PART THREE: DYNAMIC TRIAXIAL TESTING

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Overview: This three part series has been written to introduce one of the most versatile tests in the geotechnical laboratory – the triaxial test. The papers provide a detailed introduction to the subject of triaxial testing, including the many variations available for assessing soil response across a range of engineering applications. The series is split into the following topics:

1. Introduction to triaxial testing.
2. Advanced triaxial testing.
3. **Dynamic triaxial testing.**

INTRODUCTION

This paper presents the dynamic cyclic triaxial testing of soils in the laboratory. It briefly discusses why dynamic tests are required, the soil parameters that may be obtained, the differences between static and dynamic triaxial systems, the general method for conducting a dynamic cyclic test, and a new development relating to dynamic cyclic triaxial apparatuses.

Why conduct a dynamic cyclic triaxial test?

The soil deposits in many geotechnical engineering projects undergo dynamic cyclic loadings during their design lifetime. These loadings may be due to environmental factors, such as seismic activity and ocean storms, or human activities, such as passing traffic and vibrating machinery installed on a structure or site. Importantly, the soil response generated by these dynamic cyclic loadings is typically more complex than that considered when conducting static analyses, requiring engineers to investigate the dynamic behaviour of soils in the laboratory, as well as in the field. As previously discussed in Part One and Part Two of this series, the triaxial test provides a convenient and versatile method for assessing soil behaviour in the laboratory, and can be performed with static and dynamic loadings. Note Figure 1 displays examples of soil failures due to strong earthquake motions and repeated subgrade loading from high-speed rail transit.

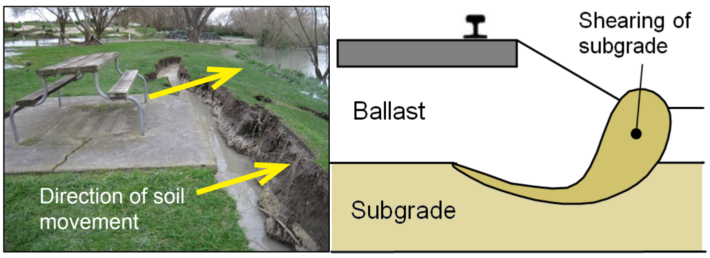

Figure 1 – Earthquake-induced lateral spreading (left); illustration of progressive railway subgrade shear failure due to repeated load cycles (right, reproduced from Mott MacDonald, 2011).

What is the frequency of a dynamic cyclic load?

The nature of cyclic loading applied to a soil deposit is highly dependent on the loading source. This means the loading waveform may be relatively uniform and essentially consist of a single frequency (e.g. a vibrating machine), or somewhat random and contain a range of frequencies (e.g. an earthquake). Applying such complex waveforms to a soil specimen in the laboratory requires sophisticated test systems, and while such systems are available, dynamic cyclic loading records have historically been approximated by uniform sinusoidal, square or triangular waveforms of a single frequency. With this in mind, Table 1 presents typical test frequency ranges of uniform sinusoidal loadings used in a cyclic triaxial test to approximate a range of dynamic loading situations. Note the division between static and dynamic frequencies is generally considered to be in the order of 0.05 - 0.1 Hz (Ishihara, 1996).

Table 1 – Typical test frequency ranges for cyclic triaxial testing.

Loading type	Typical test frequency
Wave action	0.1 Hz
Wind action	0.1 - 1 Hz
Earthquake	1 Hz
Rail transit	> 1 Hz
Vibrating machinery	≤ 20 Hz

How does the dynamic cyclic response of soil differ from static response?

There are broadly two main aspects of dynamic cyclic loading that differentiate the soil response from traditional static behaviour. These are:

- The reversal of applied stress
- The rate-dependency of soil response

Note that other dynamic phenomena, such as resonance, may also be important to consider when assessing the performance of a soil deposit (O'Reilly & Brown, 1991), however such factors are not discussed in detail in this paper.

(i) Reversal of applied stress

Reversing the stress applied to a soil element refers to variation in sign of the rate of stress increase. More simply for triaxial testing, this typically means oscillating between increasing and decreasing values of deviator stress q applied to a soil test specimen. This definition therefore highlights that stress reversal is not necessarily unique to dynamic loadings, but instead any situation in which the loading applied to a soil element is cyclic in nature.

