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Development of a dynamic simple shear apparatus with confining pressure

Développement d'un appareil de cisaillement simple dynamique avec pression de confinement

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ABSTRACT: The optimisation of design practises for high cost engineering projects requires the use of advanced testing methods and the design of advanced laboratory equipment. This paper presents the development of a Dynamic Simple Shear testing (DSS-C) apparatus with Confining pressure. The great advantage of the DSS-C is the ability to more accurately simulate in-situ stresses, by subjecting specimens to controlled lateral stress boundary conditions. The cylindrical soil specimens can be subjected to saturation, with the use of the back pressure line, and isotropic consolidation prior to shearing. Anisotropic consolidation can also be performed, as well as consolidation under K_0 conditions. Horizontal loading can be either static or cyclic, and shearing can be implemented either in terms of load (stress controlled) or displacement (strain controlled). Moreover, the liquefaction potential of granular soils can be evaluated. Control of the apparatus and data logging are done through user-friendly software, which also provides the ability to automate the procedure, minimising human involvement. The results from DSS-C tests are used in many engineering applications, especially for the evaluation of the behaviour of offshore structures which are subjected to cyclic loading due to wind, waves, earthquakes and ice sheet movements.

RÉSUMÉ: L'optimisation des pratiques de conception pour les projets d'ingénierie à coût élevé nécessite l'utilisation de méthodes de test avancées et la conception d'équipements de laboratoire avancés. Cet article présente le développement d’un appareil d’essai de cisaillement simple dynamique (DSS-C) avec pression de confinement. Le grand avantage du DSS-C réside dans sa capacité à simuler avec plus de précision les contraintes in situ, en soumettant les échantillons à des conditions aux limites en contraintes latérales contrôlées. Les éprouvettes de sol cylindriques peuvent être saturées en utilisation une contre-pression, et soumises à une consolidation isotrope avant l’étape de cisaillement proprement dite. Une consolidation anisotrope peut également être effectuée, ainsi qu'une consolidation dans des conditions K0. Le chargement horizontal peut être statique ou cyclique, et le cisaillement peut être mis en œuvre en termes de charge (contrainte contrôlée) ou de déplacement (déformation contrôlée). De plus, le potentiel de liquéfaction des sols granulaires peut être évalué. Le contrôle de l'appareil et l'enregistrement des données sont effectués à l'aide d'un logiciel convivial permettant également d'automatiser la procédure d’essai en minimisant les interventions humaines. Les résultats des tests DSS-C sont utilisés dans de nombreuses applications, notamment pour évaluer le comportement des structures en mer (offshore) soumises à des chargements cycliques dus au vent, aux vagues, aux tremblements de terre et aux mouvements de la calotte glaciaire.

Keywords: Cyclic; Simple Shear; Confined Pressure; Liquefaction

1 INTRODUCTION

Simple shear tests are becoming very popular nowadays, mainly because they provide reliable estimations of the undrained shear strength of soils. Even though triaxial tests are well established and used by the geotechnical society, simple shear tests are attracting more attention due to the small specimen size and the mode of shearing which closely resembles the deformation condition imposed under many offshore foundation systems (Joer et al, 2011).

There are two main types of simple shear tests in cylindrical specimens, the direct simple shear and the simple shear with cell confinement (Carraro, 2017). In both tests, specimens are sheared by directly loading their top and bottom horizontal boundaries. During a direct simple shear test, the specimen is restrained within a stack of concentric rigid rings or with a wire-reinforced membrane. These methods provide K_o stress conditions as lateral deformation is restricted. Even though direct simple shear tests are very popular, they do not provide the ability to directly measure the lateral stress on the specimen, nor the pore water pressure. On the other hand, in simple shear tests with confining pressure the specimens are imposed to a controlled lateral stress boundary condition. Moreover, the confining pressure allows the saturation of the specimen prior to shearing and the measurement of the pore water pressure at every stage of the test. This also allows the performance of liquefaction tests in soils.

Several simple shear systems have been developed during the last few years in the soil laboratory industry. The most well-known are the SGI apparatus (Kjellman, 1951), in which the specimen is constrained by rigid discs and the NGI type apparatus (Bjerrum and Landva, 1966), in which a reinforced membrane is used. At the University of Western Australian (UWA) type (Mao and Fahey, 2003), the soil specimen is protected by an unreinforced rubber membrane whilst cell pressure is applied.

