INFLUENCE OF INITIAL STATE OF STRESS AND AMPLITUDE OF DISPLACEMENT ON THE CYLIC BEHAVIOUR OF INTERFACE

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ABSTRACT
The behaviour of interfaces during cyclic loading may be influenced by many factors including the frequency and the amplitude of applied stresses, and amplitude of displacements. In this experimental study, two–way cyclic tests are conducted on a soil-structure interface to investigate the effect of initial state of stress and the amplitude of tangential displacement on the behaviour of the interface, which is between dry loose sand and a steel plate. The tests are performed at constant normal stress using a simple shear type interface apparatus. The effect of initial state of stress is investigated by conducting tests at three different values of normal stress acting on the interface. In the same manner, the effect of the amount of displacement of the steel plate is determined by varying the amplitude of displacement. Each soil specimen is subjected to ten displacement cycles after which the specimen is sheared to failure.

RÉSUMÉ
Le comportement des interfaces pendant des essais cycliques peut être influencé par plusieurs facteurs, incluant la fréquence et l'amplitude des contraintes appliquées ainsi que l'amplitude des déformations. Dans la présente étude expérimentale, des tests cycliques bidirectionnels sont conduits sur une interface entre sol et structure pour déterminer l'influence des contraintes initiales et l'amplitude de déplacement tangentiel. L'interaction au niveau de l'interface a lieu entre un échantillon de sable lâche et un plateau d'acier. Les tests sont conduits avec un appareil de cisaillement simple pour interface en maintenant constante la contrainte normale. Cette investigation est conduite en utilisant trois valeurs distinctes de contraintes normales et trois valeurs distinctes d'amplitudes de déplacement tangentiel afin de déterminer leurs influences respectives sur le comportement de l'interface. Chaque échantillon est soumis à 10 cycles de déplacements tangentiels avant d'être rompu lors du onzième cycle.

1. INTRODUCTION

The performance of structures, which are interacting with soils, is significantly influenced by the mechanical behaviour of soils. Similarly, for a vast majority of problems, the behaviour of soil in the interface layer plays an important role in the magnitude of load that can be transferred between the structure and soil. The interface is defined as a thin layer of soil next to the contact surface between a structure and the soil mass. The soil behaviour in the interface layer is characterized by a high displacement gradient (Vardoulakis and Unterreiner, 1995). The thickness of the interface layer has been reported in the literature by a number of researchers. Although there is no single value commonly agreed upon, the interface thickness ranges from a few times to sixteen times the mean diameter of soil particles.

The load displacement response of interfaces has been the subject of many experimental and theoretical studies due to its importance in geotechnical design (Potyondy, 1961; Desai, 1981; Yoshimi and Kishida. 1981a, 1981b; Acar et. al. 1982; Desai et al. 1985; Boulon and Plytas,1986; Uesugi and Kishida, 1986a, 1986b; Uesugi, et al. 1988; Boulon, 1989). Various other related papers on this subject can be found in a publication edited by Selvaduari and Boulon (1995). The majority of interface studies deal only with monotonic loading conditions. The state of knowledge for the monotonic behaviour of soils is rather advanced and many models are available for the prediction of the behaviour of soils in a soil mass subjected to monotonic loading conditions. However, most of these models do not handle well the cyclic response of soils in interfaces. Cyclic loading conditions, which are encountered during earthquake activities, the operation of machinery, or wave action on marine structures, present a more realistic loading condition that many geotechnical structures may undergo during their lifetime. Therefore, a sound understanding of the behaviour of interfaces subjected to cyclic loading is of paramount importance.

The objective of this paper is to present the results of an investigation on the cyclic behaviour of loose sand in a soil structure interface. This paper complements a previous experimental study on loose sand (Evgin and Assane Oumarou, 2004), which was performed under a constant normal stress of 100 kPa without investigating the effect of initial state of stress. In the current study, the influence of both the initial state of stress and the amplitude of tangential displacement on the cyclic behaviour of an interface is investigated.

