Three-dimensional Large-scale test of soil-structure interface

Tri-dimensionnel test de l'interface sol-structurale sur grandes échelles

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ABSTRACT

A large-scale test apparatus was designed and developed to investigate three-dimensional monotonic and cyclic behavior of soil-structure interfaces. Hydraulic servo controlled loading system can apply three-dimensional high loadings on soil-structure interfaces. A measurement system was also accommodated. The effectiveness and reliability of this apparatus was verified by a group of tests of the interface behavior between gravel and a steel plate.

RÉSUMÉ

Un dispositif d'essai sur grande échelles a été conçu et mis au point pour enquêter sur des tri-dimensionnel monotone et cyclique comportements des interfaces sol-structurales. Le système de chargement contrôlé par un hydraulique servo peut appliquer des tri-dimensionnelles charges élevées sur les interfaces sol-structurales. Un système de mesure a également été accepté. L'efficacité et la fiabilité de cet appareil a été vérifié par un groupe de tests des comportements de l'interface entre le gravier et une plaque d'acier.

Keywords :interface; apparatus; gravelly soil; test

1 INTRODUCTION

Due to the constraints of structures, the contact zone of soil and structure exhibits significantly different mechanic responses from the soil itself, which is defined as interface. Interfaces extensively exist in practical engineering, such as earth-rock dam, face rockfill dam, expressway, retaining wall, and so on.

The direction of main shear stress on the interface changes continuously during shear application, indicating the three-dimensional loading condition of the interface between soil and structure in practical engineering. However, most of the test devices developed to perform the interface test were designed to study the behavior of interface under two-dimensional loading conditions. Test devices applied to study the interface behavior include direct shear apparatus (Potyondy, 1961; Clough and Duncan, 1971; Desai and Drumm, 1985; Brandt, 1985; Yin et al., 1994; Hu and Pu, 2004; Zhang and Zhang, 2006), simple shear apparatus (Uesugi and Kishida., 1986; Uesugi et al. 1989; Fakharian, 1996), the ring shear apparatus (Brummund and Leonards, 1973), ring torsion device (Yoshimi and Kishida, 1981) and so on.

This paper present a three-dimensional soil-structure interface test apparatus, 80t 3D Multifunction Apparatus for Soil mechanics (3DMAS), for 2 and 3 - dimensional study of monotonic and cyclic behaviors of various interfaces, especially the interface between gravel soil and structure, under different kinds of conditions. Meanwhile, the apparatus has the attribute of modular design and its function can be easily expanded. The structure of 3DMAS is described in detail. Then a group of tests of gravel-steel plate interface has been performed to verify its effectiveness and reliability.

2 DETAILS OF 3DMAS

Figure 1 and Figure 2 exhibit the overall schematic view and photograph of the 3DMAS. It consists of the following main components: (1) reaction frame; (2) loading system; (3) structure plate and soil container; and (4) control and measure system. Cartesian coordinate system is established to describe the apparatus clearly. The z-axe is along vertical direction and positive upwards. The x-axe and y-axe are the two orthogonal directions on the horizontal plane. Thus all kinds of shear paths acting on the interface can be achieved by decomposing it in x-axe and y-axe.

