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Test study on behavior of interface between structure and coarse grained soil

Le comportement de l'interface entre la structure et le sol rugueux

Ga Zhang & Jian-Min Zhang
Institution of Geotechnical Engineering, Tsinghua University, Beijing, 100084, China
zhangga@tsinghua.edu.cn

ABSTRACT

The monotonic and cyclic behavior of the interface between structure and coarse grained soil was investigated through tests. A series of tests on the interfaces between ideal rough steel plate and gravel were conducted with a large-scale test apparatus. The stress and deformation of the interface were measured. The behavior of such kind of interface were therefore discovered or summarized, including: (1) the shear strength was well proportional to the normal stress; (2) no obvious strain softening behavior was exhibited; (3) the normal displacement gradually accumulated with well-regulated variation within a shear cycle; (4) the behavior evolved to a stable state; (5) the mechanical response was related to the shear direction; and (6) the roughness of structure, the behavior of the soil and the normal stress were main influence factors on the behavior.
Keywords: interface, coarse grained soil, test, behavior, cyclic

RÉSUMÉ

Le comportement monotone et cyclique de l'interface entre la structure et le sol rugueux a été étudié dans les essais. Une série d'essais sur les interfaces entre l'assiette acier rugueuse idéale et le gravier ont été conduits avec un appareil d'examen d'une grande graduation. La pression et la difformité de l'interface ont été mesurées. Donc le comportement de cette sorte d'interface a été découvert et a été résumé ainsi, y compris: (1) la force des cisailles est bonne proportionnellement à la force normale, (2) non comportement évidente du tension amollissant est exposé; (3) le déplacement normal graduel est accumulé avec variation bon-réglé en un cycle des cisailles; (4) le comportement est évolué à un état stable; (5) la réponse mécanique est celle concernant du côté des cisailles; et (6) la rugosité de la structure, le comportement du sol et la pression normale sont les premiers facteurs sur le comportement.
Mots Clés: interface, sol rugueux, essai, comportement monotone et cyclique

1 INTRODUCTION

The monotonic and cyclic behavior of the soil-structure interface has a significant effect on the mechanical response of soil-structure system. As a vital approach, many tests had been conducted to study the behavior and its main influence factors of kinds of soil-structure interfaces.

Potyondy (1961) studied the influence of the roughness of structure on the behavior of sand-structure interface through a series of direct shear tests. Desai and Drumm (1985) performed plenty of cyclic shear tests and then indicated that the shear stress of sand-concrete interface could be expressed as a function of normal stress, relative displacement, number of loading cycles and initial density of sand. Uesugi and Kishida (1986, 1989) conducted a series of monotonic and cyclic tests on the behavior of sand-steel interface with a cyclic simple shear device. Fakharian et al. (1996) observed three-dimension monotonic and cyclic stress-strain relationship response of sand-steel interface under several kinds of normal boundary conditions with a newly developed simple shear apparatus, C3DSSI. Comprehensive studies on the monotonic and cyclic behavior of soil-structure interface had also been carried out with different test devices (e.g., Clough and Duncan, 1971; Brummund and Leonards, 1973; Coyle and Sulaiman, 1967). Attempts were also made on the microscopic deformation observations of soil-structure interface during test.

Most available tests put their emphasis on the behavior of the interface between structure and sand or clay. Hardly systematically studied were the behavior of the interface between structure and a kind of coarse grained soil — graveled soil which usually includes gravel and other soil with larger grain size. Such category of coarse grained soil has been a great concern in the design, construction and maintenance of rockfill embankment, cut-off wall, speed-railway and other projects in geotechnical engineering. Therefore, the authors performed a series of tests to investigate the behavior of the interface between structure and graveled soil with a large-scale test apparatus. The objective of this paper is to present typical, serialized test results on the monotonic and cyclic behavior of the interface between structure and graveled soil.

2 TEST DETAILS

2.1 *Apparatus*

The tests were conducted with a large-scale apparatus referred to as "TsingHua- 20 tonne Cyclic Shear Apparatus for Soil-Structure Interface", which was also called "TH-20t CSASSI" for simplification. The apparatus was specially developed to study the monotonic and cyclic behavior of the interface between structure and coarse grained soil (Zhang and Zhang, 2003). Fig. 1 shows a photographic view of the apparatus.

TH-20t CSASSI could be employed to conduct monotonic and cyclic shear tests of the interface between soil and kinds of structure materials commonly used in civil engineering such as steel, geotextile and concrete. Any of three normal boundary conditions, including constant stress, constant displacement and constant stiffness, could be directly applied on the interface with high accuracy. TH-20t CSASSI could automatically provide high loads up to 200kN in both directions tangential and normal to the interface with stepless speed changing. The stress and displacement of the interface in both directions tangential and normal to the interface could be measured with corresponding sensors and their acquisition was fully computerized. Moreover, the movement and crushing of soil particles could be observed and then recorded into high-resolution digital photos through a thick organic glass window.

