Front. Archit. Civ. Eng. China 2009, 3(1): 85–92
DOI 10.1007/s11709-009-0013-6

RESEARCH ARTICLE

R. R. SHAKIR, Jungao ZHU

Behavior of compacted clay-concrete interface

Abstract Tests of interface between compacted clay and concrete were conducted systematically using interface simple shear test apparatus. The samples, having same dry density with different water content ratio, were prepared. Two types of concrete with different surface roughness, i.e., relatively smooth and relatively rough surface roughness, were also prepared. The main objectives of this paper are to show the effect of water content, normal stress and rough surface on the shear stress-shear displacement relationship of clay-concrete interface. The following were concluded in this study: 1) the interface shear sliding dominates the interface shear displacement behavior for both cases of relatively rough and smooth concrete surface except when the clay water content is greater than 16% for the case of rough concrete surface where the shear failure occurs in the body of the clay sample; 2) the results of interface shear strength obtained by direct shear test were different from that of simple shear test for the case of rough concrete surface; 3) two types of interface failure mechanism may change each other with different water content ratio; 4) the interface shear strength increases with increasing water content ratio especially for the case of clay-rough concrete surface interface.

Keywords soil structure interaction, simple shear test, interface, friction, compacted clay, interface modeling

1 Introduction

Compacted soil structure interface systems are encountered in various geotechnical engineering projects like: earth dams, retaining walls, earth reinforcement, shallow foundations and pile foundations. The understanding of the behavior of soil structure interface plays an important role in calculating strength especially for the system, depending on friction in the calculated bearing capacity like piles. Compacted soil is unsaturated soil which can be analyzed in total stress or effective stress term. Few studies have been obtained for unsaturated soil structure interface [1,2]. To solve the geotechnical engineering problem, the stress-strain relationship and the description of deformation and sliding have to be studied. Many studies have been presented to describe the behavior of soil structure interface using different types of apparatus.

Earlier comprehensive study of soil structure interface was conducted by Potyondy [3]. It was postulated that the most important factors affecting friction are intensive normal stress, moisture content, roughness and the composition of soil. Following him, direct shear was used extensively to study the interface between sand and concrete by other researchers [4]. Large direct shear has been utilized to show the distribution of shear stress along the shear plane of soil concrete interface [5]. Acar et al. [6], using direct shear, concluded that the ratio of interfacial friction to internal friction angle was independent of the void ratio and then on relative density. Direct shear apparatus with sample box of size (305 mm×305 mm) has been used to investigate the behavior of sand-concrete interface under cyclic loading [7]. Another type of direct shear apparatus has been used to study sand-steel interface with microscope test to follow the sand particle movement [8]. The mechanical characteristics of the interface between sand and concrete have been studied using direct shear under relatively high stress [9]; however, steel plates with different roughness were used instead of concrete to avoid the limitation of wearing in concrete. The dual direct shear apparatus has been developed and used to study the sand-steel interface [10]. An extended type of direct shear device has been developed to deal with soil structure interface in three dimensional loading [11].

Other devices used to elaborate interface shear experiments could be grouped into ring shear apparatus, ring simple shear apparatus, cylinder shear apparatus, pull-out apparatus and simple shear apparatus. Ring shear (torsion) apparatus has been used to study soil-steel interface under constant volume and constant stress condition [12]. Ring simple shear apparatus has been used with membrane to

Received July 21, 2008; accepted November 18, 2008

R. R. SHAKIR (✉), Jungao ZHU
Geotechnical Research Institute, Hohai University, Nanjing 210098, China
E-mail: rrshakir@yahoo.com

test concrete soil interface [13]. Cylinder shear apparatus has been developed to study soil structure interface [14] which has many advantages but it is difficult to use. For pull-out apparatus, there are different kinds: pull-out of inclusion cylindrical form device [15,16], and recently the soil pile slip apparatus [17]. Each apparatus has merits and limitations. The well documented comparison between interface shear apparatus were presented by Kisheda et al. [18], Paikowsky et al. [10] and recently by Corfdir et al. [14].

Simple shear apparatus was developed by Uesuge et al. [19,20]. It was used in a series of studies on sand structure interface. Tsubakihara et al. [21,22] studied the friction between normally consolidated clay and steel plate using simple shear and shear box direct shear test apparatus. In their apparatus pore water pressure can be calculated during the test and roughness of steel was regarded as a factor that influences the relation of shear stress-strain. It was postulated that the interface shear sliding dominates the interface shear for the case of roughness less than the critical value while the interface shear agrees with shear within the soil for the case where roughness is larger than the critical value. Furthermore, it was stated that the speed of shear affects the maximum interface resistance. Wang et al. [23] studied the interface between clay with different water content and concrete but one type of concrete surface roughness was used. Simple shear and shear box device was utilized to test the interface between sand-mild steel [19], the influential factor on the friction between sand and steel [20], the behavior of the particle near the interface layer [24], and the friction between dry sand and concrete [25].

