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Development of an earthquake simulator for soft soils: Multidirectional Shear Testing Device

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Abstract. Testing soils for earthquake and dynamic loads requires advanced equipment able to assess the effects of hydromechanical coupling on the soil response. The majority of laboratory element tests are either “slow tests”, which intend to approach drained conditions throughout the soil sample in order to obtain reliable pore water pressure measurements, or “fast undrained tests”, where flow is prevented by closing the drainage lines. However, many natural loads, including earthquakes, impose a wide range of high loading frequencies, typically triggering a partially drained response in the field. Although the rate effect plays an important role in soil behaviour, its investigation is hindered by the limitations of existing equipment. In addition, the ability to apply multidirectional loading to soil elements in the laboratory is important to fully understand the soil response under earthquakes. Currently, multidirectional simple shear devices are used to study the soil behaviour under earthquake loadings. Nevertheless, many shear devices suffer from stresses and strains non-uniformities, which could potentially mislead data interpretation and constitutive models development. This paper presents an innovative multidirectional shear device developed in the section of Geoengineering at TU Delft, which can apply higher loading frequencies compared to previous equipment and a wider variety of multidirectional cyclic loading patterns. The apparatus is equipped with advanced sensors, also developed at TU Delft, to capture the local response of specimens. The sensors are installed to reduce a priori assumptions on the soil response, better interpret the element experimental results and further investigate the rate effect of applied loading. Preliminary performance test results are provided to illustrate the complex load conditions which can be achieved.

1. Introduction

In the Netherlands, induced seismic activity is recorded from the Groningen gas field, with the highest magnitude ever registered of M_L 3.6 at Huizinge. Although the magnitude of these induced earthquakes is relatively low compared to the one of natural earthquakes, they may cause damage to buildings and infrastructures due to their shallow depths and high site amplification in areas covered by soft soils [1]. To accurately assess the seismic risk posed by these repeated, low-magnitude events, which span a frequency range of 1 to 20 Hz, it is essential to improve our understanding of how soft soils respond to them. To the aim of comprehensive understanding, it is essential to consider the effect of multi-directional loading, as numerous studies have demonstrated that the response is influenced by multiple loading directions [2-6].

Direct simple shear (DSS) equipment is commonly used to study soil behaviour under cyclic and dynamic loading. A few multi-directional DSS systems have been developed to explore the soil behaviour under seismic loads. The initial results were not completely satisfactory due to various difficulties encountered in the development of the equipment. Jaime [7] highlighted overestimation of the shear strains in a two-directional cyclic simple shear because of mechanical compliances. Ishihara et al. [8] introduced a multi-directional simple shear apparatus with cell pressure and back pressure control, which allows direct pore pressure measurement. The authors encountered issues related to top cap rocking and significant mechanical friction. Boulanger et al. [9] designed and fabricated the UCB-2D apparatus, which significantly reduced the mechanical compliances. In addition, the machine adopted high-capacity pneumatic servo valves to provide quick response to control signals. Duku et al. [10] described a servo-hydraulic, digitally controlled multi-directional simple shear device, able to reproduce realistic earthquake histories with a strain-controlled procedure and were able to minimise the cross-coupling effect between the two horizontal loading axes. However, the installation of a dual axis load cell to obtain post-friction force measurement was found to increase the mechanical compliance. Rutherford et al. [11] developed a multi-directional simple shear system together with a multi-axis load cell. The system allows back pressure saturation and can apply complicated loading pattern such as circular or eight-shaped. Since then, several commercial multi-directional simple shear equipment have been made available [12, 13], however, typically limited to a range of frequencies with a maximum of 5 Hz. Shafiee et al. [14] improved the apparatus built by Duku et al. [10] so that the device can apply realistic earthquake loadings with stress controlled. Recently, Bhaumik et al. [15] presented a new multi-directional simple shear device based on the design of Rutherford et al. [11]. The major advantages over the previous systems are the capability of imposing real-time, not scaled-down, realistic earthquake loadings and the possibility of measuring shear wave velocity with bender elements.

The traditional limitations of simple shear devices are inherited by the previous multi-directional simple shear equipment [16-24]. The primary drawback of these shear devices is the inability to control the shear stress acting on the specimen lateral side, which prevents the achievement of a uniform stress state, despite the common assumption. Additionally, conventional setups cannot measure lateral stresses, leaving a gap in knowledge regarding the stress state and stress path of the sample.

Accurate measurement of pore water pressure is crucial in testing soils, due to the need of evaluating the influence of hydro-mechanical coupling on the response of the solid skeleton. With a traditional setup, pore water pressure in simple shear devices is obtained through either the change of vertical stress in constant height tests or by using a pressure transducer installed at the bottom of the sample. To ensure reliable measurement of pore water pressure, the tests must be performed slowly enough depending on the hydraulic conductivity and the size of the sample being tested [25]. However, recent studies have shown that equalisation of pore water pressure may be very difficult to achieve in soft soils, even under monotonic loading programme [26]. This is a significant concern, particularly given the high loading frequency of earthquakes, under which rate effects play an important role on the response of soft soils [27-29]. To fully understand the cyclic behaviour of organic soft soils, it is necessary to conduct not only "slow" tests, but also "fast" tests.