Fig.1 photograph of TH-20t CSASSI

2.2 *Materials*

A series of ideal rough steel plates were used in tests in order to understand how the roughness of structure affected the behavior of the interface. The surface contacting the soil of such steel plate was designed with standard shape so that the roughness could be only adjusted by changing the peak-to-valley height, which was defined as “roughness degree”, *R*. Three roughness degrees of the steel plates including 0.1mm, 1mm and 10mm were selected for the tests.

A kind of conglomerate gravel with major angularity was used in the interface tests as a typical graveled soil. Two kinds of grain size distributions were selected: one type was referred to as “homogeneous gravel” and the other, “composite gravel”. The grain size of the homogeneous gravel had a nearly uniform distribution from 2mm to 10mm (the average grain size, d_{50}, was 7.1mm), which was compacted to the design dry density of 1.75g/cm^3 for the tests. The grain size of the composite gravel had a wider distribution from 2mm to 40mm (the average grain size, d_{50}, was 10mm), which was compacted to the design dry density of 2.0g/cm^3 for the tests. The triaxial compress test results showed both of the gravels exhibited dilation in volumetric strain after a little compression at first when the confining pressure was quite small (e.g., 0.1MPa) while continuous compression in volumetric strain when the confining pressure was large (e.g., 0.8MPa). As a result, it can be concluded that the gravel and normal stress adopted in this paper were both representative for the study on the behavior of the interface between structure and graveled soil.

2.3 *Conditions*

Monotonic and cyclic shear application styles were employed in tests under three normal boundary conditions including constant stress, constant displacement and constant stiffness boundary conditions. Several levels of normal stress including 100kPa, 200kPa, 400kPa and 700kPa were selected for tests under constant normal stress boundary condition. As a result, a total of about 100 tests were conducted.

The soil sample was installed into the soil container by compacting to the design dry density by layers. The interface between steel plate and gravel was 50cm in length and 36cm in width, which was maintained invariable during shear test. All the shear tests were displacement controlled with 1mm/min at the loading rate. The stress and displacement in both tangential and normal to the interface were both measured and recorded.

3 RESULTS

Typical monotonic and cyclic test results of the interface between ideal rough steel plate and gravel were dissertated in the following texts. The behavior of the interface between structure and coarse grained soil was then discussed based on the results. Since the size of the interface was maintained constant during test, the normal displacement exhibited the same rule as the volumetric change of the interface. In this paper, the normal displacement was defined positive if the interface contracted and negative if the interface dilated.

3.1 *Monotonic shear test*

Fig. 2 shows the plots of shear stress, τ, versus tangential displacement, u; and normal displacement, v, versus tangential displacement, u, of the interface between the steel plate with roughness degree of 1mm and homogeneous gravel due to monotonic shear application under constant normal stress condition.

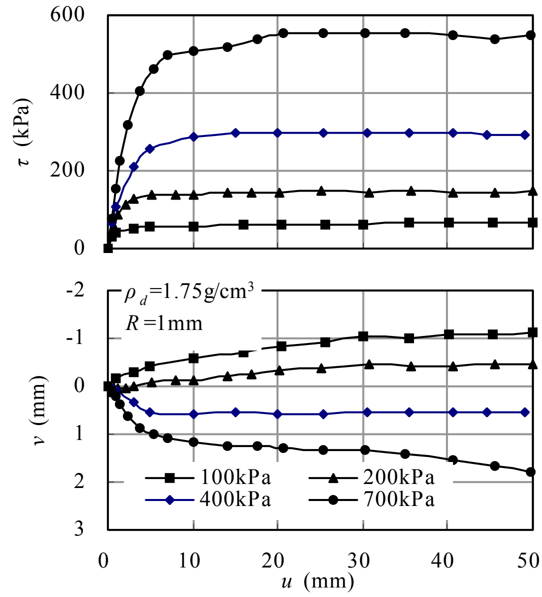

Fig.2 Monotonic test results under constant normal stress boundary condition

It can be seen in the figure that there was no obvious peak value in the plot of shear stress versus tangential displacement, which demonstrated such kind of interface exhibited no obvious strain softening behavior. Both the maximum shear stress and the initial slope of the relationship plot between the shear stress and tangential displacement would increase if the normal stress increased.

The normal displacement of the interface decreased after a small amount of increase at first if the normal stress was small while gradually increased if the normal stress was large due to monotonic shear application. It indicated that the volumetric change due to dilatancy of the interface was evidently influenced by the normal stress. That was probably because the volumetric change of the interface was mainly induced by that of the soil near the structure.