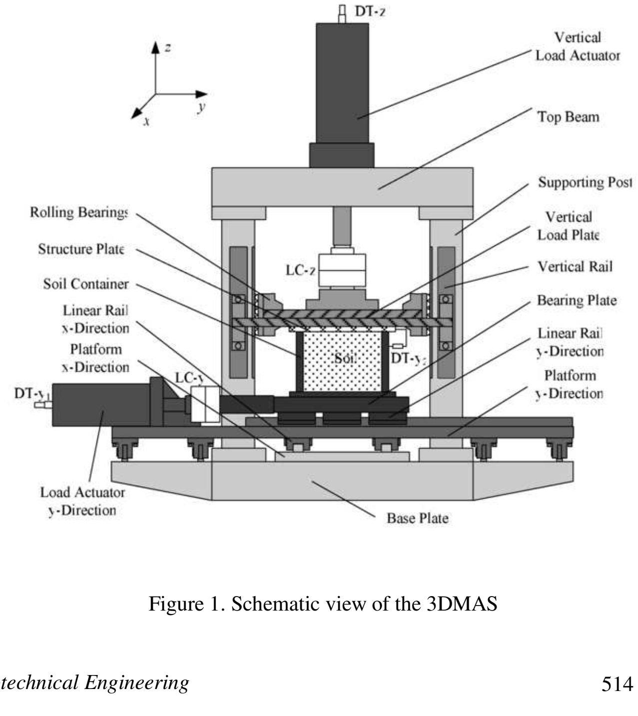

Figure 1. Schematic view of the 3DMAS

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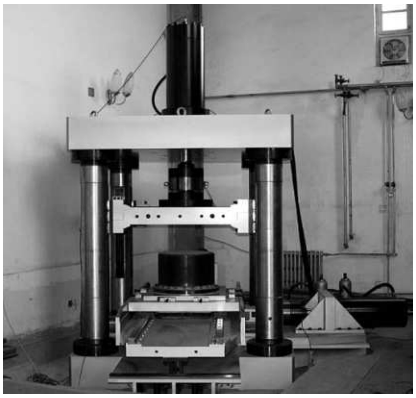


Figure 2. Photograph of the 3DMAS

2.1 *Reaction frame*

The reaction frame, consisting of top beam, base plate and four supporting posts, is designed to be extraordinarily rigid compared to the tests materials and can supply load of 800kN in vertical direction which means 4.0MPa normal pressure on a 500mm-diameter sample. The top beam and base plate is further strengthened by the ribs to enhance their bearing capability. The base plate is located on the ground with a thick concrete base to eliminate apparatus movement. And the top beam is attached with base plate by four supporting posts on which vertical rails are set used as oriented system in vertical direction.

The main performance indexes of the apparatus are listed in Table 1. The top beam and base plate are 2000mm×2000mm in area and 300mm in thickness, the supporting posts between them are all 2000mm high. This apparatus can provide enough space to put loading systems in vertical and horizontal directions, and has the maximum net space of 800mm in height, 1.0m in length and 1.0m in width. Hence large-size soil containers can be adopted and large-scale tests performed.

Table 1. Performance of the apparatus

Items	X-direction	Y-direction	Z-direction
Max load (kN)	400	400	800
Max displacement (mm)	±150	±150	±300
Max loading rate (mm/s)	100	100	200
Min loading rate (mm/s)	0.1	0.1	0.1
Measuring accuracy (%)	0.1	0.1	0.1
Max loading frequency (Hz)	0.5	0.5	0.5
Max size of sample (mm)	500	500	-

2.2 *Loading system*

The loading system, including those in horizontal direction and in vertical direction, allows application of monotonic and cyclic load with displacement or load control.

The horizontal loading system, made of loading platform, linear rails and hydraulic servo actuator, includes orthogonal ones in x-direction and y-direction. In x-direction, the loading platform is fixed on the base plate, and the linear rolling rails and hydraulic servo actuator are fixed on the loading platform. The piston-rod of hydraulic servo actuator is connected with y-direction loading system, of which the loading platform lies on the linear rolling rails in x-direction. And the piston-rod of hydraulic servo actuator in y-direction is attached with bearing plate, on which soil container is located. The horizontal loading system can divide the horizontal movement into two orthogonal ones in x- and y- directions, respectively controlled by two hydraulic servo systems accurately. Thus the bearing plate is able to make any horizontal movement freely, and all kinds of shearing paths can be realized, such as cross, circular, elliptical and any other user-defined paths.