This paper presents the specifications and capabilities of a Dynamic Simple Shear system with confining pressure that has been developed by VJTech Ltd. The system is combined with a powerful software tool that allows automation of the testing procedure and analysis of the raw data.

2 DYNAMIC SIMPLE SHEAR TESTS

2.1 Description of DSS-C tests

The use of confining pressure in DSS-C tests allows the measurement of pore water pressure and, thus, the effective horizontal stress. A 2D representation of a soil element subjected to a DSS-C test is shown in Figure 1. The sample has an initial diameter D and initial height h. During the saturation stage (Figure 1a), the horizontal and vertical total stresses are given by:

$$\sigma_h = \sigma_c \tag{1}$$

$$\sigma_v = \sigma_h + q \tag{2}$$

where σ_h and σ_v are the total horizontal and vertical stresses, respectively, σ_c is the confining pressure and q is the deviator stress. Pore water pressure is measured at the bottom of the specimen and it is assumed that it becomes uniform in the soil profile after some period of time. Pore water pressure (u) is given by:

$$u = u_{BP} + u_c \tag{3}$$

where u_{BP} is the Back Pressure (BP) applied to the specimen and u_c the excess pore water pressure.

Since the soil specimen is allowed to saturate, pore water pressure can be measured throughout the test procedure. Therefore, horizontal (σ_h') and vertical (σ_v') effective stresses are determined as:

$$\sigma_h' = \sigma_c - u \tag{4}$$

$$\sigma_v' = \sigma_c + q - u \tag{5}$$

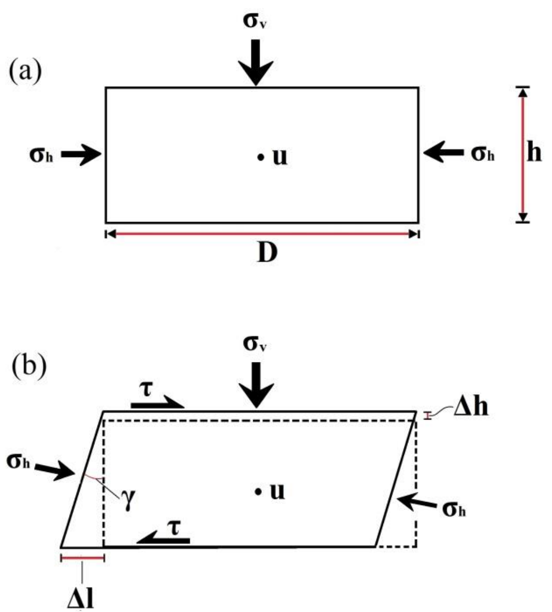

Figure 1. 2D representation of stresses and deformations acting on a cylindrical specimen subjected into Direct Simple Shear test (a) during saturation/consolidation and (b) during shearing.

2.1.1 Saturation

The saturation of the specimen is usually performed with the procedure followed in the standard triaxial tests. This involves the elevation of the back pressure to dissolve the pore air into pore water, whilst maintaining a constant effective stress. This can be done either by elevating the BP incrementally (step method) or by increasing it at a constant rate (ramp method). The level of saturation is determined by the b-value, which is calculated as:

$$b = \frac{du}{d\sigma_c} \tag{6}$$

where $d\sigma_c$ is the undrained increment of the cell pressure and *du* the correspondent increment in pore water pressure. For most soils, full saturation is achieved when the b-value gets higher than 0.95.

2.1.2 Consolidation

The saturation stage can be followed by an isotropic consolidation stage, in which the initial effective stresses are established. During anisotropic consolidation, the specimen is slowly brought under a specific stress ratio K, where K = σ_h/σ_v. Figure 2 presents the variation of the stress ratio during saturation (line AC) and isotropic consolidation (point C). Until the end of isotropic consolidation, K remains equal to 1 as any increment in total stresses comes only from the variation of the confining pressure σ_c. During anisotropic consolidation, the sample is brought under a stress state where K≠1, with higher vertical (K<1) or horizontal (K>1) stress.

Moreover, K_o consolidation (i.e. without lateral deformation) can be performed with the use of an automated control loop by the software. Since the specimen is fully saturated prior to K_o consolidation, any change in the sample volume will be measured by the amount of water that drains out of the soil. The effective horizontal stress is then ramped up to the desired value. The control loop applies changes in the vertical stress (or sample height) in order to eliminate induced radial strains during the consolidation process.