The limitations of existing multi-directional shear systems and the importance of understanding soft soils behaviour under cyclic/dynamic conditions, have led to the design and manufacturing of a new cutting-edge dynamic equipment to investigate the multidirectional hydro-mechanical coupled response of the soft organic clays and peats found in the Netherlands' deltaic regions. The new apparatus addresses the need for limited mechanical compliance, allows for higher loading frequencies, provides accurate measures of stress, strain, and pore water pressure, under both slow and fast loading rates.

This paper presents the innovative multidirectional shear testing device developed in the section of Geoengineering at TU Delft, which has following features:

(1) digitally controlled, servo-hydraulic actuators in the x, y, and z axis
(2) capability to reproduce real time history of earthquakes
(3) automatic control of cell and back pressure, enabling versatile stress paths
(4) in-house developed local response sensors providing comprehensive information on the hydro-mechanical coupled response

(5) P-wave and S-wave bender element measurement, to complement the information on the small-strain response.

2. Description of the earthquake simulator for soft soils

Pyke et al. [30] assessed the impact of bi-directional shaking on the settlement of dry sands. In the study, the authors used a small shaking table placed horizontally atop a larger one. This design remains a crucial reference point for apparatus involving multi-directional simple shear loading. The earthquake simulator for soft soils, named CYC-DoSS, developed at TU Delft adopts the same mechanical layout for its simplicity and effectiveness. The CYC-DoSS apparatus consists of five main subsystems, including: (1) loading and mechanical components; (2) cell pressure and back pressure controller; (3) control and data acquisition units; (4) bender elements unit; and (5) local response sensors. The primary loading and mechanical components of CYC-DoSS device are illustrated in Figure 1.

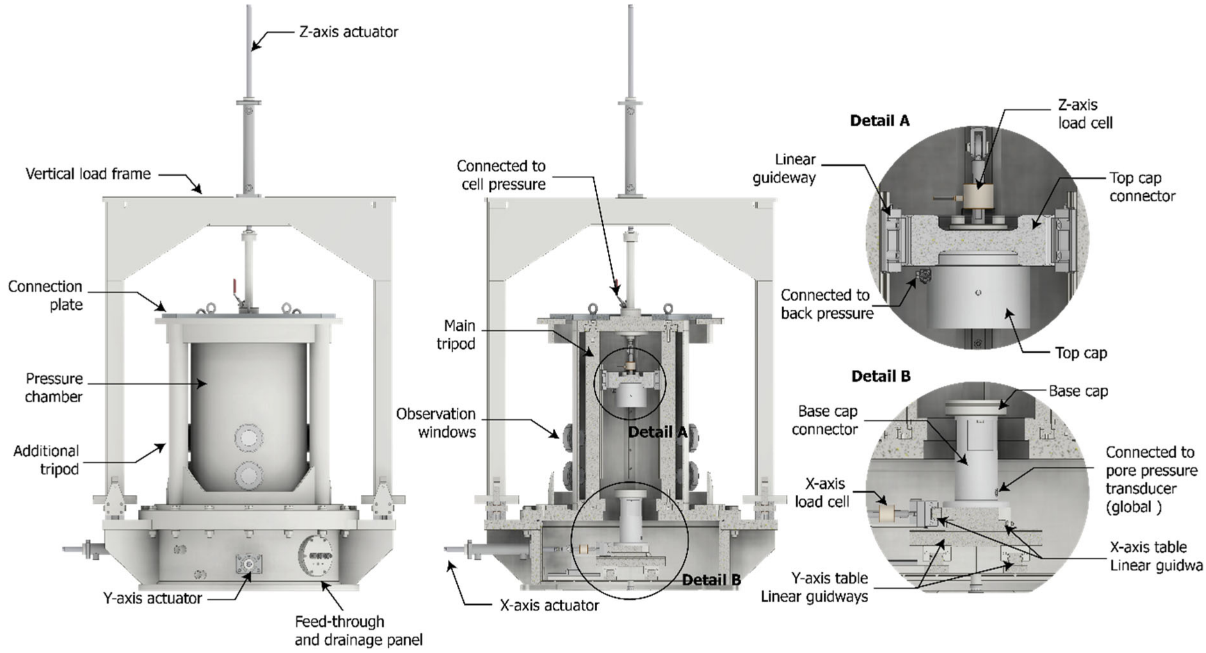


Figure 1. Illustration of the loading and mechanical components of CYC-DoSS.

