Emerging Trends in Cyclic Triaxial Testing

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Introduction

Because of its widespread use for many years in assessing static properties of soils, early efforts at developing equipment to measure cyclic soil response focused on adding dynamic capabilities to conventional triaxial testing systems (eg. Chan and Mulilis, 1976), while the stiffness of soils were usually evaluated with resonant column methods. Initially such devices were only capable of resolving the response at moderate to large strains, which suited their application to investigating liquefaction triggering and seismic settlements. Over the years, however, many researchers (eg. Kokusho, 1980; Ladd and Dutko, 1985, among many others) have extended the capabilities of cyclic triaxial systems to measure the cyclic response at progressively smaller strain levels, allowing the use of these systems to effectively measure dynamic properties (modulus and damping) down into the elastic strain range.

This paper does not seek to provide a complete review of the evolution of cyclic triaxial methods, nor can it describe the full range of research applications in which they have been applied: they are too numerous. Instead, this paper will provide a brief review of the primary features, advantages and limitations of cyclic triaxial testing; comments on the way in which these features and limitations have shaped the development of new testing techniques, and a description of the major categories of research in which they are being utilized. Finally, a few observations on other potential uses are proposed to stimulate discussion at this workshop. As the subject of the Workshop is primarily on dynamic soil and site response, the focus will be on applications related to characterizing modulus and damping, rather than liquefaction assessment – although this distinction should probably not be as rigid as is often stated.

Components of Cyclic Triaxial Testing

When equipped to measure dynamic soil response, cyclic triaxial systems typically include computer controlled actuators, capable of stress or strain controlled cyclic loading, and usually are designed to axially load cylindrical specimens which are sealed within a pressurized chamber, and which usually also provide independent control of the pore pressure within the specimen. In order to provide accurate application of the small stresses required to induce small cycles of strain, the actuators may be smaller in diameter and have lower capacities than those used to shear specimens to failure. The other key distinguishing features of such systems lie in the types, sensitivities and locations of the instrumentation (Figure 1). Following the terminology of Scholey et al (1995), accurate measurement of stresses and strains at low loading levels requires "internal" load cells and displacement transducers, since external sensors are likely to be too greatly affected by friction, compliance, and other corruption outside the chamber. Even better is the use of "local" deformation transducers, which evaluate the strains induced over the middle portion of the specimen, away from the specimen end caps and the associated bedding errors and/or protected zones which can lead to erroneous "global" (cap-to-cap) measurements.

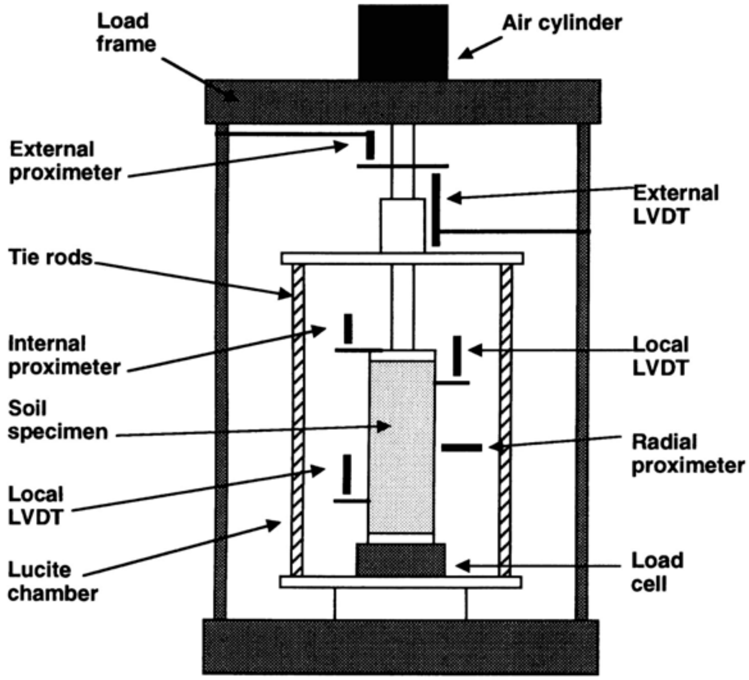

Figure 1: Schematic showing locations of instrumentation in cyclic triaxial testing (Scholey et al)

<u>Limitations and Advantages of Cyclic Triaxial Testing</u>

The disadvantages of using cyclic triaxial systems to measure dynamic properties are widely discussed, and are primarily related to the unrealistic nature of the loading, compared to the general model of seismic loading consisting of horizontal shear stresses superimposed on the *in situ* stresses. This leads to issues involving:

- **Reversal of principal stresses** through an isotropic condition twice in every cycle, rather than smooth rotation of the principal stresses.
- **Orientation of applied shear stresses**. For tube samples retrieved in a vertical orientation from the field, the maximum shear stresses during cyclic loading are imposed on planes that are steeply inclined from the horizontal. Natural soils exhibiting anisotropic fabric, often due to deposition in horizontal layers, may respond quite differently to shear stresses of the same magnitude, but imposed on horizontal planes. For these materials (or stress conditions), there is no single "correct" shear modulus, as it varies with orientation, but the value provided by triaxial testing is typically not of the greatest interest
- **Direct measurement of Young's Modulus (E)**, rather than the desired shear modulus (G). Since axial stresses and displacements are typically the direct measurements, conversion to shear strains and shear modulus requires information about Poisson's ratio of the soil. This is obtained either by measurement and interpretation of the radial strains, or through their control by testing saturated, undrained specimens.

