Geomechanics and Engineering, *Vol. 12, No. 3 (2017) 399-415*
DOI: https://doi.org/10.12989/gae.2017.12.3.399

Tests of the interface between structures and filling soil of mountain area airport

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(*Received June 29, 2016, Revised October 25, 2016, Accepted November 04, 2016*)

Abstract. A series of direct shear tests were conducted to investigate the frictional properties of the interface between structures and the filling soil of Chongqing airport fourth stage expansion project. Two types of structures are investigated, one is low carbon steel and the other is the bedrock sampled from the site. The influence of soil water content, surface roughness and material types of structure were analyzed. The tests show that the interface friction and shear displacement curve has no softening stage and the curve shape is close to the Clough-Duncan hyperbola, while the soil is mainly shear contraction during testing. The interface frictional resistance and normal stress curve meets the Mohr-Coulomb criterion and the derived friction angle and frictional resistance of interface increase as surface roughness increases but is always lower than the internal friction angle and shear strength of soil respectively. When surface roughness is much larger than soil grain size, soil-structure interface is nearly shear surface in soil. In addition to the geometry of structural surface, the material types of structure also affects the performance of soil-structure interface. The wet interface frictional resistance will become lower than the natural one under specific conditions.

Keywords: direct shear test; gravel sand; steel; sand rock; surface roughness; water content; friction angle; frictional resistance

1. Introduction

The complex topographic and geological condition in the mid-west mountainous regions of China determines that airport construction in these regions is always high fill project with many stability problems. The original construction sites of some airports are usually covered by some soft soil layers, which are suggested to be removed when it is feasible before high fill construction. Thus, the filling soil is directly overlaid on the bedrock. So it’s significant to investigate the statics characteristic of the contact interface between the filling soil and bedrock, especially when interface is moist by water.

Many researches about interface between soil and structure have been conducted. Potyondy (1961) studied the interface friction between sand, clay, cohesive granular soil, silt (rock flour) and

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

steel, wood, concrete by direct shear tests. The results show that soil water content, normal stress, material types of structure and surface roughness have influence on interface friction, and the interface frictional resistance is lower than the soil shear strength. It also shows that interface frictional resistance can be expressed in a similar way to Coulomb line. Clough and Duncan (1971) investigated the interface between sand and concrete by direct shear tests, and the results show that the relationship between interface friction and shear displacement is hyperbola.

Tsubakihara and Kishida (1993a, b) investigated the interface between clay and steel by simple shear tests and direct shear tests. The results show that soil density and water content have influence on interface frictional properties, and there is a critical surface roughness. When surface roughness of steel is greater than critical surface roughness, the interface frictional resistance approximates soil shear strength and fail occurs in clay. On the contrary, when surface roughness of steel is less than critical surface roughness, the interface frictional resistance is lower than soil shear strength and fail occurs on interface.

Fakharian and Evgin (1996) found that soil is shear contraction when structure surface is smooth, and when structure surface is rough, soil is shear contraction at first and then occurs obvious shear dilatancy. Vanapalli *et al*. (1996) and Oberg and Sallfors (1997) suggested that matric suction increases as the soil desaturates, which results a nonlinear increase in shear strength. Tuncer *et al*. (2005) found that interface frictional resistance remains stable when structure surface roughness increases to a certain value and the value approximates half of soil mean grain size.

Zhang and Zhang (2006a, b) developed a large-scale direct shear apparatus to investigate the monotonic and cyclic behavior of soil-structure interface and did some preliminary study, the results show that interface frictional resistance is stable and independent of the number of shear cycles. They also investigated the interface between steel and gravelly soil by a large-scale test apparatus. The results show that interface frictional resistance is proportional to normal stress, and the interface is insignificant strain softening.

Shakir and Zhu (2009) investigated the interface between compacted clay and concrete by simple shear tests. The tests show that water content, surface roughness and normal stress have influence on the shear stress-shear displacement relationship and the interface shear strength increases as soil water content increases when concrete surface is rough.

Mortara *et al*. (2010) investigated the interface between sand and smooth steel plate by constant normal stiffness direct shear tests. The shear stress-shear displacement curve shows that shear stress increases very fast at first, and then reaches a constant value. Borana *et al*. (2015) investigated the unsaturated soil-steel interfaces by suction-controlled direct shear tests. The tests show that shear strength and dilatancy increase as matric suction increases.

Basmenj *et al*. (2016) investigated the tangential adhesion between mixed soil of sand and clay and mental surface by modified direct shear tests. The results show that tangential adhesion decreases as the soil water content increasees. Cabalar (2016) investigated the cyclic behavior of the interface between sand and structural materials by cyclic direct shear test apparatus. The tests show that the shape and size of sand grains, characteristics of structural materials and loading rate have influence on results.

This paper conducted a series of direct shear tests between soil and structure. From the test results, we can obtain interface frictional properties, the relationship between interface friction and shear displacement, and the relationship between testing soil's normal displacement and shear displacement. Thus, we can analyze the influence of soil water content, surface roughness and material types of structure, and we focus on whether interface is weaker than soil and whether wet interface is weakened by water.

2. Testing materials and direct shear apparatus

2.1 Testing soil

Testing soil comes from the high filled ground of Chongqing airport fourth stage expansion project. Particles that smaller than 0.075 mm and larger than 5 mm were removed and the grading curve is shown in Fig. 1.

According to the classification method of Code for Design of Building Foundation (GB50007-2011), testing soil is gravel sand. In order to investigate the influence of soil water content, natural soil-structure interface and wet soil-structure interface were both studied. The physical properties of test soil are shown in Table 1. The water content of wet soil is 18.7% and saturation is 39.9%.