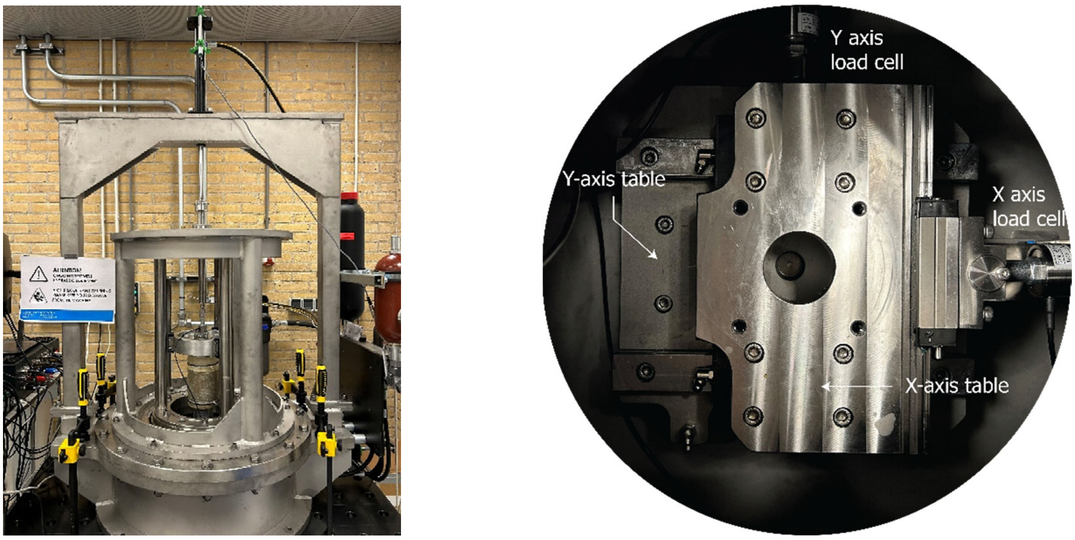
2.1. Loading and mechanical system

The loading and mechanical system consists of two primary components: the vertical load frame and the horizontal shaking platform. A Z-axis actuator with a cross-sectional area of 290 mm² is mounted on top of the load frame and can apply a vertical force of up to 10 kN to the soil sample through a top cap connector (refer to Detail A in Figure 1). This top cap connector assembly is linked to low-friction linear guideways situated on the main tripod (also see Detail A in Figure 1). The main tripod is interconnected with an additional tripod via a top connection plate, a design that enhances rotational stiffness and reduces the likelihood of lateral movement and top cap rocking.

The actuator possesses a total stroke of 200 mm (±100 mm), allowing for the accommodation of a sample up to 250 mm in height, making the device suitable for use as a cyclic triaxial device. Driven by a hydraulic servo valve (HSV-1) with a 40 L/min flow rate, the limiting factors of the actuators at high loading frequencies (>15 Hz) are the hydraulic pump pressure capacity and the mass of the moving assembly [10]. Consequently, the top cap assembly is composed of aluminium to reduce the mass. In addition, a miniature submersible load cell with a capacity of ±5 kN is employed for the Z-axis load cell. This load cell, weighing approximately 0.07 kg, is significantly lighter than traditional submersible load cells (~1 kg). The load cell accuracy is ±0.5% of full scale, equivalent to ±3.18 kPa for a 100 mm diameter sample. Compared to the values reported by other researchers [9,15], this error margin is larger.

To improve the accuracy, a load cell with a lower capacity can be employed. The Z-axis displacement is measured by a potentiometer with a 200mm range and an accuracy of 0.05%.

The horizontal forces are applied with two hydraulic actuators, which are perpendicular to each other. They have the same cross section area and maximum capacity as the Z-axis one. The actuators with a stroke of 100 mm (±50 mm) are controlled by two independent hydraulic servo valves with 40 L/min flow rate (HSV-2 and HSV-3). The Y-axis actuator is connected to the lower table lying on low-friction guideways, which can only move in Y direction. On top of the Y-axis table, the X-axis table is mounted on another set of low-friction guideways as shown in Figure 2. Two independent servo valves allow moving the shaking platform to any position on the horizontal plane. The shaking platform is connected to the base cap. The specification of the two horizontal load cells is same as the vertical one. The X and Y axis displacements are measured by a potentiometer with a 100mm range and an accuracy of 0.07%.



(a) (b)

Figure 2. Photo of (a)CYC-DoSS device (b)shaking platfrom of CYC-DoSS device.

The friction forces of the guideways in the X, Y and Z axis, without sample mounted, are around 9N, 12N and 7N, equivalent to 1.15kP, 1.53kPa, and 0.89kPa on a 100 mm diameter sample. The friction calibration allows correcting the reading of the load cells when testing at low stress level. As an alternative, a multi-axis load cell mounted above the sample could have been adopted to obtain post-friction loads [10, 11, 15]. Nevertheless, calibration of the friction load was preferred to the latter solution because of the increase of the mechanical compliance observed with multi-axis load cell [10].

