Cyclic degradation of shaft resistance for piles embedded in silica sand

Dégradation cyclique de la résistance du fût pour pieux encastrés dans un sable siliceux

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ABSTRACT: A recently developed interface apparatus, C3DSSI, has been used to study the degradation of maximum shear stress of an interface between a steel plate and a medium Silica sand in two-way cyclic tangential-displacement-controlled experiments. The results provided an explanation for the degradation of shaft resistance of piles embedded in sand. The tests were conducted under constant normal stress as well as constant normal stiffness conditions. It is shown that the reduction in maximum shear stress is attributed not only to the reduction of normal stress with cycles, but also to the amount of mobilized sliding displacement. The reduction in maximum shear stress is very large when failure is experienced at the interface.

RÉSUMÉ: Un appareil d'interface récemment développé, le C3DSSI, a été utilisé pour étudier la réduction de la résistance maximale en cisaillement d'une interface entre une plaque d'acier et un sable sislica moyen lors d'essais bi-directionnels cycliques avec contrôle du déplacement tangentiel. Les résultats fournissent une explication de la réduction de la résistance du fût de pieux encastrés dans du sable. Les essais ont été effectués dans des conditions de contrainte normale constante, ainsi que dans des conditions de rigidité normale constante. Il est démontré que la réduction de la contrainte maximale en cisaillement est attribuée non seulment a la réduction de la contrainte normale avec les cycles, mais aussi a l'importance de la déformation par glissement. La réduction de la contrainte maximale en cisaillement est trés importante quand de point de défaillance se trouve à l'interface.

1 INTRODUCTION

At working loads, piles transfer the majority of their load to soil through friction between the pile shaft and surrounding soil. The cyclic loads such as earthquake, wind, and waves cause degradation of the shaft resistance as observed from model tests as well as field tests (Chan and Hanna 1980; Poulos 1981; Poulos 1984; Turner and Kulhawy 1990). Failure of piles arising from cyclic degradation of shaft resistance is recognized to be predominant under two-way cyclic loading conditions (Poulos 1989).

Uesugi et al. (1989) and Uesugi and Kishida (1991) stated that the dominant factor in the degradation of the frictional resistance is the sliding displacement at the pile-soil interface. They presented the results of both one-way and two-way cyclic tests between sand and a steel surface, under the condition of constant normal stress, by using a simple shear soil container. The simple shear soil container distinguishes the sliding displacement at the interface from the shear deformation of soil mass. It was shown that at small displacement amplitudes, the mobilized maximum shear stress increased with the increase in the number of cycles. Eventually, however, when the peak value of shear was reached, the maximum shear stress started to decrease with the number of cycles and after a certain number of cycles, the hysterisis curves converged to a loop.

Poulos (1989) attributed the degradation in shaft resistance to the compressibility of the soil, which results in a large reduction in soil volume near the pile shaft due to cyclic loading. This volume reduction leads to a reduction in normal stress, and consequently to a reduction or "degradation" of the shaft resistance.

Interface tests under the condition of constant normal stiffness are normally used to measure the frictional resistance between a pile shaft and soil to study the degradation phenomenon. Boulon and Foray (1986) conducted laboratory tests between sand and a structural material under monotonic loading conditions. Ooi and Carter (1987) conducted cyclic constant normal stiffness tests on interfaces between calcareous rock joints. Airey et al. (1992) and Tabucanon et al. (1995) confirmed experimentally the idea expressed by Poulos, by conducting two-way cyclic displacement controlled tests under constant normal stiffness condition, using a direct shear box. These investigations were mostly focused on the calcareous sands because of their greater compressibility.

A recently developed interface apparatus, C3DSSI, i.e. Cyclic 3-Dimensional Simple Shear Interface testing (Evgin and Fakharian 1995, 1996; Fakharian 1996; Fakharian and Evgin 1996), is employed in this study for further investigation of the degradation phenomenon. A simple shear soil container used in C3DSSI permits separation of the sliding displacement at the interface from the simple shear deformation of the soil mass. A computer-controlled pneumatic actuator is used to simulate the constant normal stress and constant normal stiffness conditions. It is, therefore, possible to study the cyclic soil-steel interface behaviour in detail.