The experimental program is presented in the next section followed by the presentation and interpretation of the experimental results.

2. EXPERIMENTAL SETUP

2.1 Apparatus

The experimental study is conducted using an apparatus, which is referred to as **C**yclic **3 D**imensional **S**imple **S**hear testing of soil structure **I**nterface (C3DSSI). The apparatus was developed by Fakharian and Evgin (1993). It is the first interface apparatus, which offers three- dimensional loading capabilities, reported in the literature. The apparatus allows testing under various boundary conditions (i.e. constant normal load, constant volume, and constant stiffness).

A motorized air regulator, which is operated by a built-in stepper motor, adjusts the pressure for the E / P actuator to apply the load in the normal direction. Two steppers motors apply loads in the tangential (horizontal) plane. The sliding displacement (slip) can be distinguished from the shear deformation of the soil sample. The controls and data-acquisition are performed by a closed-loop computer-controlled system. Hence, various interface-shearing paths can be realized.

2.2 Interface material

The interface is between dry loose sand and a steel plate. The roughness of the steel plate can be changed. Kishida and Uesugi (1987) provided some experimental data that showed the influence of the roughness of the steel plate on the mobilized shear stress in the interface material. In the present investigation, the roughness of the steel plate is maintained constant at 25μm for a sampling length of 0.8 mm. This roughness value remains unchanged for all the tests done in the investigation since the focus here is to determine the influence of initial state of stress and amplitude of horizontal displacement on interface behaviour.

A direct shear type rigid container or a simple shear type container can be used for testing. In the current study, a simple shear type container is used. The soil container is formed from a stack of anodized, Teflon coated, square shape aluminum plates. The use of the stack of aluminum plates reduces the undesirable effect of stress concentration observed at the container edges. In fact, the edge effect is more pronounced when a rigid box is used. Unlike the direct shear container, the use of the stack of aluminum plates has the advantage of allowing the separate measurement of sliding displacement and displacement due to shear deformation of soil at the interface. Note that the displacement of the steel plate is equal to the summation of the sliding displacement and the displacement due to shear deformation of soil at the interface.

The aluminum plates are available in thickness of 1.0 mm and 2.0 mm. On the front vertical face of the soil container, a vertical line was drawn on each aluminum plate using a sharp knife. The role of the vertical line is explained in the next paragraph. The height of the soil container is 29 mm and it has a horizontal cross sectional area of 100 mm $\times$100 mm. The area of the steel plate is much larger than the soil surface; therefore, the area of contact surface remains constant as the horizontal displacement continues to increase.

Prior to testing, the short vertical lines drawn on the aluminum plates are aligned. The stack of aluminum plates is lubricated to allow the sand container to follow the deformation of the sand mass with minimum frictional resistance. When the sand is sheared, the positions of the aluminum plates change, i.e., the lines on the aluminum plates are no longer along the same line as illustrated in Figure 1. Note that the vertical scale in this figure is exaggerated with respect to the horizontal scale in order to better illustrate the plate movements. These results provide the necessary information for the determination of the shear deformation in the sand sample and the slip at the contact surface. Based on these observations, the soil sample is divided into two parts: soil mass and interface layer.

During each test, two LVDTs are used to measure horizontal displacements. The first LVDT measures the horizontal displacement of the steel plate with respect to the top aluminum plate (i.e. total tangential displacement) while the second LVDT records the horizontal displacement of the aluminum plate at the soil interface with respect to the top aluminum plate (i.e. shearing displacement of the soil sample). The measurements of these two LVDTs allow the calculation of slip taking place at the interface. A third LVDT is used to measure the change in sample height. During a test, the normal stress is maintained constant and the tangential shear stress is measured.