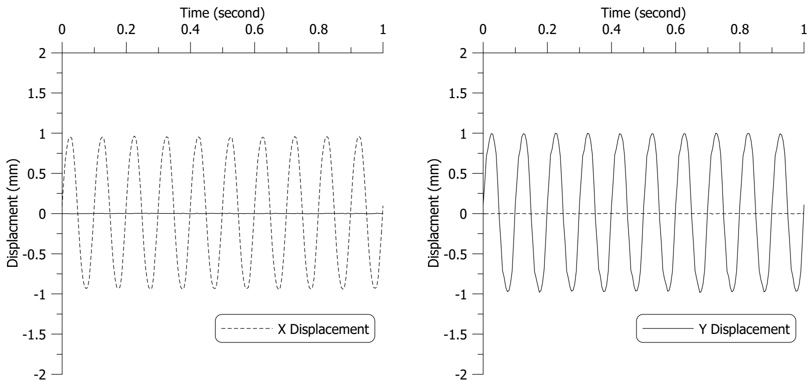
The cross-coupling effect in multi-directional shear devices refers to the impact of movement along one axis on the movement occurring along another axis [10]. To assess the cross-coupling effect in CYC-DoSS, two distinct harmonic sine waves with varying loading frequencies and amplitudes were initially applied, firstly on the X-axis table (Y-axis table holding) and then on the Y-axis table (X-axis table holding). The first harmonic wave features a 5mm amplitude at 0.5 Hz frequency, while the second harmonic wave has a 1mm amplitude at 10 Hz frequency. The recorded result shows there is almost zero displacement measured on the holding axis, which indicates that CYC-DoSS has no observable cross-coupling effect. The X and Y displacement recorded during the motion of the other axis are presented in Figure 3 as an example.

2.2. Cell pressure and back pressure controller

The CYC-DoSS provides control over both cell and back pressures by means of a pressure chamber. The pressure chamber, constructed from stainless steel, has a maximum design pressure of 500 kPa. It is filled with water, and air pressure is applied on top of the cell using a pneumatic controller (GDSPPC)

Journal of Physics: Conference Series **2647** (2024) 142006 doi:10.1088/1742-6596/2647/14/142006

from GDS Instruments. The compressibility of the air helps in minimizing fluctuations in the cell pressure as the load rams move in and out during testing. A pressure transducer is connected to the chamber for measuring the cell pressure during testing. In traditional simple shear apparatus, an equivalent "constant volume" condition is adopted by constraining the lateral boundary using stacked rings or reinforced membranes and maintaining the sample height to reproduce undrained field conditions [31]. The equivalent pore pressure is derived from changes in applied total vertical stress. Dyvik et al. (1987) concluded that the equivalent "constant volume" produces results akin to truly undrained tests on normally consolidated Drammen clay. However, a recent study on sand suggests that the conventional approach for determining equivalent pore pressure in constant volume tests conflicts with the fact that pore pressure is isotropic [32]. As a result, to conduct genuinely undrained tests, the CYC-DoSS is equipped with an advanced pressure/volume controller (ADVDPC) from GDS Instruments, which offers back pressure and back volume control and measurement. The back pressure/volume controller has a maximum pressure and volume capacity of 1 MPa and 1000 cm^3, respectively. The accuracy of the controller is 0.1% for both pressure and volume. By using cell pressure and back pressure the CYC-DoSS allows versatile stress paths and back pressure saturation. Additionally, it makes it feasible to determine the lateral stress of a saturated sample with constant height and no drainage. Under such conditions a constant average area or zero lateral strain is expected. [9]. Consequently, there is no need for rigid lateral support for the sample to constrain lateral strain development, allowing the specimen to be simply enclosed in a normal latex membrane.



(a) (b)

Figure 3. X and Y displacement during the motion of (a)X axis (b)Y axis.

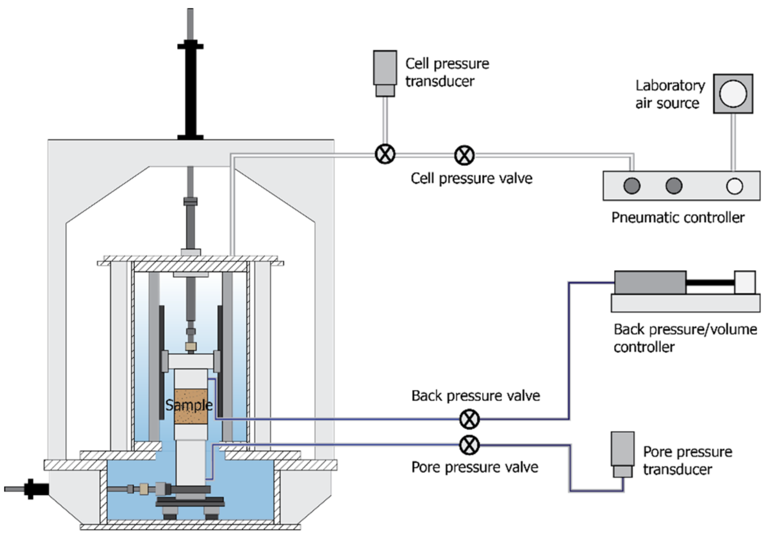


Figure 4. Illustration of the cell and back pressure systems.