Examples of two cyclic loading patterns that may be used during a cyclic triaxial test are displayed in Figure 2 - here one-way loading refers to cases in which the applied stress does not change sign (e.g. remains positive at all times), while two-way loading corresponds to cases in which the applied stress does change sign (i.e. alternates between positive and negative values). Note the time taken for loading to complete one cycle is given by the loading period, T, while the magnitude of loading is described by the amplitude, A. The frequency of loading, f, is the inverse of the period ($1/T$).

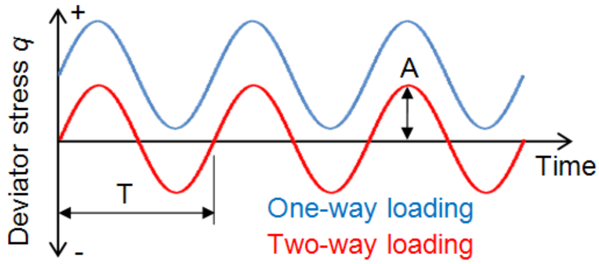

Figure 2 – One-way and two-way cyclic loading patterns. Note T = loading period and A = loading amplitude.

Two principal features of soil response when undergoing stress reversal are: (1) the accumulation of plastic shear strain; (2) generation of excess pore water pressure. Importantly, these features only occur once the soil behaviour becomes elasto-plastic, which approximately corresponds to applied shear strains in the order of 0.01 % or larger (Ishihara, 1996). At shear strains below 0.01 % most soil behaviour tends to be purely elastic.

Plastic shear strain is the increment of soil deformation that is permanent or irrecoverable. For a single load cycle it can be quantified by comparing the shear strain at the beginning of the cycle with that at the end of the load cycle. While this increment of plastic strain produced during a single cycle may be relatively small, the cumulative effect from numerous loading cycles can be potentially significant. To demonstrate this feature, the deviator stress-shear strain response of a triaxial sand specimen undergoing cyclic loading is displayed in Figure 3. Here the increment of plastic shear strain observed during the first load cycle is in the order of 0.2 %, yet after 50 load cycles the accumulated shear strain applied to the soil exceeds 4 %.

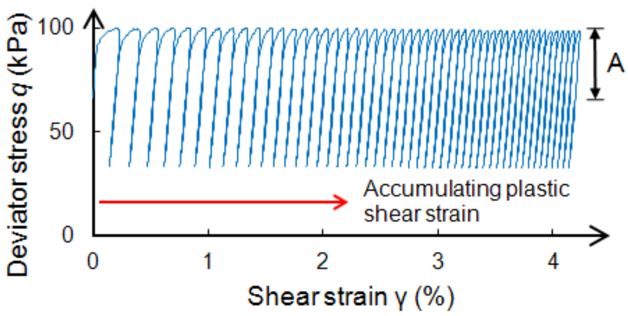

Figure 3 – Accumulation of plastic shear strain during an undrained cyclic loading test on a sand specimen.

Figure 3 additionally highlights the tendency for the plastic strain increment to reduce as an increasing number of loading cycles are applied to a soil. At some point during loading this increment becomes insignificant when compared with the recoverable strain observed during a single cycle, at which point the soil response can be termed 'resilient.'

Excess pore water pressure generation refers to the change in pore pressure that occurs within a saturated soil as a load is applied. During cyclic loading this feature is dependent upon the drainage conditions of the soil and the loading rate; if a high permeability soil is loaded and/or the loading rate is relatively slow, then the pore water will have sufficient time to drain and the pressure to dissipate. Such a situation results in no generation of excess pore pressure, and is modelled during a triaxial test by keeping the drainage lines to the test specimen open (i.e. by maintaining fully drained conditions). On the other hand, if a soil has a low permeability, or the loading rate is sufficiently fast, excess pore pressure may be produced. This is modelled during a triaxial test by closing the drainage lines to the test specimen (i.e. by maintaining undrained conditions).

In practice a build up of excess pore pressure reduces the effective stress applied to a soil deposit, which in some cases may trigger complete failure of the soil. A well-known example of this is the liquefaction of sand deposits - here the rapid cyclic loading produced by an earthquake causes the pore pressure to rise more quickly than it can be dissipated, even though sand is a relatively permeable material. Once the effective stress of the sand approaches zero the ability of the soil to resist shear loading is lost, resulting in significant soil deformations.