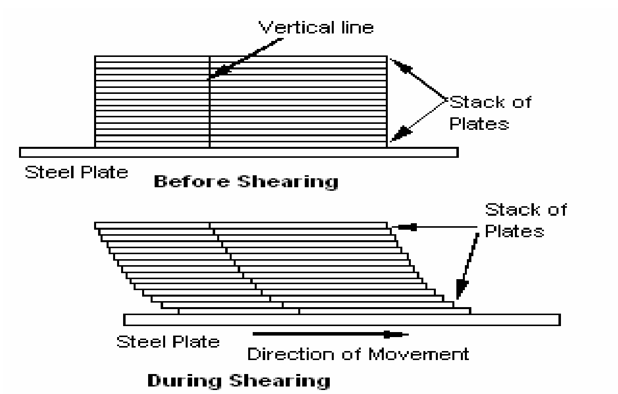

Figure 1. Positions of aluminum plates before shearing and during shearing the sample.

2.3 Sample preparation

The preparation of loose sand sample is achieved by spooning sand gently into the container. After filling the container, a suction device is used to level the top of the soil sample. The leveling of the top surface of the soil sample helps a more uniform distribution of the applied normal load across the sample surface.

3. EXPERIMENTAL RESULTS

Nine cyclic tests were conducted in this investigation. Each test was characterized by the magnitude of the applied normal stress and the amplitude of the tangential (horizontal) displacement. The magnitude of the average normal stress was kept constant at 100, 200 and 300 kPa in different tests. For each normal stress value, three tests were performed with the following displacement amplitudes: 1 mm, 2 mm and 3 mm in the horizontal direction. During each test, the soil sample was subjected to ten cycles of displacement after which the sample was sheared to failure.

On the figures presented next, the numbers beside the letters A and σ_n represent the amplitude of the displacement and the applied normal stress, respectively. Figures 2, 3 and 4 show the relations of shear stress versus horizontal displacement and changes in the sample height versus the horizontal displacement of the steel plate at a normal stress of 100 kPa for amplitudes of displacement of 1, 2 and 3 mm, respectively.

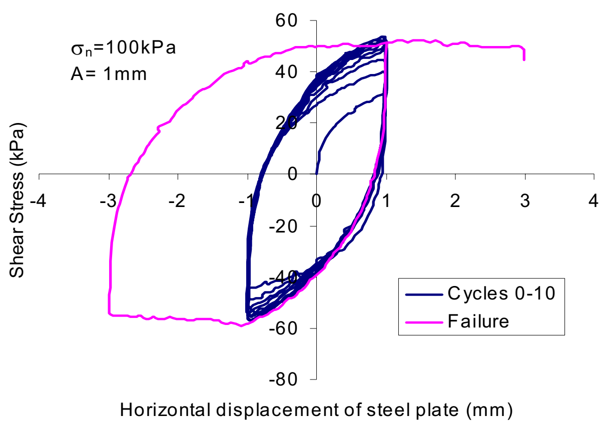

Figure 2a. Shear stress versus horizontal displacement of steel plate.

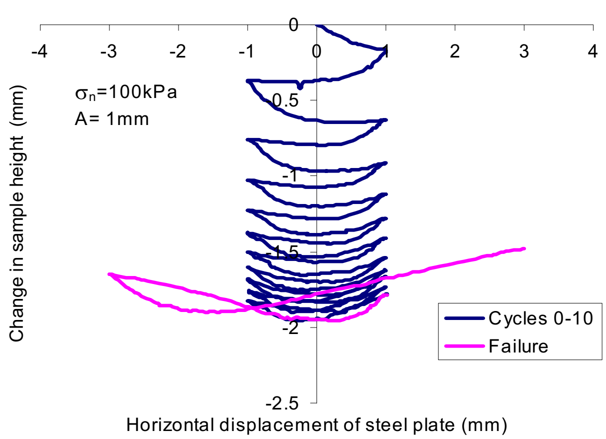

Figure 2b. Change in sample height versus horizontal displacement of steel plate.

