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AN EXPERIMENTAL STUDY OF THE BEHAVIOUR OF INTERFACE SHEARING BETWEEN FINE GRAINED SOILS AND STEEL

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Abstract

The shear strength, when large displacements occur, at the interface between two types of clays and steel has been studied in the ring shear apparatus. The results obtained indicate that the surface roughness and the average diameter of particles have a significant effect on the interfacial shear strength.. According to roughness, two shearing modes are likely to take place: shearing at the interface and shearing within the soil. For soil- soil shearing, the "pre-sheared" clay shear strength is likely to be either equal (neutral effect) or greater (positive effect) than that obtained for not pre-sheared samples. However, in interface tests, the clays tested may exhibit neutral, positive or negative effect.

***Keywords**: fine grained soil - residual strength - ring shear apparatus – surface roughness - interface - laboratory test - soil-structure interaction – large displacement*

Résumé

Une étude de la résistance au cisaillement, dans le domaine des grands déplacements, à l'interface entre deux types d'argile et l'acier a été réalisée au moyen de l'appareil de cisaillement annulaire. Les résultats obtenus indiquent que la rugosité de surface et le diamètre moyen des particules ont un effet significatif sur la résistance au cisaillement à l'interface. Selon la rugosité, deux modes de cisaillement sont susceptibles de se produire: un cisaillement à l'interface et un cisaillement au sein du sol. Dans le cas d'un cisaillement argile-argile, la résistance au cisaillement " pré-cisaillé " est susceptible d'être soit égale (effet neutre), soit plus grande (effet positive) que celle obtenue pour des échantillons non pré-cisaillés.. Cependant, dans les essais d'interface, les argiles étudiées peuvent enregistrer un effet neutre, positif ou négatif .

***Mots clés**: sols fins - résistance résiduelle - appareil de cisaillement annulaire – rugosité de surface - interface - essai de laboratoire - interaction sol-structure - Déplacement important.*

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ملخص

تمت دراسة مقاومة القص عندما تحدث تشوهات كبيرة بين طينين ذوي نوعية مختلفة من جهة وبين الفولاذ من جهة أخرى، على مستوى سطح بيني، بواسطة جهاز القص الحلقي. أظهرت النتائج المتحصل عليها أن خشونة السطح والقطر المتوسط للحبيبات لهما تأثير بالغ الأهمية على مقاومة القص على مستوى السطح البيني. بدلالة الخشونة، يمكن أن يحدث: قص على مستوى السطح البيني أو قص ضمن التربة. في حالة خضوع قص مسبق طين-طين، فإن مقاومة القص قد تكون لها نفس القيمة (تأثير محايد) أو قيمة أعلى (تأثير إجابي) من تلك المترتبة عندما لا يحدث قص مسبق. بينما في حالة قص تربة- سطح بيني أظهرت الأتربة المدروسة تأثيرا محايدا، إجابيا أو سلبيا.

***الكلمات المفتاحية:** تربة ناعمة، مقاومة متبقية، جهاز القص الحلقي، خشونة سطح، سطح بيني، تجربة مخبر، تفاعل تربة-إنشاء، إزاحة مهمة.*

Friction at the interface between soils and solid materials in practical problems, such as skin friction around piles, is an important phenomenon in geotechnical engineering. It is generally recognised that the vertical load applied to the pile head is mostly supported by the interface shearing resistance at the interface pile – soil. As a result of installation and subsequent loading, the behaviour of the pile at failure depends on the strength and deformation properties of the soil adjacent to the pile at large displacements.

There are several suggestions in the literature regarding the effective angle of friction δ' mobilized at or near the pile-soil interface. Recent proposals [1] assumed that it is appropriate to use the residual angle of internal friction φ_r' for δ'. However, since φ'_r is likely to be affected by interface roughness and shearing conditions, it seems more appropriate to take into account the residual angle of friction at the interface soil-solid material δ'_r [2].

More research work have been conducted to study shearing at the interface between sand and solid interfaces than for clays, which resulted in less studies regarding the mechanisms involved in the shearing at the interface in clays. Furthermore, only few studies regarding large displacement have been carried out. Although studies regarding interface behaviour of piles have been conducted mainly by means of in- situ large scale piles loading tests, their results cannot be generalized to predict the behaviour of other piles. On the contrary, laboratory shear tests at the interface are very useful to study the fundamental behaviour of lateral friction around piles because they have well defined boundary limit conditions and only small soil samples are needed to conduct interface tests.

According to Lupini *et al.* [3], three shearing modes are likely to take place as far as soil-soil shearing at large displacement is concerned : a turbulent mode in soils with a high proportion of rotund particles or with platy particles of high interparticle friction, in which preferred particle platy particle does not occur, a sliding mode in which a low strength shear surface of strongly oriented low friction platy particles form, and a transitional mode involving both turbulent and sliding shear.

