Contact surface roughness analysis of pile and soil using ABS 3D printing materials

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Abstract. It is more difficult to measure the side resistance of the soil-structure contact surface during the pile pulling process. Only overcome the side resistance can be pulled out smoothly on the pile. Three kinds of test specimens were printed out by 3D printing equipment of the Acrylonitrile Butadiene Styrene (ABS) material to simulate the roughness of the soil-structure interface. The basic physical properties of two types of soil under the geological conditions of the pile to be pulled are tested through the geotechnical test, and the soil-structure constitutive theory and the roughness theory are introduced. The distribution of maximum shear stress at the contact surface is obtained by direct shear tests on the test specimens with different roughness, and the shear stage is analyzed with the contact surface. The results demonstrate that the mechanical properties of yellow clay are better than black clay for the two types of soil on the pile side. The shear stress changes with the increase of roughness and normal load during the direct shear process, which the maximum values of the two types of soil are at 60% of roughness and 300 kPa of normal load.

1. Introduction
During bridge construction, steel-pipe piles are used as a temporary support system for bearing various construction loads. After bridge construction has been completed, the temporary support system is dismantled, which results in problems related to the drawing of steel-pipe piles from the strata. To evaluate the pile pulling, it is necessary to study the response of the interface of soil with the structural element (Strahler et al. 2016). It is more difficult to measure the side resistance of the soil-structure contact surface during the pile pulling process, which due to the complexity of soil-structure interface (Jiang et al. 2014). The interrelationship between soil and structure has discussed through simple shear interface tests (Di et al. 2015), and direct shear interface tests (Vangla and Gali 2016). Cheng et al. (2019) experimental results shown that the resistance is influenced from the model roughness. Based on the results of these researchers, including the constitutive relationship model (Lu et al. 2017), many shear properties (Zhang et al. 2018) influenced such as surface roughness, grain size and initial density of soil.

Currently, there is few discussions on the adoption of the Acrylonitrile Butadiene Styrene (ABS) and the effect of different roughness of the soil-structure interface, moreover, the mechanism of soil-
structure interface needed further investigation during direct shear process. Three kinds of test specimens were printed out by 3D printing equipment to simulate the roughness of pile-soil interface, then a series of laboratory tests of soil-structure interface direct shear tests under the various normal stresses (100, 200 and 300 kPa) and different roughness (30, 42 and 60%) are executed the research of the interface behavior in macroscopic perspective. The interface constitutive model, mechanical properties of the soil, stage analysis on direct shear process are analyzed with experiment.

2. Study Background

2.1 Project information for the pile-pulling
This paper considers the pile-pulling project of Jianning Bridge as the research object. Jianning Bridge is located in Shishou City, Hubei Province, China. This paper uses the deepest steel-pipe pile as the research object. The longest depth of penetration is 26 m, and the pile is mainly in the clay layer. In this section, the pile-soil direct shear was studied during the pile pulling process (Fig.1). Chattopadhyay and Pise (1986) showed that the area of the breakage surface was relied on the soil-structure shearing resistance during pile pulling process. Therefore, the soil-structure interaction can be simulated by direct shear test.

![Fig.1 The sketch map of pile-soil interface](image)

2.2 Shear constitutive relation
The deformation of the contact surface of soil and structure on the tangential plane is regarded as a two-dimensional problem. A three-dimensional constitutive model of the soil on the interface is established based on the compression deformation law in the normal direction. In $\tau-\sigma_n$ space, the model form is as follows:

$$
\begin{bmatrix}
\frac{d\tau}{d\sigma_n}
\end{bmatrix} = 
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
\frac{d\gamma}{d\varepsilon_v}
\end{bmatrix}
$$

(1)

Where A is the coefficient reflecting the tangential strain increment $d\gamma$, which reflects the shear stress increment $d\tau$; B is the coefficient reflecting the volumetric strain increment $d\varepsilon_v$ caused by the shear stress increment $d\tau$; C is the coefficient reflecting the tangential strain $d\gamma$ caused by the normal pressure $d\sigma_n$, it is generally considered that normal stress does not produce tangential deformation, so let $C=0$; D is a coefficient reflecting the volumetric strain increment $d\varepsilon_v$ which reflects the normal pressure $d\sigma_n$.