2 APPARATUS AND TEST MATERIALS

The interface apparatus, C3DSSI, is capable of 3D testing of interfaces between two materials. Three orthogonal forces can be applied independently on the interface plane to induce the normal stress, σ_n, in the *z*-direction, and the shear stresses, τ_x and τ_y, in the *x*- and *y*-directions, respectively. In this study, however, the tests were performed under two-dimensional loading conditions, i.e. in the *z*- and *x*-directions.

A simple shear box is used as the soil container with an inside area of 100 mm × 100 mm. Two tangential displacements are measured to distinguish between the sliding displacement along the contact surface and the shear deformation of the soil mass. Figure 1 illustrates the schematic diagrams of tangential displacements in the *x*-direction. The total tangential displacement, u_{xa}, is measured between the top aluminium plate and the steel plate by the LVDT, a_x. The shear deformation of the

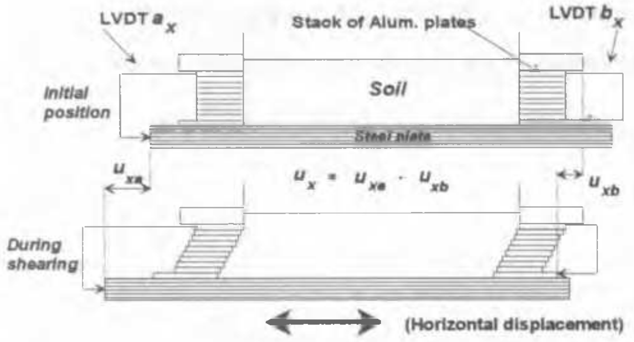

Figure. 1. Schematic diagrams of tangential displacements.

soil mass, u_{xb}, is measured by the LVDT, b_x, which reads the relative tangential displacement between the top and bottom aluminium plates. The sliding displacement at the soil-steel interface, u_x, is obtained from $u_x = u_{xa} - u_{xb}$ (Fig. 1).

The tests were conducted on an interface between a dry medium Silica sand and a rough steel plate. The sand was deposited by using a Multiple-Sieving-Pluviation Method. The initial height of the sand sample was always 20 mm.

The construction material was a low carbon steel plate with a surface roughness, R_{max}, of 25 mm (L = 0.8 mm). The relative density of the sand was 84% at the beginning of each test.

3 TEST RESULTS

Two main contributing factors identified as the cause of the degradation in shaft resistance of piles are: *(i)* increase in sliding displacement at the interface, and *(ii)* reduction in normal effective stress due to a change in normal displacement. Two series of test results are presented here to investigate the influence of these two factors on the degradation phenomenon.

3.1 *Two-way cyclic constant normal stress test*

A two-way cyclic tangential-displacement controlled test was conducted under a constant normal stress of 100 kPa. Total number of cycles was 55 at a frequency of 1/200 Hz and the amplitude of the total tangential displacement, u_{xa}, was 0.75 mm which was smaller than the u_{xa} of 1.4 mm at peak strength for a monotonic test under the same normal stress (Evgin and Fakharian 1996). The results at cycles 1, 12, and 55 are presented in Fig. 2. The amplitude of the sliding displacement at the interface and the shear deformation of sand mass varied with cycles (Figs 2*c* and 2*d*). A gradual compression was observed in the sand mass in such a way that the rate of compression decreased with cycles (Fig. 2*b*).

The peak shear strength was reached at cycle 12. It is observed that the shear stress, which was 72.0 kPa at the maximum displacement amplitude during the first cycle, reached a peak of 83.0 kPa at cycle 12 after which the shear stress decreased and stabilized at 60.0 kPa. These observations agree qualitatively well with the results reported by Uesugi et al. (1989).

During the first cycle, the maximum shear deformation of sand mass was 0.5 mm, i.e. 2/3 of the total displacement amplitude of 0.75 mm. As number of cycles increased, the shear deformation amplitude for the sand mass reduced and the sliding displacement amplitude at the interface increased. The shear deformation amplitude reduced to a value of 0.15 mm, and sliding displacement amplitude increased to 0.6 mm, thereafter they remained at these values. The stabilization took place after about 30 cycles, which is equivalent to the time at which the shear stress variations became negligible at 6000 seconds.