2.3. Control and data acquisition system

Figure 5 illustrates the control and data acquisition system of the CYC-DoSS, with only one actuator shown for the sake of clarity. A conventional PC-based control system with a PID control algorithm running on a desktop can suffer from latency in processing feedback signals and generating command signals, which hinders the ability of the device to accurately replicate command signals for high loading frequency [10]. The CYC-DoSS uses a high-speed microcontroller board (Teensy 4.1) for its real-time control system. A PID control algorithm is implemented within the microcontroller. The theoretical maximum sampling rate of the internal feedback loop is up to 100 kHz. The control system offers four analog input channels for the feedback signal of the PID controller, including load and displacement. The built-in function generator of the microcontroller can provide four different functions: ramp, square, triangle, and sine. To simulate the real-time history of an earthquake, a software-based user-defined waveform function generator is also employed. Additionally, an automatic testing algorithm is developed to enable versatile stress path application based on cell pressure, back pressure, and back volume measurements. The USB-6343 data acquisition box from National Instruments connects to the microcontroller and other sensors for data recording during tests. This box features 32 analog input channels and a maximum sampling rate exceeding 15 kHz.

2.4. Bender elements

The small-strain shear modulus, G_{max}, provides valuable soil information relevant to numerous geotechnical engineering applications, particularly in simplified assessment of soil response under cyclic or dynamic loadings [33]. In the laboratory, G_{max} can be obtained from shear wave velocity measurements using bender elements. Moreover, shear wave velocity allows for a more direct comparison of laboratory and field soil states [15].

A bender element is a two-layer piezoelectric transducer made of two conductive outer electrodes, two piezoceramic sheets, and a conductive metal shim at the centre [34]. An excitation voltage produces a displacement in the source transducer, sending a wave through the sample. This wave generates a displacement in the receiver, inducing a voltage that can be measured. The bender elements installed in CYC-DoSS are combined P and S wave transducers manufactured by GDS Instruments, consisting of two element inserts. The S-wave transmitter/P wave receiver is installed in the top cap, while the P-wave transmitter/S-wave receiver is in the base cap.

The S wave transmitter includes two piezoceramic strips polarized in the same direction. When an excitation voltage is applied, one strip extends and the other contracts, causing the strips to bend. The two strips in the receiver are polarised by the wave motion in opposite directions, as illustrated in Figure 6. The P wave transmitter consists of two piezoceramic strips polarized in opposite directions. When an excitation voltage is applied, both strips extend or contract. The two strips in the receiver are polarised by the wave motion in same directions, as also depicted in Figure 6.

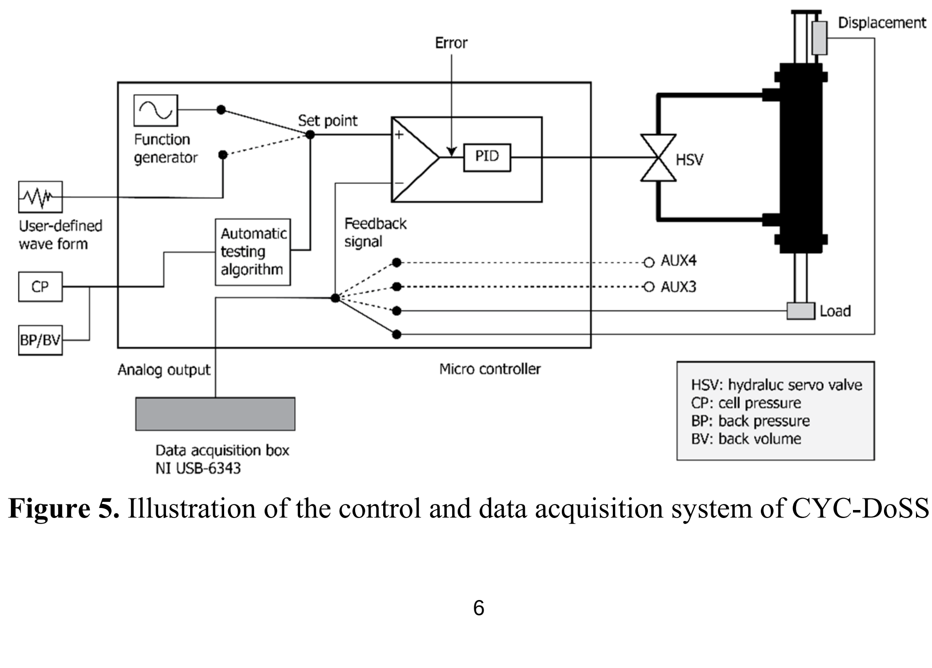


Figure 5. Illustration of the control and data acquisition system of CYC-DoSS.