3. Experimental test

3.1 Roughness of the structure interface
In recent years, the mechanical characteristics of polymers have attracted more attention. Polymers are widely used in structural components of aeronautical, automobile, military vehicles and engineering, particularly the Acrylonitrile Butadiene Styrene (ABS). The ABS material has good impact strength that one of the most popular plastic at present, which usually preferred engineering plastic for 3D printing for melt deposition. It performs better in terms of ductility crack toughness and fatigue than
other plastic materials (Hajideh et al. 2018). In addition, 3D printing can be used to simulate different rough indications of piles because it provides almost infinite geometric degrees of freedom. The surface roughness of steel piles is often complex and unpredictable because of the underground driving conditions. In this study, the rough interface may be related to the surface of rusted steel interface. In order to simulate the surface roughness of the pile, the Acrylonitrile Butadiene Styrene (ABS) molds were established to cast the pile specimens, as shown in Fig. 2.

3.2 Definition of roughness

The surface roughness of the engineering structure is always described by indexes of wavelength, surface shape, and groove depth. In spite of these parameters represent the roughness of surface in absolute terms, it is important how the rough surface interacts with the soil in soil-structure interaction, and it is also affected by the surface asperities and the relative size of soil particles.

Tovar-Valencia et al. (2017) proposed the definition of the normalized roughness $R$. Roughness is the main factor to determine the shear resistance of the soil-structure interface. The surface roughness is changed by 3D-print different numbers of regular grooves on the ABS surface, and the surface roughness is quantitatively evaluated by sand filling method (Cheng et al. 2019). Therefore, different roughness types are set to represent the rough state of the pile itself. As showing in Fig. 2, three conventional roughness designs for steel pile surfaces were used to simplify the in situ complex roughness contained in soil-structure interface sites.

When surface roughness $R$ is evaluated quantitatively, the formula can be expressed as follows:

$$R = n \cdot \frac{V_i}{S}$$

(2)
Where \( n \) represents the number of grooves on the model surface, \( V \) is the standard sand volugroove. 
\( S \) is the surface area of the model.

4. Experimental results

4.1 Soil sample

The clay soil physical properties have been presented in Table 1.

Table 1. The basic properties of the clay

| Property                | Clay  | Specific gravity | Liquid limit, LL | Plastic limit, PL | Plasticity index | Optimum moisture content(%) | Max. dry density (kg/m\(^3\)) |
|-------------------------|-------|------------------|------------------|-------------------|------------------|------------------------------|------------------------------|
| Black                   | 2.56  | 39.4             | 17.3             | 28                | 16.5             | 1520                         |                              |
| Yellow                  | 2.72  | 39.8             | 18.5             | 32                | 16.0             | 1650                         |                              |

4.2 Mechanical properties of the soil

The direct shear meter is simple and convenient, which can ensure the shear occurs at the contact surface and the size of the contact surface was always the same have advantages. The shear stresses surveyed at critical state were plotted against the corresponding normal stresses to identify the cohesive force and the friction angle of the soil, which the maximum shear stress at critical state of yellow clay is 220 kPa and black clay is 150 kPa. The different shear stress the effect of two kinds of soil that the strength of yellow clay was higher than that of black clay.

4.3 Direct shear test on soil-strtrface

After remodelled the soil, and then cutting ring a specimen with a dimension of with a diameter of 61.8 mm and a height of 10 mm and inserted into the shear box for direct shear test. The 3D printing specimens having a height of 10 mm was put on the bottom of the soil to simulate the soil-structure interface.

According to the direct shear test rules, the normal load should be maintained for a period of time then the test can be started. A constant horizontal speed of 0.2 mm/min was adopted on the system till a shear displacement of 8 mm was reached, while the shear stress and displacement were recorded. Therefore, in this study, we generated different specimens to independently evaluate the shear behavior of soil-structure interface. The soil sample after direct shear test failure of yellow clay are shows in Fig. 3. The direct shear test of the soil-structure interface results for two soil as an example, which four different vertical normal stresses (100, 200, and 300 kPa) were applied (Fig. 4).