In this study, compacted clay concrete interface was studied using simple shear device which has the advantage of separating the total deformation into sliding and deformation. The clay soil used in this study has constant dry density with different water content ratios. In spite of using unsaturated soil, the analysis of behavior was in total stress with reference to water content ratio.

2 Experiments

Figure 1 shows the schematic diagram for the interface simple shear apparatus used in this study. This device was designed originally for the Geotechnical Research Institute to test soil structure interface under dynamic load. In this study, it was modified and used for clay concrete interface test under monotonic load. Containers with inner size of 107 mm×107 mm were manufactured and filled with concrete mortar, as it will be explained in the next section. These containers consist of a rectangular base plate of 115 mm×115 mm welded with four plates of size of 115 mm×40 mm. The concrete box was fixed to a brass base plate by two 6 mm bolts from the bottom. The area of clay-concrete contact does not change because the concrete dimension is greater than the contact area of the clay sample even when sliding displacement occurs. The sample container is a stack of rings manufactured from aluminum with thickness of 1.4 mm and diameter of 60 mm, see Fig.1. The rings were lubricated to minimize the friction induced between them in order to make deformation of clay mass occur freely. The height of the sample was 10 mm. Normal displacement is measured by strain mechanical gauge with accuracy of 0.001 mm/digit which is the same type used for tangential displacement.

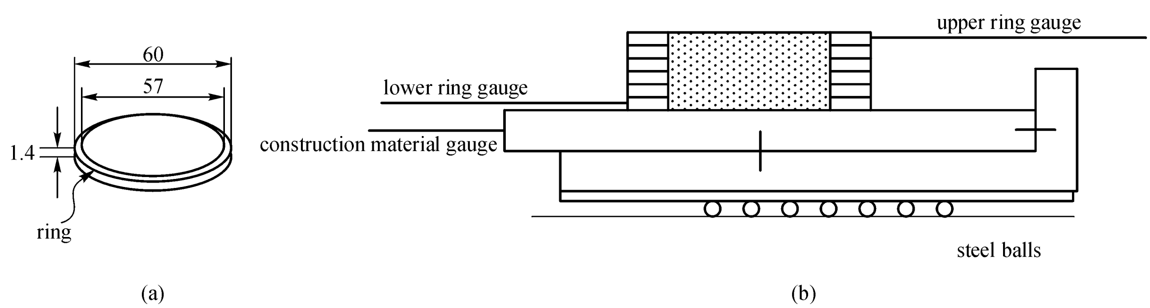

Fig. 1 Schematic view for the simple shear apparatus. (a) Ring dimensions (unit: mm); (b) simple shear apparatus

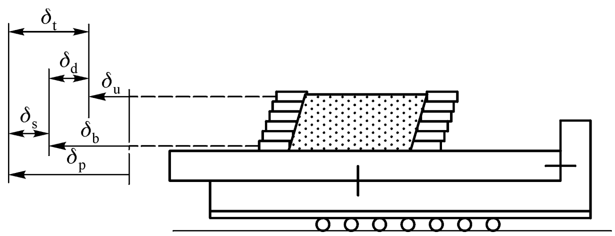

Fig. 2 Schematic diagram of sliding, deformation and total shear displacement

Figure 2 shows the schematic diagram for the method of calculating the sliding and deformation displacement due to shear stress application. The sliding displacement is measured by subtracting the displacement of the bottom ring which is located in contact with concrete from the displacement of concrete i.e., ($\delta_s = \delta_p - \delta_b$). The deformation displacement due to shear stress application is calculated by subtracting the sliding displacement from the displacement of the top ring of the stack of rings ($\delta_d = \delta_b - \delta_u$). The total displacement is calculated by adding the sliding displacement to the deformation displacement ($\delta_t = \delta_s + \delta_d$). Thus in simple shear test, displacement can be divided into shear sliding displacement and shear deformation displacement through which the behavior of interface and the importance of each one of them can be understood.

3 Soil structure interface materials

3.1 Preparation of concrete

Concrete structural material was prepared so that the strength value is a practical value, at the same time it can be sheared with clay repeatedly with minimum wear on the surface. Two boxes were manufactured as concrete mortar container. These boxes, which consist of four pieces welded to a plate at the bottom, were used to minimize the deformation during shear interface testing and were used as external reinforcement. It was fastened by bolts to another brass plate which slides on sliding steel balls as shown in (Fig. 3).