The object of this study is to clarify the frictional behaviour between fine grained soils and steel at large displacements using ring shear tests by means of the Bromhead ring shear apparatus. The effect of pre-shearing on the slow residual coefficient of friction between soil and steel interface of varying roughness were investigated. After the slow residual coefficient of friction had been established fast shearing was performed. The shear load was then removed, and the specimen allowed to consolidate. After the pause, shearing to the slow residual state was commenced again at the initial drained rate of shearing.

APPARATUS AND TEST PROCEDURE

It is now well established in the literature that the ring shear apparatus offer the best mean of studying shearing resistance when soils undergo large displacements. It is also recommended for interface studies. Kishida and Uesugi [4], after reviewing different apparatuses used in the study of shear strength at the soil – solid material interface, concluded that the ring shear apparatus is the ideal machine for this kind of investigation because of its unlimited interface. This machine has been designed to solve certain problems encountered with the reversal shear box. In the latter, the sample is placed in a Casagrande type box, consolidated under a vertical pressure and sheared alternatively in opposite directions around its initial position. Failure takes place along the plane of the separation between upper and lower boxes. The main disadvantage of this test concerns the variation of shearing area which lead to a non uniform shear stress distribution. Moreover changing the direction of shearing lead each time to a secondary peak. Several studies regarding soil – structure interaction involving large displacement have been conducted for different materials using ring shear apparatus [5, 6, 7].

The Bromhead ring shear apparatus, as a result of its design is well suited for interface tests. In fact, it needs only to replace the original loading platen ring by a ring having the same dimensions made of a different material in order to determine the interface strength between the soil and the material considered. The principle of interface ring shear test is illustrated in figure 1. A complete description of the apparatus, its design and principles of operation is given by Bromhead [8]. The ring shear specimen is annular with an inside diameter of 7 cm and an outside diameter of 10 cm. Drainage is provided by two bronze porous stones secured to the bottom of the specimen container and to the top loading platen. The specimen, which is 5 mm deep, is confined between pairs of inner and outer confining rings. It is loaded normally through a top loading platen by a dead

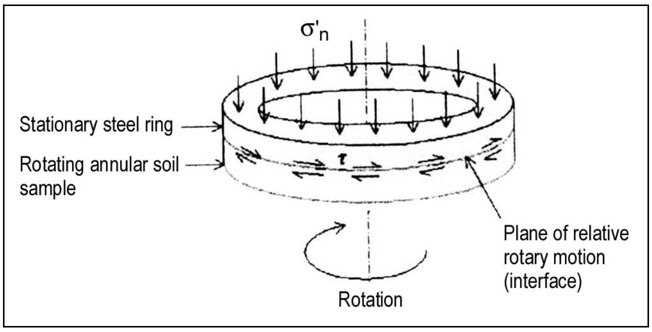

Figure 1: Principle of interface ring shear test.

load lever system. Rotation is imparted to the specimen container through a variable ratio gearbox, and torque transferred to the specimen is measured by two matched proving rings acting on a torque arm fixed to the top loading platen. The sample assembly is surrounded by a Perspex water bath to prevent the sample from drying out during testing. Figure 2 shows a general view of the apparatus used. It will be noted that linear displacement transducers have been added to supplement the dial gages so that data can be recorded automatically during prolonged tests. The apparatus is displacement–controlled and allows the measurement of the residual strength of a shear zone formed near the upper part of the annular specimen or between the specimen and a rigid plate (interface).

Figure 2: General view of test equipment.

Because of the sample container dimensions relatively small soil quantity was needed for conducting a test in the Bromhead apparatus. Since both initial soil structure [9] and water content [10] were found to have no significant effect on residual strength, a sample in a remoulded state has been used. Test specimen were prepared by kneading evenly soil paste into the annular space in the Bromhead ring shear device. The sample was produced by mixing dry soil with deionised water at the liquid limit. After ensuring a thorough mixing, it was then left to dry until it reached a water content equivalent to 1.5 times the plasticity limit approximately. Consolidation was then initiated at a normal stress of 70 kN/m^2. Once consolidation was complete shearing took place. Shearing of the specimen involved initially a slow shearing, at rate of shearing of 0.0356 mm/min, which should ensure full dissipation of excess pore water pressure, until residual conditions are established (stage 1). After the slow drained residual strength had been established, the shear stress was reduced to zero and fast shearing was performed at a rate of shearing of 44.52 mm/min (stage 2). Immediately after fast shearing, the shear load was removed. After a pause for consolidation, re-shearing at the low rate (i.e. 0.0356 mm/min) was restarted again (stage 3). Particular emphasis is given to the behaviour at large displacement of the two slow shearing stages.