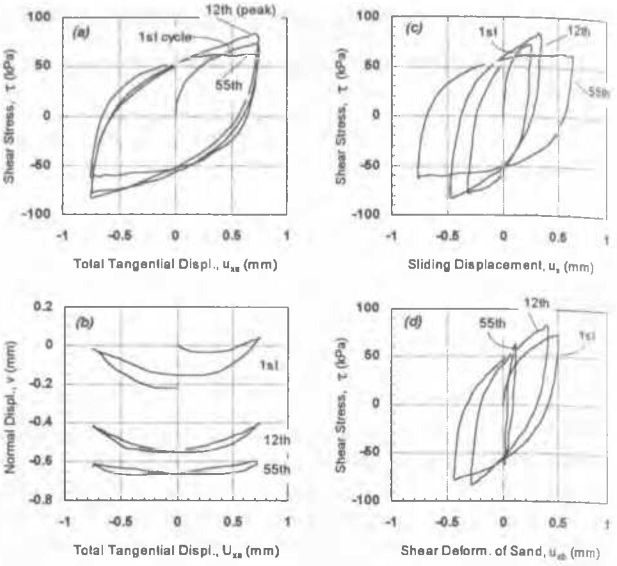

Figure 2. Two-way cyclic tangential-displacement-controlled test under *constant normal stress* condition.

The stiffening of the sand mass with cycles resulted in a gradual decrease in the maximum shear deformation in the sand mass. The stiffer response of the sand mass caused the sliding displacement of the interface to increase and the peak and residual strengths to mobilize.

3.2 *Two-way cyclic constant normal stiffness tests*

The results of a typical test are presented first in Figs. 3 through 5, to identify the main characteristics of the behaviour of a sand-steel interface under constant normal stiffness condition in two-way tangential displacement controlled tests. The testing procedure was the same as that presented for the 2-D cyclic test under constant normal stress condition, except that a constant normal stiffness of 400 kPa/mm was imposed in the direction normal to the interface plane. The initial normal stress, σ_{no}, was 300 kPa. The specimen was subjected to 50 cycles of displacements at a total tangential displacement amplitude of 0.75 mm at a frequency of 1/200 Hz.

Figure 3 shows that the mobilized shear stress reduced with increase in number of cycles in such a way that the rate of reduction was high within the first few cycles. The mobilized shear stress which was 170 kPa at the displacement amplitude of 0.75 mm during the first cycle, dropped to 50 kPa in the 50th cycle.

The shear stress was normalized by the corresponding normal stress and was plotted against tangential displacements (Fig. 4). The variations of stress ratio, τ / σ_n, with total tangential displacement, sliding displacement, and shear deformation of sand mass exhibited exactly the same behaviour as the results of tests under constant normal stress tests (Fig. 2). For example, Fig. 4*c* illustrates the variations of stress ratio with sliding displacement which is identical to Fig. 2*c*. The mobilized stress ratio, τ / σ_n, which was 0.61 at the maximum tangential displacement during first cycle, increased to 0.8 at cycle 12, and subsequently decreased to a residual value of 0.6. Despite the fact that the mobilized shear stress decreased from the beginning of cycles, the stress ratio followed exactly the same pattern of a typical 2-D displacement controlled cyclic test behaviour under constant

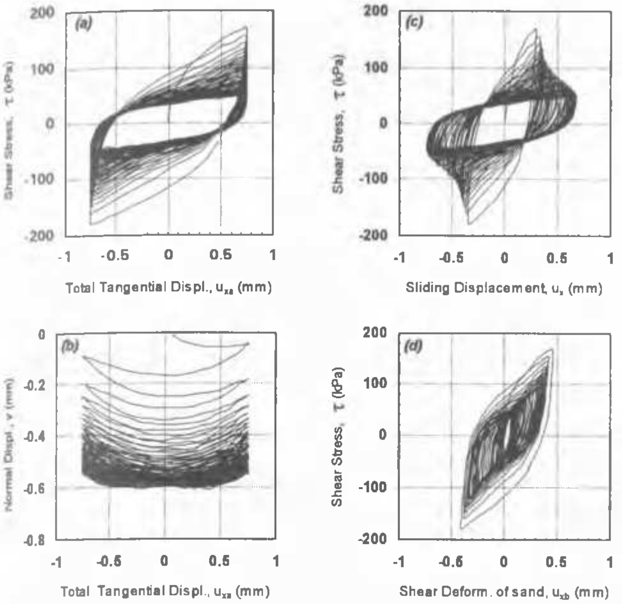

Figure 3. Two-way cyclic tangential-displacement-controlled test under *constant normal stiffness* condition.