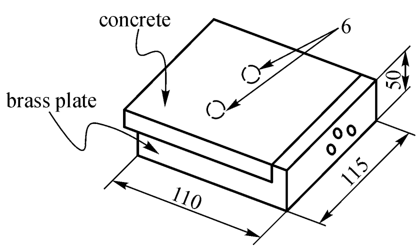

Fig. 3 Base plate and concrete box (unit: mm)

The concrete was prepared by first mixing the sand and cement, adding water with 60% water cement ratio and mixing gradually, subsequently filling the two boxes with concrete. The ratio of cement to sand was (1:2.5). They were filled by scratch then the surface was leveled using a spatula. To prepare different types of surface roughness: the surface of the concrete was finished by passing the spatula horizontally in order to obtain a smooth surface while lines were made by spatula along the vertical direction to the direction of shearing in order to obtain rough surface. The dimension of each box is 115 mm×115 mm×40 mm. It was fastened by two screws to the brass base plate; the diameter of the screw was 6 mm. The two boxes of concrete were embedded under wet sand for five months, and then they were used in the interface testing with clay.

3.2 Preparation of clay soil sample

The main properties of clay such as plastic limit (PL), liquid limit (LL) and specific gravity (Gs) were obtained based on the Chinese Standard, see Table 1. The dry density of the clay is 1.65 g/cm^3 and the optimum water content (W_c) is about 18%. Clay soil was prepared with three different water contents: 10%, 16% and 21%. Water was added to the clay and after mixing, they were saved in a nylon bag to ensure equal distribution of water content. The samples were compacted by pressing the soil to a constant volume so that it will obtain constant dry density where the weights of the soil samples were calculated from the weight-volume soil relationship.

Table 1 Main properties of clay

LL	PL	PLI.	Gs	dry density/(g/cm^3)	W_c/%
35.08	19.98	15.1	2.68	1.65	18

4 Testing method

The test specimen was prepared inside the frame of rings by filling the container with clay then it was compacted by pressing method so that it has the same dry density with different water content ratio. The sample was positioned on concrete construction material under its gravity weight. It means that the specimen stands on most of the concrete surface asperities which can be classified according to its roughness profile, into micro level, nano level and so on. There is no full contact between the samples and concrete in the contact area at the beginning of the test because the sample was considered as quasi-solid sample except for the case of clay with high water content. The normal load was applied on the sample then directly tangential load is applied. The sliding displacement and deformation displacement were measured for the two cases of clay-rough and smooth concrete surface interface.

5 Simple shear test results

5.1 Sliding displacement vs deformation displacement

Figure 4 shows the relations between shear sliding displacement and shear deformation displacement for three normal stress values 50 kPa, 100 kPa and 150 kPa for the case of clay-rough surface concrete interface. It can be noticed from Figs. 4(a) and (b) for water content of 10%

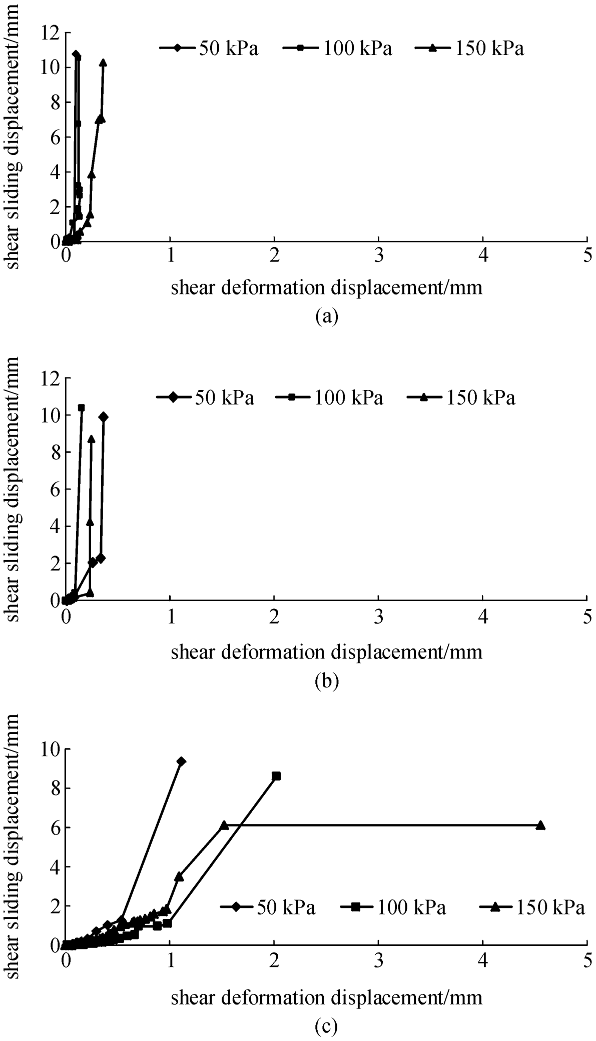

Fig. 4 Relationship between shear sliding displacement and shear deformation displacement for clay-rough surface concrete interface. (a) $W_c = 10\%$; (b) $W_c = 16\%$; (c) $W_c = 21\%$