In vertical direction, the loading system provides normal load or displacement on the interface with high accuracy, which is composed of hydraulic servo actuator, vertical load plate and eight vertical rails on supporting posts. The hydraulic servo actuator is fixed vertically on the top beam and connected with vertical load plate, on whose corners eight rolling bearings are installed and moves along vertical rails while it moves up and down. This vertical loading system ensures that the vertical load plate and structure plate remain horizontal when they move up and down and hence that the tested interface receives uniform normal stress.

2.3 *Structure plate and soil container*

The structure plate, such as steel plate, geotextile, concrete and other commonly used structure materials, is attached to vertical load plate, keeps immovable in horizontal direction during shear application, and can be easily replaced. The area of the structure plate is generally 1m×1m, properly larger than the soil container. Therefore the area of the contact surface and also of the interface remains constant during test process.

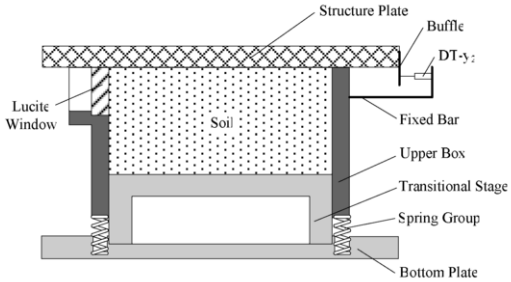


Figure 3. Schematic view of a typical soil container

The 3DMAS is equipped with a series of soil containers of different shapes (square and circle), different sizes (500mm and 300mm) and different types (direct shear and simple shear). Figure 3 provides a schematically view of a typical soil container. It is a steel container, consisting of a bottom plate, a transitional stage, a spring group, an upper box and a lucite window. The bottom plate is located on the bearing plate using screws. On the bottom plate is fixed the transitional stage and surrounding holes at regular interval, in which springs are placed. Then the upper box is placed on spring group. The length and coefficient of spring group are chosen to ensure that the upper box is able of going up and down freely during shear application. The volumetric change of interface due to shearing can be well reflected and measured through the displacement of the upper box. The lucite windows at the top of upper box in both x- and y-direction can observe and analyze the movement and physical evolution of the interface by digital photo and particle-imaging techniques.

2.4 *Control and measure system*

The control and measure system, involving displacement and stress of the interface in all directions, is fully automatic and computerized. The loads in x-, y- and z-directions are supplied by hydraulic motive actuator and measured by highly accurate load cells set between piston rod and connecting section. The displacement in vertical direction is measured by DT-z, and the relative displacements in horizontal directions are measured by DT-x_2 and DT-y_2 which are fastened on the fixed bars screwed up with soil container. The two transducers directly measure the displacements between structure plate and soil, eliminate connection void and guarantee the measuring accuracy. The two additional transducers (DT-x_1 and DT-y_1) are used to set the position of bearing plate during the preparation of the test.

The 3DMAS is capable of applying load and displacement control in x-, y- and z-directions. It can provide any shear paths in horizontal direction and in z-direction realizes three typical normal boundary conditions generally used in laboratory experiments, including constant normal stress, constant volume, and constant normal stiffness conditions.

Three orthogonal forces or displacements can be applied respectively and simultaneously, and the hydraulic servo system adopted in each direction can generate the desired force or displacement on the interface with high accuracy, such as the normal stress σ or normal displacement u_z in z-direction, and the shear stresses τ_x, τ_y or tangential displacements u_x, u_y in x- and y- directions.

2.5 *Summary*

As described above, the new features of the 3DMAS include the following: 1) it has high loading capability and can provide large-scale test sample; 2) it has an accurate three-dimensional loading system supported by hydraulic servo system; 3) three kinds of boundary conditions can be easily applied in vertical direction; 4) numbers of different shear paths including user-defined shear paths can be imposed with load or displacement control in tangential direction; 5) the control and measure system is computerized and automatic, and the load and displacement are easily and accurately controlled and measured. The 3DMAS is suitable for soil mechanics investigation, especially for the three-dimensional monotonic and cyclic behavior of the interface between gravel soil and structure under different kinds of conditions.