Fig. 2 also indicated that the tangential displacement needed to the state at which the normal displacement became steady was much larger than the tangential displacement needed to the state at which the shear stress became steady. In other words, the shear stress and the normal displacement grew asynchronously, which demonstrated the shear strain and the volumetric strain maybe had different deformation mechanism due to shear application. That should be paid attention to in the modeling of the behavior of the interface between structure and coarse grained soil.

Fig. 3 shows the plot of the shear strength, τ_f, versus the normal stress, σ, of the interface between the steel plate with roughness of 1mm and the homogeneous gravel, in which the shear strength was defined as the maximum shear stress of the interface due to monotonic shear application under constant normal stress condition. It can be seen that the shear strength was well proportional to the normal stress. It demonstrated that the shear strength of the interface between steel plate and gravel could be formulated with the Mohr-Coulomb strength criteria with a parameter, friction angle, φ, i.e.,

$$\tau_f = \sigma \cdot \tan \varphi \tag{1}$$

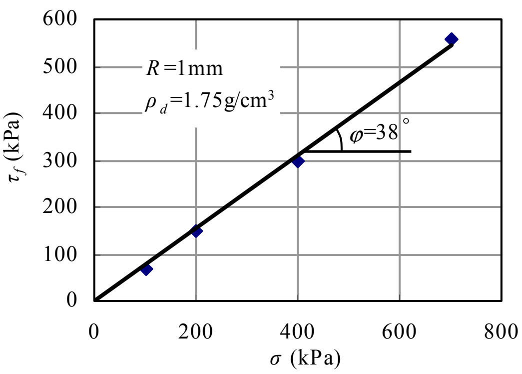

Fig.3 Shear strength of the interface between steel plate and gravel

Table 1 shows the friction angle, φ, of the interfaces between the steel plate with different roughness and the two gravels. For the interfaces between the different steel plates and the same gravel, the friction angle was larger if the steel plate was rougher. For the interfaces between the same kind of steel plate and different gravels, the friction angle of the interface between the plate and composite gravel was a bit larger than that of the interface between the steel plate and homogeneous gravel. The test results also indicated that the roughness of the structure had effect on the stress-strain relationship of the interface between steel plate and gravel.

As a result, it can be concluded that the roughness of the structure, the behavior of soil and the normal stress were main factors affecting the behavior of the interface between structure and graveled soil.

Table 1 friction angle of different kinds of interfaces

inter-face	soil	homogeneous gravel			composite gravel		
	roughness degree of the steel plate (mm)	0.1	1	10	0.1	1	10
friction angle (degree)		31	38	42	38	39	42

3.2 *cyclic shear test*

Fig. 4 shows the plots of history of the shear stress, τ, the normal displacement, v, of the interface due to a two-way cyclic shear application under constant normal stress of 700kPa. It can be seen that the maximum value of the shear stress varied little in different cycle. In other words, the shear strength of the interface was nearly invariable due to cyclic shear application. The normal displacement accumulated but well-regulated varied within a single cycle. The normal displacement tended stable with a decreased accumulation velocity due to cyclic shear application.

Fig. 5 shows the plots of shear stress, τ, versus tangential displacement, u; normal stress, σ, versus tangential displacement, u, within different shear cycles due to the same loading application as Fig. 4. The plot of shear stress versus tangential displacement within a single cycle was nearly closed. The loading relationship curve between the shear stress and the tangential displacement became steeper during test. The maximum value of the shear stress in the initial shear direction was smaller than the one in the reverse shear direction. On the other hand, the initial slope of the unloading relationship curve between the shear stress and the tangential displacement in the initial shear direction was larger than the one in the reverse shear direction.

It can be seen from Figs. 4-5 that the normal displacement varied in a well-regulated manner within a single shear cycle. When the interface was unloaded, its normal displacement would always increase to a certain extent, which demonstrated that the soil near the structure exhibited a compression due to unloading. The normal displacement behaved asymmetrical response when the interface was applied with the symmetrical, two-way cyclic tangential displacement after monotonic shear application. To describe concretely, as illustrated in Fig. 5, the normal displacement of the interface mainly exhibited an increase tendency in the initial shear direction while exhibited a decrease tendency in the reverse shear direction. This tendency became more obvious after several shear cycles.

A new behavior was discovered that the mechanical behavior such as shear strength and volumetric change was related to the shear direction. Such new behavior was defined “aeolotropy of interface” in this paper to distinguish from the concept “anisotropy” in traditional mechanics. The further tests showed that the monotonic or initial shear history was one of the main factors to the extent of aeolotropy of interface for a given interface between structure and coarse grained soil.