2.1.3 Monotonic shearing

Monotonic (non-cyclic) shearing can be conducted under drained or undrained conditions. In undrained shearing, sample volume changes are not allowed, thus sample volume *V* will be:

$$V = \frac{\pi D_c^2}{4} \times h_c \tag{7}$$

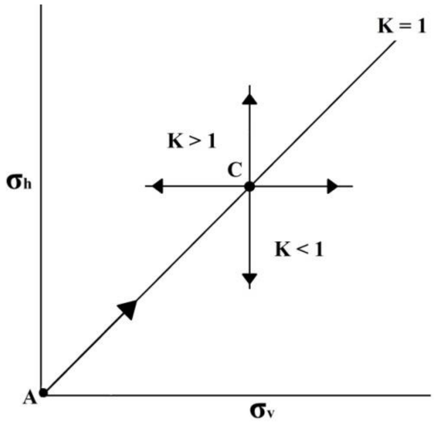

Figure 2. Variation of stress ratio K during saturation and consolidation. Point A corresponds to the state at the start of saturation while point C to the state at the start and end of consolidation.

where D_c the diameter and h_c the height of the specimen at the end of the consolidation stage. The sample is loaded horizontally at a constant rate of displacement or stress. Time-dependent deformation can be determined under constant effective shear stress loading for a prolonged period of time. This procedure can be used to perform creep tests under undrained conditions and determine the creep behaviour of the soil. The shear strain (γ) is determined as:

$$\gamma = \Delta l/(h_c + \Delta h) \tag{8}$$

where Δl is the horizontal displacement and Δh the change in the sample height due to shearing. Δh is positive at soil expansion and negative at soil contraction.

During undrained shear loading, total vertical stress is maintained constant by adjusting the confining pressure. At the same time, the height of the sample is maintained constant using the vertical actuator. On the other hand, during drained loading, total vertical stress is maintained constant by altering the vertical load, whilst the confining pressure remains unchanged.

2.1.4 Cyclic shearing

Standard waveforms can be selected by the user for the application of the cyclic loading (e.g. sinusoidal, triangular, rectangular). These waveforms can be used to apply the horizontal loading either in terms of shear stress or horizontal displacement. Moreover, user-defined waveforms can be used to simulate actual ground movements during an earthquake or explosion. Cyclic loading can be either drained or undrained. Total vertical stress is kept constant during the test, by adjusting the confining pressure (in undrained tests), or the vertical load (in drained tests). After the cyclic loading, the specimen can be tested under monotonic shear to determine the implications to its shear strength.

Moreover, the measurement of pore water pressure allows performance of liquefaction tests in a DSS-C apparatus. The specimen is subjected to undrained cyclic loading and the excess pore water pressure is determined. Pore Pressure Ratio (PPR) is defined as:

$$PPR = \Delta u_{cc}/\sigma_v \tag{9}$$

where Δu_{cc} the excess pore water pressure built up during the cyclic loading and σ_v the total vertical stress. According to Seed (1979), the development of strain is significant when the PPR exceeds 0.6. In contractive sands however, large strain might develop even at lower PPR.

3 DSS-C APPARATUS

The DSS-C apparatus has been designed and implemented by VJTech Ltd. The system consists of two separate units: the main DSS-C unit which includes all the mechanical parts of the apparatus and the Dynamic Servo Controller (DSC) unit (Figure 3). A Hydraulic dual channel Automatic Pressure Controller (APCH) is used to apply and control the cell and back pressures. The DSC unit is connected to a PC through USB or Ethernet connection, which allows the control of the apparatus and the automation of the test through sophisticated software. The specifications of the system can be seen in Table 1. A more detailed description of the system follows.

Figure 3. DSS-C system

Table 1. Specifications of the DSS-C system with electromechanical actuators

Feature	Maximum value
Frequency	5 Hz
Load	5 kN
Confining pressure	2000 kPa
Back pressure	2000 kPa
Horizontal travel	± 25 mm
Vertical travel	± 15 mm

3.1 DSS-C Unit

The DSS-C unit (Figure 4a) consists of the confining cell which accommodates the soil specimen, one vertical and one horizontal actuator, and the transducers for measuring axial and shear strain (displacement transducers) as well as axial and shear stress (load cells).