INTERFACES USED

Ring shear tests have been conducted in order to study the effect of the interface soil–construction material type on the residual shear strength. This was achieved by using instead of the original bronze interface (OI) in the loading platen, stainless steel rings with varying roughness having the same dimensions as the original ring, and a sufficient thickness to spread the vertical charge uniformly. In this study four different stainless steel interfaces with different roughness degrees have been used : a smooth interface (SI1), two interfaces of intermediate roughness (SI2 and SI3) and a rough interface (SI4). Stainless steel interfaces were used to avoid roughness changes during testing due to rust. The roughness of each specimen was finished to a specified roughness. The smooth one was obtained by plane rectification while the rough ones were obtained by milling. The latter were obtained with squared teeth knurls allowing a well formed and precise milling. The depth of impression can be adjusted according to the pressures applied to the knurls to obtain different roughness. The resulting profiles are shown in figure 3 which represent the rings used in this investigation. The finished steel surface was thoroughly cleaned by acetone before shearing tests.

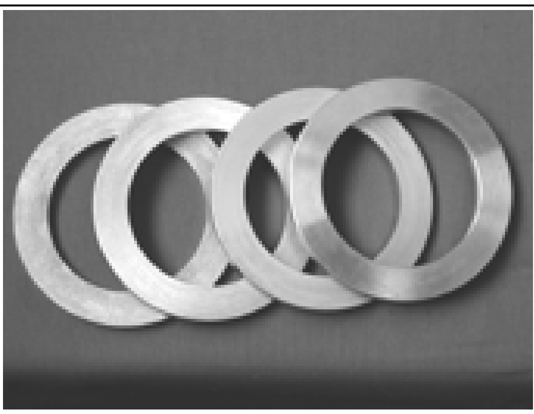

Figure 3: Steel rings used.

Many investigators have shown that surface roughness plays a very important role in interface behaviour [11, 12, 13, etc]. Various definitions of roughness have been proposed in studies of interface shear. The roughness R_{max} (L_a=2.5mm) is defined as the relative height between the highest peak and the lowest trough along a surface profile over an analysis length (L_a) of 2.5mm. The latter is a parameter of surface roughness only and does not involve particle size. In the present study a method of roughness description which is standard in tribology was adopted, the centre line average, R_a, which is the arithmetical mean of the areas of all profile values of the roughness profile:

$$R_a = \frac{1}{L_a}\int_0^{L_a} |y(x)| dx \quad (1)$$

where, $y(x)$: height values of roughness profile

L_a : analysis length taken into account for roughness definition

The method proposed by Subba Rao et. al. [14], which uses a relative roughness R was also adopted. It consists to normalise R_a with respect to the average diameter of the soil particles D_{av}. The latter can be obtained from the grain size distribution curve of the soil studied, using an arithmetical scale for the particles sizes. The average diameters of kaolin and bentonite are given in Table 1. R is defined as:

$$R = \frac{R_a}{D_{av}} \quad (2)$$

Properties	Kaolin	Bentonite
Liquid limit, w_l (%)	64.5	299.1
Plastic limit, w_p (%)	32.2	71.3
Plasticity index, I_p (%)	32.3	227.8
Clay fraction (% < 2µm)	76	87
Average diameter, D_{av} (µm)	8.59	4.08
Density of solid particles, G_s	2.64	2.59

Table 1: Index properties of kaolin and bentonite.

Measurements of the roughness were made by means of laser profilometer. A typical measured surface roughness profile is shown in figure 4. Since the distribution of asperities along the surfaces for the different specimens is not uniform, the average value of roughness parameters computed in 10 different locations was taken into consideration. Tables 2 and 3 give the values of R_a , R_{max} and R of measured roughness of interface surfaces. As indicated R_a values are comprised between 1.6µm and 40.2µm. Measurements of surface roughness of steel piles and pile models, reported by Tika [5], indicated that R_a values are comprised between 2 and 25 µm. These show that the interfaces roughness used in the tests is representative of the surface texture of a typical pile.

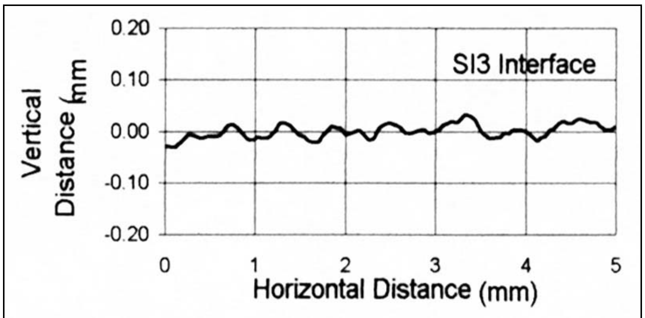

Figure 4: A typical roughness profile of a steel interface.

Roughness Parameters	SI1	SI2	SI3	SI4
R_a	1.6	7.6	12.1	40.2
R_{max}	6.8	37.6	54.6	176.6

Table 2: Values of R_a and R_{max}.

Interfaces	Kaolin	Bentonite
SI1	0.18	0.39
SI2	0.88	1.86
SI3	1.41	2.97
SI4	4.68	9.85

Table 3: Values of *R*.

