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ABSTRACT

Using a frictionless triaxial apparatus, sand specimens can be tested at relatively high axial strains, even while liquefying. However, liquefying specimens have extremely nonlinear stiffness, thus standard PID control does not perform well. To maintain control over applied loads, the PID controller was modified to adapt to disturbed soil states.

The proposed methods expand the scope of testing towards options which are otherwise inaccessible by triaxial testing.

INTRODUCTION

A single diameter height specimen tested using frictionless triaxial apparatus is very durable. It can be compressed beyond yielding and pulled back to initial length – both drained and undrained. Such specimens yield isotopically, without forming a dominant shear rupture (in contrast to conventional triaxial apparatus). If no water is added, unsaturated specimens can develop multiple failure planes simultaneously (Fig. 1). Whereas saturated specimens – do not form shear rupture at all when compressed.

Due to isotropic strain (and stress) distribution, specimen durability increases dramatically. A fully saturated sample can be crushed beyond 10% axial strain without forming a shear band or bulging. And the deformation remains reversible, the sample can be pulled back to initial length, liquefied, drained and repeatedly cyclic tested in one, long, aggressive sequence. A sample liquefied and drained 6 times is shown in Fig. 2. The extreme scope of testing is obtained using two factors. First – mechanical properties of the frictionless apparatus, which preserves the specimen shape and durability. Second – load control methods, which adapt to changing specimen stiffness and strength, thus ensuring the end plates will stay in contact with the specimen being tested.

Triaxial apparatus is rather simple in construction. At the bottom a piston moves up and down, moving the bottom end plate with it. At the top, and end plate is fixed to a load cell (Ibsen, L. B., 1995). A proportional integral distance (PID) controller can move the bottom piston to a user defined target position (U) or force (F), where F is measured by the load cell. Thus, a PID controlled can operate either in displacement mode or force mode (U or F mode).

In standard tests target U or target F can be specified manually, or set to follow a pre-defined wave shape (sinusoidal, saw tooth, square wave, etc.). These options are available by default in the software used to control the (dynamic) Danish triaxial apparatus. Each wave shape has unique benefits and limitations.

Linear ramp loading

The most basic type of loading is linear ramp. The load is applied at a constant rate, either $\Delta F/\Delta t$ or $\Delta U/\Delta t$, towards the target F or U. Cyclic loading tests start with linear ramp "preloading" towards the average Force (Fa). A linear loading path can be seen going towards Fa in Figs. 3-6. The produced loading path looks like a line, but the PID controller is adjusting piston position a thousand times per second – to keep the real time value of F or U "on target".

One must recognize that the PID controller is predicting how many "injections of oil" need to be supplied to the piston, in effort to keep the measured F (or U) "on target". The number of injections is calibrated by three coefficients – P, I and D. The coefficients are found through trial and error and as long as F (or U) response remains somewhat linear the PID calibration performs well. The PID controller works especially well with U control. Hydraulic fluid is extremely stiff, thus the same number of oil injections will produce the same amount of displacement regardless of how stiff or soft the specimen becomes.

F controlled loading is different. Number of oil injections necessary to keep F "on target" vary with specimen stiffness. If a system was near linear elastic, there would be no problem, but stiffness can change a lot in sand specimens, thus F-PID control can fail. PID controller calibrated "too stiff" can resonate – oscillate out of control (see Fig.3). Whereas relaxed values cause F-PID to lag behind the F target. This makes applying F cycles on liquefying specimens very complicated. Standard PID controllers are simply not robust enough.

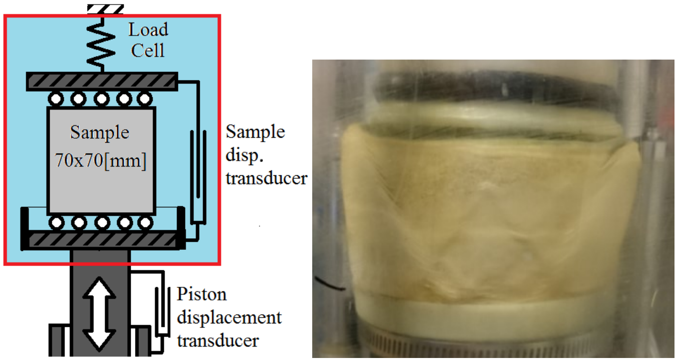

Fig. 1 Schematic of test setup and axially compressed (20% strain) dry, unsaturated Aalborg no.1 sand, resulting in 6 overlapping shear bands.