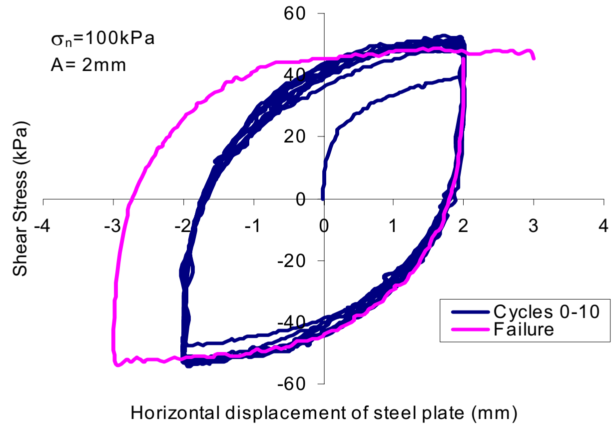

Figure 3a. Shear stress versus horizontal displacement of steel plate.

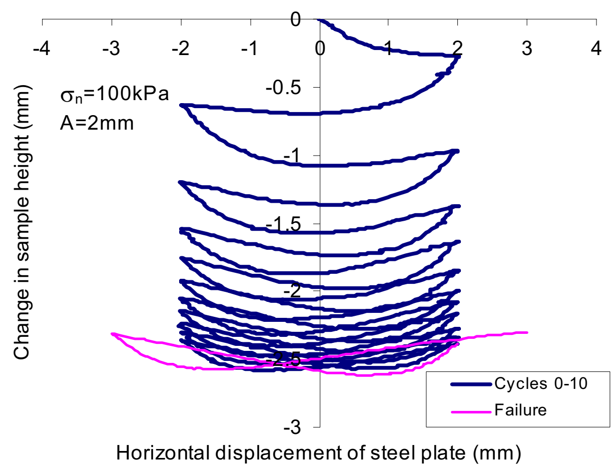

Figure 3b. Change in sample height versus horizontal displacement of steel plate.

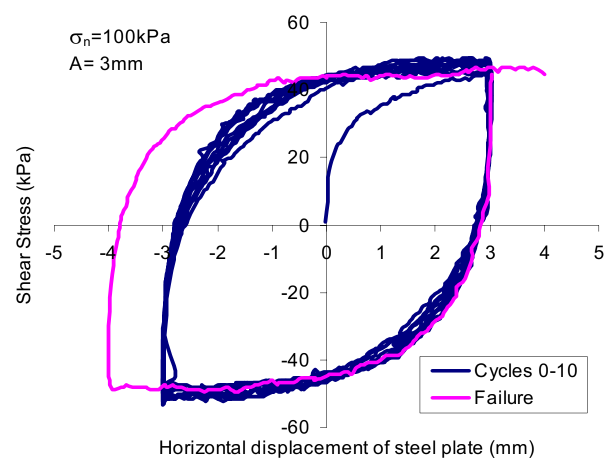

Figure 4a. Shear stress versus horizontal displacement of steel plate.

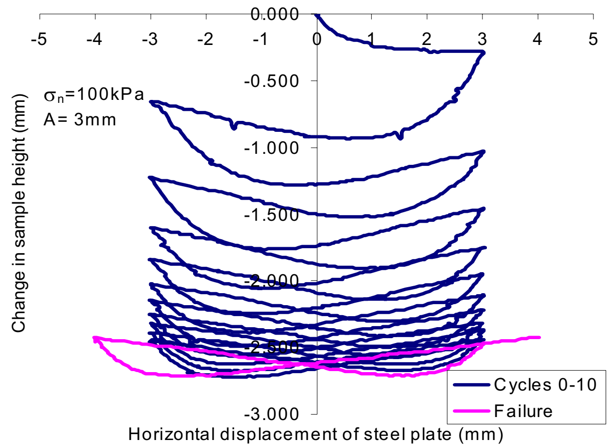

Figure 4b. Change in sample height versus horizontal displacement of steel plate.