and 16% that the deformation displacement is insignificant and it does not exceed 0.35 mm for the three values of normal stress used in this study while shear sliding causes substantial displacement for the test. The insignificance of the deformation displacement means that interface shear strength depends mainly on sliding strength i.e. the asperities of concrete govern the movement of the sample. Furthermore, it can be seen that the deformation displacement is influenced not only by normal stress but also by soil moisture content. For the case where the water content of clay is 21%, the results show high deformation compared to the case with other moisture content and failure occurs inside the sample for the case of normal stress 150 kPa (see Fig. 4(c)).

5.2 Shear stress-total shear displacement relations

The results obtained from the tests were presented in curves of applied shear stress against total shear displacement so that the shear displacement will not only reflect the characteristics of interface behavior but also the behavior of the body of soil, which is not in contact with concrete. From Fig. 5 it can be seen that normal stress is an important factor that increases the shear strength of the interface, at the same time it increases the shear strength when clay moisture content increases, which will be discussed later in Section 6.

The total displacement before yielding is small and close to 0.6 mm for the case of clay with water content 10% while it increases with increasing moisture content. The greatest amount of displacement among all cases was found to be close to 2 mm for the case of clay-rough concrete interface when $W_c = 21\%$ (see Fig. 5(c)). It may be attributed to the state of clay which becomes more plastic with increasing water content. After this amount of displacement and approximately after the governing of sliding displacement, the interface shear strength will be very small and so the sample continues sliding until failure occurs. For the case of interface between compacted clay and smooth concrete surface, the effect of normal stress and moisture content, in general shows differences in interface shear displacement characteristics compared to that of interface with rough concrete surface. The total shear displacement was small and the amount of shear deformation before yielding is smaller than the case of clay-rough concrete surface interface. With respect to the interface shear strength, it depends on the effect of normal stress also but it is less than the case of interface of rough concrete surface.

Since the compacted clay has high density and the normal stress range is 50 kPa to 150 kPa, the deformation displacement is small and depends mainly on the asperities of concrete and water content ratio. On the other hand, the sliding displacement is the substantial displacement and the interface strength will depend on the strength to sliding. According to that, the small value of the interface shear strength of clay-smooth concrete compared to clay-rough concrete can be interpreted obviously (see Figs. 5(c) and (f)).

6 Interface shear strength and moisture content effect

6.1 Rough concrete

Figure 6 shows the interface shear strength relation between normal stress and applied shear stress at failure. The shear failure is taken approximately as the value opposite to 15% of the total shear displacement which is customarily used for curves that do not show clear point of shear failure. It is known that the interface shear strength of clay consists of two components: adhesion and friction which are expressed by the old familiar relation of Coulomb $\tau_s = c + \sigma \tan\delta$, here δ is the contact friction.