On the other hand, there are some attractive advantages to cyclic triaxial testing, including:

- Cyclic triaxial systems are ***relatively*** common, easy to run and inexpensive. This could be important if data is needed by practitioners requiring data for design in a relatively short time.
- A good system can measure over a **wide range of strains, and strain rates** (Figure 2)
- Triaxial systems provide **direct and independent control (and measurement) of the axisymmetric consolidation stresses**, allowing for varying degrees of anisotropic consolidation
- Because of its relatively simple design, systems can be scaled-up for testing of **large specimens**
- Most cyclic triaxial systems provide for **true saturation** (through the application of back-pressure) and therefore the measurement of the **effective stress response with pore pressure generation**.

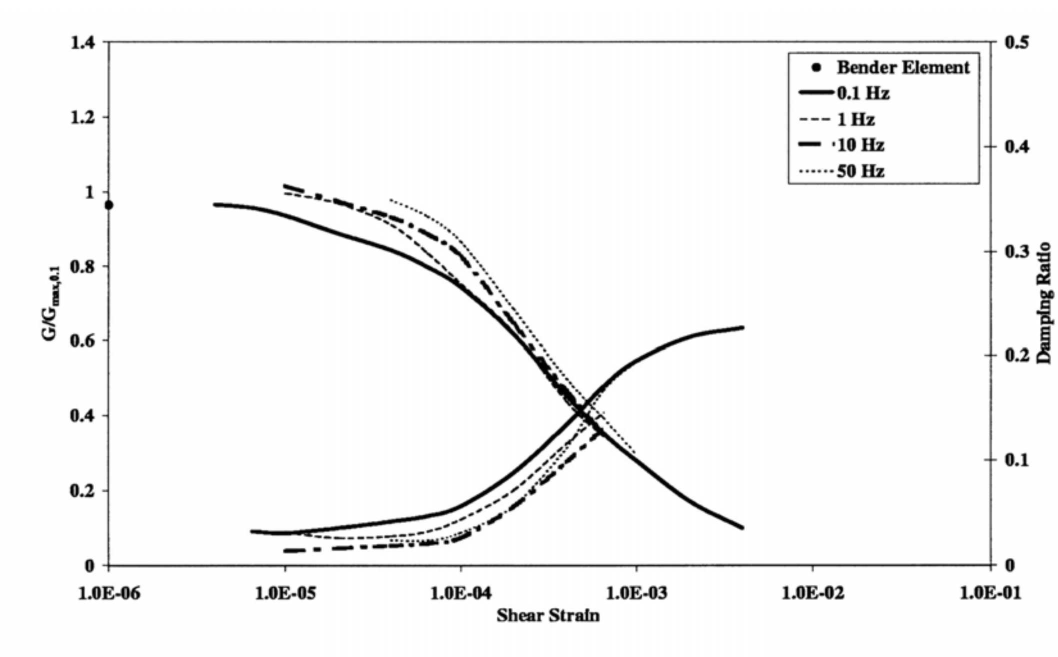

Figure 2: Example of frequency effects on modulus and damping of reconstituted clay (Gookin et al)

Recent trends in Cyclic Triaxial testing

In surveying the literature, one finds that recent research has focused both on addressing the natural deficiencies of cyclic triaxial loading systems, and on exploiting its strengths where possible. One very popular category of research is the enhancement of measured dynamic properties through the use of supplementary sensors and measurement techniques. These include:

- Wave velocity sensors (such as bender elements, shear elements, P-wave transducers, and accelerometers) which provide small strain (<10^{-3} %) modulus values to complement the larger strain measurements obtained by the cyclic loading. This approach is valuable also in that it provides a link to field measurements, as they are obtained using a loading mechanism similar to the field V_S methods used to normalize and "correct" the lab data to account for disturbance effects and other discrepancies between the lab and field data. An additional benefit to such systems is that the velocity measurements can be oriented in multiple directions, and hence can provide valuable information on variations in anisotropic modulus as a function of orientation (eg. Kuwano et al, 2000)

- A wide variety of "local" transducers, which are often mounted on the middle of the specimen to provide measurement of axial, radial or shear strains of the specimen itself. These can include conventional LVDTs and proximity transducers, or less common devices such as inclinometer gages, the Local Deformation Transducer, Hall Effect gages, and radial strain calipers. Scholey et al (1995) provide an excellent review of many such devices. Newer devices continue to appear as well, including radial gages based on cantilever bending (Besuelle and Desrues, 2001) and the Elastomer Gage (Safaqah, 2003). These devices are important for accurate assessment of the axial and radial strains, which help to address the difficulty in converting cyclic triaxial data to a shear modulus desired for site response modeling.

