GDS Instruments’ Technical Note: Adaptive Control for the Dynamic Cyclic Testing of Soils

Introduction

The dynamic cyclic response of soil is important to many geotechnical engineering projects, including those in which structures and/or soil deposits may be subjected to earthquake, wave, wind and traffic loadings. During such loadings the effects of stress reversal, rate-dependency and other dynamic phenomena create highly complex soil response (O’Reilly and Brown, 1991), which may not be captured during traditional static geotechnical testing. Recognising this fact, laboratory element testing has evolved to enable dynamic tests to be performed on soil specimens using a wide range of test apparatuses, allowing determination of, amongst other parameters, the dynamic cyclic strength of a soil. This strength is often found for saturated granular soils to assess their resistance to earthquake loadings, and is typically determined at large strain levels, in the order of 1 % double amplitude axial strain and above for triaxial test specimens (ASTM D5311-11; JGS 0541-2000).

Performing cyclic tests on soil specimens at dynamic frequencies, which in this instance covers a frequency range from 0.1 Hz to 2.0 Hz, does however present challenges for the test apparatus being used. In particular, the system employed to control the loading actuator has a significant effect on the uniformity of loading amplitude that can be maintained throughout a test, especially as specimen stiffness changes. Given that international test standards require a uniform application of load until large strain or specimen failure is reached, the system used to control the loading actuator forms an important component of the overall test apparatus.

This paper presents a development to the loading actuator control system used within a dynamic cyclic triaxial apparatus produced by GDS Instruments. This development, a form of adaptive PID control, reduces a need from the operator for specimen-specific tuning, and improves apparatus response as a soil specimen softens. Assessment of the development in control system is performed within the context of sand liquefaction and its testing in the laboratory.

Problem/Case Study – Sand Liquefaction

Soil liquefaction occurs when a saturated granular material, such as clean or silty sand, transforms from a solid to liquefied state during cyclic shear loading. In 1964 significant earthquakes in Alaska, USA and Niigata, Japan highlighted the damage this phenomenon can cause, leading to a simplified procedure for assessing liquefaction resistance to be proposed (Seed and Idriss, 1971). While the simplified procedure assesses the resistance of a soil based on field test data (e.g., CPT), many studies have been performed in the laboratory to investigate liquefaction resistance through cyclic testing of soil elements.

When using the triaxial apparatus to investigate liquefaction in the laboratory, soil specimens are firstly saturated, consolidated (often isotropically), and then cyclically sheared under undrained conditions until a state of failure is reached. The cyclic stress ratio, CSR, is used to define the magnitude of the cyclic shearing, and is reported with the number of cycles required to reach failure. By testing a number of specimens prepared to the same initial conditions (e.g., the same initial density, effective confining stress) and varying CSR values, cyclic strength curves may be plotted. An example of these curves as produced in the JGS 0541-2000 test standard is displayed in Figure 1, along with damage caused to structures due to liquefaction in the 1964 Niigata earthquake.