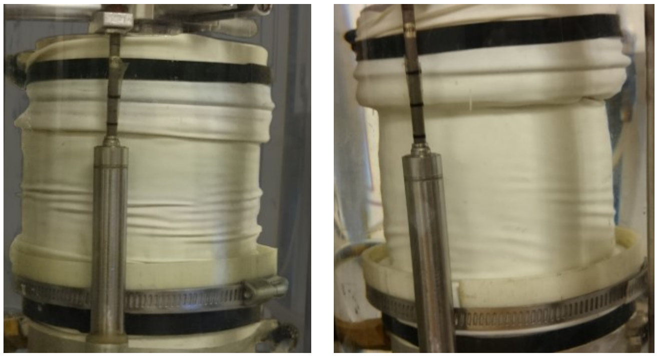

Fig. 2 Saturated, undrained samples. 10% axial compression strain on the left. On the right - 6 times compressed to failure, pulled to initial length and drained with cyclic testing in between. Geometry remained satisfactory.

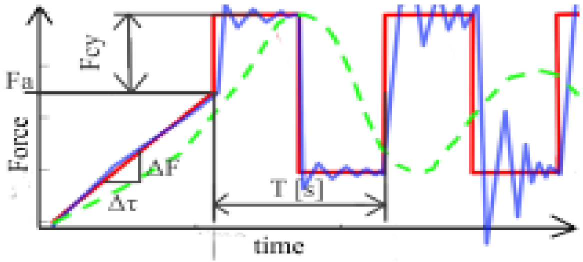

Fig. 4 Square wave loading with 2 cases of bad tuning illustrated on top

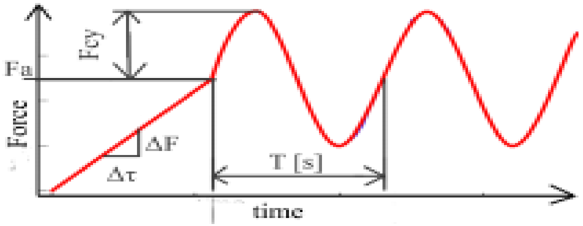

Fig. 5 Sinusoidal loading shape.

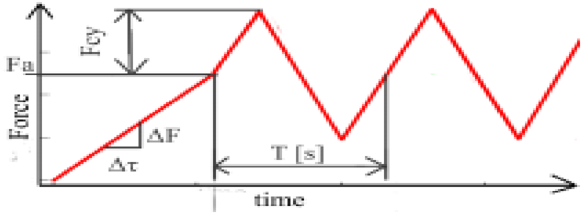

Fig. 6 Saw tooth loading

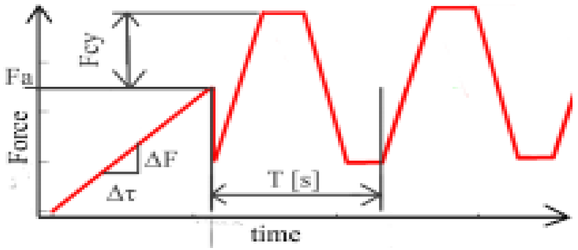

Fig. 3 Trapezoid loading

Square wave loading

Square wave (Fig.3) has very steep transition from one peak to another. This makes it great for tuning the PID controller, as square waves expose resonance or overdamping. PID control has 3 coefficients – position, integral and derivative. These three determine how aggressively the piston reaches for the target. The three are normally calibrated through trial and error, while the test is running.

In F mode, PID coefficients depend on specimen stiffness. The number of oils injections required to reach target F changes with specimen stiffness. Thus, different parameters of F-PID are necessary at different stiffness. However, no such problems are present during U-PID calibration: hydraulic piston is grossly overpowered, thus the correlation between U and oil injections remains the same, regardless of the specimen stiffness. Which makes U-PID calibration stable at all times.