2.2 Structure material

In the soil-structure system, steel and sand rock was chosen as structure. Steel is low carbon steel and sand rock is sampled from the bedrock of Chongqing airport. Steel and sand rock was machined into cylinder of 61.5 mm in diameter and 20 mm in height. The surface of structure is jagged and surface roughness is defined as the height of the groove. The picture and cross-

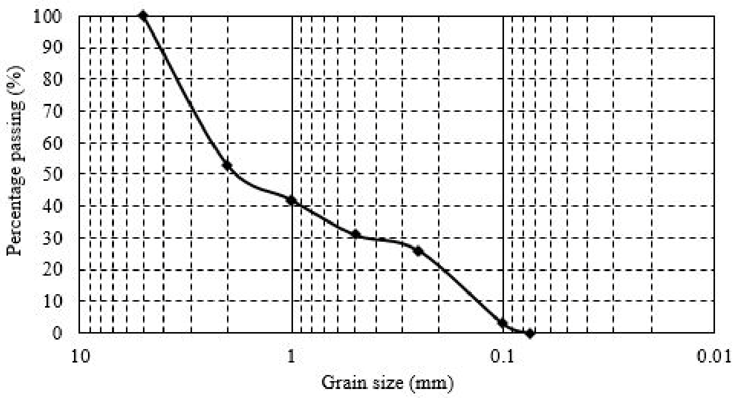
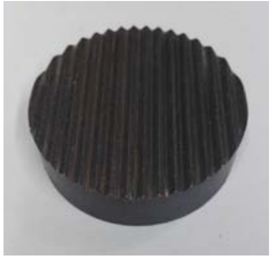


Fig. 1 Grading curve of testing soil

Table 1 Physical properties of testing soil

Properties	Natural soil
Mean grain size (mm)	1.9
Non-uniform coefficient	19.2
Curvature coefficient	0.65
Density (g/cm3)	1.21
Water content (%)	1.6
Specific gravity of soil grain	2.688
Dry density (g/cm3)	1.19
Void ratio	1.26
Saturation (%)	3.4

(a) Steel sample (surface roughness is 0.4 mm)



(b) Steel sample (surface roughness is 2.0 mm)

(c) Sand rock sample (surface roughness is 0.4 mm)

(d) Sand rock sample (surface roughness is 2.0 mm)

Fig. 2 Structure samples

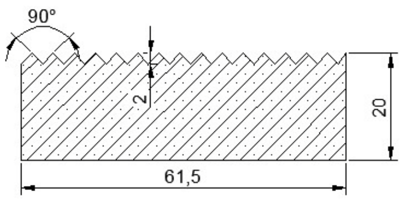


Fig. 3 Cross-section of structure sample (surface roughness is 2.0 mm)

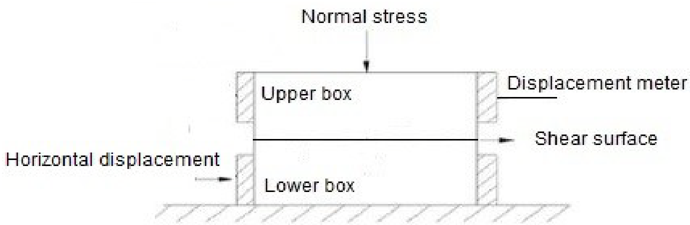


Fig. 4 Schematic diagram of direct shear apparatus

section of structure sample which surface roughness is 2 mm is shown in Figs. 2 and 3.

Because of the limitation of processing conditions, the surface roughness of steel are 0, 0.1, 0.2, 0.4, 1.0, 2.0 mm, and sand rock are 0, 0.4, 1.0, 2.0 mm.

2.3 Direct shear apparatus

The layout of the apparatus is shown in Fig. 4. The apparatus accommodates shear box, normal pressure system, propulsion system of lower box's horizontal displacement and displacement measurement of upper box. The displacement meter of upper box connects a spring. Structure is put in the lower box, upper box contains soil, porous stone and filter paper from the bottom up. Shear surface is the interface between soil and structure. The displacement loading speed of lower box is 0.8 mm/min for wet soil and 2.4 mm/min for natural soil. The horizontal displacement of upper box is measured and shear displacement of shear surface is horizontal displacement of lower box minus horizontal displacement of upper box. Shear stress of shear surface is multiplying shear displacement of upper box by stiffness of spring.

3. Testing results of interface direct shear test

The same experiment was conducted three times to verify the repeatability. The variation coefficient of interface frictional resistance is acceptable, for example, variation coefficient is 7.06% in natural soil-steel (roughness is 0.1 mm) interface under 200 kPa normal stress, 2.37% in natural soil-steel (roughness is 1.0 mm) interface under 300 kPa normal stress and 4.80% in natural soil-steel (roughness is 2.0 mm) interface under 100 kPa normal stress. According to soil direct shear test, the internal friction angle of natural soil is 31.1° and wet soil is 34.3°. From the soil-structure interface testing results, frictional properties, interface friction-shear displacement curve and normal displacement-shear displacement curve were obtained.

3.1 Frictional properties

The relationship between friction angle of soil-structure interface and surface roughness of structure, the relationship between interface frictional resistance and surface roughness of structure, and interface frictional resistance-normal stress curve are frictional properties of soil-structure interface.

3.1.1 Friction angle of soil-structure interface

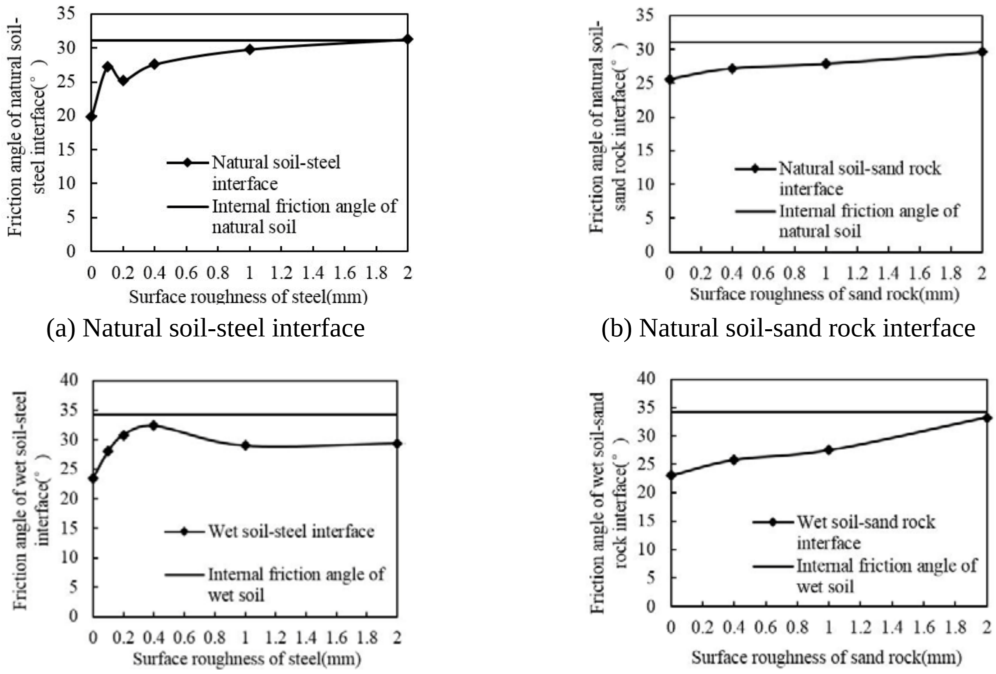
The value of interface friction angle under each surface roughness is shown in Table 2. Relative roughness, or normalized roughness, is defined as surface roughness divided by mean grain size of soil (Kishida and Uesugi 1987, Hossain and Yin 2014, Gan and Fredlund 1994, Borana *et al*. 2016a, b). The friction angle of soil-structure interface and surface roughness of structure curve is shown in Fig. 5.