![Fig.3 Soil sample after direct shear test failure of yellow clay](image-url)
Fig. 4 The direct shear test of two soils with different vertical normal stress and different roughness: (a) 100 kPa, (b) 200 kPa, (c) 300 kPa

Fig. 4 has shown plots of shear stress versus displacement for the direct interface shear tests on the yellow soil and black soil, taking into account four different vertical normal stresses (100, 200, and 300 kPa). For specimens with greater roughness, the critical-state interface shear stress is greater. When the shear displacement of the soil was about 2 mm, the shear stress was stable and reached a critical state. It can be seen that the shear stress was increased by increasing the magnitude of confining pressure. When considering the same interface, for yellow soil, the mobilized interface shear stress is greater at the peak and critical conditions, which have similar morphology to black soil. The interface of the two soils with the roughness of 30%, which yellow soil shear stress is 65.1% greater than black soil obtained from the tests performed when the vertical normal stress is 300 kPa, and when the roughness increases by 60% that the shear stress increases is 67.5%. The roughness reveals the contact area between the surface of the engineering structure and the soil, that the similar result were reported for Tovar-Valencia et al. (2017), which that larger interface strength can be mobilized if the roughness of the continuum material surface is increased.
5. Conclusion
1. The mechanical properties of yellow clay are better than black clay for the two types of soil on the pile side.

2. The shear stresses surveyed at critical state were plotted against the corresponding normal stresses to identify the cohesive force and the friction angle of the soil, which the maximum shear stress at critical state of yellow clay is 220 kPa and black clay is 150 kPa.

3. The interface of the two soils with the roughness of 30%, which yellow soil shear stress is 65.1% greater than black soil obtained from the tests performed when the vertical normal stress is 300 kPa, and when the roughness increases by 60% that the shear stress increases is 67.5%.

4. The shear stress changes with the increase of roughness and normal load during the direct shear process, which the maximum values of the two types of soil are at 60% of roughness and 300 kPa of normal load.

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References
[1] Chattopadhyay, B. C., & Pise, P. J. (1986). Uplift capacity of piles in sand. Journal of geotechnical engineering, 112(9), 888-904.
[2] Cheng, H., Wang, X., Zhang, J., Liu, Q., & Liu, W. (2019), Large-scale Direct Shear Tests of Interfaces Between Different Soils and Concrete Considering Roughness Effect. Advanced Engineering Sciences, 51(05), 117-125.
[3] Di Donna, A., Ferrari, A., & Laloui, L. (2015). Experimental investigations of the soil–concrete interface: physical mechanisms, cyclic mobilization, and behaviour at different temperatures. Canadian Geotechnical Journal, 53(4), 659-672.
[4] Hajideh, M. R., Farahani, M., & Ramezani, N. M. (2018). Reinforced dissimilar friction stir weld of polypropylene to acrylonitrile butadiene styrene with copper nanopowder. Journal of Manufacturing Processes, 32, 445-454.
[5] Jiang, D.J., Wang, X., Liu, D.R., Xia, Q., (2014). Experimental study of stability of piled foundation with thermosyphons of power transmission tower along qinghai—tibet railway in permafrost regions. Chinese Journal of Rock Mechanics and Engineering, 33, 4258-4263.
[6] Lu, Y., Wang, L., Li, Z., & Sun, H. (2017). Experimental study on the shear behavior of regular sandstone joints filled with cement grout. Rock Mechanics and Rock Engineering, 50(5), 1321-1336.
[7] Strahler, A. W., Walters, J. J., & Stuedlein, A. W. (2016). Frictional resistance of closely spaced steel reinforcement strips used in MSE walls. Journal of Geotechnical and Geoenvironmental Engineering, 142(8), 04016030.https://doi.org/10.1061/(ASCE)GT.1943-5606.0001492.
[8] Tovar-Valencia, R. D., Galvis-Castro, A., Salgado, R., & Prezzi, M. (2017). Effect of surface roughness on the shaft resistance of displacement model piles in sand. Journal of Geotechnical and Geoenvironmental Engineering, 144(3), 04017120.
[9] Vangla, P., & Gali, M. L. (2016). Effect of particle size of sand and surface asperities of reinforcement on their interface shear behaviour. Geotextiles and Geomembranes, 44(3), 254-268.
[10] Zhang Z., Zhang X., Tang Y., & Cui, Y., (2018a). Discrete element analysis of a cross-river
tunnel under random vibration levels induced by trains operating during the flood season. Journal of Zhejiang University-Science A, 19(5), 346-366. DOI: 10.1631/jzus.A1700002.