Journal of Physics: Conference Series **2647** (2024) 142006 doi:10.1088/1742-6596/2647/14/142006

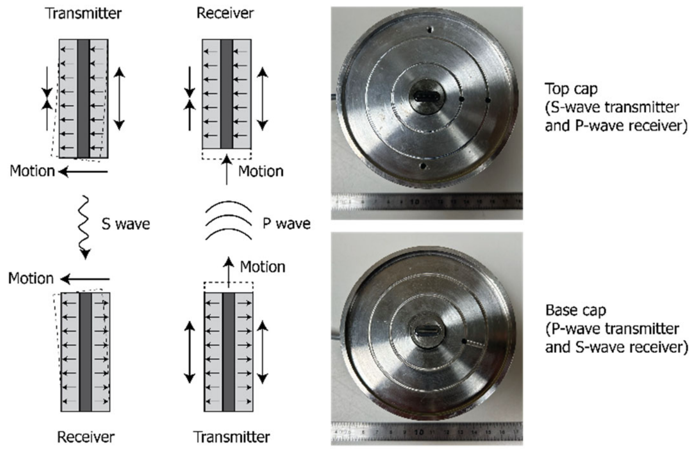


Figure 6. Working principle of bender elements (after GDS Bender Elements Hardware Handbook) and top/base cap of CYC-DoSS with element inserts.

2.5. Local response sensors

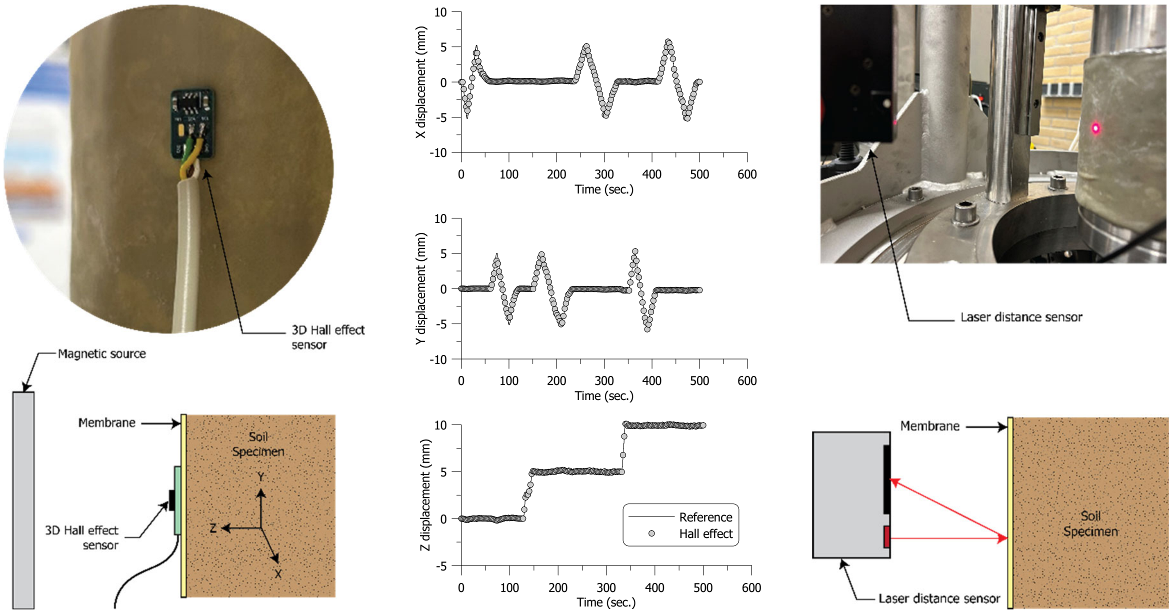
Studies on monotonic soil behaviour have shown that stresses, strain, and pore pressure are seldom uniform within the specimen during element testing, particularly in soft soils [26, 35]. Non-uniformities can become more significant during multi-directional loading, and pore pressure equalisation within the specimen may not be achieved at high loading frequencies. To improve the understanding of element experimental results and further explore the hydro-mechanical coupling response under multi-directional cyclic loading, advanced sensors have been developed at TU Delft.

Local displacement and pore pressure sensors have been employed in triaxial shear apparatus to enhance the interpretation of laboratory experimental observations [36-38]. In simple shear devices, the limitation of unknown horizontal stresses can be partially addressed using special wire-reinforced membranes or null pressure sensors [32, 39]. To the authors' knowledge, local response sensors have not yet been implemented in multi-directional cyclic shear devices, with a key challenge being the presence of stacked rings or wire-reinforced membranes.

The CYC-DoSS device offers fully controlled cell pressure and back pressure/volume, along with an automatic testing algorithm, allowing the maintenance of K_0 conditions during both consolidation and undrained cyclic shear stages. As a result, tests can be conducted without stacked rings or wire-reinforced membranes, enabling the installation of local response sensors. Nevertheless, it should be noted that the K_0 condition in CYC-DoSS is achieved under zero “average” lateral strain.