The confining cell has the ability to withstand cell pressures up to 2000 kPa. The cell wall consists of a 20 mm thick acrylic cylinder which is practically non-deformable at the range of pressures that are usually applied during tests. Two zero volume change on/off valves are located at the base of the cell through which cell and back pressures can be applied using the pressure controllers. Another valve at the base of the cell is connected to the PWP port through which the pore water pressure can be measured. Finally, the confining pressure is determined more accurately by measuring it with an external pressure transducer through a fourth valve on the cell. The external transducer acts as a feedback to the pressure controller allowing for very fast compensation of the cell pressure when this is affected by the movement of the horizontal load ram. Moreover, with the external pressure transducer, the expansion of the water pipes does not affect the measurement of the cell pressure. Cell pressure compensation is furthermore assisted by a balance ram which is part of the horizontal loading ram. The balance ram will pump water in or out of the cell, depending on the direction of the ram movement, helping to eliminate the pressure change caused by that movement.

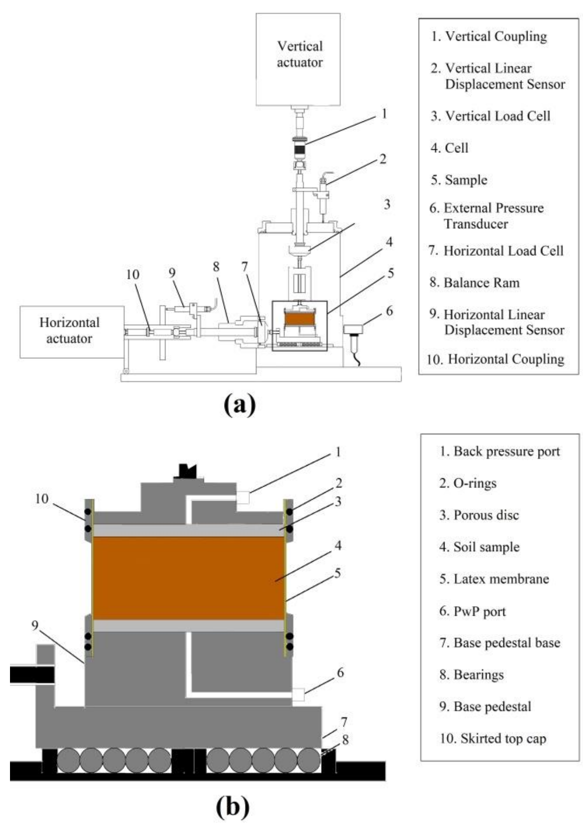

Figure 4. (a) Plain view of the DSS-C unit and (b) base pedestal.

The base pedestal (Figure 4b) can accommodate samples of 26/70 or 38/100 mm (height/diameter) in size. The resultant ratio h/d is 0.37 and 0.38, respectively, and is close to the upper bound of 0.32 used by Vucetic & Lacasse (1982) and close to the mean ratio of 0.4 used by Carraro (2017) with the UWA type. The base pedestal comprises a coarse porous stone onto which the soil specimen is placed. The porous stone is saturated prior to the start of the test by soaking it in de-aired water for 24 hours. The top cap also comprises a porous stone which allows water from the back pressure line to pass within the sample during saturation. Moreover, through the same port, the specimen is drained during consolidation. Both base pedestal and top cap have a 2 mm long perimeter skirt to prevent the specimen slipping across the interface. The pedestal sits on bearings which allow free movement across the horizontal load axis.

The top cap is fixed to the vertical actuator before a test starts using the vertical bearing assembly. A spindle is fixed onto the top cap on one side, and the load cell to the other. The mechanism of the vertical bearing assembly allows movement of the top cap along the vertical axis but restrains any lateral movements. In this way, σ_1 is always acting vertically and does not rotate during shearing. During saturation and isotropic consolidation, the vertical actuator controls the vertical load which is applied to the sample. By ensuring that this stays constant during this procedure, the confining pressure is applied equally to the sample ensuring isotropic loading conditions.

Cell and back pressures are controlled through a dual channel hydraulic pressure controller with a maximum capacity of 3500 kPa. An integrated 24 bit analogue-to-digital converter offers the ability of high resolution (0.1 kPa). The controller is able to process up to 4000 samples per second and therefore has the ability to compensate quickly to any changes caused to the confining pressure due to the ram movement.