3 TYPICAL RESULTS

The 3DMAS has been employed to perform hundreds of monotonic and cyclic tests of various kinds of interfaces between gravel soil and structure, under different boundary conditions, various control mode and kinds of shear paths. Presented in this paper are a series of typical results from interface tests between gravel soil and a steel plate to confirm the effectiveness and reliability of the apparatus. Since the sample area is invariable during testing, the normal displacement is regarded as the volumetric change of the interface. The normal displacement is defined as positive if the interface contracts and negative if it dilates.

3.1 *Test materials*

The soil adopted for the interface tests is gravel soil used as cushion material in Jishixia CFRD. The grain size of the homogeneous gravel has a nearly uniform distribution from 5mm to 12mm, with the average grain size of 7.5mm.

The structure plate is a rough steel plate artificially prepared with regular permutation of small quadrangular frustum pyramids on the surface towards to the soil (Figure 5). The peak-to-valley height of the steel plate, namely the height of small quadrangular frustum pyramids, is the same and defined as "degree of roughness" *R*. The degree of roughness *R* of the steel plate used is 1mm.

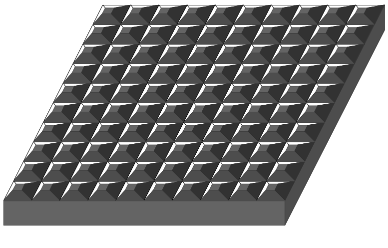
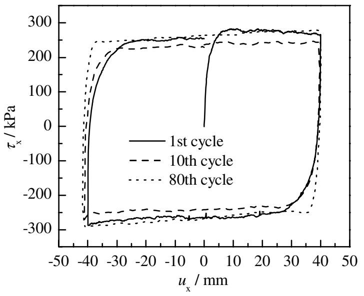


Figure 5. Schematic view of the rough steel plate

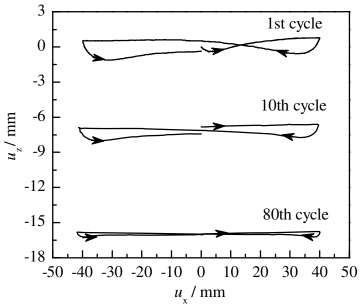
3.2 *Displacement-controlled results under constant normal stress condition*

Figure 6 gives cyclic test results shearing along x-direction with the control of tangential displacement u_x=40mm under constant normal stress σ=400kPa, including τ_x-u_x curves, u_z-u_x curves in cycle *N*=1, 10, 80, and u_z-*N* curve. The τ_x-u_x curves demonstrate that the shear stress increases with tangential displacement increasing then tends to a stable value when shear application starts; this indicates that such an interface exhibits no significant strain softening. With the application of cyclic shear under constant normal stress of 400kPa, the maximum shear stress varies little in different shear cycles, which demonstrates that the shear strength of the interface is nearly stable. It also can be discovered that the modulus gradually increases in unloading process and reloading application in opposite direction.

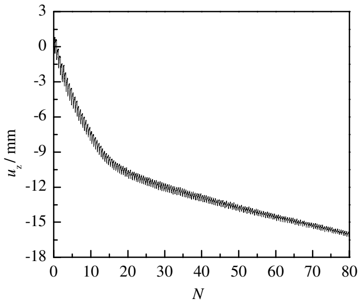
The normal displacement presents fluctuation phenomenon (Figure 6 (b) and (c)). This indicates that the interface dilates and compresses due to shear application and its volumetric variation can be divided into reversible and irreversible parts (Zhang and Zhang, 2006). The irreversible volumetric variation increases but the rate decreases with increasing number of shear cycles, and the reversible volumetric variations are almost the same in every cycle, which well agree with previous conclusions made by other researchers (Zhang and Zhang, 2006). These suggest that the 3DMAS can effectively and reliably represent the monotonic and cyclic behaviors of the interface between gravel soil and structure.