Figs. 5(a)-(d) show that: (1) Friction angle of interface is lower than internal friction angle of soil. (2) Friction angle of interface is minimum when surface roughness is 0 mm. (3) Friction angle of interface increases as the surface roughness increases. When surface roughness is much larger than soil grain size, soil-structure interface is nearly soil shear surface, so interface friction is approaching internal friction angle of soil. Fig. 5 shows this trend.

Fig. 5(a) shows that when surface roughness of steel is 0.1 mm (relative roughness is about 0.05), friction angle of interface reaches a local peak. And when surface roughness of steel is 2.0 mm (relative roughness is about 1), friction angle of interface proceeds internal friction angle of soil. Fig. 5(c) shows that when surface roughness of steel is greater than or equal to 0 mm and less than or equal to 0.4 mm, friction angle of interface increases at a decreasing rate as the surface roughness increases. When surface roughness of steel is greater than 0.4 mm and less than or equal to 2.0 mm, friction angle of interface decreases to a relative stable value as the surface roughness increases. When surface roughness of steel is 0.4 mm, friction angle of interface is maximum.

Table 2 Friction angle of soil-structure interface

Surface roughness of structure	0 mm	0.1 mm	0.2 mm	0.4 mm	1.0 mm	2.0 mm
Natural soil-steel interface	19.8°	27.2°	25.2°	27.6°	29.8°	31.3°
Natural soil-sand rock interface	25.6°	-	-	27.2°	27.9°	29.6°
Wet soil-steel interface	23.4°	28.0°	30.8°	32.4°	29.0°	29.4°
Wet soil-sand rock interface	23.1°	-	-	25.8°	27.5°	33.2°



(a) Natural soil-steel interface (b) Natural soil-sand rock interface

(c) Wet soil-steel interface (d) Wet soil-sand rock interface

Fig. 5 Effects of surface roughness on friction angle

There are local peak and global peak respectively in the curves of Figs. 5(a) and (c), which is totally different from Figs. 5(b) and (d). This indicates that soil-steel interface is different from soil-sand rock interface and structural material type has influence on interface friction angle.

3.1.2 Interface frictional resistance of soil-structure interface

The value of interface frictional resistance under different normal stress and surface roughness is shown in Tables 3-6, respectively. Frictional resistance of soil-structure interface and surface roughness of structure curve is shown in Fig. 6.

Figs. 6(a)-(d) show that: (1) Frictional resistance of interface is minimum when surface roughness is 0 mm. (2) Frictional resistance of interface increases as the surface roughness increases.

Figs. 6(a) and (c) show that when surface roughness of steel is 0.1 mm (relative roughness is about 0.05), frictional resistance of interface has a local peak.

Fig. 6(d) shows that frictional resistance slightly decreases at first, and then increasing as the

Table 3 Frictional resistance of natural soil-steel interface

Normal stress (kPa)	100	200	300	400
Surface roughness (mm)	Frictional resistance (kPa)			
0	22.13	54.01	105.3	158.56
0.1	29.35	93.76	150.47	218.97
0.2	35.76	86.24	140.04	195.96
0.4	44.5	98.67	149.77	218.63
1.0	47.82	106.15	168.18	238.52
2.0	55.04	117.78	184.56	244.24

Table 4 Frictional resistance of natural soil-sand rock interface

Normal stress (kPa)	100	200	300	400
Surface roughness (mm)	Frictional resistance (kPa)			
0	26.78	99.86	134.32	201.53
0.4	37.34	106.69	143.66	214.51
1.0	43.98	112.59	141.73	224.06
2.0	49.68	129.66	142.95	242.08

Table 5 Frictional resistance of wet soil-steel interface

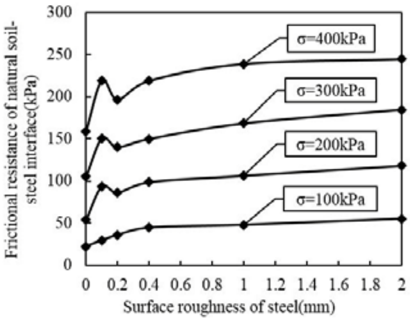
Normal stress(kPa)	100	200	300	400
Surface roughness(mm)	Frictional resistance(kPa)			
0	46.05	99.80	148.12	174.44
0.1	59.08	121.53	182.18	215.80
0.2	60.23	108.94	171.47	238.49
0.4	68.16	121.04	180.69	259.63
1.0	71.79	125.11	179.53	238.15
2.0	67.13	132.36	177.01	240.22

Table 6 Frictional resistance of wet soil-sand rock interface

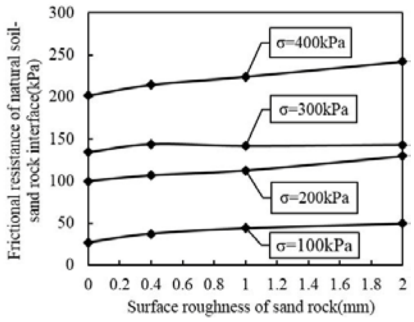
Normal stress (kPa)	100	200	300	400
Surface roughness (mm)	Frictional resistance (kPa)			
0	64.03	118.53	158.82	192.45
0.4	59.61	101.74	181.4	194.31
1.0	67.49	124.13	178.54	222.59
2.0	66.05	138.46	203.68	262.2

surface roughness of sand rock increases. When surface roughness of sand rock is 0.4 mm, frictional resistance of interface is minimum.