An advanced displacement sensing unit has been developed to track and record the lateral strain of specimens during testing. The unit consists of a laser distance sensor and a 3D Hall effect sensor. The 3D Hall effect sensor used is the TMAG 5273 from Texas Instruments, which has flux density that varies with the distance between the sensor and the magnetic source. The X, Y, and Z positions can be determined analytically using the measured flux density. Preliminary proof of concept test results, presented in Figure 7 (a), show that the sensor can accurately capture movement in X, Y, and Z directions with a maximum error of 1mm. It should be noted that these accuracies are strictly based on analytical equations, and a dedicated calibration procedure could further improve the accuracy.

Laser distance sensors are also employed in the CYC-DoSS device (as seen in Figure 7 (b)) to measure the lateral deformation. These sensors offer advantages over Hall effect sensors, such as higher sampling rate and accuracy, but they cannot provide 3D position information. Incorporating both types of sensors in CYC-DoSS ensures more reliable lateral strain measurements.



(a) (b) (c)

Figure 7. (a) 3D hall effect sensor (b) 3D hall effect sensor test results (c) laser distance sensor.

Local measurement of pore pressure is crucial understand the soil response under multi-directional cyclic loading. By obtaining pore pressure information not only at the boundaries but also within the sample, experimental results can be interpreted more effectively using numerical back-analysis. Consequently, achieving pore pressure equalisation throughout the entire sample may not be necessary, as the detailed pore pressure data allows for a more comprehensive analysis of soil behaviour. The CYC-DoSS system incorporates the FOP-M fibre optic pressure sensor from FISO for local pore pressure sensing. Utilizing White-Light Fabry-Pérot Interferometry technology, the sensor measures the pressure based on the deflection of a silicon diaphragm. The adopted model can provide 1% accuracy under several adverse conditions like temperature fluctuations, electromagnetic interference, humidity, and vibration. The sensor is attached to the specimen using a silicone rubber connector, as illustrated in Figure 8. Additionally, Figure 8 presents the results of a calibration ramp performed up to 600 kPa, demonstrating the sensor's performance and capabilities.

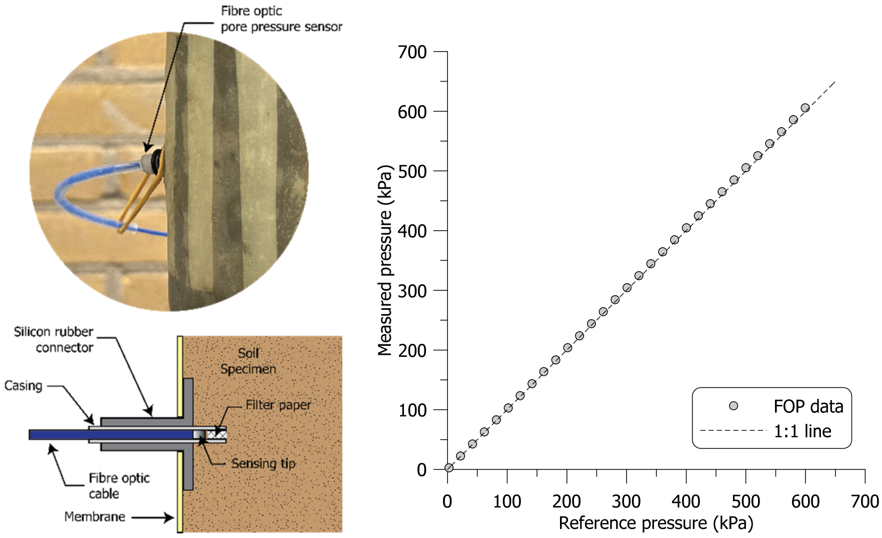


Figure 8. Fibre optic pressure sensor and results of a calibration ramp.

In addition to local displacement and pore pressure sensors, MEMS accelerometers are also installed in the CYC-DoSS system to measure acceleration during multi-directional cyclic tests. The inclusion of accelerometers enables the possibility of conducting acceleration-controlled tests, which is the most ideal method for replicating real loading conditions experienced during earthquakes.

3. Preliminary trial test results

The capabilities of the CYC-DoSS device are demonstrated preliminarily using a soft organic soil sample, mounted without cell and back pressure, and tested under various loading conditions. It is important to note that the hydraulic pump is set up at half of full pressure, and the PID parameters are tuned for 1 Hz loading.

Figure 9 (a) and (b) display a circular loading pattern with 2 mm amplitude and 1 Hz frequency on the horizontal plane (X and Y axes), showing reasonable actuator control. Figure 9 (c) and (d) depict a butterfly-shaped loading pattern with 2 mm amplitude, also yielding reasonable results. An 8-shaped loading pattern is achieved by switching the loading frequency in the X and Y axes, as shown in Figure 9 (e).

To assess higher loading frequency performance, a 25 Hz loading with 0.7 mm amplitude is applied to the X-axis actuator, as seen in Figure 9 (f). The results are less satisfactory compared to those at lower frequencies. However, considering the hydraulic pressure is at half capacity and the PID parameters are not tuned for high loading frequencies, it is expected that the performance will improve with full pressure and optimal tuning of PID parameters.