The figures 5 and 6 show the relations of shear stress versus horizontal displacement and changes in the sample height versus the horizontal displacement of the steel plate at a normal stress of 200 kPa for amplitudes of displacement of 1 and 3 mm, respectively. Figure 7 displays the relation of shear stress versus horizontal displacement and changes in the sample height versus the horizontal displacement of the steel plate at a normal stress of 300 kPa for 3 mm amplitude of displacement.

As mentioned earlier, the experimental setup offers the possibility of making a distinction between sliding displacement at the contact surface and the horizontal displacement of the soil at the bottom of the interface. Figures 8 and 9 show the relation between the shear stress developed in soil samples and the horizontal displacement of the soil at the bottom of the interface.

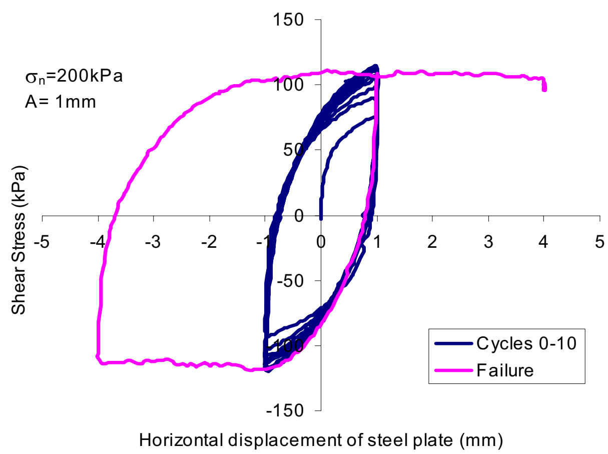

Figure 5a. Shear stress versus horizontal displacement of steel plate.

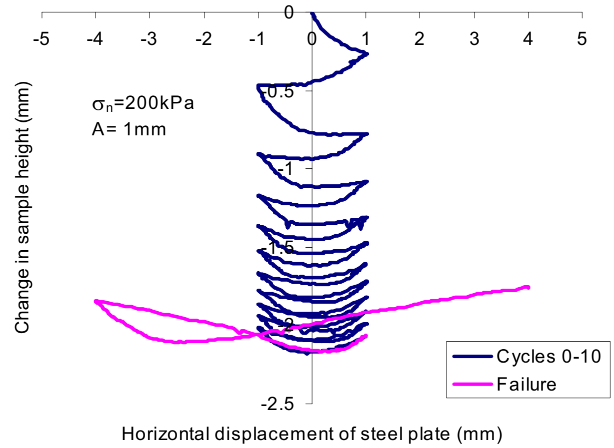

Figure 5b. Change in sample height versus horizontal displacement of steel plate.

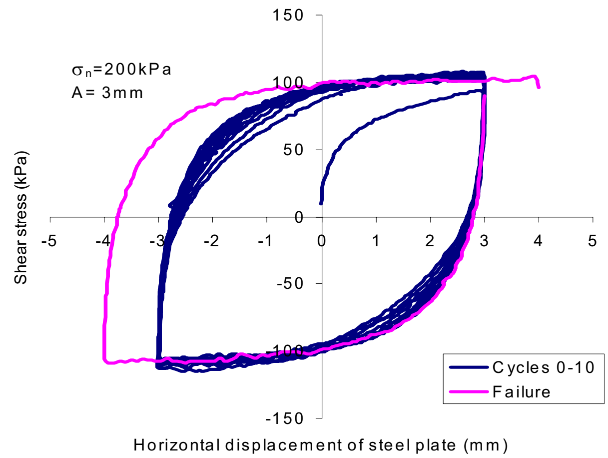

Figure 6a. Shear stress versus horizontal displacement of steel plate.

