NEW PRODUCT DEVELOPMENT:

A MULTI-DIRECTIONAL DYNAMIC CYCLIC DIRECT SIMPLE SHEAR APPARATUS

Writing for **theGeotechnica** *this month are the* GDS Instruments' *Technical Team. This month GDS turn their focus to their newly developed product, a multi-directional dynamic cyclic direct simple shear apparatus.*

What is a multi-directional laboratory test apparatus?

A significant majority of test apparatuses traditionally used in soil laboratories shear soil elements in a single direction only. Examples include the direct shear apparatus, in which a test specimen is sheared in a single horizontal direction following application of normal stress, and the triaxial apparatus, in which soil elements are compressed or extended vertically following completion of saturation and consolidation. Such apparatuses may be termed uni-directional, as the direction of shearing is fixed to one specific axis.

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It is however possible to design and build more advanced apparatuses in which soil elements can be sheared in more than one direction – such apparatuses may therefore be termed multi-directional. To highlight this idea, Figure 1 displays a three-dimensional and plan view of a soil element subjected to vertical normal stress and shear stresses applied from two directions (τ_X and τ_Y). Here the application of τ_y perpendicular to τ_X leads to a resultant shear stress, τ_{XY}, acting in a direction different to the X and Y components. Further to this, changing the relative magnitudes of τ_X and τ_Y vary the direction in which τ_{XY} acts, enabling shear in any horizontal direction to be specified and applied.

What effect does multi-directional loading have on soil response?

Although many laboratory test apparatuses are uni-directional, loading conditions in the field are typically three-dimensional in nature. This includes cyclic stresses induced during earthquake shaking, and the cyclic loadings applied to offshore structures as the direction of wind and wave action varies. Recognising this difference between field loading and laboratory simplification, a number of studies reported in the geotechnical literature have investigated the effect uni-directional and multi-directional loadings have on soil strength and deformation. An early example regarding soil response during earthquakes include the shake table tests reported by Pyke et al. (1975), during which dry sand settlements were shown to increase significantly when multi-directional shaking was used in place of uni-directional shaking. More recently, work conducted at the Hamburg University of Technology (TUHH) by Dührkop and Grabe (2008) has shown that laterally-loaded mono-piles used to support offshore wind turbines accumulate larger displacements when the applied cyclic loadings are multi-directional.

With the difference in load directionality between the field and laboratory equipment recognised, a number of multi-directional laboratory apparatuses have been constructed by various institutions at points throughout the evolution of soil mechanics. These include the multi-directional direct simple shear apparatuses reported by Ishihara and Yamazaki (1980), Boulanger et al. (1993), and Rutherford and Biscontin (2013), which were produced to study topics ranging from sand response during multi-directional earthquake shaking, to rate and load direction effects on pore pressure generation in marine clays.