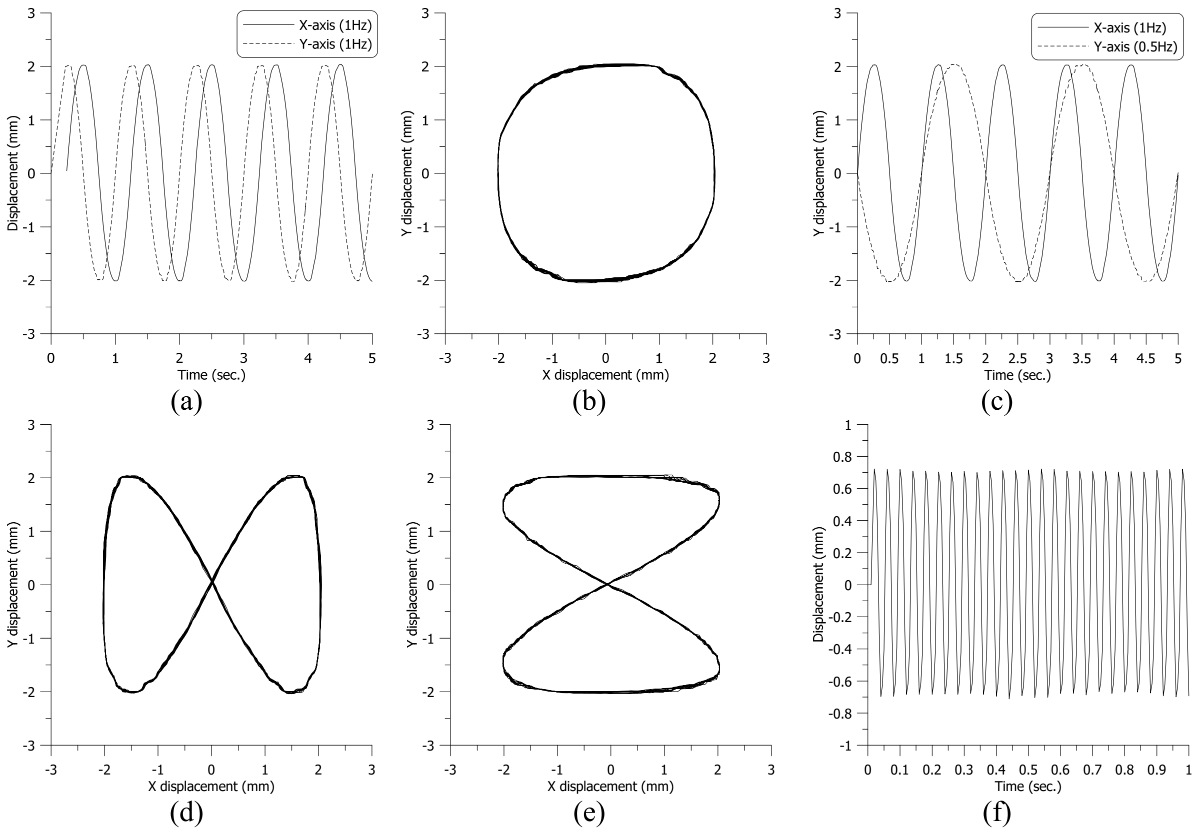


Figure 9. (a) Displacements time history of circular loading pattern; (b) X versus Y displacement of circular loading pattern; (c) Displacements time history of butterfly-shaped loading pattern; (d) X versus Y displacement of butterfly-shaped loading pattern (e) X versus Y displacement of 8-shaped loading pattern; (f) Displacements time history of a 25 Hz loading.

Journal of Physics: Conference Series **2647** (2024) 142006 doi:10.1088/1742-6596/2647/14/142006

4. Summary and conclusions

The work presents the conceptual design and the electro-mechanical development of a cutting-edge earthquake simulator for soft soils, named CYC-DoSS device. The design of the apparatus augments rotational stiffness while simultaneously minimising lateral movement and top cap rocking, achieved through the implementation of a robust double-tripod system. The device is equipped with digitally controlled, servo-hydraulic actuators in the x, y, and z axes to be capable of replicating real-time histories of earthquakes. The CYC-DoSS device overcomes certain limitations inherent in traditional simple shear apparatus, such as unreliable pore pressure measurement and indeterminate lateral stresses, thanks to an automatically controlled cell and back pressure system.

The novel concept relies on the incorporation of in-house developed local response sensors, able to collect comprehensive data on the coupled hydro-mechanical response of the soil sample. This includes information such as deformation, pore pressure and acceleration, an insight which was unavailable in earlier devices. To further enrich the data collected on the small-strain response and to bridge the gap between laboratory and field observations, P-wave and S-wave bender element measurements were incorporated into the CYC-DoSS device.

The device can achieve 0.7 mm amplitude at 25 Hz loading frequency, showcasing advanced functionality of the CYC-DoSS for comprehensive soil testing and analysis under cyclic/dynamic loadings. The capabilities of the device are demonstrated through trial tests performed following cyclic circular, butterfly-shape and 8-shape loading patterns.

Acknowledgments

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