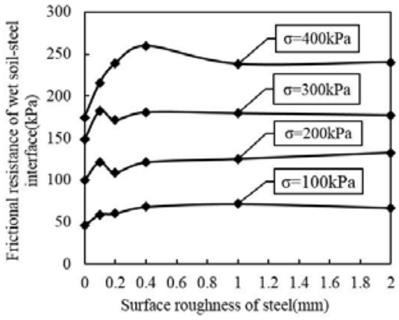
The difference between Figs. 6(a), (c) and Figs. 6(b), (d) further indicates that except for



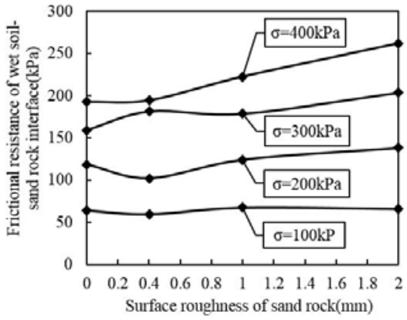
(a) Natural soil-steel interface



(b) Natural soil-sand rock interface



(c) Wet soil-steel interface



(d) Wet soil-sand rock interface

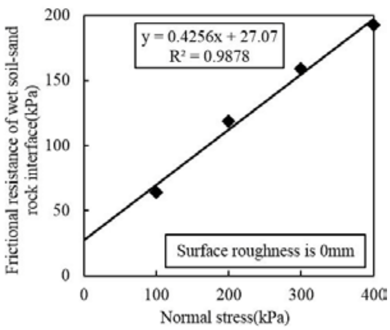
Fig. 6 Effects of surface roughness on frictional resistance

structure's surface geometry, structure's material type also affects the frictional resistance of soil-structure interface.

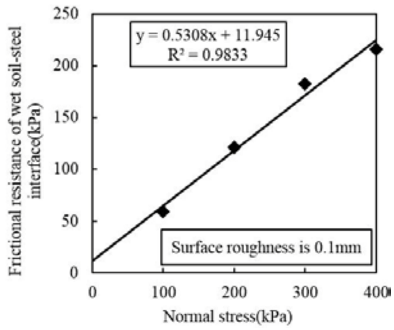
3.1.3 Interface frictional resistance and normal stress curve

Interface frictional resistance and normal stress curve is shown in Fig. 7.

The fitting method of Fig. 7 is least square method, and the intercept of trend curve on the vertical coordinate is 0 when soil is natural. Figs. 7(a)-(f) show that the relationship between

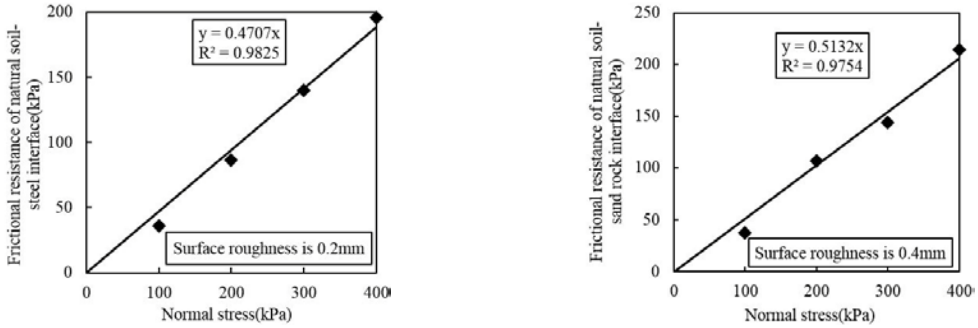


(a) Wet soil-sand rock interface of 0 mm roughness

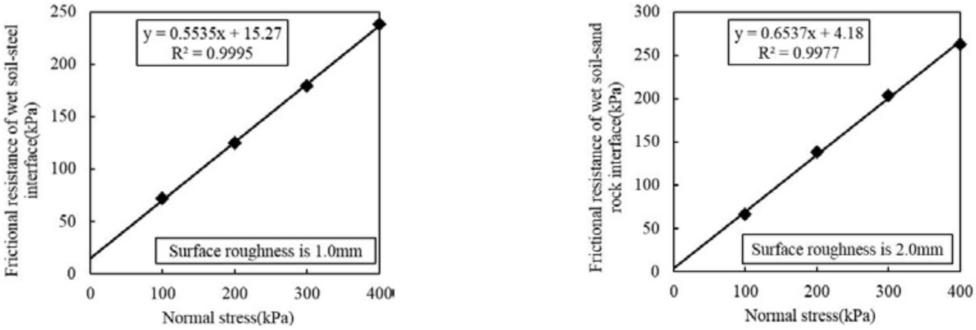


(b) Wet soil-steel interface of 0.1 mm roughness

Fig. 7 Interface frictional resistance and normal stress curve



(c) Natural soil-steel interface of 0.2 mm roughness (d) Natural soil-sand rock interface of 0.4 mm roughness