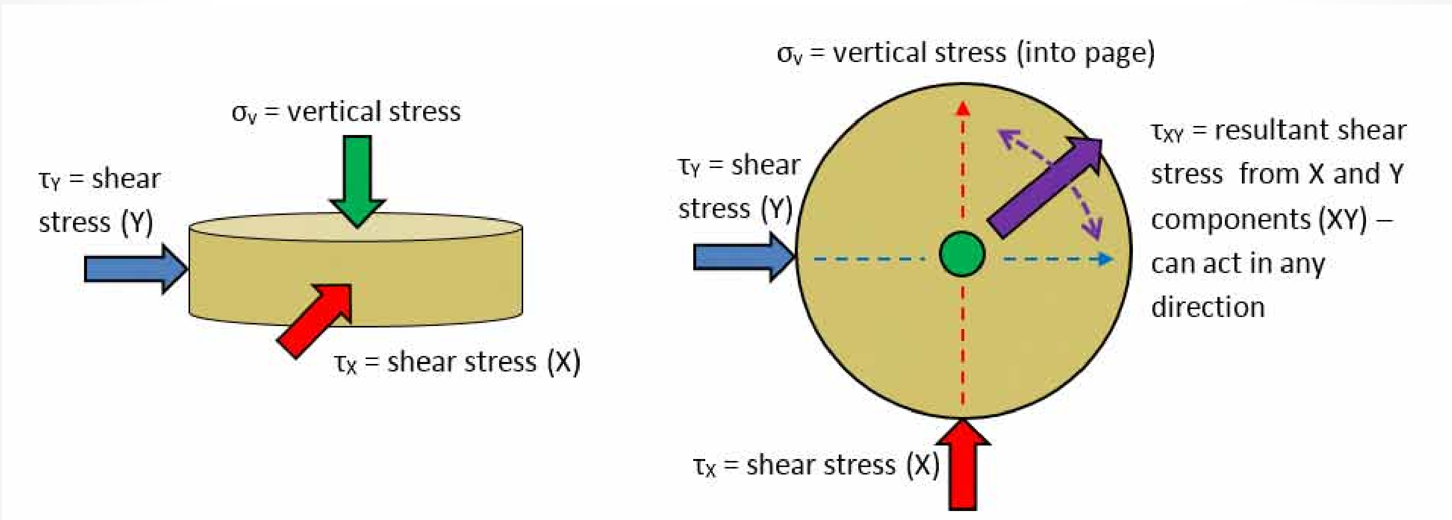

Figure 1 – 3D and plan view of a soil element, showing shear stresses τ_X and τ_Y applied along two axes (in red and blue). Note the direction of the resultant stress, τ_{XY}, can be varied by changing the relative magnitudes of τ_X and τ_Y.

The direct simple shear apparatus

First built by the Royal Swedish Geotechnical Institute in 1936 and reported by Kjellman (1951), the direct simple shear apparatus (DSS) is a relatively common sight in soil testing laboratories today.

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Its popularity stems from a number of practical advantages over traditionally-used devices such as the triaxial apparatus, including the ability to deform soil elements in plane strain and smoothly rotate the principal stress directions. Such loading conditions are often representative of those observed in the field, including where the soil adjacent to friction piles is deformed, or when approximating the stress state applied to soils underlying offshore structures. Direct simple shear has also been suggested to better represent the soil response to vertically-propagating shear waves generated by earthquakes when compared with the triaxial test. These advantages have therefore made DSS testing an important addition to laboratory investigations during many engineering projects.

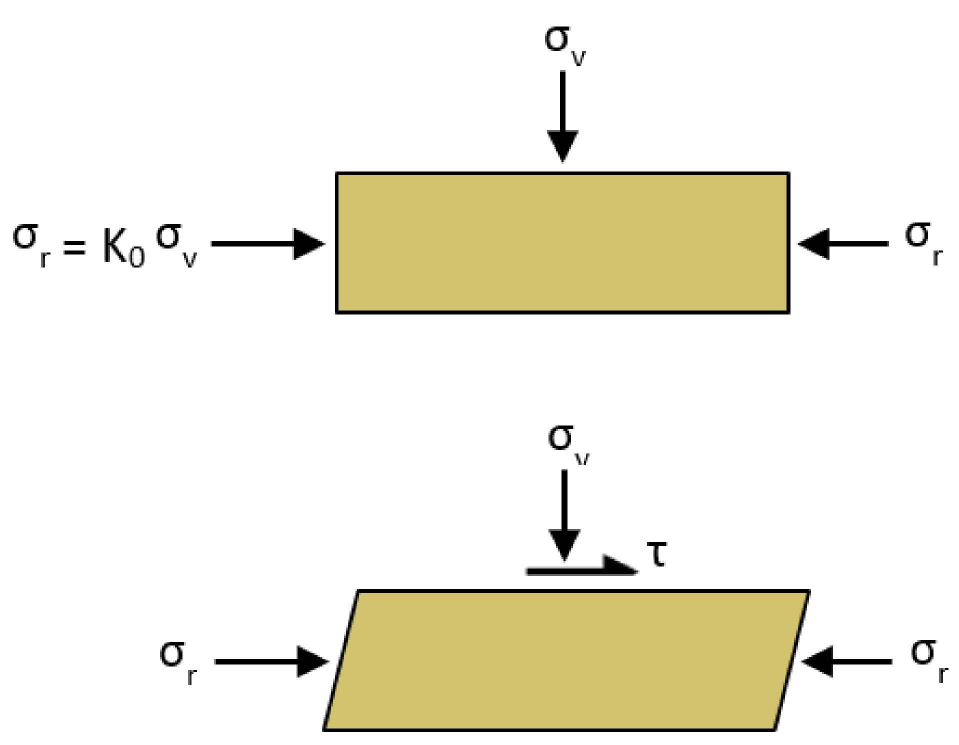

Figure 2 – Boundary stresses in the direct simple shear test during (a) consolidation (K_0 conditions), and (b) specimen shearing. Note a lack of a complementary shear stress during shearing, one of the DSS test's limitations.