TEST MATERIALS

The soils used in this investigation are two very plastic clays, namely: Kaolin (K) and Bentonite (B). Their index properties are presented in Table 1 and the grading curves are given in figure 5. Kaolin is an industrial clay which is constituted mainly from kaolinite and bentonite contains about 80% of calcium montmorillonite.

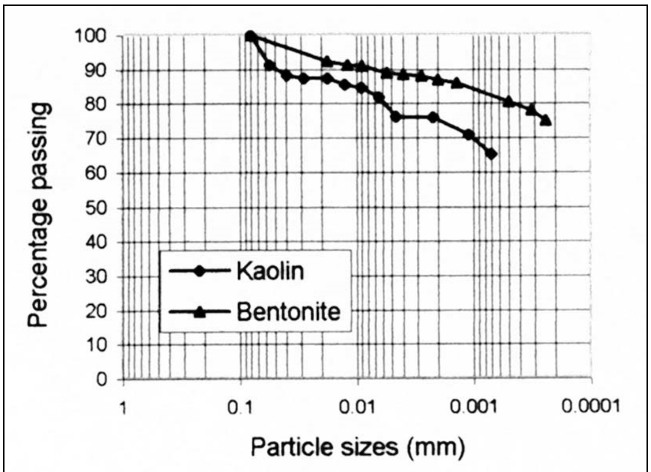

Figure 5: Grading curves.

Mineralogy is an important factor governing shearing mechanism as far as soils subject to large displacement are concerned [3, 15]. It was found that soils which had an important illite and/or kaolinite content had a higher residual strength than soils with a high montmorillonite content. It is also likely to affect shearing behaviour at the soil – solid material interface. The most important factors which characterise mineralogy are the size and the shape. The most common clay minerals (illite, chlorite, kaolinite, montmorillonite) have a flat shape but their size and their thickness which are the most important characteristics vary in large limits. Clay particles are very small, they have often dimensions smaller than 1µm. Kaolinite particles have a diameter of about 1µm and a thickness of 0,1µm. It is quite important for a clay particle. Montmorillonite particles are much smaller and thinner.

TEST RESULTS AND DISCUSSION

The friction shearing between the soil and the interface is often represented by the friction coefficient τ/σ'_n. Where τ and σ'_n are the shearing and normal effective stresses acting at the soil – solid material interface. Two types of friction coefficients are used: the peak friction coefficient and the residual friction coefficient. Figure 6 shows friction coefficient – tangential displacement curves obtained for kaolin samples sheared against steel. The results obtained are summarised in tables 4 and 5. OI refers to the original interface which allows a soil – soil shearing. SI1, SI2, SI3 and SI4 refer respectively to the steel interfaces. The last column in theses tables give the percentage increase or decrease of the pre-sheared τ_r/σ'_n compared to that of the first stage. It is important to emphasize that the present study concern residual shear strength rather than peak shear strength.

Soil-soil shearing

The first slow shearing stage of the standard ring shear tests (i.e. KOI & BOI), where soil – soil shearing takes place, have shown that both materials exhibit a brittle behaviour. Each test showed first a well defined peak in the friction coefficient – tangential displacement curve. Bentonite and kaolin have peak angles of friction of 17.8° and 19.3° respectively. The development of peak strength is derived primarily from the destruction breakdown of the bonds in the soil structure. This develops relatively high strengths over a small displacement. The peak strength obtained for these tests is a remoulded one because the specimen used is disturbed. As a result the value of φ_p' measured in the ring shear apparatus is lower than that obtained in the triaxial apparatus.

Regarding large displacements, mean values of 4.3° and 14.0° were obtained for bentonite and kaolin, respectively. The latter contain large proportions of clay particles (87% and 76% respectively). Since both soils are formed predominantly by clay particles of platy shape, brittleness is due only to particle orientation The energy or force required to accomplish the full parallel arrangement accounts for the major component of residual strength. Thus the residual shearing mode which governs the behaviour at large displacement is the sliding mode as defined by Lupini et al [3]. In this mode the clay particles adopt a parallel face to face structure with little interlocking oriented in the direction of shearing, as a result less resistance is offered to sliding. Lupini suggested that soils exhibiting such a mode of behaviour will have values of φ_r' ranging from 5° to 20°. Furthermore Skempton [15] showed that when the percentage of clay mineral of a soil exceeds 50% it will exhibit the sliding mode. The shearing resistance is mainly governed by the sliding friction of the clay minerals, the residual angles of friction being approximately 15° for the kaolinite and 5° for the montmorillonite.