To quantify pore pressure build-up during a triaxial test, the excess pore pressure ratio r_u is often used. This is defined by the ratio of pore pressure change during loading to the effective stress applied at the beginning of loading. Therefore when $r_u = 0$ the pore pressure is equal to the applied back pressure, while when $r_u = 1$ the pore pressure is equal to the confining pressure and the effective stress has reduced to zero. Such response is displayed in Figure 4, which details the generation of excess pore pressure during an undrained cyclic test on a sand specimen. Note the ratio may also be expressed as a percentage.

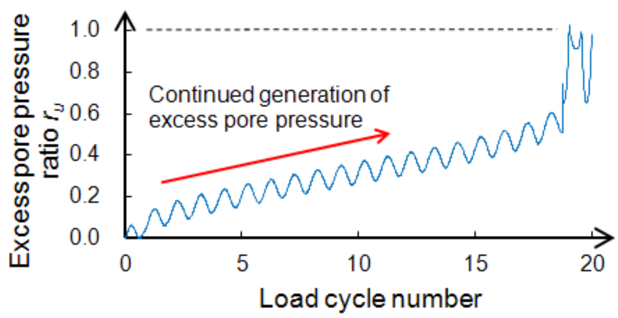

Figure 4 – Generation of excess pore water pressure during an undrained cyclic loading test on a sand specimen.

(ii) Rate-dependency of soil response

The rate at which loading is applied has been shown to significantly affect the response of a soil. In general, faster loading rates result in stiffer and stronger response for cohesive soils, an observation that has been made when testing specimens under monotonic (loading in one direction only) and cyclic conditions. Note again the effect of loading rate is typically only noticeable once the shear strain of a soil enters the elasto-plastic range.

Interestingly the rate-dependency of soil response is due to two factors. The first is the effect of inter-particle viscosity, and the second is the effect the loading rate has on a soil's ability to dissipate excess pore pressure. As inter-particle viscosity is not a characteristic of granular soils (e.g. sands and gravels), only the generation of excess pore pressure is a factor for such materials. This means the response of granular soils is relatively independent of the loading rate when testing in laboratory systems, assuming the drainage conditions that would occur in the field are maintained (e.g. the test specimen is left undrained if modelling rapid cyclic loadings).

To highlight the effect the loading rate has on the response of cohesive soils, cyclic strength curves for laboratory-prepared Kaolin clay specimens are presented in Figure 5. Here all test specimens were isotropically consolidated to a mean effective stress of 98 kPa, and then cyclically loaded under undrained conditions using varying amplitudes of deviator stress until a failure criterion of 10 % double amplitude (peak-to-peak) axial strain was reached. Note the cyclic stress ratio (CSR) is defined as half the applied deviator stress amplitude divided by the applied initial mean effective stress.

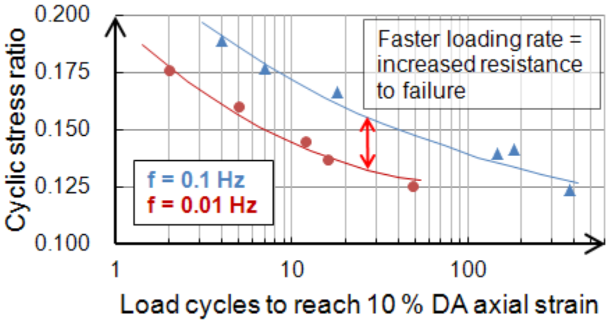

Figure 5 – Cyclic strength curves of Kaolin specimens for loading frequencies equal to 0.1 Hz and 0.01 Hz (data from Özaydin and Erguvanli, 1980).

Figure 5 clearly shows the Kaolin test specimens require increased loading amplitudes to reach failure in the same number of cycles for faster rates of loading. This observed strength gain is typically in the order of 9 % for each log cycle increase in the loading frequency (Boulanger and Idriss, 2006).