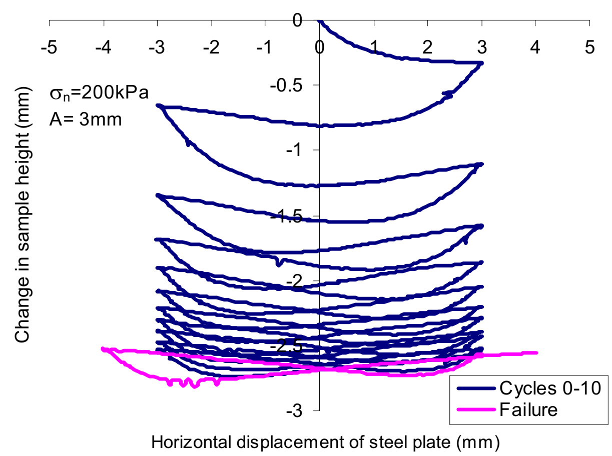

Figure 6b. Change in sample height versus horizontal displacement of steel plate.

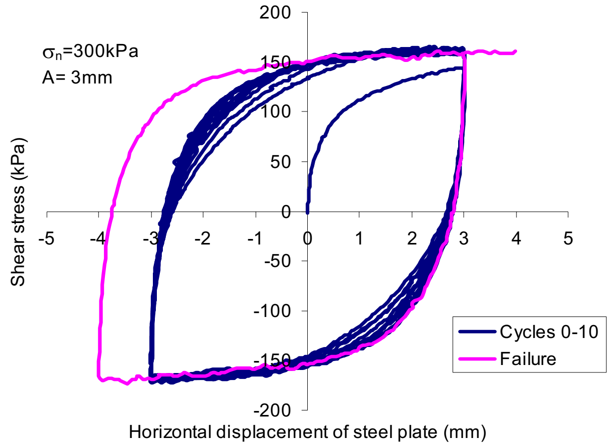

Figure 7a. Shear stress versus horizontal displacement of steel plate.

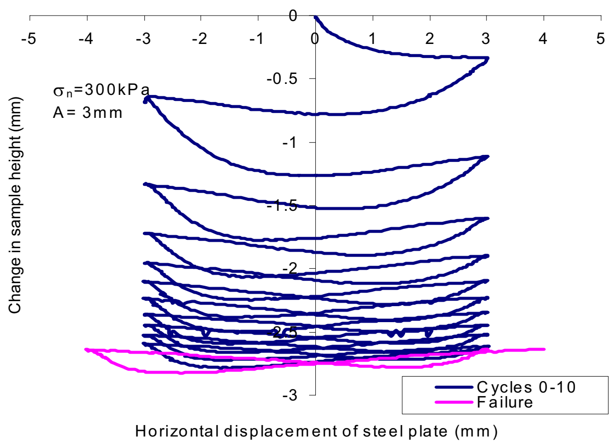

Figure 7b. Change in sample height versus horizontal displacement of steel plate.

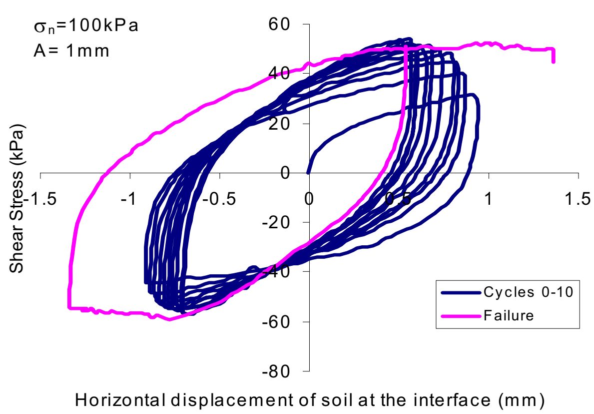

Figure 8. Shear stress versus tangential displacement of soil sample.