Interface shearing

Although shearing mechanism is influenced by roughness, the interface shear strength at large displacement is still governed by the sliding mode. As far

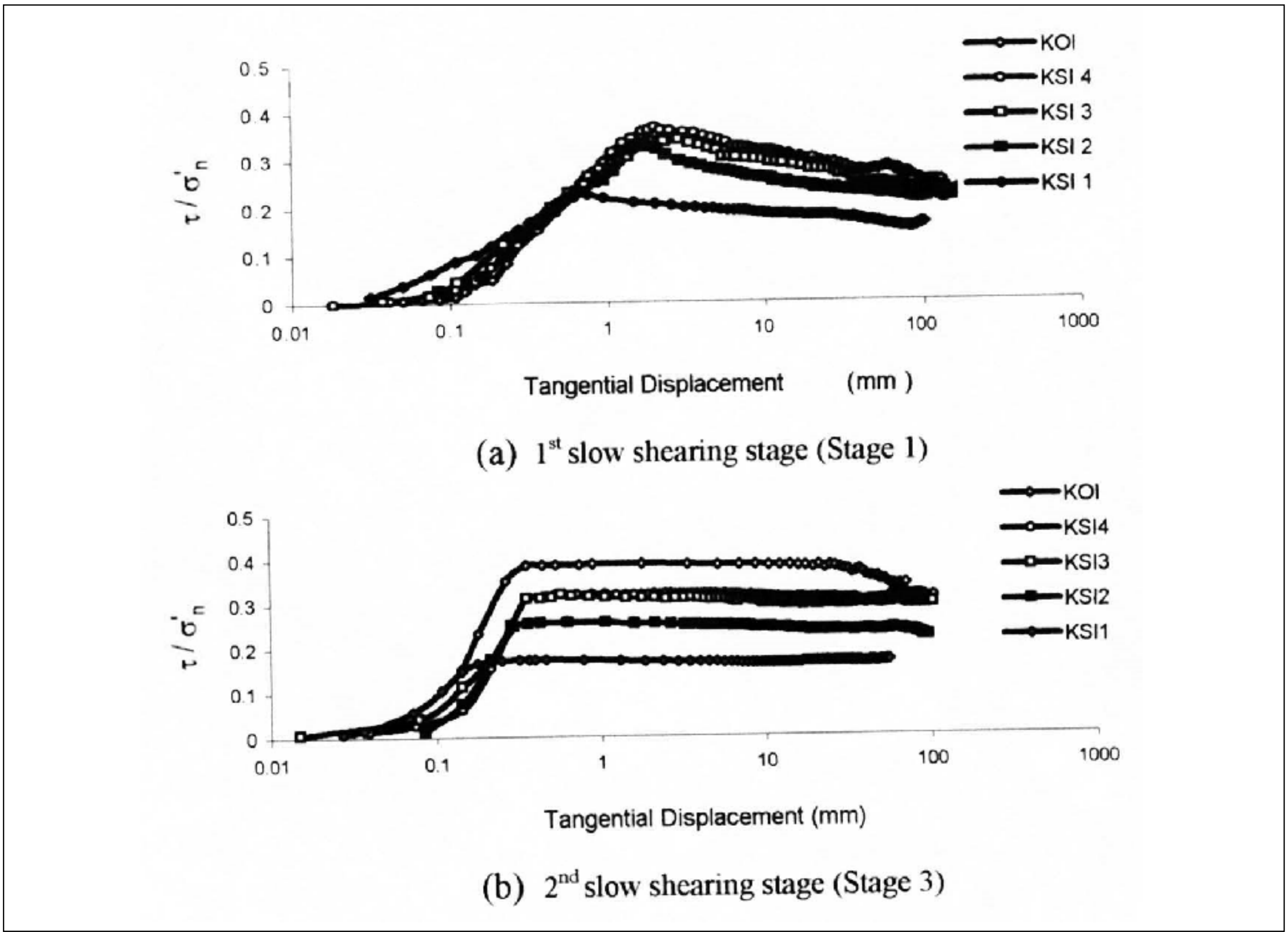

Figure 6: Typical friction coefficient – tangential displacement curves of kaolin-steel interfaces.

	First Slow Shearing Stage				Second Slow Shearing Stage				
TEST	τ_p/σ_n'	φ_p' or δ_p' (deg)	τ_r/σ_n'	φ_r' or δ_r' (deg)	τ_p/σ_n'	φ_p' or δ_p' (deg)	τ_r/σ_n'	φ_r' or δ_r' (deg)	% increase
KOI	0.351	19.3	0.250	14.0	0.388	21.2	0.337	18.6	34.8
KSI4	0.368	20.2	0.220	12.4	0.320	17.7	0.308	17.2	40.0
KSI3	0.341	18.8	0.227	12.8	0.320	17.7	0.297	16.5	30.8
KSI2	0.330	18.3	0.216	12.2	0.256	14.3	0.234	13.2	8.33
KSI1	0.210	11.9	0.150	8.5	0.174	11.3	0.150	8.5	0.0

Table 4: Results of tests on kaolin.