Of course the DSS test does come with limitations, as do all laboratory tests. Here an inability to apply complementary shear stresses along the specimen sides (see Figure 2) results in non-uniform stresses being

Figure 3 – The variable direction dynamic cyclic simple shear apparatus (VDDCSS), designed and built by GDS Instruments in cooperation with TUHH.

developed during shear, while there is also potential (when using less-rigid test systems) for significant relative motion, or 'rocking', to occur between the top and base specimen

> **"However despite these known limitations, the DSS test has continued to be a useful laboratory tool..."**

platens. However despite these known limitations, the DSS test has continued to be a useful laboratory tool when investigating the response of cohesive and granular soils under static and dynamic loading conditions.

Given the usefulness of the DSS test, and the recognised effect multi-directional loads may have on soil response, GDS Instruments designed and built a new multi-directional direct simple shear apparatus in cooperation with TUHH. This was done as part of the continued TUHH work investigating the response of offshore mono-piles during multi-directional loading.

New product development: The GDS VDDCSS

The variable direction dynamic cyclic simple shear apparatus (VDDCSS), designed by GDS Instruments in cooperation with TUHH, and shown in Figure 3, is an SGI-style DSS device based around the GDS uni-directional dynamic cyclic simple shear

> **"Here the test specimen is laterally confined using a standard latex membrane..."**

system (EMDCSS). Here the test specimen is laterally confined using a standard latex membrane and stack of Teflon-coated rings, which enables K_0 conditions to be maintained during consolidation, and radial deformations prevented during specimen shearing. Note reinforced membranes may also be used within the apparatus.

With three electro-mechanical actuators used instead of the two required for uni-directional testing, the VDDCSS operates at frequencies up to 1 Hz via specifically-designed system firmware, applying shear stresses to specimens in any horizontal direction. In addition to its third axis positioned perpendicular to