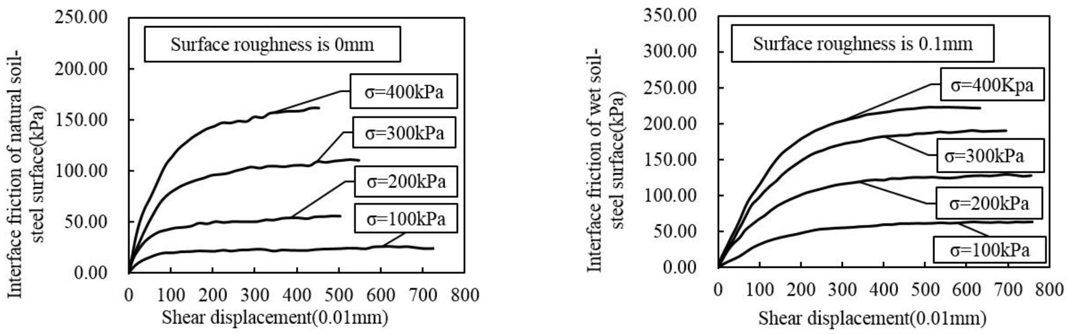
(e) Wet soil-steel interface of 1.0 mm roughness (f) Wet soil-sand rock interface of 2.0 mm roughness

Fig. 7 Continued

interface frictional resistance and normal stress meets the Mohr-Coulomb criterion. Interface friction can be expressed as shown in Eq. (1)

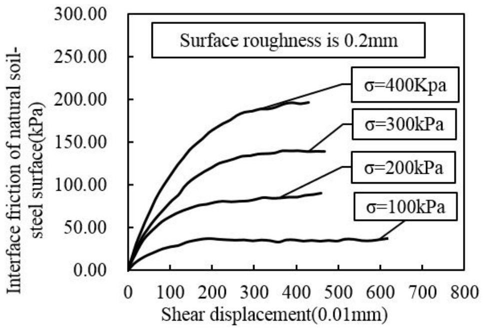
$$\tau_i = C_i + \sigma \cdot \tan\phi_i \tag{1}$$

In Eq. (1), τ_i is interface friction, C_i is interface cohesion, σ is normal stress, ϕ_i is friction

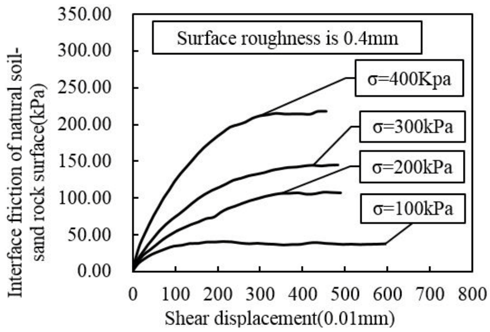


(a) Natural soil-steel interface of 0 mm roughness (b) Wet soil-steel interface of 0.1 mm roughness

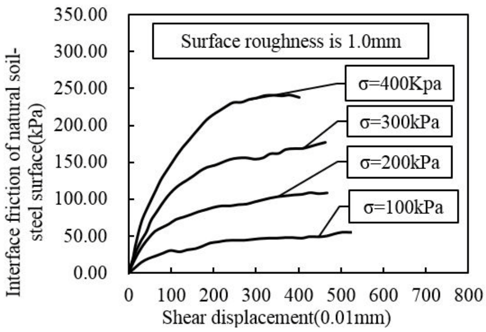
Fig. 8 Interface friction-shear displacement curve



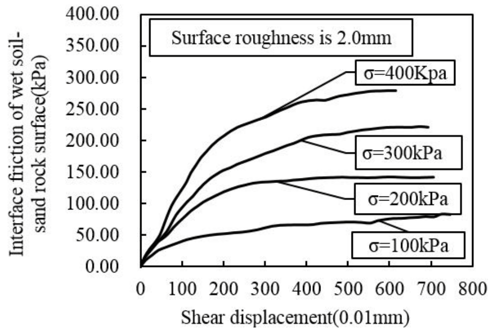
(c) Natural soil-steel interface of 0.2 mm roughness



(d) Natural soil-sand rock interface of 0.4 mm roughness



(e) Natural soil-steel interface of 1.0 mm roughness



(f) Wet soil-sand rock interface of 2.0 mm roughness

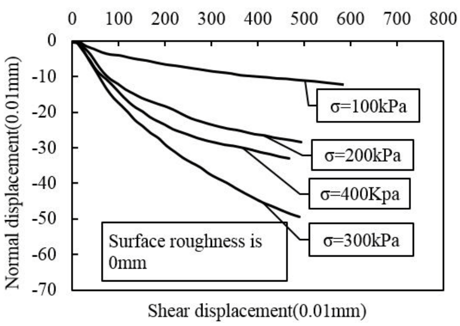
Fig. 8 Continued

angle of interface.

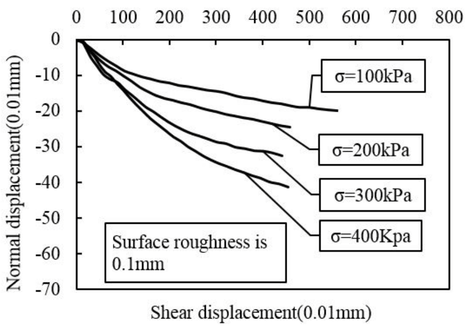
3.2 Interface friction-shear displacement curve

The interface friction-shear displacement curve is shown in Fig. 8.

Figs. 8(a)-(f) show that: (1) Initial stiffness of the same interface is different under each normal

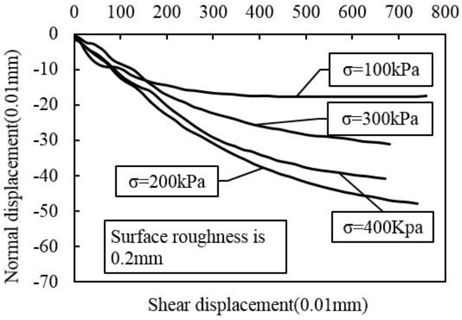


(a) Natural soil-sand rock interface of 0 mm roughness

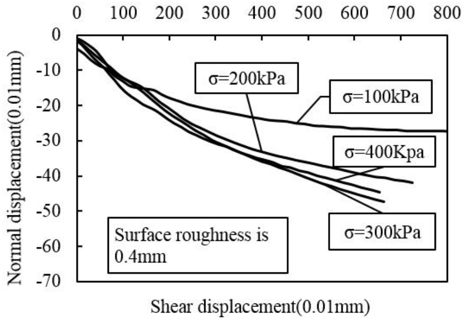


(b) Natural soil-steel interface of 0.1 mm roughness

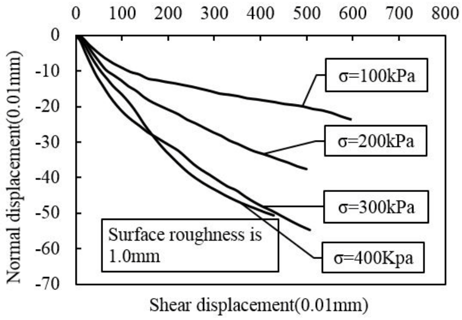
Fig. 9 Normal displacement-shear displacement curve