The stress-displacement relationship within a single shear cycle became more and more similar with the shear cycle number increased, especially under higher normal stress condition. For example, as illustrated in Fig. 5, the plots of the shear stress versus the tangential displacement within the cycle 31, 60 and 85 were basically uniform. Meanwhile, the loading relationship curve between the shear stress and the tangential displacement became linear, tending to be a line as the unloading relationship curve. The accumulation of the normal displacement and the development of the relationship between the normal and tangential displacement within a single cycle also became slow and slow. It demonstrated that the mechanical response of the interface between structure and coarse grained soil evolved from an initial state to a stable state due to shear application. The normal stress was a main influence factor to the evolution velocity: the larger the velocity was if the larger the normal stress was.

Fig. 6 shows the history of the tangential displacement, u, the shear stress, τ, the normal stress, σ, the normal displacement, v, of the interface between steel plate (R=1mm) and homogeneous gravel due to cyclic shear application under constant stiffness boundary condition. The stiffness, K, was maintained 40kPa/mm during test and the initial normal stress was 400kPa. It can be seen that the shear stress decreased as a whole because the normal stress decreased with a fixed proportion to the increase of normal displacement. The stress- displacement relationship response exhibited a similar rule as the one under constant normal stress condition. The test results also indicated that the shear strength of such interface was proportional to the normal stress under constant stiffness condition.

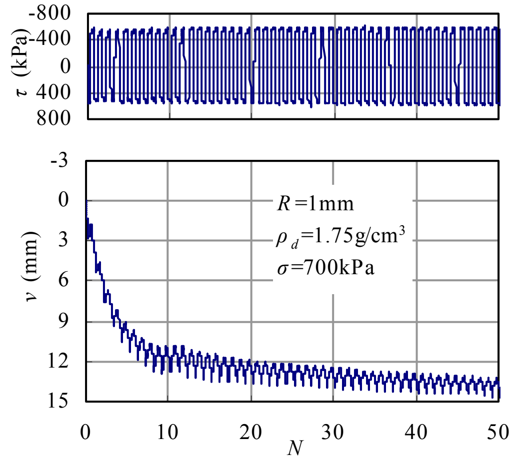

Fig.4 Cyclic history under constant normal stress boundary condition

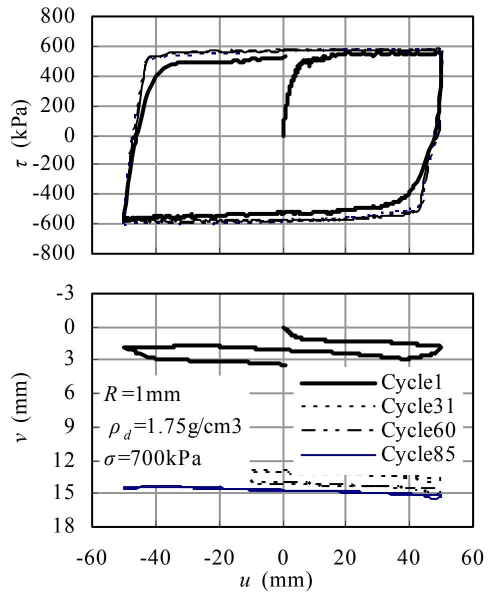

Fig.5 Cyclic stress-displacement relationship under constant normal stress boundary condition

4 CONCLUSIONS

A series of monotonic and cyclic tests of the interfaces between ideal rough steel plate and gravel were conducted with a large-scale test apparatus. The stress and deformation of the interface were measured and analyzed. The monotonic and cyclic behavior of interface between structure and coarse grained soil were discovered or summarized based on test results, including:

(1) The shear strength was well proportional to the normal stress and nearly independent on cyclic shear cycles number.
(2) The interface exhibited no obvious strain softening behavior. The normal displacement accumulated and the accumulation velocity decreased with the shear cycle number increased, but well-regulated varied within a single shear cycle. The behavior evolved to a stable state due to shear application.
(3) A new concept "aeolotropy of interface" was presented to describe the test fact that the mechanical response was related to the shear direction due to cyclic shear application.
(4) The roughness of structure, the behavior of soil and the normal stress were main influence factors on the behavior.

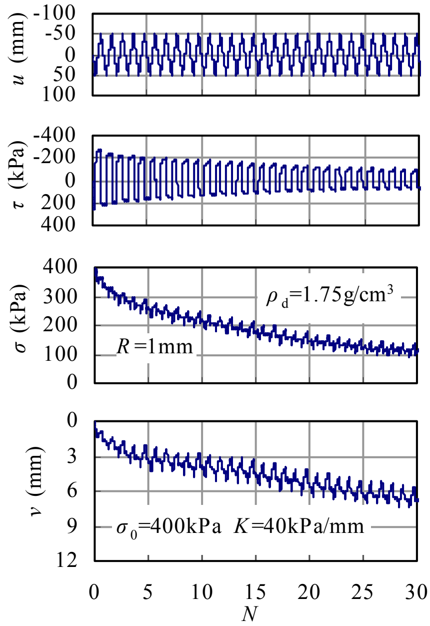

Fig.6 Cyclic history under constant normal stiffness boundary condition

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