PARAMETERS OBTAINED FROM DYNAMIC CYCLIC TRIAXIAL TESTS

Although dynamic cyclic triaxial tests may be used to investigate many aspects of the dynamic cyclic response of soils, two commonly-used test standards are:

- ASTM D3999-11 (Determination of the Modulus and Damping Properties of Soils Using the Cyclic Triaxial Apparatus)
- ASTM D5311-11 (Load Controlled Cyclic Triaxial Strength of Soil)

ASTM D3999-11 is primarily used to determine the degradation in secant Young's modulus E, and increase in damping coefficient D, of a soil specimen as the applied axial strain ε_a is increased. Note estimates for the shear modulus G and applied shear strain γ may also be obtained through use of Poisson's ratio μ, which is equal to 0.5 for undrained conditions.

ASTM D5311-11 is used to determine the cyclic strength of a soil specimen by loading the soil under undrained conditions until a given failure criterion is reached. Typically failure is defined by the excess pore pressure ratio r_u reaching 1.0, or some limiting value of double amplitude (DA) axial strain ε_a being exceeded (20 % is specified in the test standard, although 5 % is often used for liquefaction studies). If multiple specimens are tested with different cyclic stress ratios applied, then cyclic strength curves like those shown in Figure 5 may be generated.

Each of the above test standards importantly specifies that cyclic loading must be applied dynamically to the test specimens. Here ASTM D3999-11 states loading must be carried out at frequencies between 0.5 Hz to 1 Hz, while ASTM D5311-11 allows for loading frequencies between 0.1 Hz to 2 Hz (with 1 Hz preferred). This means traditional static triaxial apparatuses are generally not suitable for performing cyclic loadings as per the test standards, and a dynamic cyclic triaxial apparatus is instead required.

DIFFERENCES BETWEEN STATIC AND DYNAMIC CYCLIC TRIAXIAL APPARATUSES

The primary differences between a static triaxial apparatus and a dynamic cyclic triaxial apparatus are: (i) the load frame; (ii) the control and data acquisition hardware; (iii) the control software. These differences are briefly reviewed in the following text.

(i) Load frame

A clear difference between a static and dynamic cyclic triaxial test on a soil specimen is the rate of loading. A dynamic cyclic triaxial load frame must contain an actuator that is capable of applying cyclic axial loads at dynamic frequencies (e.g. up to at least 2 Hz), but also capable of applying large axial strains to test specimens (e.g. 20 % DA ε_a) at these dynamic frequencies. Given the power required to move a loading actuator is proportional to the loading frequency squared, dynamic cyclic triaxial load frames tend to be larger and more advanced than those required for static triaxial testing.

(ii) Control and data acquisition hardware

As the loading rate is faster during a dynamic cyclic triaxial test, the hardware used to control the load frame and acquire data from the apparatus transducers must be capable of running at dynamic speeds. Specifically, the control system must enable a uniform sinusoidal loading waveform to be applied to the soil specimen, while at least 40 points of data should be acquired per loading cycle (this is equivalent to a data logging frequency of 80 Hz when loading at a rate of 2 Hz).

(iii) Control software

The control software used to perform a dynamic cyclic triaxial test must be capable of allowing the user to specify the required cyclic loading parameters (e.g. frequency, load amplitude), and also select the failure criterion for loading to be halted, such as a specific limiting axial strain. Note some dynamic cyclic triaxial apparatuses, such as the GDS dynamic triaxial system displayed in Figure 6, have additional functionality for advanced research purposes that enable non-standard loading waveforms to be applied to test specimens (e.g. time histories from earthquake acceleration records).

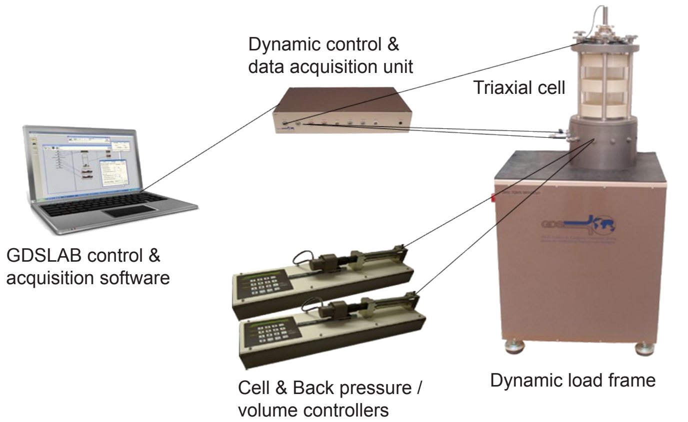

Figure 6 – GDS Dynamic Triaxial Testing System (DYNTTS) components.