	First slow shearing				Second slow shearing				
TEST	τ_p/σ_n'	φ_p' or δ_p' (deg)	τ_r/σ_n'	φ_r' or δ_r' (deg)	τ_p/σ_n'	φ_p' or δ_p' (deg)	τ_r/σ_n'	φ_r' or δ_r' (deg)	% decrease
BOI	0.322	17.8	0.075	4.3	0.156	4.3	0.075	4.3	0.0
BSI4	0.349	19.2	0.106	6.1	0.166	4.2	0.073	4.2	-31.1
BSI3	0.295	16.4	0.106	6.1	0.147	4.0	0.070	4.0	-34.0
BSI2	0.283	15.8	0.104	5.9	0.138	5.4	0.069	3.9	-33.6
BSI1	0.150	8.5	0.051	2.9	0.049	2.3	0.041	2.3	-19.6

Table 5: Results of tests on bentonite.

as interface shearing tests between kaolin and steel are concerned, τ_r/σ'_n values were found to vary between 0.216 and 0.227, with δ'_r/φ'_r equals approximately to 0.9, for SI2, SI3 and SI4, which is lower than the soil – soil value which is 0.250. As expected the smooth interface (SI1) gave an extremely lower value (i.e. 0.150). The differences between the maximum and the minimum friction coefficients were found to vary between about 29% and 40%.

The values of the residual friction coefficients obtained for soil B indicated that δ'_r/φ'_r is likely to be greater than unity. Values of about 1.4 were obtained regarding interfaces SI2, SI3 and SI4. According to Subba Rao et al [16] the maximum limit value of δ_p/φ'_p is unity for very rough surfaces. However this conclusion was drawn as a result of fine grained soils-steel interface tests with a maximum roughness corresponding to R_a equals to 13.98µm. Furthermore Tsubikahara and Kishida [17] obtained, regarding tests conducted by means of direct shear box on a reconstituted marine clay sheared to a displacement of about 10mm, that the shearing resistance is likely to be about 25% greater than the shearing resistance of the soil especially for interfaces for which R_{max} is greater than 10µm (L_a=0.2mm). Such result is likely to be attributed to mineralogy and roughness degree. Steel rings asperities embed into the samples tested resulting in failure planes formed just outside the embedded face of the solid material thus, a soil-soil failure surface resulted. It is suggested that for large displacements, when the main clay mineral component is montmorillonite, the clay matrix adjacent to the interface is likely to be dragged through a thicker zone, compared to that which would occur for soil-soil friction, resulting in interface friction higher than internal values.

Effect of pre-shearing

Shearing a sample which have been previously sheared is similar to the conditions which exist in the vicinity of a pile where the soil has experienced large disturbance due to installation. For driven piles it is established in the literature that residual conditions are reached as a result of installation because considerable disturbance occurs [18]. Owing to pile installation, shear planes may be created in the clay adjacent to pile-soil interface. Therefore it seems appropriate to take into consideration the "pre-sheared" value of the residual angle. In addition only a small displacement may be required to establish the new residual state on a pre-sheared specimen [19].

It is convenient to discuss the effect of pre-shearing from the first slow stage (i.e. stage 1). As indicated in the stress deformation curves examples of figure 5, the shapes of the first shearing stage curves were somewhat different from that of the second shearing stage, especially the parts of the curves which represent the early stages of the tests. In the former, there is an abrupt decrease in strength beyond the peak and the residual angle was mobilised at relatively large displacements. In the second slow shearing stage (i.e. stage 3), following fast shearing, there was almost no brittle behaviour and a slight peak was again observed. The pre-sheared peak strength observed is presumably caused by the change in the soil structure which occurs as a result of the preceding fast shearing. The application of a high rate of shearing may change the overall arrangement of particles caused by the development of the residual strength of the first shearing stage. Therefore more work will be required to re-orientate the particles again to the direction of shearing.

On the basis of the tests conducted regarding soil-soil shearing, it would appear that pre-shearing has an effect on the measured residual strength of kaolin. Comparison of the residual strengths of pre-sheared and non pre-sheared specimens showed that kaolin is subjected to an increase of strength of about 35%. On the other hand bentonite does not seem to be affected. This agrees with the results obtained by Lemos et al. [20]. They showed that if a shear zone is formed at residual strength by slow drained shearing in the ring shear apparatus and then subjected to fast sharing, in the following slow shearing the slow residual strength can be either higher than the residual strength or equal to the latter.

For interface shearing the pattern of behaviour is somewhat different. It depends on clay type and surface roughness. As shown in figure 7, for kaolin–steel tests the residual angles of internal friction of pre-sheared specimens were found to be higher than those of specimens not sheared previously with a trend towards increasing with roughness. Test KSI1 which was conducted using the smoothest interface gave a residual value equal to that found for the first slow shearing stage. The effect of pre-shearing is also clearly evident for bentonite. However this appears to have a negative effect as τ_r/σ'_n values are about 20% to 34% smaller than the corresponding ones of not pre-sheared samples. A decrease of about 20% in strength was obtained for the smoothest interface (SI1). For the remaining interfaces the residual strength was about 30%, thus indicating that for values of R_a <6 there seems to be no further decrease in strength. The phenomenon explained above is thought to be a consequence of mineralogy composition. The results obtained from the tests performed allow the formulation of a soil model linking the strength on a pre-existing shear zone with clay type and surface roughness of solid material, particularly when a sliding mode is likely to take place. This model can be used in the study of the shaft adhesion of piles and especially in the prediction of the residual angle of internal friction soil-construction material, δ'_r, using an effective stress approach.