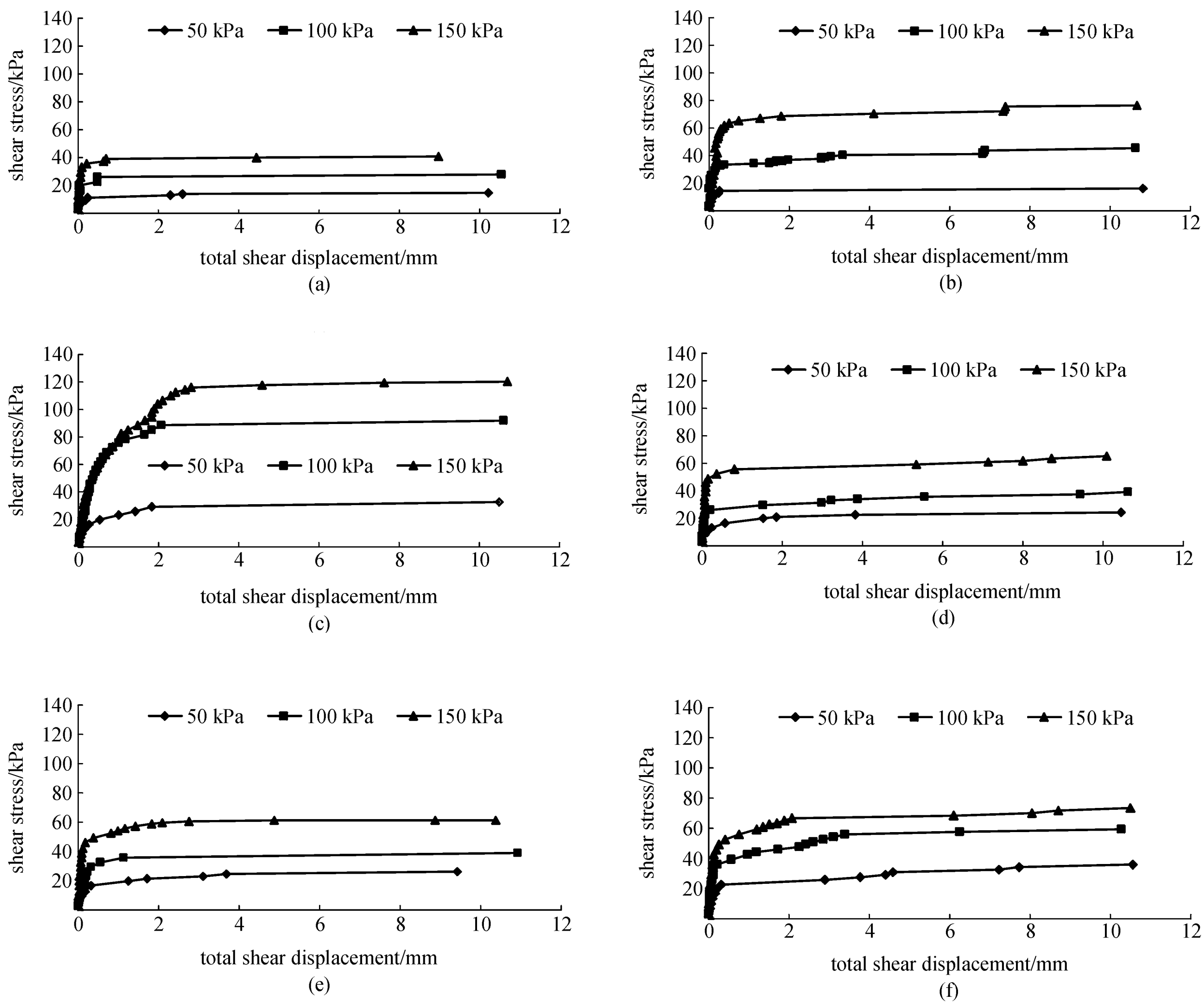

Fig. 5 Relationship between shear stress and total shear displacement for case of clay-rough concrete and smooth-concrete surface interface. (a) $W_c = 10\%$, rough concrete; (b) $W_c = 16\%$, rough concrete; (c) $W_c = 21\%$, rough concrete; (d) $W_c = 10\%$, smooth concrete; (e) $W_c = 16\%$, smooth concrete; (f) $W_c = 21\%$, smooth concrete

The Mohr Coulomb formula was proven to be a valid formula for the shear stress-normal stress relation. The relation is linear and the adhesion is indicated as the interception point with shear stress axis when normal stress is equal to zero. Figure 7 shows the relation between shear stress at failure and water content for normal stresses of 50 kPa, 100 kPa and 150 kPa. It can be seen that the interface shear strength increased with increasing moisture content. The shear strength increased highly with respect to the second component "angle of contact friction" when the clay water content is greater than 16%. In another form it can be concluded from these results that there are two angles of contact friction, the first is between 10% and 16% of clay water content and the second between 16% and 21% of water content. It is known from literature that the friction strength decreases when the surfaces of dissimilar materials are wet while in this study an opposite conclusion was found. It may be attributed to the concrete surface being dry and clay was used with different water content which means there are different states of the material. Also, with increasing moisture content the clay shows more compressibility response which makes the density of clay increase throughout loading and the bottom of clay has full contacted with the concrete surface in most levels of asperities size.