Another broad category of cyclic triaxial research on dynamic properties encompasses the application of the method to "special soils". These include materials such as peats of various compositions (Figure 3), gravels, silts, calcareous sands, remediated soils, municipal solid waste, Geofoam, and others. Testing of these materials is often important since it may not be clear how any "empirical" estimation could be made based on classical correlations with index properties. The flexibility of enlarging triaxial systems to accommodate large specimen sizes plays an important role here, in that some of these materials contain particle sizes much too large to test in conventionally-sized laboratory specimens. The large specimen size also facilitates the implementation of the sort of supplementary sensors described above, since such systems often require some "elbow room" to mount and monitor.

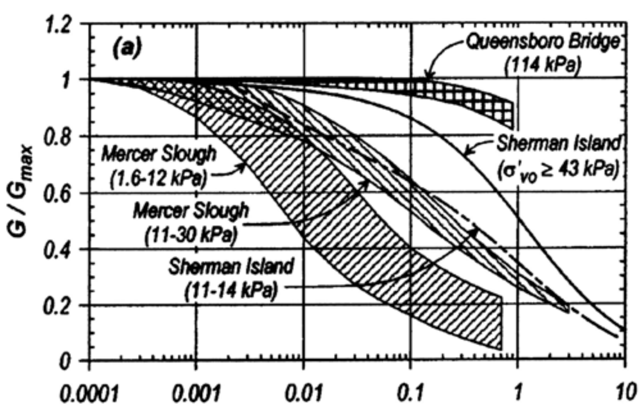

Figure 3: Compilation normalized modulus data on different peat soils (Wehling et al, 2003)

Issues for Further Discussion

Discrepancies are often observed between modulus and damping values measured in different lab devices, particularly between those lab values and the stiffness that is inferred from field velocity measurements. As lab testing goes, the sensitivity of dynamic properties to small procedural and instrumentation changes is also relatively high, leading to a situation in which it is difficult to establish with confidence whether a particular system is providing the “right” data. Ironing out these discrepancies is an important research task, so that the resulting data can be used with confidence in practice.

Finally, while there has historically been a clear distinction between cyclic testing performed for liquefaction assessment, and cyclic testing performed for dynamic properties to predict site response, there is an important range of situations in which the stress-strain response of saturated soils are likely to be important. Such soils may soften considerably during an earthquake, change the shape of their hysteresis loops considerably, and yet not reach a state of “classical” liquefaction, particularly if they are subjected to significant consolidation shear stresses from an adjacent structure. Accurate description or prediction of the seismic response of overlying materials (and effects on the adjacent structure) will depend on proper characterization of this softened response. While the cyclic triaxial test is not uniquely qualified for evaluating such behavior, meaningful measurement does require saturation and observation of the pore pressure response, which most cyclic triaxial systems are well equipped to perform.

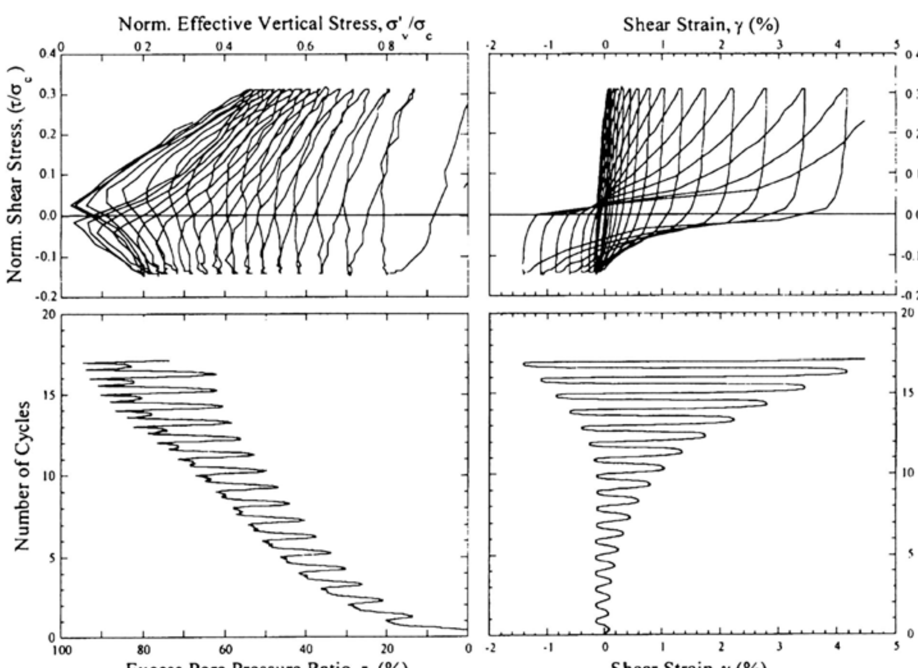

Figure 4: Softening response due to pore pressure generation (Kammerer et al, 2001)

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