Sinusoidal loading

Sinusoid wave (Fig.4) has smooth curves, making it easier for F-PID to catch up with real time measurements at the peaks. This wave shape is stable over a wider range of specimen stiffness, as the smooth shape reduces the danger of resonating and/or under/over-loading a specimen. But during liquefaction it was found impossible to maintain a stable sinusoidal shape using F-PID control (shown in Fig.7).

Saw tooth loading

Cycles of linear ramp unloading/reloading can be combined into a saw-tooth pattern (Fig. 6). This is advantageous for testing deformation cycles. The loading rate (du) is constant during such loading cycles, this allows to isolate individual components within equation of motion:

$$F=K\cdot u+C\cdot du+M\cdot ddu \qquad (1)$$

Where u is displacement, $du = \Delta U/\Delta t$ (first derivative, loading rate), ddu – second derivative (acceleration). And K, C and M are stiffness, damping and mass components. To model dynamic sand response, the K, C and M need to be treated as nonlinear functions. Therefore it is crucial to isolate them one at a time. If U cycles are applied at increasingly slower du, a quasi-static K will emerge. Once K curvature is quasi-static, further reduction in du will not produce changes in measurement. But if du is increased (cycle frequency increased), the quasi-static stiffness path will start changing, and the deviation will be caused by C component. Thus, U-PID saw-tooth loads allow to separate K from C, from M, all behaving like nonlinear state defendants.

Trapezoid loading

If saw-tooth peaks are paused for a brief moment – trapezoidal wave is shaped (Fig.6). The flat peaks can be used for observing stress relaxation (U-PID) and strain creep (F-PID) with each cycle. Allowing specimens to stabilizer at the peaks can ensure quasi-static response is being measured.

STRAIN AND STRESS VS U AND F

The default control methods are limited to F and U control. Yet, specimens are tested for stress and strain. Thus, it would be good if U and F could be applied in ways which target stress and strain. This is where standard PID is modified to meet triaxial testing.

Converting piston U to specimen strain takes some compromises. Piston displacement does not match specimen deformation "exactly". As Fig.1 shows, piston displacement is re-distributed between the specimen and the load cell (load cell deforms like a spring too). However, the load cell is a very stiff spring. Even more so during liquefaction, when the specimen becomes soft, and in a series spring system, the softest spring absorbs largest proportion of deformation (in this case, the specimen absorbs most of the deformation). Thus, even though PID control has no access to real specimen deformation, the

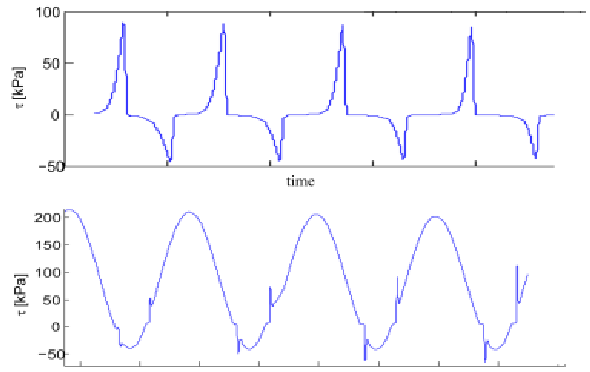

Fig. 7 Performance of script loading (top) compared with to F PIC controlled sinusoidal loading (bottom), acting on liquefying specimen.

piston position can be used as a close substitute. Especially during liquefaction.

Given these observations, true strain can be obtained as:

$$\varepsilon = \ln\left(1 - \frac{\Delta U}{H_0}\right) \tag{2}$$

Where H_0 is initial specimen height. In addition, undrained specimens have constant volume – thus, predictable cross-section to obtain stresses from. True (absolute) stress can be obtained as:

$$\tau = \frac{q}{2} = (F/A_0) \cdot (1 + \varepsilon) \tag{3}$$

Where A0 is the initial cross-section area of a specimen, and $(1 + \varepsilon)$ accounts for change in cross-section during loading. Note, here the stress measured is "absolute", not "effective".