PERFORMING A DYNAMIC CYCLIC TRIAXIAL TEST

A dynamic cyclic triaxial test essentially requires the same processes that are used when conducting traditional static triaxial tests, with significant differences only arising at the shearing stage and during analysis of the soil response. This means the descriptions of specimen preparation, saturation and consolidation given in Part One of this series are still valid for dynamic cyclic tests, although a selection of additional suggestions that may be useful when preparing for a series of dynamic cyclic tests are listed in the following:

- Prepare for extension loading - if a two-way loading pattern is to be applied to a test specimen, the soil will be placed in a state of extension (i.e. radial stress σ_r > axial stress σ_a). In this case the specimen top-cap will need to be locked to the load ram to enable application of extension forces. Such connections are not always used during static triaxial tests, so should be considered when preparing an apparatus for cyclic testing. Note all GDS triaxial systems are supplied with an extension top-cap and vylastic sleeve, as displayed in Figure 7, which enable this connection to be made before or after isotropic consolidation has been completed.

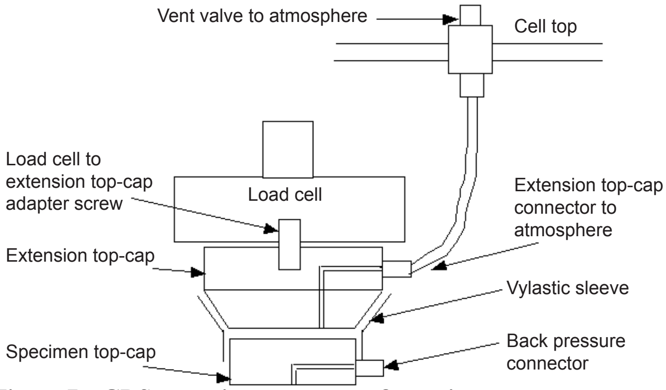

Figure 7 – GDS extension top-cap configuration.

- Select the appropriate control parameter - most dynamic cyclic triaxial apparatuses allow testing to be performed under load control or displacement control. In some instances, such as the cyclic strength tests specified in ASTM D5311-11, loading will need to be applied using load control (i.e. a specific amplitude of load must be targeted). In other cases, such as when defining the degradation of *E* as per ASTM D3999-11, there exists a choice as to which control parameter is used (i.e. a load amplitude or a displacement amplitude may be targeted). In the case of defining the degradation of *E,* it may be more appropriate to conduct loading using displacement control, as this allows specific applied axial strains to be targeted. The benefit obtained here is the degradation of E may be systematically defined, without prematurely over-straining the test specimen.

- Ensure accuracy and resolution of deformation measurements - as discussed Part Two of this series, unavoidable system compliance adversely affects the measurement of soil deformation in the small strain range. For some dynamic cyclic testing this is not an important consideration, particularly when interest lies in the large strain soil response (e.g. cyclic strength tests) where the magnitude of system compliance is insignificant compared with the applied strain. However when the small strain response is important, such as during definition of the degradation of *E* and increase in *D*, it may be necessary to consider the use of local strain transducers placed directly on to the test specimen. Such additions significantly improve the accuracy and resolution of deformation measurements, which in turn provide a better estimation of *E* and *D* (along with *G* and γ) in the small strain range.

- Consider the effect of loading frequency - although a loading frequency of 1 Hz is preferred when conducting cyclic strength tests (ASTM D5311-11), pore pressure measurements taken at the specimen ends have been shown to be unreliable when testing cohesive specimens at this frequency magnitude. This is due to non-uniform pressure distributions being generated within the test specimen, which suggests pore pressure data obtained from high frequency cohesive soil tests should be treated with care. Note local pore pressure measurements may be taken at the specimen mid-height (see Part Two of this series for further details), however non-uniform pressure distributions still lead to such measurements being potentially unrepresentative of the total specimen response (Zergoun & Vaid, 1994).