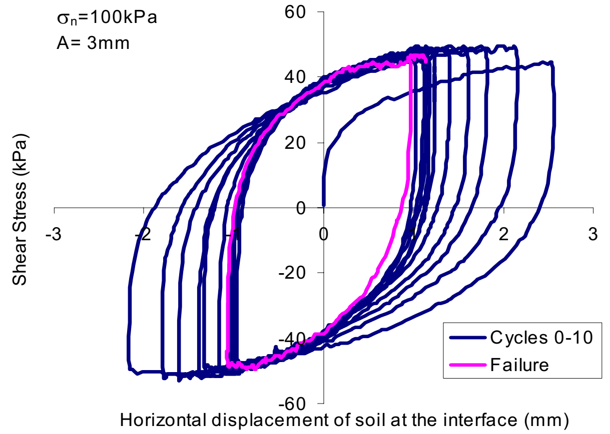

Figure 9. Shear stress versus tangential displacement of soil sample.

Table1. Maximum shear stress recorded at selected cycles for normal stress values of 100 kPa and 300 kPa. Displacement amplitudes are 1, 2 and 3 mm.

Cycle Number	Shear stress (kPa) σ_n=100 kPa			Shear stress (kPa) σ_n=300 kPa		
	1 mm	2 mm	3 mm	1 mm	2 mm	3 mm
0	31.2	39.3	44.7	114.6	135.6	142.4
1	41.7	47.8	49.5	139.7	159.0	164.5
5	52.5	51.6	48.8	171.9	175.3	166.8
10	55.3	50.5	47.5	179.7	174.6	164.8

Table2. Change in sample height at selected cycles for normal stress values of 100 kPa and 300 kPa. Displacement amplitudes are 1, 2 and 3 mm.

Cycle Number	Vertical displacement (mm) σ_n=100 kPa			Vertical displacement (mm) σ_n=300 kPa		
	1 mm	2 mm	3 mm	1 mm	2 mm	3 mm
0	-0.17	-0.27	0.28	-0.31	-0.32	-0.33
1	-0.50	-0.80	-1.03	-0.69	-0.87	-0.90
5	-1.39	-1.97	-2.11	-1.68	-2.11	-2.16
10	-1.81	-2.38	-2.47	-2.17	-2.61	-2.61

Table 3. Horizontal displacement of soil at the interface at selected cycles for normal stress values of 100 kPa and 300 kPa. Displacement amplitudes are 1, 2 and 3 mm.

Cycle Number	Soil displacement (mm) σ_n=100 kPa			Soil displacement (mm) σ_n=300 kPa		
	1 mm	2 mm	3 mm	1 mm	2 mm	3 mm
0	0.94	1.72	2.53	0.90	1.77	2.54
1	0.89	1.58	2.16	0.81	1.65	2.08
5	0.74	1.07	1.28	0.65	1.00	1.09
10	0.62	0.83	0.97	0.51	0.65	0.75

4. INTERPRETATION OF RESULTS

In general, the behaviour of the interface in these cyclic tests using loose sand can be summarized as follows.

- Shear stress increases with increasing number of cycles at a diminishing rate.
- The sample height decreases at a diminishing rate for increasing number of cycles.
- Amount of slip portion of the total horizontal displacement decreases continuously.

With respect to the shear stress increase with increasing number of cycles, Desai et al (1985) reported similar observations in tests performed on sand-concrete interfaces. Shahrour and Rezaie (1997) also made the same observation while performing cyclic direct shear type interface tests on loose sand.

In the present study, the experimental results are analyzed by taking into consideration the effects of initial state of stress and amplitude of displacement on the shear stress, the vertical compression or extension of the soil sample, and the sliding displacement occurring at the interface. A summary of test results is provided in Tables 1, 2 and 3.

4.1 Effect of initial state of stress

The shear stress mobilized at the interface increases as the normal stress acting on the contact surface increases. The ratio of shear stress to normal stress (stress ratio) depends on the applied normal stress (Table 1). For example, the stress ratio is 0.55 for a normal stress of 100 kPa and 1 mm amplitude of horizontal displacement (Figure 2a). For similar test conditions, i.e. same amplitude of displacement and number of cycles, the stress ratio is 0.60 at a normal stress of 300 kPa. It can be stated that the stress ratio increases with increasing initial state of stress.