6.2 Smooth concrete

Figure 8 shows the interface shear strength relation for the case of clay-smooth concrete interface. It can be seen that the interface shear strength is less than that for the case of rough concrete surface. The relation between shear stress and normal stress is linear except when the clay has a water content of 10%. It is divided into two parts in the range of

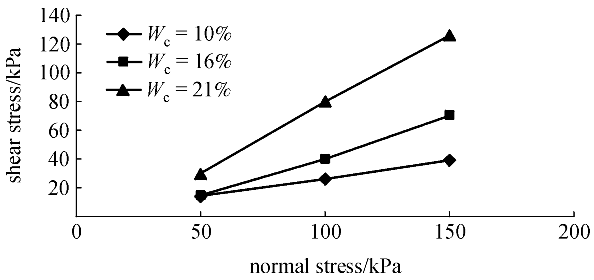

Fig. 6 Relationship between shear stress and normal stress for clay-rough surface concrete interface

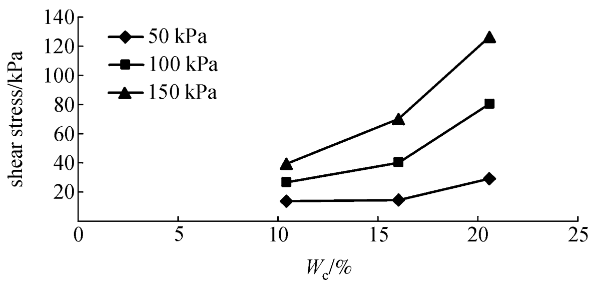

Fig. 7 Relationship between shear stress and water content ratio for clay-rough surface concrete interface

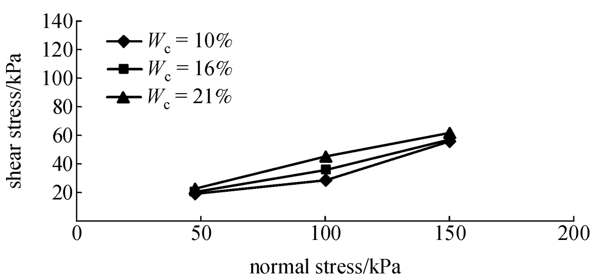

Fig. 8 Relationship between shear stress and normal stress for clay-smooth surface concrete interface

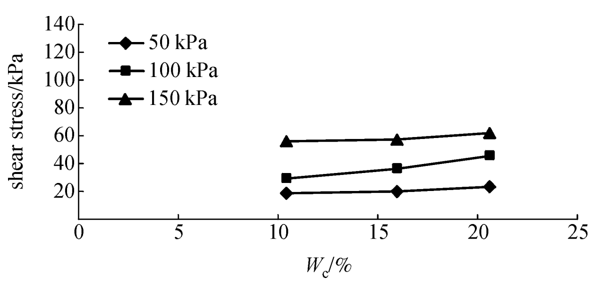

Fig. 9 Relationship between shear stress and water content ratio for clay-smooth surface concrete interface

normal stress that has been applied. The first is between 50 kPa and 100 kPa while the second is between 100 kPa and 150 kPa. Each part has its own interface strength components. The effect of water content on shear stress is less than that of rough concrete. Figure 9 shows the relation between shear stress and water content for three normal stress values: 50 kPa, 100 kPa and 150 kPa. Generally, the effect of water content for each case of normal stress is insignificant particularly when the water content was 10% and 21%.

7 Transition mechanism failure (TMF)

According to the relation between shear sliding displacement and shear deformation displacement (see Figs. 4 and 7) and the shape of contact area of the sample inspection at the end of the test (see Fig. 10), two types of mechanism failure can be proposed.

Figure 10(a) shows the first mechanism failure. The clay with dry density of about 1.65 g/cm^3 and water content of 10% may behave as quasi-solid material where hardness dominates the behavior of sliding and wearing occurs in the contact area of clay. The aforementioned results show that the shear deformation displacement is insignificant and shear sliding displacement is of great value, therefore the mechanism of failure will depend on the clay sample sliding i.e. the deformed shape in the clay contact area.

The second type of mechanism of failure depends on the deformation in the body of the sample. It was inspected that the shape of failure is similar to (see Fig.10(b)) what happens in the case of clay rough concrete interface when the water content ratio is about 21%. Because of high density and high water content of the clay sample, it undergoes high compressibility which leads to full contact of two dissimilar materials. The sliding takes place while the part of the contact area undergoes stress concentration and then deformation displacement occurs as it is indicated in the contact area schematic (see Fig.10(b)). The point of transition from one mechanism to another is determined by the critical value of water content which is considered as 16%. The second mechanism is referred to the case when the normal stress is 150 kPa and water content is 21%.

8 Direct shear test

The frame of rings in the simple shear test was replaced by a circular box to compare the interface shear results with that of the simple shear test. The same descriptions of preparation of samples were used. The results obtained from this test are presented in terms of the interface shear strength and interface shear water content relation as shown in Figs.11 and 12.