Two submersible internal load cells are used to provide accurate determination of the vertical and horizontal loads. The advantage of this load cell type is that the measurements are not affected by cell pressure variations and friction of the loading ram. Horizontal and vertical displacement can be measured using high accuracy linear displacement transducers (resolution of 1μm). Alternatively, displacement can be determined indirectly with the use of the electromechanical encoder by interpreting the motor's pulses into actual displacement of the ram.

3.2 DSC unit

The Dynamic Servo Controller (DSC) unit is used to control the electromechanical actuators. It consists of two individual single-axis units which are combined to provide the control to both axes, vertical and horizontal. The two single-axis units are synchronised to ensure consistent data logging during all stages of the test. Each single-axis unit has a built-in encoder and up to 7 analogue input channels. They have high speed data acquisition which enables of logging of up to 500 samples per second. The DSCs are controlled from a PC via Ethernet over local area network, or using a USB connection.

The two electro-mechanical dynamic actuators are able to provide a maximum load of 5 kN and cyclic control up to a maximum of 5 Hz. They both include a physical magnetic limit switch which disables their operation when the travel of the motor reaches the maximum. The maximum travel for the vertical actuator is ± 15 mm and for the horizontal actuator is ± 25 mm. The DSC also benefits from a protection system for the transducers which eliminates the possibility of damage.

3.3 Clisp Studio

Operation of the DSS-C system is performed using the software package Clisp Studio. The software provides the necessary interface to store, analyse and visualise raw data, control the DSC unit and the pressure controllers and automate saturation and consolidation procedures. Clisp Studio provides the ability to perform monotonic and cyclic shear tests offering a range of options to tailor the testing procedure. Moreover, a specially designed liquefaction stage has been implemented into the software.

A simple shear test using VJTech DSS-C setup can include the following stages and individual runs (schedules). However, the test can be tailored by the user to meet the specific requirements of the test.

3.3.1 Saturation

The sample can be saturated by elevating the back pressure, either in steps or gradually (ramping method). Using an automatic solenoid valve, connected to the back pressure line, the procedure can be automated until the saturation is achieved.

3.3.2 Consolidation

Isotropic consolidation can be followed by a number of anisotropic runs during which the specimen is subjected into different stress states. The user has also the option to perform K_o consolidation with the diameter of the specimen kept constant whilst total vertical stress is changing. The selection of the appropriate consolidation schedules allows for the representation of the full stress history of the soil specimen before it is subjected to shear stress loading.

3.3.3 Static loading

Several static shear loading schedules can be created, controlling either the horizontal displacement or shear stress under drained or undrained conditions.

3.3.4 Cyclic loading

This stage consists of a drained pre-shearing schedule, where the sample can be brought to a specific stress state or subjected to an initial cyclic loading. This can be followed by a number of undrained cyclic loading schedules, where cyclic loading is applied to the specimen, either in terms of shear stress or horizontal displacement. A monotonic shearing schedule can then follow to determine the shear strength characteristics of the sample and the implications of the cyclic loading.

3.3.5 Liquefaction

This stage consists of an undrained cyclic loading schedule where either the shear stress or horizontal displacement are controlled. This schedule can be set to pause when the PPR reaches a user defined value. A pore pressure dissipation schedule can be followed to determine the volumetric strain of the specimen after the cyclic loading. Then, the effective vertical and horizontal stress at the end of the cyclic loading can be recovered. Finally, a monotonic shear schedule can be performed to determine the shear strength of the specimen after having been subjected to the liquefaction stage.

4 CONCLUSIONS

A new testing apparatus has been implemented by VJTech to perform simple shear tests in soils under confining pressure. In this type of test, a soil specimen is allowed to deform laterally without any constrains, as in normal simple shear devices. A full stress history can be applied to the specimen, prior to shearing, by applying various consolidation runs. The great advantage of the system is the measurement of the pore water pressure which is achievable due to the saturation of the sample using the same techniques as in standard triaxial tests. This allows the determination of the effective horizontal stress in the specimen. Several tests can be performed at a maximum load of 5 kN and maximum frequency of 5 Hz, including monotonic shearing, cyclic (drained or undrained) shearing and liquefaction.

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