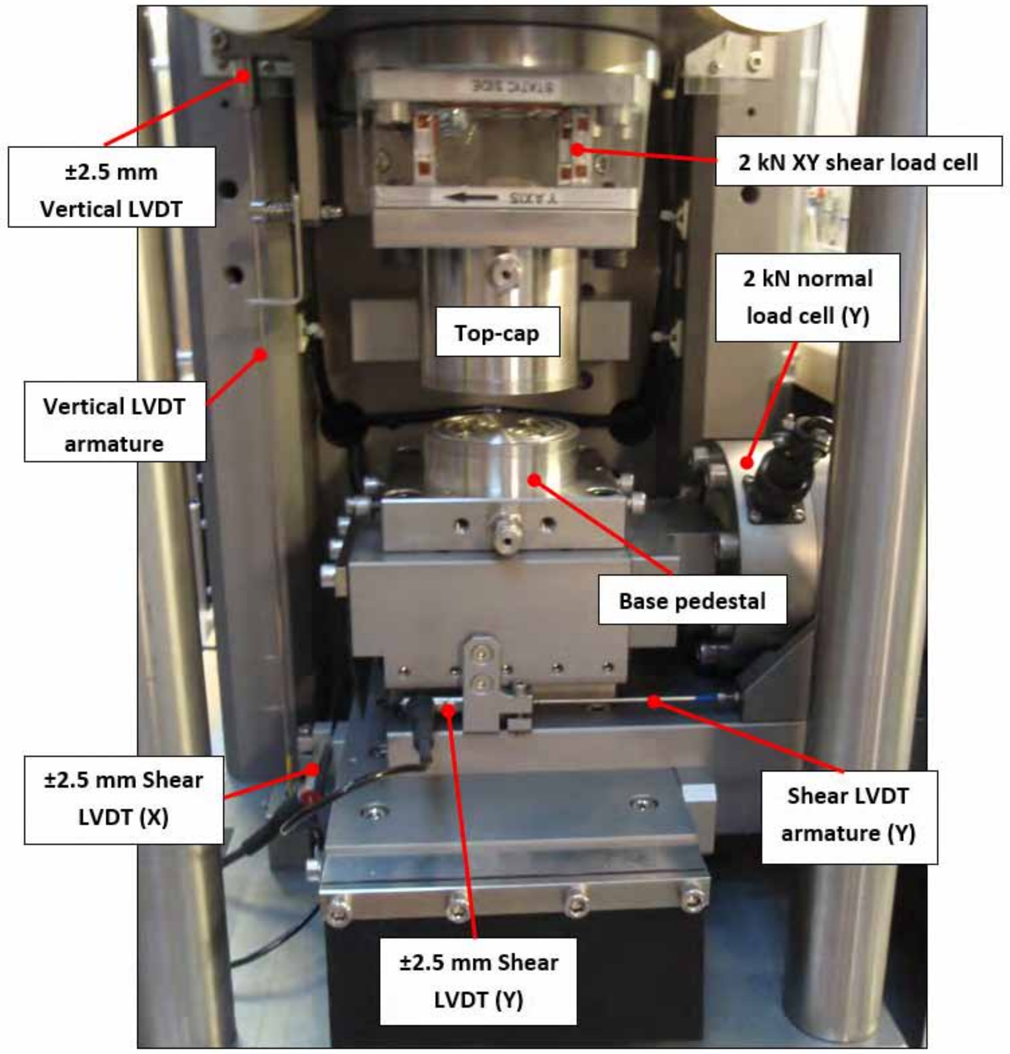

Figure 4 – VDDCSS platens and transducers (load and displacement). Note some system transducers are not shown in this photo.

the primary shear actuator, the VDDCSS uses the same rigid frame developed for the EMDCSS, reducing system compliance and relative motion between the specimen platens.

> **"The apparatus also contains four load cells for measuring normal and horizontal loads..."**

The apparatus also contains four load cells for measuring normal and horizontal loads, including one mounted directly above the top-cap to eliminate friction error when taking horizontal load readings. To measure displacements, three low-range LVDTs are positioned around the specimen platens, complementing the displacement readings obtained from the high-accuracy actuator encoders. Many of the apparatus transducers can be seen in Figure 4.

Combined with control and acquisition through their

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GDSLab software, the VDDCSS enables complex dynamic cyclic multi-directional tests to be performed with relative ease

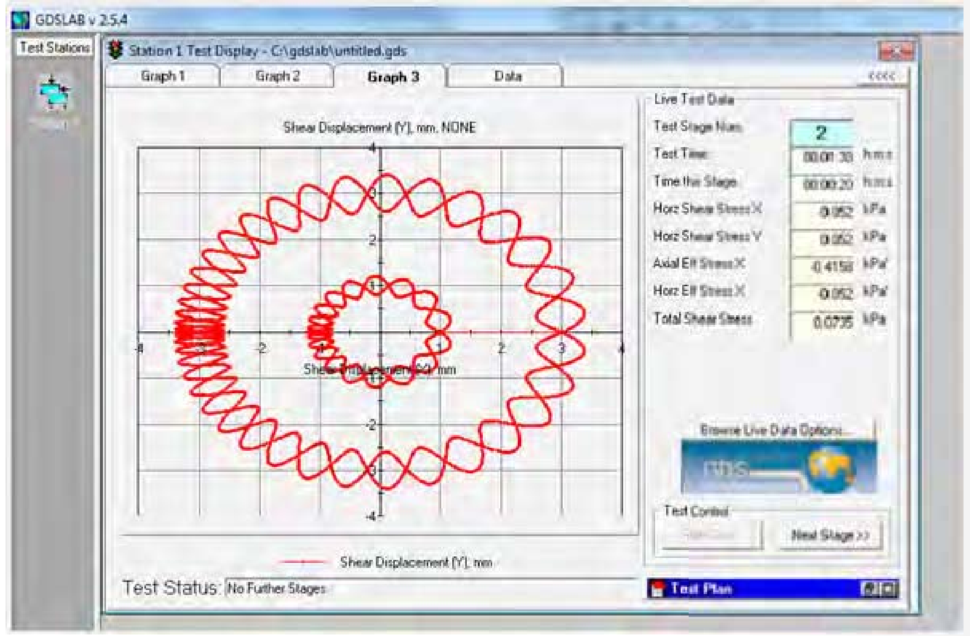


Figure 5 – Complex response of the VDDCSS displayed within the GDSLab software.

(complex apparatus response can be viewed in Figure 5), while outputting stress and strain calculations to file. Further information regarding the VDDCSS can be found at www.gdsinstruments.com/gds-products/variable-direction-dynamic-cyclic-simple-shear, which includes a video showing the apparatus in operation.