Absolute (undrained) stress limits are predictable. Firstly, undrained yielding always occurs when pore pressure drops to near -100 kPa, thus undrained yielding can be predicted by monitoring real time pore pressure. Secondly, undrained yielding strength can be approximated with equation:

$$\tau_{min,max} = \frac{(Cp + 100) \cdot \tan\varphi}{\frac{2}{3} \cdot \tan\varphi \pm 1} \tag{4}$$

where Cp and φ are the chamber pressure and the friction angle, respectively. The constant of 100 kPa, representing cavitation limit. The theoretical limit for cavitation is 100kPa (absolute vacuum), but in tests, cavitation of de-aired specimens occurred near -85 kPa Thus, using 85 (or slightly less) instead of 100 could be an option providing more realistic estimates.

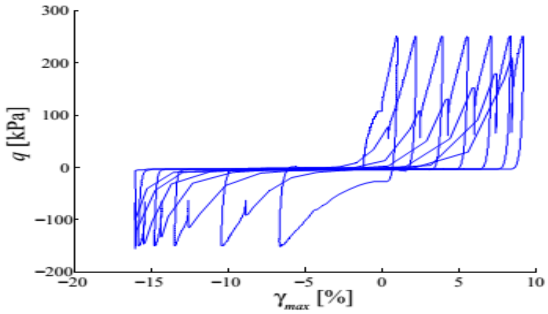

Fig. 8 Force controlled liquefaction response (REF SOREN). If loaded further the first of "double peaks" will go beyond the maximum stress level.

LIQUEFACTION

The challenge of measuring liquefaction in cyclic loaded specimens, using the Danish triaxial apparatus was attempted by Nielsen & Ibsen, 2013. Two way loaded sinusoidal F-PID cycles were applied, and the PID controlled produced "overshooting" peaks (visible in bottom picture of Fig.7).

Overshoot occurs because of rapidly changing stiffness of liquefied specimens. There is a "pure plastic gap" when crossing q=0 axis, thus changes in stiffness are tremendous when loading direction is reversed (see Fig.9). In pure plastic zone F-PID will produce acceleration which will accumulate into large loading velocity (du component). F-PID accelerates and de-accelerates with a minor delay, thus, it will not be able to stop once the target F is reached. And to make matters worse, after F-PID exceeds the target F it will attempt to unload assuming linear stiffness. But unloading stiffness is much steeper in sand, thus the "overshoot" will be followed by "undershoot". This F-PID behavior cannot be prevented using the PID coefficients. Make the piston more aggressive and it will oscillate out of control around the target F value. Relax the settings – and overloading/under-loading will get worse. However, U-PID has no such problems. U-PID is unconditionally stable. The only problem is targeting F values using U-PID for input.

Targeting F using U-PID

The problem with using U-PID is that F plays no role in U-PID algorithm. One has to specify the targeted U and the U-PID will control oil injections required to reach the U target. Thus, to target F instead, it is necessary to monitor real time F values, and change the targeted U value once the F limits are reached. Luckily, the MOOG station allows to monitor real time F using scripts (Troya & Sabaliauskas, 2014). Furthermore, not only F limits can be observed, but F can be converted into τ within the script using Eq's (2,3).

A script can take measurement of F a few thousand times per second. Measurements can be converted to τ within the same millisecond, and du direction is reversed once τ peak was reached. The principle is very simple, each time τ peak is triggered, loading direction is reversed (see Fig. 9). However, it

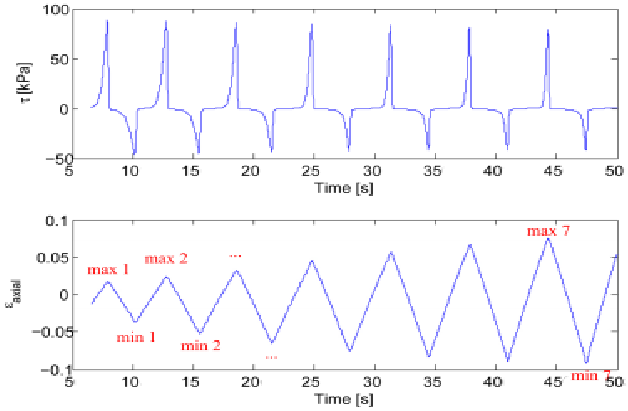

Fig. 9 Adopting strain controlled liquefaction loading. Stress time series on top. Strain time series in the bottom.