It can be seen from Fig. 11 that the relation of interface shear strength is not linear as in the case of simple shear test but it seems to be convex and even the magnitude of the two components of shear strength: angle of contact friction and adhesion are different compared to the case of simple shear test. This can be attributed to the differences

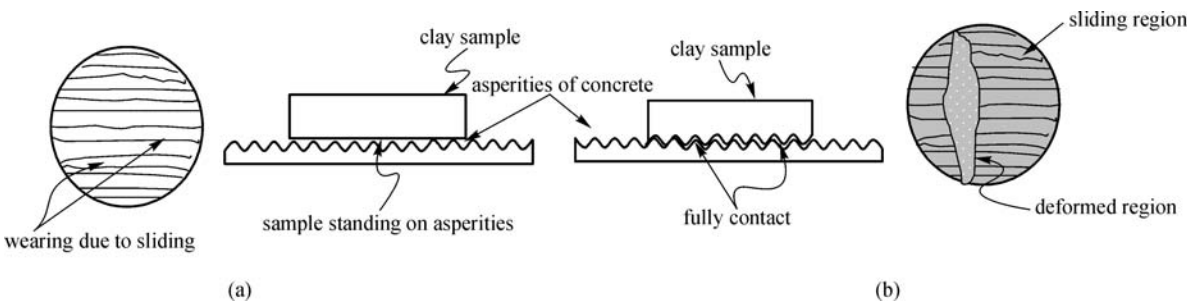

Fig. 10 Simulated shape of clay contact area due to interface shearing with concrete. (a) Clay with W_c= 10%, σ_n = 50 kPa, 100 kPa, 150 kPa; (b) Clay with W_c= 21%, σ_n= 150 kPa

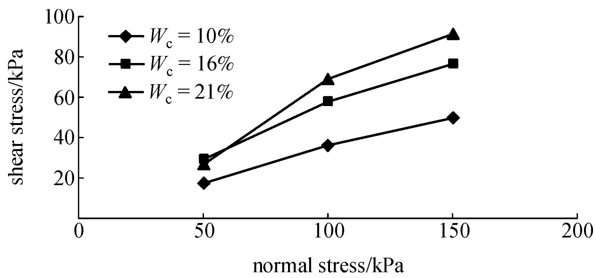

Fig. 11 Relationship between shear stress and normal stress for clay-rough surface concrete interface using direct shear test

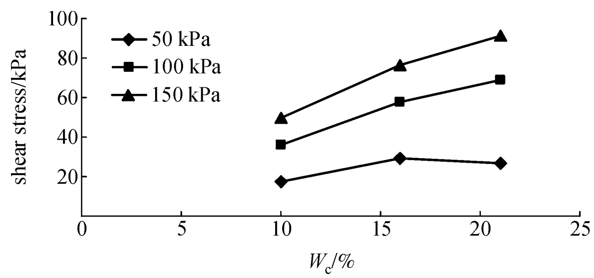

Fig. 12 Relationship between shear stress and water content ratio for clay-rough surface concrete using direct shear test

between the two experiments of simple and box shear apparatus where in box shear, the specimen is forced to have one plane of shear failure while for simple shear the distortion occurs freely in the body of soil. Figure 12 shows the relation between shear failure and water content which are also different compared to the simple shear test. Here water content affects the results so it makes the curve convex while for the simple shear it is concave.

9 Conclusions

A series of experiments was carried out on compacted clay concrete interface using simple shear apparatus. The value of dry density of clay was high and the experiment was conducted under monotonic loading. Two types of concrete were used: relatively rough and relatively smooth. Generally, compacted clay concrete interface shows an insignificant shear deformation displacement particularly when relatively smooth concrete surface is used. The shear sliding displacement continues after the point where shear deformation displacement was decayed. When the test was carried out on rough concrete interface, clay with water content of 21% and high density under normal stress of 150 kPa, the deformation inside the clay sample was more than the sliding displacement. The sample continues in deformation until failure occurs. Water content is also found to be the key factor that affects the behavior of the interface. It was concluded from the results that moisture water content reduces the shear deformation strength while it increases the shear sliding strength. Since deformation displacement was found to be significant, interface shear strength increases especially when water content is 21%. The results obtained from the simple shear test were compared with the results obtained from the direct shear test. It was concluded that the results of the direct shear test obtain shear strength greater than that of the simple shear test and the interface shear strength was not linear compared with that obtained from the simple shear test.

Acknowledgements This research was supported by the China Scholarship Council (No. 2006368T15). Financial support from project "Test study on the properties of coarse-grained soils for high earth rockfill dam under high and complex stress conditions" from the National Nature Science Foundation of China (Grant No. 50639050) and Er-Tan hydraulicpower limited company is appreciated. The authors would like to thank Mr. Zhang Yangga and the technician of the laboratory in the Geotechnical Research Institute Mrs. Yun Yan for their assistance at the primary stage of laboratory work.