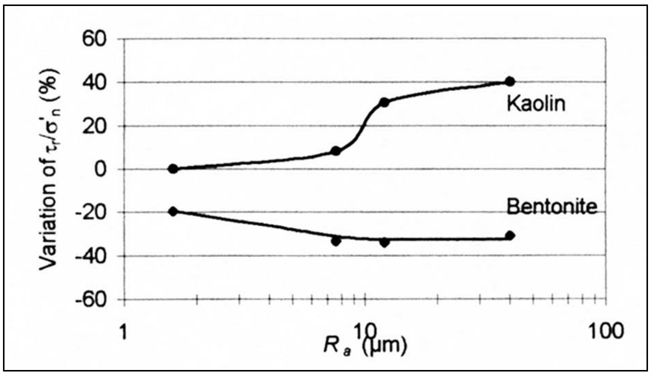

Figure 7: Effect of roughness on the variation of τ_r/σ'_n.

Effect of surface roughness

The interface tests show that kaolin and bentonite exhibit also the sliding mode. The variation of τ/σ'_n with R_a for first shearing stages is given in figures 8 and 9. As one can expect τ/σ'_n increases with R_a. However the trend is different whether first or second shearing is considered. For the latter, the difference between the interface coefficients for kaolin and bentonite becomes bigger with an increase in the roughness. While for the former, the difference is more or less the same, whatever the roughness. The difference in the residual interface friction angle for these interfaces is about 6.6°. It is also evident that kaolin has higher shear strengths, presumably because of particle minerals and dimensions.

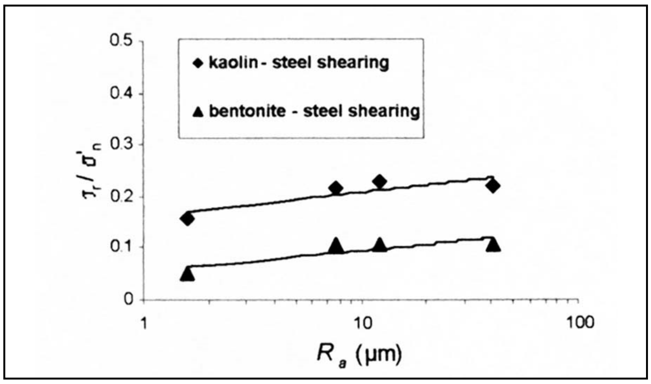

Figure 8: Effect of roughness for the first slow shearing stage.

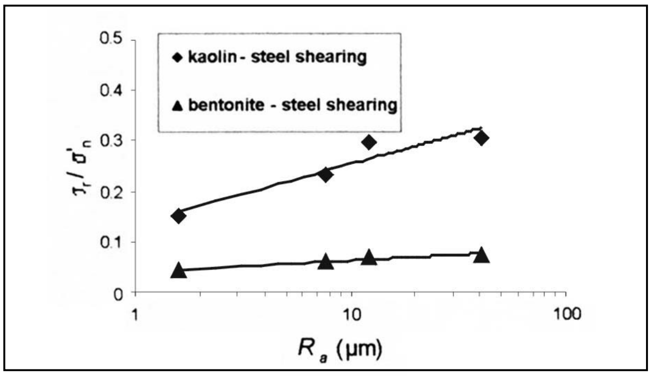

Figure 9: Effect of roughness for the second slow shearing stage.

The results are also analysed in figures 10 and 11 which shows the variation of δ_r/φ_r' with the relative roughness R. As can be seen for large displacements, and for both first and second slow shearing the residual friction coefficient increases with increasing relative roughness. A single empirical relationship fits the data pertaining to the two soils for large displacements when kaolin and bentonite are pre-sheared. However, this is not the case when the specimen is not pre-sheared especially for values of R greater than about 2.

From the results analysis based on R , two modes of interface shearing are postulated for both not pre-sheared and pre-sheared clays :

- a mode in which full sliding at the interface takes place for smooth interfaces (R<1 for first slow shearing stage and R<2 for second slow shearing stage, approximately). The friction coefficient is then smaller than that obtained in the case of a soil-soil shearing. Sliding is confined to the interface and only particles close to the interface surface are involved in the interaction between the soil and the interface. As a result a low strength shear surface of strongly oriented platy particles develops which may give a major difference between clay-clay and interface resistance for very smooth interfaces. Under this surface soil fabric does not seem to affected by shearing. Sliding occurs along a steel-soil contact surface as long as R is smaller than the critical value and in this domain a roughness increase may result in slight increasing interface shearing resistance. However such smooth surfaces are unlikely to be encountered in practice.