NEW DEVELOPMENT FOR A DYNAMIC CYCLIC TRIAXIAL APPARATUS

As already discussed in this paper, dynamic cyclic triaxial apparatuses generally allow testing to be performed under load control or displacement control. The performance of a given apparatus under each type of control is typically governed by the system used to apply the loading; the most common systems use electro-mechanical, hydraulic or pneumatic actuators.

GDS dynamic cyclic triaxial apparatuses predominantly use an electro-mechanical system, as this system allows precise control when targeting values of axial displacement and velocity. This is achieved by using motors within the load frames that have high resolution shaft encoders, combined with a fixed gearing for the actuation system. To perform load controlled tests, actuator velocity targets are constantly updated and set by the system firmware, requiring use of closed-loop feedback from the apparatus load cell to successfully maintain a target load amplitude. Traditionally, as for the other loading systems mentioned above (i.e. hydraulic and pneumatic actuators), this control method has employed proportional-integral-derivative (PID) feedback, which inherently has the following limitations:

- Requirement for the user to specify an estimate of the test specimen stiffness
- Decrease in apparatus responsiveness if significant changes in the specimen stiffness occur

To improve the functionality and response of dynamic cyclic triaxial apparatuses, development has been carried out within GDS to implement an adaptive control method. While this new control method still employs PID feedback, it additionally contains ‘Feedforward’ (FF) and system ‘Observer’ terms that assist in adjusting the actuator velocity target *u* in real-time, thus maintaining a more consistent load amplitude, particularly when the specimen stiffness is rapidly changing. Figure 8 shows a high-level component block diagram of this new adaptive control method.

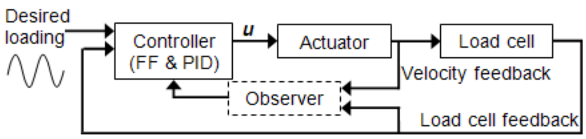

Figure 8 – New adaptive control method for GDS Dynamic Triaxial Testing System (DYNTTS).

Testing performed in a GDS DYNTTS has shown the new control method to provide a significant improvement over the traditional PID method, particularly as changes in specimen stiffness occur. Dynamic undrained two-way cyclic tests performed on saturated medium density sand specimens at 0.1 Hz have shown the adaptive control method maintaining a load amplitude of approximately 87 % of target following the onset of liquefaction, even as the double amplitude axial strain surpasses 20 %. This compares favourably with the performance of the traditional PID method, which enabled approximately 7 % double amplitude axial strain to be applied post-liquefaction, with the maintained load amplitude reducing below 10 % of the target.

The adaptive control method is now a standard inclusion with the GDS DYNTTS. Note the traditional PID feedback method may also be selected by the user if desired.

REFERENCES & FURTHER READING

ASTM Standard D3999, “Standard Tests Methods for the Determination of the Modulus and Damping Properties of Soils Using the Cyclic Triaxial Apparatus,” ASTM International, West Conshohocken, PA, 2013, DOI: 10.1520/D3999-11.

ASTM Standard D5311, “Standard Tests Methods for Load Controlled Cyclic Triaxial Strength of Soil,” ASTM International, West Conshohocken, PA, 2013, DOI: 10.1520/D5311-11.

Boulanger, R. W. & Idriss, I. M. 2006. *Liquefaction Susceptibility Criteria for Silts and Clays*. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 132, No. 11, p 1413-1426.

Ishihara, K. 1996. Soil Behaviour in Earthquake Geotechnics, Oxford, Clarendon Press.

Mott MacDonald. 2011. RSSB 1386 (Revised) The effects of railway traffic on embankment stability. Final Report, Croydon, Mott MacDonald.

O’Reilly, M. P. & Brown, S. F. 1991. Cyclic Loading of Soils: from theory to design, Glasgow and London, Blackie.

Özaydin, K. & Erguvanli, Â. 1980. *The generation of pore pressures in clayey soils during earthquakes*. Proc., 7th World Conf. on Earthquake Engineering, Vol. 3, p 326-330.

Zergoun, M. & Vaid, Y. P. 1994. *Effective stress response of clay to undrained cyclic loading*. Canadian Geotechnical Journal, Vol. 31, p 714-727.