References

1. Miller G A, Hamid T B. Interface direct shear testing of unsaturated soil. Geotechnical Testing Journal, 2006, 30(3): 182–191
2. Fleming I R, Sharma J S, Jogi M B. Shear strength of geomembrane-soil interface under unsaturated conditions. Geotextile and Geomembranes, 2006, 24: 274–284
3. Potyondy J G. Skin friction between various soils and construction materials. Geotechnique, 1961, 11(4): 831–853

4. Clough G W, Duncan J M. Finite element analyses of retaining wall behavior. Journal of the Soil Mechanics and Foundations Division, ASCE, 1971, 97(12): 1657– 1673
5. Yin Z Z, Zhu H, Xu G H. A study of deformation in the interface between soil and concrete. Computers and Geotechnics, 1995, 17 (1): 75– 92
6. Acar Y B, Durgunoglu H T, Tumay M T. Interface properties of sand. Journal of Geotechnical Engineering, ASCE, 1982, 108(4): 648– 654
7. Desai C, Drumm C, Zaman M. Cyclic testing and modeling of interfaces. Journal of Geotechnical Engineering, ASCE, 1985, 111 (6): 793– 815
8. Hu L M, Pu J L. Testing and Modeling of soil-structure interface. Journal of Geotechnical and Geoenvironmental Engineering, 2004, 130(8): 851– 360
9. Zhou G Q, Xia H C, Zhao G S, Zhou J. Nonlinear elastic constitutive model of soil structure interfaces under relatively high normal stress. Journal of China University of Mining and Technology, 2007, 17(3): 301– 305
10. Paikowsky S G, Player C M, Connors P J. A dual interface apparatus for testing unrestricted friction of soil along solid surfaces. Geotechnical Testing Journal, 1995, 18(2): 168– 193
11. Evgin E, Fakharian K. Effect of stress paths on the behavior of sand-steel interfaces. Canadian Geotechnical Journal, 1996, 33(6): 853– 865
12. Yoshimi Y, Kishida T. A ring torsion apparatus for evaluating friction between soil and metal surfaces. Geotechnical Testing Journal, 1981, 4(4): 145– 152
13. Huck P J, Saxena S K. Response of soil-concrete interface at high pressure. In: Proceedings of the Tenth International Conference on Soil Mechanics and Foundation Engineering, Stockholm, 15– 19 June, 1981. The Netherlands: A. A. Balkema, Rotterdam, 1981, 2: 141– 144
14. Corfdir A, Lerat P, Vardoulakis L. A cylinder shear apparatus. Geotechnical Testing Journal, 2004, 27(5): 447– 455
15. Coyle H M, Sulaiman I. Skin friction for steel piles in sand. Journal of the Soil Mechanics and Foundations Division, ASCE, 1967, 93 (6): 261– 270
16. Brummund N F, Leonards G A. Experimental study of static and dynamic friction between sand and typical construction materials. Journal of Testing and Evaluation, ASTM, 1973, 1(2): 162– 165
17. Reddy E S, Chapman D N, O'Reilly M. Design and performance of soil – pile-slip test apparatus for tension piles. Geotechnical Testing Journal, 1998, 21(2): 132– 139
18. Kisheda H, Uesugi M. Tests of interface between sand and steel in the simple shear apparatus. Geotechnique, 1987, 37(1): 45– 52
19. Uesugi M, Kishida H. Influential factors of friction between steel and dry sands. Soils and Foundations, 1986, 26(2): 33– 46
20. Uesugi M, Kishida H. Frictional resistance at yield between dry sand and mild steel. Soils and Foundations, 1986, 26(2): 139– 149
21. Tsubakihara Y, Kisheda H, Nishiyama T. Friction between cohesive soils and steel. Soils and Foundations, 1993, 33(2): 145– 156
22. Tsubakihara Y, Kisheda H. Frictional behavior between normally consolidated clay and steel by two direct shear type apparatus. Soils and Foundations, 1993, 33(2):1– 13
23. Wang W, Lu T H. Modeling experiment on interface shearing behavior between concrete and unsaturated soil with various degrees of saturation. In: Yin Z Z, Yuan J P, Chiu A C F. Proceedings of the 3rd Asian Conference on Unsaturated Soils, Nanjing, China. Beijing: Science Press, 2007, 315– 318
24. Uesugi M, Kisheda H, Tsubakihara Y. Behavior of sand particles in sand steel friction. Soils and Foundations, 1988, 28(1): 107– 118
25. Uesugi M, Kishida H, Uchikawa Y. Friction between dry sand and concrete under monotonic and repeated loading. Soils and Foundations, 1990, 30(1): 115– 128