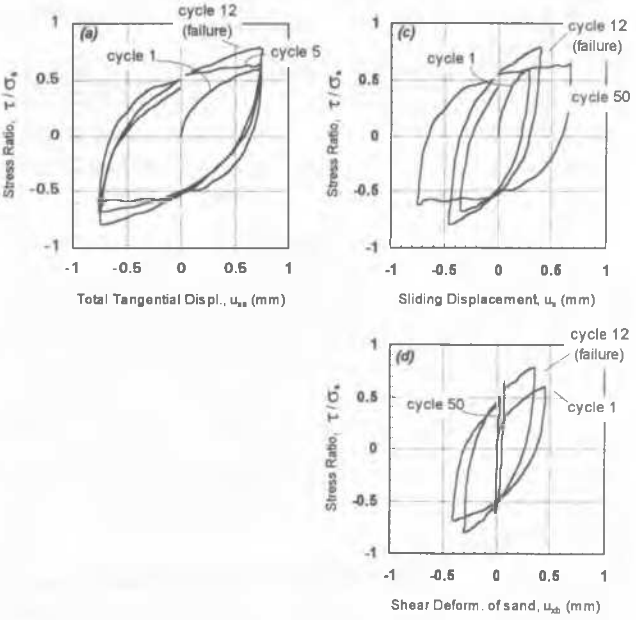

Figure 4. Normalized results of Fig. 3 at cycles 1, 12, and 50.

normal stress condition. The failure occurred at the interface at cycle 12, after which the stress ratio approached a residual value.

The results also indicate that the sliding displacement at the interface and shear deformation of the sand mass underwent the same variations as in the case of constant normal stress tests. With increase in the number of cycles, the amplitude of shear deformation of the sand mass decreased while the sliding displacement amplitude increased. The variations of shear stress, stress ratio, and normal stress with time are shown in Fig. 5. A rapid reduction in shear stress and normal stress continued up to about 30 cycles (time 6000 sec.) after which these stresses approached their respective residual values. The peak stress ratio, $(\tau / \sigma_n)_{peak}$ was reached at cycle 12 equivalent to 2400 seconds (Fig. 5*b*). Due to compressive behaviour of sand under cyclic loads, the normal stress had to decrease eventually (Fig. 5*c*) in parallel with the normal displacement, in order to maintain the normal stiffness, *K*, at the designated value of 400 kPa/mm throughout cycles. The rapid reduction of the normal stress with cycles contributed to the rapid reduction of the mobilized shear stress, which is the so-called degradation of maximum shear stress with cycles.

It is shown that both factors are contributing to the shear stress degradation, simultaneously. The first factor, proposed by Uesugi *et al.* (1989) and Uesugi and Kishida (1991), attributed the reduction in maximum stress ratio, τ / σ_n, to the sliding displacement at the interface, and it was considered to be the dominant factor. That idea was true within the framework of their experimental results, which was limited to one-way and two-way cyclic displacement controlled tests under the condition of constant normal stress. The second factor (Poulos 1989) was attributed to the reduction in normal effective stress due to the change in normal displacement. Using the calcareous sediments, which are highly compressible due to crushing of the particles during shearing, was one reason to conclude that the reduction in normal displacement was the dominant factor. Since the direct shear box as the soil container would not permit to distinguish between the sliding displacement and shear deformation of the sand mass, it would not be possible to observe the first factor.

The stress ratio variations, τ / σ_n, shown in Figs. 4 and 5*b*, resemble the shear stress variations in similar tests under constant normal stress conditions, which indicate that the interface has experienced failure. This observation is in favour of the first factor that the sliding displacement is a dominant factor. Figures 2, 5*a*, and 5*c*, which illustrate the decrease in both maximum shear stress and normal stress with increase in cycles, provide support for the second factor that the reduction in volume of the soil mass and the normal displacements, result in the reduction of maximum shear stress.

Another test was conducted at a total tangential displacement amplitude of 0.25 mm. The variations of shear stress, stress ratio, and normal stress with cycles are presented in Fig. 6. Although the mean normal stress dropped substantially during cycles (from 300 to about 110 kPa), the maximum shear stress decreased only slightly (from 138 kPa in the 1st cycle to about 90 kPa in the 50th cycle). The stress ratio variations (Fig. 6*b*) showed gradual increase with cycles, but no failure was observed.

These comparisons demonstrate how the total tangential displacement amplitude affects the degradation of the maximum shear stress with cycles. If the magnitude of total tangential displacement is not large enough to cause failure at the interface, i.e., no softening is observed in τ / σ_n, the reduction in maximum shear stress would not be very high despite a considerable reduction in the normal stress. Maximum shear stress, however, reduced even when failure did not occur which was the result of a decrease in the normal stress due to the compression of sand.