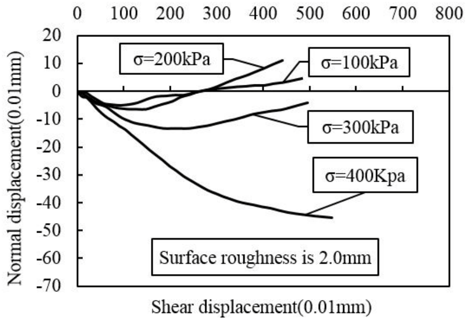
(c) Wet soil-steel interface of 0.2 mm roughness



(d) Wet soil-steel interface of 0.4 mm roughness



(e) Natural soil- sand rock interface of 1.0 mm roughness



(f) Natural soil-steel interface of 2.0 mm roughness

Fig. 9 Continued

press. (2) The interface friction and shear displacement curve is without softening and close to the Clough-Duncan hyperbola.

3.3 Normal displacement-shear displacement curve

The normal displacement-shear displacement curve is shown in Fig. 9.

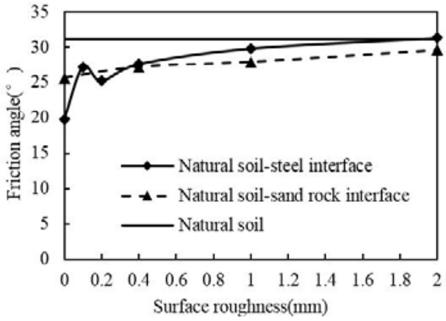
Figs. 9(a)-(f) show that the relationship between normal displacement and shear displacement is mainly shear contraction.

Fig. 9(f) shows that when surface roughness of steel is 2 mm and when normal stress is low, the normal displacement-shear displacement curve is shear contraction at first, and then is obvious shear dilatancy.

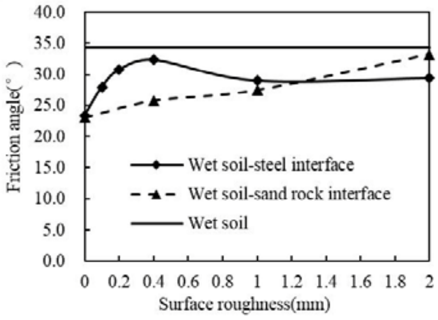
4. Comparison of testing results

4.1 Material types of structure

The relationship between friction angle and surface roughness, and the relationship between frictional resistance and surface roughness were analyzed to research the influence of material types of structure.



(a) Natural soil



(b) Wet soil

Fig. 10 Effects of material types of structure on friction angle

4.1.1 Friction angle

The internal friction angle of natural soil is 31.1° and wet soil is 34.3°. The friction angle of soil-structure interface is shown in Table 2. The friction angle and surface roughness curve is shown in Fig. 10. Figs. 10(a) and (b) show that friction angle of interface is lower than internal friction angle of soil.

Fig. 10(a) shows that: (1) When surface roughness is less than 0.4 mm, friction angle of natural soil-sand rock interface is larger than natural soil-steel interface. (2) When surface roughness is greater than or equal to 0.4mm and less than or equal to 2.0 mm, friction angle of natural soil-steel interface is larger than natural soil-sand rock interface. (3) When surface roughness of steel is 0.1 mm (relative roughness is about 0.05), friction angle of interface occurs a local peak.

Fig. 10(b) shows that: (1) When surface roughness is less than or equal to 1.0 mm, friction angle of wet soil-steel interface is larger than wet soil-sand rock interface. (2) When surface roughness is equal to 2.0 mm, friction angle of wet soil-sand rock interface is larger than wet soil-steel interface.

4.1.2 Frictional resistance

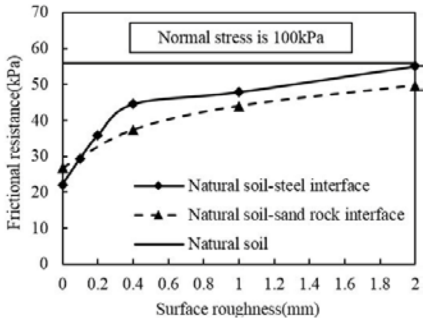
The shear strength of soil is shown in Table 7, and the interface frictional resistance is shown in Tables 3-6, respectively. The relationship between frictional resistance of shear surface and surface roughness is shown in Figs. 11 and 12.

Figs. 11(a)-(d) show that: (1) Interface frictional resistance is lower than shear strength of soil, which means interface is weaker than soil. (2) As surface roughness increases, frictional resistance of natural soil-sand rock interface is larger than natural soil-steel interface at first, and then natural soil-steel interface is larger than natural soil-sand rock interface, which in accordance with the change trend of friction angle. (3) When surface roughness of steel is 0.1 mm (relative roughness is about 0.05), interface frictional resistance occurs a local peak.

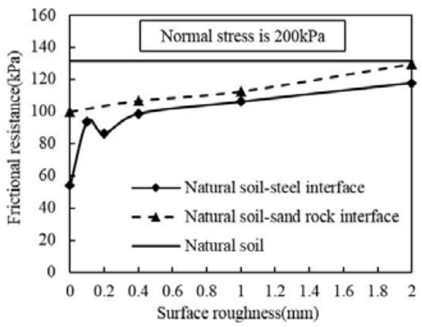
Figs. 12(a)-(d) show that: (1) Interface frictional resistance is lower than shear strength of soil, which means interface is weaker than soil. (2) When surface roughness is 0 mm, frictional resistance of wet soil-sand rock interface is larger than wet soil-steel interface. The possible reason is that when surface roughness is 0 mm, the micro roughness of sand rock is more rough than steel. (3) As surface roughness increases, frictional resistance of wet soil-steel interface is larger than wet soil-sand rock interface at first, and then wet soil-sand rock interface is larger than wet soil-steel interface, which in accordance with the change trend of friction angle.