(a) τ_x-u_x curves



(b) u_z-u_x curves



(c)u_z-*N* curve

Figure 6. Cyclic displacement-controlled test results along x-direction under constant normal stress condition

3.3 *Displacement-controlled results under constant normal stiffness condition*

The test was performed cyclically in circle-shear path with displacement control in tangential direction under constant normal stiffness condition. The test procedure (Figure 7) includes: 1) applying an initial normal stress σ_{z0}=400kPa on the interface; 2) setting the normal stiffness K=100kPa/mm; 3) shearing in y-direction under control of tangential displacement u_y=40mm (Figure7 ①); 4) shearing circularly under displacement control with the radius of 40mm (Figure7②-③-④-⑤); 5) finishing the test when the normal stress reduces to zero. Figure 8 gives the results of the interface test.

The normal stress reduces progressively with the cyclic shear application with the normal displacement increases concurrently. The reduction of normal stress directly leads to the decreasing of the maximum shear stress in horizontal direction. It can be obviously found in Figure 8(b) that the shear stress τ_y decreases as the normal stress reduces. Therefore, the curves between τ_x and τ_y become gradually close to circular point with increasing number of cyclic cycles (Figure 8(a)). In stress path of Figure 8(b), the normal stress does not begin from 400kPa, since the interface dilates and the normal stress increases correspondingly at the beginning of shearing (Figure 7①).

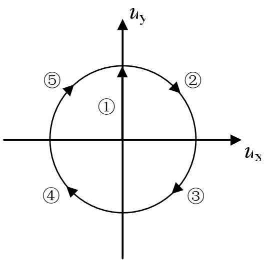
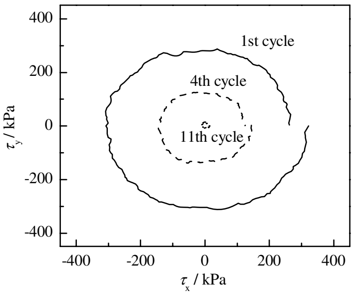
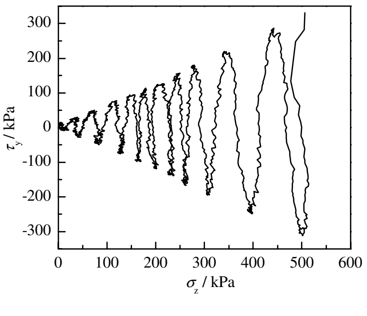


Figure 7. Cyclic circle-shear path under stress control



(a) τ_x-τ_y curves



(b) Stress path between τ_y and σ_z

Figure 8. Cyclic displacement-controlled circle-shear test results under constant normal stiffness condition

4 CONCLUSIONS

A large-scale three-dimensional apparatus, called 3DMAS, was developed to investigate the three-dimensional monotonic and cyclic behavior of a soil-structure interface. The apparatus has a number of new features: 1) it has high loading capability and can provide large-scale test sample; 2) it has an accurate three-dimensional loading system supported by hydraulic servo system; 3) three typical kinds of boundary conditions can be applied easily in normal direction; 4) numbers of different loading paths can be imposed in tangential direction; 5) the control and measure system is computerized and automatically, thus the load and displacement are easily and accurately controlled and measured. It can be used to investigate soil mechanics, especially the three-dimensional monotonic and cyclic behavior of the interface between gravel soil and structure under different kinds of conditions.

Typical monotonic and cyclic tests of the interface between gravel soil and a steel plate were conducted with the 3DMAS. The test results confirmed that the 3DMAS can effectively and reliably represent the three-dimensional behaviors of interfaces, and is an advanced device for interface mechanics research. This preliminary study also revealed that the three-dimensional behaviors of the interface are significantly different from its two-dimensional behaviors, and it is necessary to investigate the three-dimensional behaviors of interface.

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