- a mode in which shearing takes place within the soil if the value of R is greater than the critical value. The effect of roughness is then practically negligible. δ_r/φ_r' tends towards unity for kaolin for both first and second slow shearing stages whereas for not pre-sheared bentonite samples it may be greater than one. In this mode more particles (not limited to particles close the interface surface) in the sample tend to be involved in the shearing process. Nevertheless, whatever the importance of roughness, the shearing zone thickness is limited to a portion of the sample thickness. The results in the present study show also that the thickness of the clay specimen has an insignificant effect on the interface behaviour. This is explained by the fact that the failure zone is of limited thickness for interface shear tests.

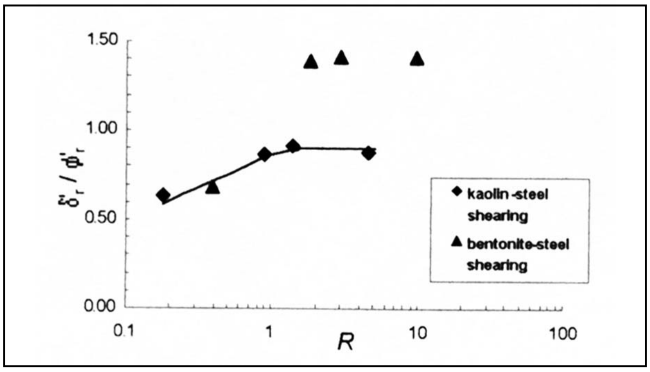

Figure 10: Variation of δ_r/φ'_r with R for the first slow shearing stage.

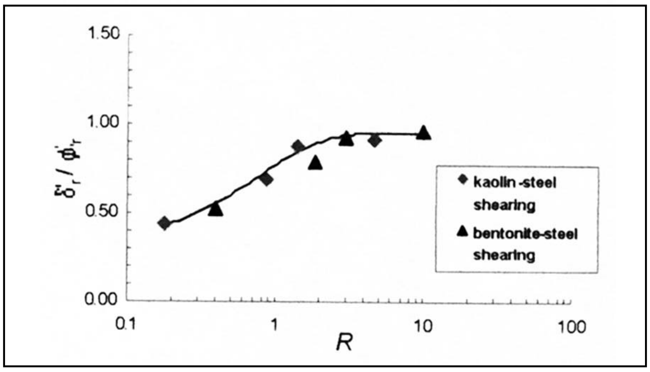

Figure 11: Variation of δ_r/φ'_r with R for the second slow shearing stage.

CONCLUSION

The shearing resistance at the interface between two types of clays and steel of different roughness have been studied at the laboratory by means of the ring shear apparatus. On the basis of data, analysis and interpretations presented in this article, the following conclusions can be drawn:

- The ring shear test can be modified to measure the shear strength at the interface between clays and solid materials. Steel and concrete interfaces have been solidly fixed in order to conduct interface tests. The main advantage of a ring shear test is that large shearing displacements can be applied in one direction until the establishment of residual conditions.

- Kaolin and bentonite samples tested exhibit the sliding shearing mode and have low residual strengths for both interface and soil-soil ring shear tests.

- The occurrence of previous shear deformations will generally have an effect on the shearing resistance at large displacement. As far as soil-soil shearing is concerned, the shearing resistance of bentonite is not affected by pre-shearing. Kaolin shear strength however is likely to have an increase of about 35%. For clay-interface shearing, pre-shearing has a positive effect regarding kaolin, as “pre-sheared” values of the residual friction coefficient are up to 40% higher than the corresponding values of not pre-sheared samples and a negative effect for bentonite since the pre-sheared values of τ_r/σ'_n were up to 34% lower than that of samples sheared for the first time. For rough steel interfaces the shearing resistance at large displacement at the interface between not pre-sheared bentonite and rough steel and concrete is likely to reach a higher resistance than the soil-soil resistance. For kaolin-steel interface the maximum resistance seems to be that of the soil.

- The clays studied showed different stress-tangential displacement behaviour with respect to roughness and mean diameter of particles. The relative roughness combines between the effect of roughness and mean diameter of particles. A more or less good correlation is obtained between R and the residual friction coefficient delimiting three modes of shearing at the interface. A good correlation is also obtained between R_a and τ_r/σ'_n for both shearing stages and clays. The latter shows different trends of increase of τ_r/σ'_n with roughness. Thus indicating that the shearing resistance at the interface depends on the interface roughness, as well as on the properties of the clay.

- Whether for pre-sheared or not pre-sheared residual shear strength at the interface between the clays studied and steel, two modes of shearing have been identified, with respect to R, either a sliding shearing mode at the interface or a shearing mode within the soil.

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