics and Engineering, 2023, 42(2): 292-306.

[4] Peng Du, Dequan Zhou, Xiaoling Liu et al. Mechanical test and action mechanism of interface between gravel soil and concrete. Frontiers in Earth Science. 2023: 1-11.

[5] Xibing Li, Weili Chen, Fuquan Chen, et al. Numerical Analysis of the Behavior of Saturated Looses and Adjacent to Structures. Engineering Mechanics, 2021, 30(6): 223-230.

[6] Yue Liang, Qi Wei, Chuang Chuang. Reciprocating Shear Characteristics of Steel-soil Interface Based on Discrete Element Method. Journal of Disaster Prevention and Mitigation Engineering, 2023, 43(4): 878-886.

[7] Yifan Zhao, Wenbai Liu. Numerical simulation on cyclic shear test of graval-structureinterface by PFC2D. Journal of Shanghai Maritime University, 2015, 36(1): 81-85.

[8] Jason T. DeJong, Zachary J. Westgate. Role of Initial State, Material Properties, and Confinement Condition on Local and Global Soil-Structure Interface Behavior. Journal of Geotechnical and Geoenvironmental Engineering. 2009, 135(11): 1646-1660.

[9] Wenbai Liu, Chunhui Fang. Numerical simulation of the effect of moving the structure on the mechanical properties of the contacting soil. Water Resources and Power, 2017, 35(2): 135-138.

[10] Liyun Tang, Yiheng Li, Yongtang Yu, et al. Study on strength deterioration, pore structure evolution and particle migration of interface between soil-rock mixture and concrete under freeze-thaw action. Journal of Glaciology and Geocryology, 2023, 45(3): 1-16.

[11] Lihong Tong, Li Fu, Changjie Xu, et al. Effects of Particle Rotation on Shear Strength of Granular Material System. Engineering Mechanics, 2023.

[12] Xin Du, ZENG Ya Zeng, Gaorui Wu, et al. Effects of Particle Shape on Friction Mechanism Based on Discrete Element Method[J]. Journal of Southwest Jiaotong University, 2012, 47(2): 252-257.

[13] Gang Ma, Wei Zhou,Xiaolin Chang, et al. Numerical study of behavior of interface between coarse-grained soil and structure by discrete-continuum coupling method[J]. Rock and Soil Mechanics, 2012, 33(11): 3454-3464.