Using the VDDCSS to investigate offshore mono-pile response at TUHH

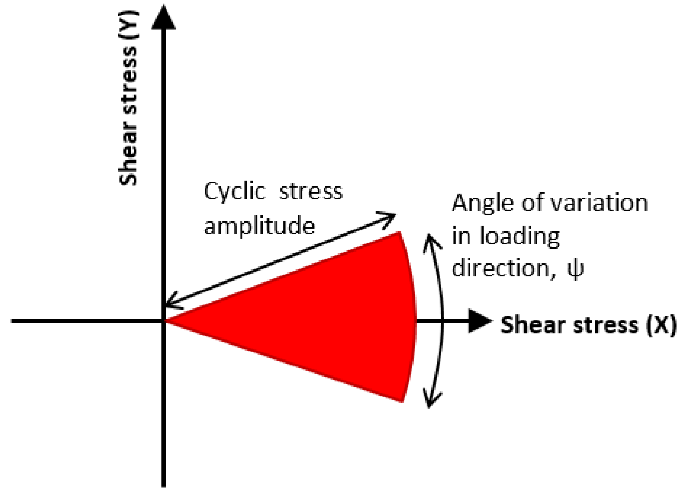
> **"The TUHH team firstly performed drained... monotonic shear tests on medium to dense sand specimens..."**

Initial testing performed at TUHH and reported by Rudolph et al. (2014) on a well-graded fine sand from the North Sea, conducted as part of their mono-pile response research, has helped to experimentally verify the VDDCSS. The TUHH team firstly performed drained (constant normal stress) monotonic shear tests on medium to dense sand specimens, checking the friction angles obtained in the VDDCSS with those previously derived from uni-directional DSS

> **"Here the TUHH team reported good agreement, with dense specimens sheared in the VDDCSS producing friction angles approximately equal to 29.5°..."**

testing. Here the TUHH team reported good agreement, with dense specimens sheared in the VDDCSS producing friction angles approximately equal to 29.5 °, compared with 30.3 ° obtained in the uni-directional DSS apparatus.

Focus then shifted to drained cyclic testing, during which a number of different loading schemes were used to model possible multi-directional loading of offshore mono-piles. This included one scheme as shown in Figure 6, for ▸▸



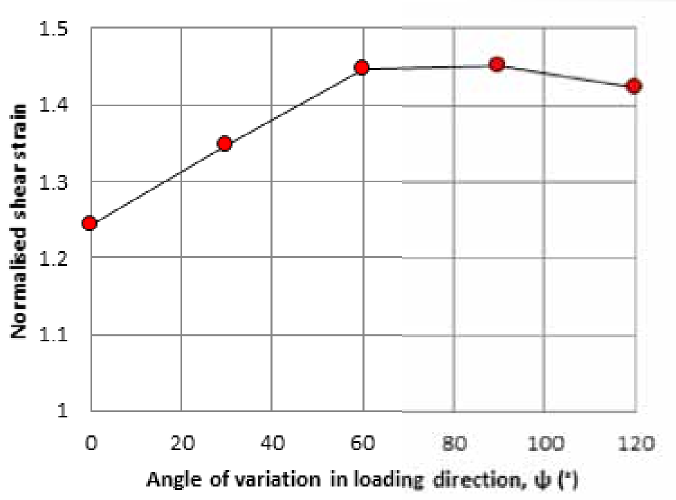


Figure 6 – One loading scheme used by Rudolph et al. (2014). Note the red sector gives the applied shear stress boundary for 1000 load cycles.

Figure 7 – Accumulation of shear strain as the variation in loading direction is increased, reproduced from Rudolph et al. (2014).

which a constant cyclic shear stress amplitude was applied, while the direction of stress was slowly varied over the course of 1000 load cycles (note this variation was controlled via a sinusoidal waveform).

"The angle of variation in loading direction, ψ, was then systematically increased throughout five tests…"

The angle of variation in loading direction, ψ, was then systematically increased throughout five tests, ranging from 0 ° (i.e., uni-directional shearing) to 120 °.

The response observed during these five tests highlighted an increase in accumulated shear strain, γ, as ψ was raised from 0 ° to 90 °. This trend is displayed in Figure 7, which has been reproduced from Rudolph et al. (2014). Here the shear strain after 30,000 load cycles, $\gamma_{30,000}$, is normalised by the shear strain recorded after completion of the first load cycle, γ_1.

In addition to shear strain, Rudolph et al. (2014) also reported an increase in volumetric strains for test specimens where the direction of loading was varied, mirroring the higher settlements observed by Pyke et al. (1975) during multi-directional shake table tests. Such agreement is encouraging to see, and with three other VDDCSS apparatuses currently installed in various laboratories around the world the GDS team look forward to reading further publications discussing the response of DSS specimens sheared in multiple directions.

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