4 CONCLUSIONS

The 2-way displacement controlled cyclic tests under the condition of constant normal stiffness indicate that the maximum shear stress decreases with increase in the number of cycles irrespective of the magnitude of the tangential displacement amplitude. The maximum shear stress begins to decrease right after cycling starts. This is an indication that the degradation of the maximum shear stress depends on the compressibility of the sand mass during cycles. The compression of sand mass causes reduction in the normal stress with cycles. The rate of decrease in maximum shear stress, however, is significantly affected by the magnitude of the tangential displacement amplitude. If the tangential displacement amplitude is sufficiently large, then the stress ratio, τ / σ_n, would reach its peak value after several cycles.

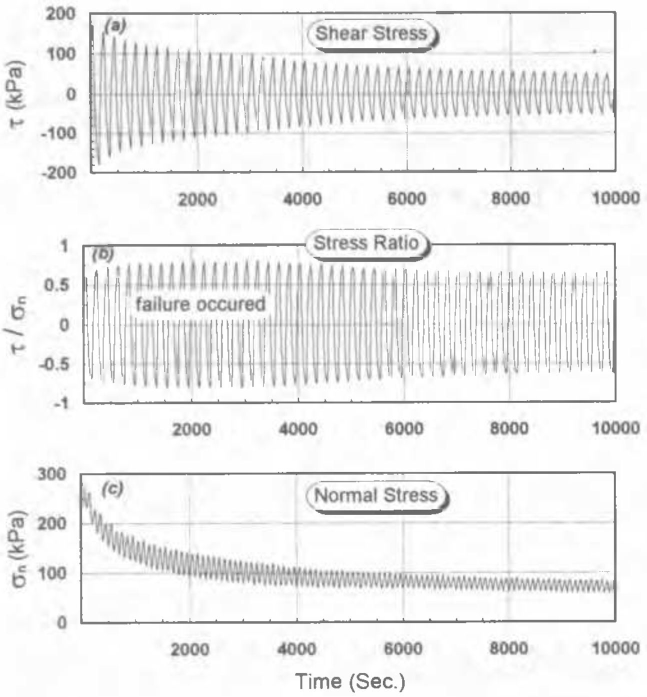

Figure 5. Variations of τ, τ / σ_n, and σ_n with time.
(total tangential displacement amplitude = 0.75 mm)

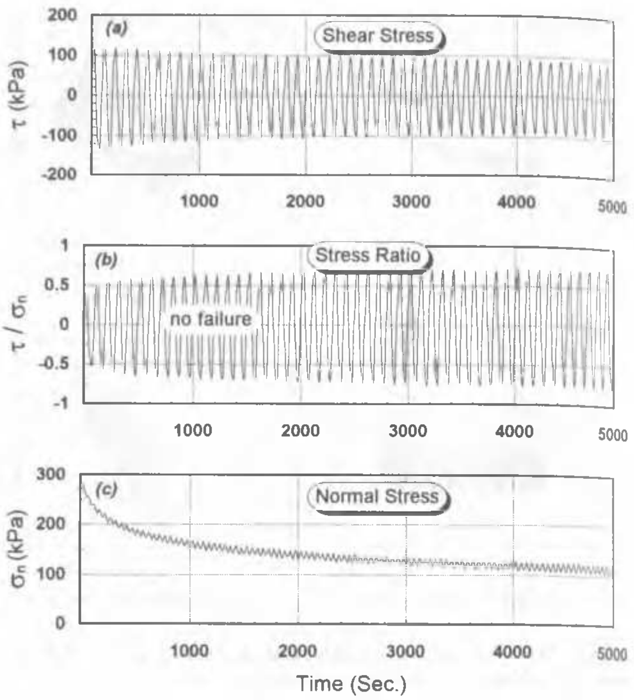

Figure 6. Variations of τ, τ / σ_n, and σ_n with time.
(total tangential displacement amplitude = 0.25 mm)

After the peak (failure), the stress ratio would approach a residual value. The reduction in maximum shear stress after failure is faster than the reduction in the maximum shear stress in the case where no failure is experienced. These are indications that the shear stress degradation is influenced not only by the compression of sand with cycles, but it also depends on the amount of mobilized sliding displacement.

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