Table 7 Shear strength of soil

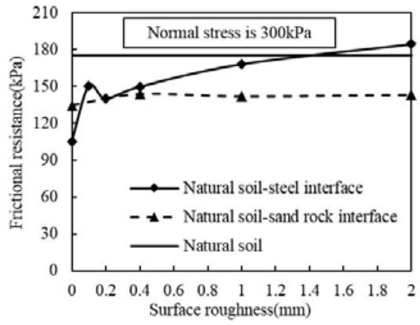
Normal stress (kPa)	100	200	300	400
Natural soil (kPa)	55.89	131.39	175.32	240.53
Wet soil (kPa)	81.85	171.73	203.8	298.51



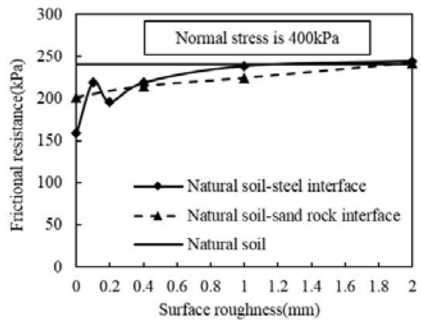
(a) Normal stress is 100 kPa



(b) Normal stress is 200 kPa



(c) Normal stress is 300 kPa



(d) Normal stress is 400 kPa

Fig. 11 Effects of material types of structure on frictional resistance of natural soil

4.2 Soil water content

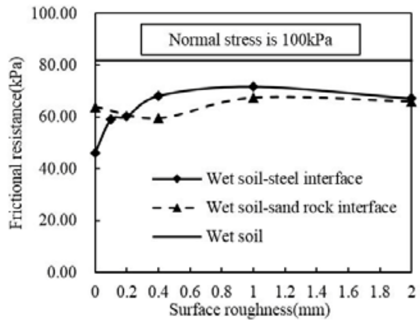
Friction angle and frictional resistance of interface were analyzed to research the influence of soil water content.

4.2.1 Interface friction angle

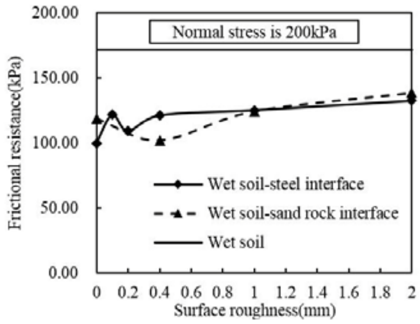
The interface friction angle and surface roughness curve is shown in Fig. 13.

Fig. 13(a) shows that: (1) When surface roughness is less than 1.0 mm, friction angle of wet soil-steel interface is larger than natural soil-steel interface. (2) When surface roughness is greater than or equal to 1.0 mm and less than or equal to 2.0 mm, friction angle of natural soil-steel interface is larger than wet soil-steel interface.

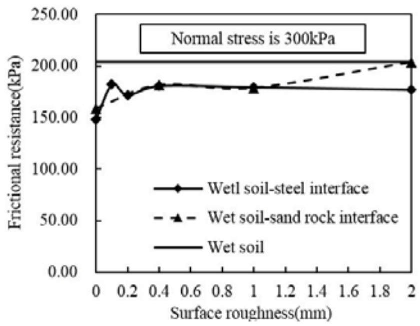
Fig. 13(b) shows that: (1) When surface roughness is less than or equal to 1.0 mm, friction angle of natural soil-sand rock interface is larger than wet soil-sand rock interface. (2) When surface roughness is equal to 2.0 mm, friction angle of wet soil-sand rock interface is larger than natural soil-sand rock interface.



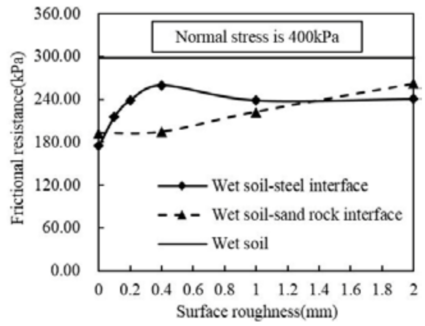
(a) Normal stress is 100 kPa



(b) Normal stress is 200 kPa

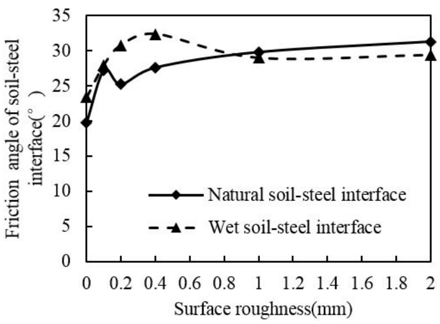


(c) Normal stress is 300 kPa

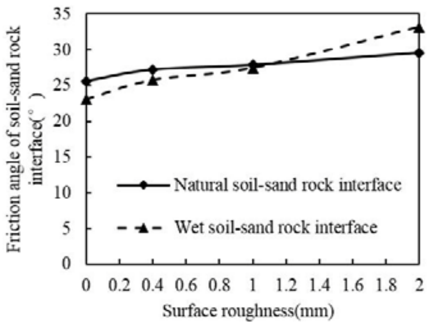


(d) Normal stress is 400 kPa

Fig. 12 Effects of material types of structure on frictional resistance of wet soil



(a) Steel



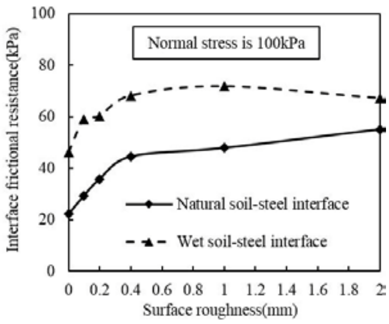
(b) Sand rock

Fig. 13 Effects of soil water content on interface friction angle

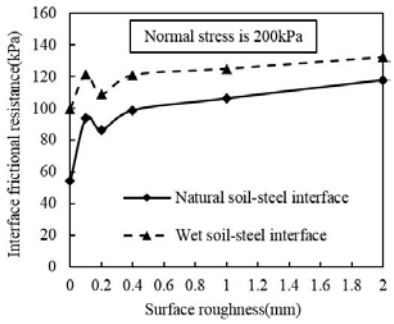
4.2.2 Interface frictional resistance

The relationship between interface frictional resistance and surface roughness is shown in Figs. 14 and 15.