Normal stress also influences the amount of change in sample height during the experiments. For larger normal stress values, the change in sample height becomes larger. Considering, the end of the 10^{th} cycle, for A=1mm, it can be seen from Table 2 that the recorded changes in sample height for normal stress values of 100 kPa and 300 kPa are 1.81mm and 2.17 mm, respectively.

Table 3 shows that the displacement of soil at the interface tends to decrease with increasing normal stress values. In other words, the sliding displacement (slip) increases for increasing values of normal stress.

4.2 Effect of displacement amplitude

The experimental results (Figures 2a, 3a and 4a) suggest that the amplitude of horizontal displacement influences the magnitude of shear stress developed during cycles. There is a positive relation between shear stress and amplitude of horizontal displacement in the initial cycles. However, the nature of this relation is reversed in the last cycles. Table 1 illustrates the relations mentioned above.

Figures 2a to 4a illustrate that the amplitude of horizontal displacement influences the rate of increase in shear stress. For example, considering the test with A=1 mm and σ_n=100 kPa, the shear stress increases from 31.2 kPa at the end of the monotonic loading part of the test to 41.7 kPa at the end of the first cycle. This represents an increase in shear stress of 26%. For the test conducted at the same normal stress with A= 3mm, the shear stress increases from 44.7 kPa at the end of the monotonic loading part to 47.5 kPa at the end of the first cycle. The increase in shear stress is now 10%. Therefore, it can be stated that the amplitude of horizontal displacement influenced the rate of increase in shear stress.

As mentioned previously, the change in sample height increases with the number of cycles. But, it is important to point out that in a given cycle the soil sample may contract and/or dilate. For A=1mm (Figures 2b and 5b), the sand sample contracts continuously with little or no dilation. However, for A=2 mm and A=3 mm, the sample contracts continuously in the first 2 to 3 cycles. But, in the subsequent cycles, the sand sample displays both, contractive and dilative characteristics within each cycle.

It is seen from Figures 2b to 4b that the change in sample height increases with the amplitude of horizontal displacement. For illustrative purpose, the ratio between the change in sample height for A=2 mm and A=1 mm are computed. The computations give a ratio of 1.32 at a normal stress of 100 kPa and 1.19 at a normal stress of 300 kPa. These ratios show that the vertical compression of the sand sample depends on the amplitude of horizontal displacement.

The comparison of the changes in sample height for A=2mm and A=3 mm shows that the changes fall in the same range. The recorded changes in sample height for A=3 mm displacement are in average 4% percent higher than those recorded for A=2 mm. These results may imply that there is a value after which the amplitude of displacement does not affect significantly the change in sample height.

It is seen from Figures 8 and 9 that the amount of slip taking place at the interface increases as the amplitude of horizontal displacement increases. The amount of slip at the end of the first monotonic loading for A=1 mm and

A=3 mm represents 6% and 16 % of the total displacement of steel plate, respectively (Figure 8). These values increase to 38% and 68%, respectively, at the end of the 10th cycle. Therefore, it can be stated that slip constitutes an important part of the total displacement. In some cases slip is bigger than the displacement of soil at the interface. Accordingly, not making a distinction between slip and shearing displacement at the interface, as is done when direct shear type interface equipment is used, will result in incomplete information on interface behaviour.

5. CONCLUSIONS

This investigation focused on the cyclic response of an interface between loose dry sand and a steel plate. In general, as the number of cycles increases the shear stress and change in sample height increases at a diminishing rate. The amount of slip occurring at the interface also increases.

The experimental investigation the initial state of stress affects the mobilized shear stress, the change in sample height and the slip occurring at the interface. Increasing values of normal stress yield increasing values in stress ratio, change in sample height and slip at the interface.

The study shows that there is a positive relation between shear stress and amplitude of displacement in the initial cycles. This relation is reversed in the last cycles. The change in sample height and the portion of sliding displacement at the interface increase with the amplitude of horizontal displacement.

The development of interface models taking in consideration these experimental observations will be of high value.

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