is not enough to merely reverse displacement direction, the loading period needs to be preserved. The distance between peak U positions is increasing with each loading cycles, thus the du value has to be updated after every peak – to cover the next distance faster (or slower) depending on how the peak position evolves during the test.

Notice how ε distance is smaller between max1-min1 compared to max7-min7 in Fig.9. The "gap" between the peaks is increasing as specimens liquefy. This is easy to account for if du component (loading rate) is updated after each peak crossing. Distance between min1 to min2 needs to be crossed with: du=(max1-min1)/T, and distance between max7 to min 7 is crossed with du=(max7-min6)/T. This allows to update du with respect to previous loading cycle. This does not provide the exact solution, as loading rate is slightly too slow, but in Fig.9 one can see the period is rather stable, and close to T=11.

Limitations

It must be noted, that F-PID is problematic only at high plasticity, and during periods of unstable stiffness. Otherwise, when stiffness is near linear, F-PID performs really well. At times when stiffness is very steep, F-PID is the only real option. At high stiffness, U-PID scripts becomes unstable, as small deformation creates large F fluctuations. Therefore, care must be taken to select the correct setting:

1. U-PID for testing nonlinear, pure plastic behavior
2. F-PID for testing linear, elastic behavior.

FUTRE WORK

Using U-PID loading, specimens survive through aggressive liquefaction. Thus, post liquefaction soil states can be researched. This is interesting for researching soil states left after earthquakes. As well as disturbed soil states encountered by offshore wind turbines.

The new testing scope allows to iterate between liquefaction and draining, which allows reach very high densities, which could not be accessed using alternative preparation methods. The specimens can be densified to the point of purely dilative state. Such "exotic" soil state (pure dilative) could be very interesting to research as a fundamental boundary limit of sand.

Foundations of structures built offshore must function in cyclic loaded environment. Thus, liquefaction and drained post-liquefaction recovery are both important. The control algorithms developed thus far are sufficient to safely liquefy, drain and re-liquefy specimens. Thus, evolution full complexity of disturbed sand stiffness can be observed.

Introducing new capabilities

Besides new testing capabilities already available, the equipment is not perfect. Some modifications can be implemented to improve it further. At the moment, two computers are connected to the (dynamic) Danish triaxial apparatus. One of them is dedicated to data acquisition. The second one – PID controller. The two computers do not communicate with each other. The PID controlled has no access to data describing the specimen itself. If the two computers were upgraded to share a common database, a whole new level of automation would become plausible: Scripts could be written to target specific densities of a specimen. Specimens could be "reset" to initial stiffness, to make data tables autonomously. Pore pressure measurements would allow to prevent undrained specimens from yielding more efficiently. In the most farfetched scenario machine learning algorithms could be implemented for data mining. Sand has extremely nonlinear stiffness, complexity of which quickly overwhelms a human observer. Given how durable and stable the specimens are, it could be plausible to generate state space maps and decision tress (such as Markov decision process) by allowing a machine learning algorithm to explore the patterns autonomously.

CONCUSION

The new found capability to test liquefied sand is stable and reliable. A specimen can be liquefied, and continued to test thereafter. As specimen durability is improved, it becomes plausible to increase complexity and aggressiveness of testing, which in turn provide access to new observations – new knowledge.

Some remaining limitations of the equipment cannot be surpassed without partial reconstruction of equipment – such as combining the separate computers into one unit. But it seems new testing scope can be reached by merely changing the software, rather than upgrading the hardware. The testing capabilities of frictionless triaxial apparatus are not exhausted yet, the equipment can reach observations far beyond conventional testing limits.

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