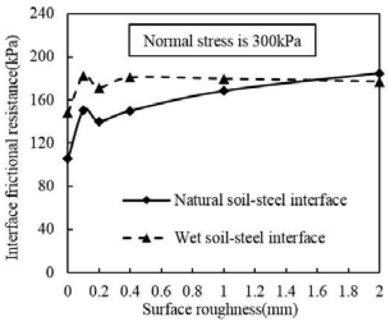
Figs. 14(a)-(d) show that: (1) When normal stress is less than or equal to 200 kPa, the frictional resistance of wet soil-steel interface is larger than natural soil-steel interface; (2) When normal stress is greater than or equal to 300 kPa, the frictional resistance of wet soil-steel interface is larger than natural soil-steel interface when surface roughness is less than or equal to 1.0 mm, and



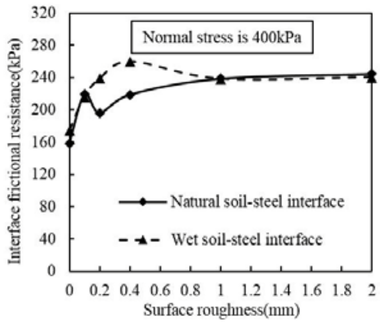
(a) Normal stress is 100 kPa



(b) Normal stress is 200 kPa



(c) Normal stress is 300 kPa

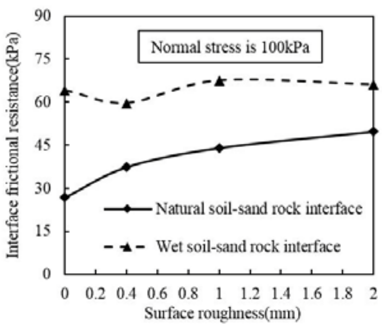


(d) Normal stress is 400 kPa

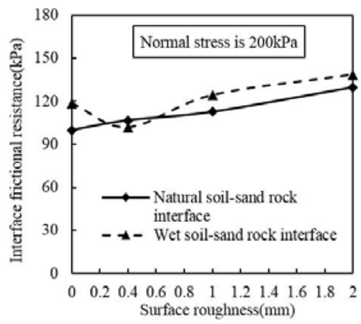
Fig. 14 Effects of soil water content on frictional resistance of soil-steel interface

the frictional resistance of wet soil-steel interface is less than natural soil-steel interface when surface roughness is equal to 2.0 m, which means the interface is weakened by water.

Figs. 15(a)-(d) show that: (1) When normal stress is less than or equal to 300 Pa, the frictional resistance of wet soil-sand rock interface is larger than natural soil- sand rock interface; (2) When normal stress is equal to 400 kPa, the frictional resistance of wet soil- sand rock interface is less than natural soil- sand rock interface when surface roughness is less than or equal to 1.0 m, which means the interface is weakened by water, the frictional resistance of wet soil-sand rock interface

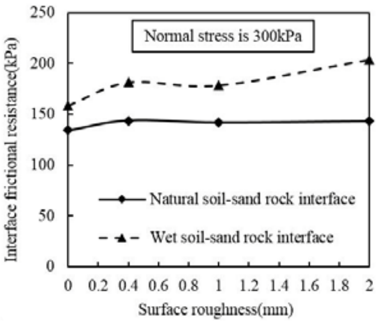


(a) Normal stress is 100 kPa

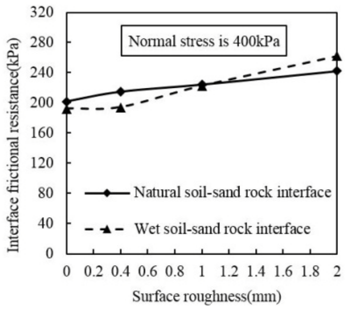


(b) Normal stress is 200 kPa

Fig. 15 Effects of soil water content on frictional resistance of soil-sand rock interface



(c) Normal stress is 300 kPa



(d) Normal stress is 400 kPa

Fig. 15 Continued

is larger than natural soil-sand rock interface when surface roughness is equal to 2.0 mm.

Natural soil is nearly drying and wet soil is unsaturated soil, so that matric suction exists in wet soil, which results the increase in interface frictional resistance.

5. Conclusions

The frictional properties of interface between filling soil and bedrock of Chongqing airport was investigated by direct shear tests. As a contrast, soil-steel interface was also investigated. The main findings of this study are as follows:

- The relationship between interface frictional resistance and normal stress meets the Mohr-Coulomb criterion. The interface friction and shear displacement curve is without softening and close to the Clough-Duncan hyperbola. The relationship between normal displacement and shear displacement is mainly shear contraction.
- The interface frictional resistance is lower than the shear strength of soil, which means the interface is weaker than soil. The friction angle and frictional resistance of interface increase as the surface roughness of structure increases. When surface roughness is much larger than soil grain size, soil-structure interface is nearly soil's shear surface, so friction angle and frictional resistance of interface is approaching internal friction angle and shear strength of soil, respectively.
- The material types of structure has significant influence on friction angle and frictional resistance of interface, which indicates that in soil-structure tests, structure surface cannot be replaced by surface with same shape but made of different material.
- Testing results show that soil water content has influence on friction angle and frictional resistance of interface. For soil-steel interface, when normal stress is high and relative roughness is approaching 1, the interface is weakened by water. For soil-sand rock interface, when normal stress is high and relative roughness is lower than 0.5, the interface is weakened by water.

Acknowledgments

This work was supported by the National Key Fundamental Research and Development Program of China (Project No. 2014CB047004).

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