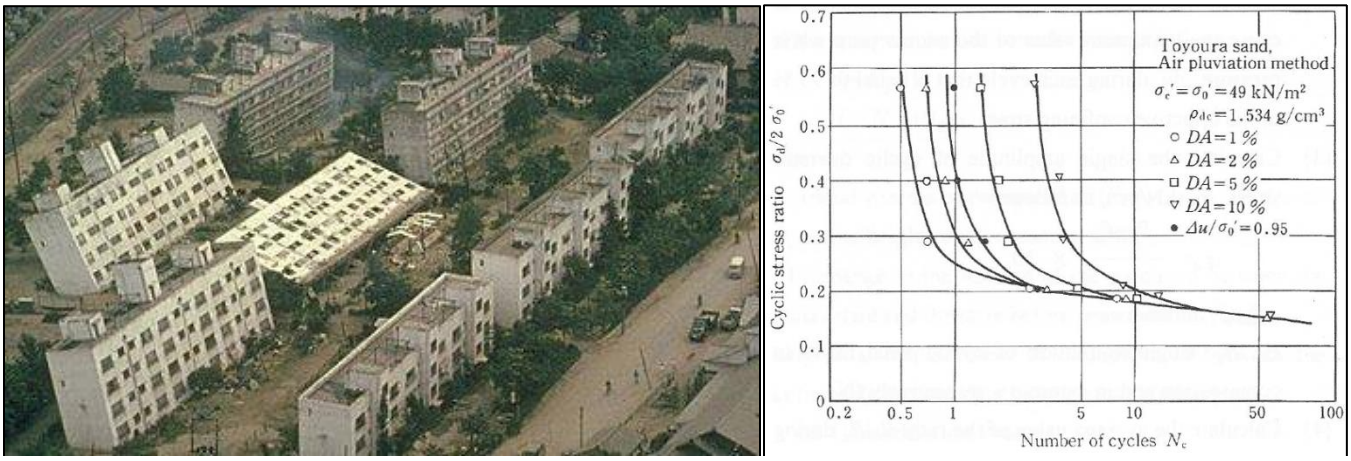

Figure 1 – Effect of soil liquefaction in the 1964 Niigata earthquake (left), and cyclic strength curves for Toyoura sand triaxial test specimens (JGS 0541-2000).

It is also important to note that granular specimens tested during liquefaction studies can be reconstituted to different initial densities, prepared using a range of methods, and confined by varying effective stresses. As such, the initial stiffness of a consolidated granular triaxial test specimen can vary by a significant amount. This variability creates implications for the tuning of a triaxial apparatus loading system, as does the soil response during undrained shearing, in which a large reduction in specimen stiffness is observed as the soil approaches a liquefied state.

Control Systems

Modern laboratory test apparatuses such as the triaxial typically apply loads and displacements to a soil specimen using an open-loop or closed-loop control system. Here open-loop control means the apparatus does not monitor the output response of interest (e.g., the axial load applied to a soil specimen), while closed-loop control means the apparatus does monitor and feedback the output response, enabling the loading actuator to be adjusted as a test progresses. This distinction understandably means laboratory apparatuses with closed-loop control systems are preferred due to the feedback they provide. Higuchi et al. (2000) demonstrated the difference in soil response when open-loop and closed-loop control methods were used within the same apparatus by performing dynamic cyclic triaxial tests on low-plasticity silt specimens. As expected, their investigation recommended the use of closed-loop control systems, and pointed out that even skilled triaxial operators could not maintain the specified loading amplitude using open-loop control as specimen stiffness reduced. This error in the loading was also shown to result in higher estimates for the liquefaction resistance of the silt.

Although preferred, there are numerous configurations for closed-loop control systems. The most basic is a system in which the difference between the specified and observed output response, the error, is fed back to the actuator controller and factored by one, two or three fixed gain values. These values are the proportional, integral, and differential gains, commonly abbreviated to PID, and the summation of these feedback terms is used to drive the loading actuator and correct the output response. Such a system is shown schematically in Figure 2, where *e* = error and *u* = summation of the feedback terms used to drive the actuator movement. Note this is the method historically used to run load-controlled tests in dynamic apparatuses produced by GDS Instruments, including the Dynamic Triaxial Testing System (DYNTTS).

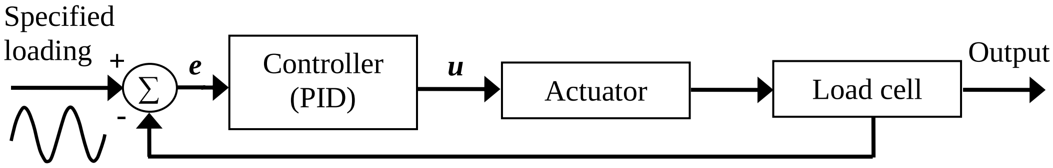

Figure 2 – Block component schematic of PID control historically used in the GDS DYNTTS.

When using PID feedback control, the loading system is tuned to optimum performance by conducting tests on a tuning specimen with consistent properties (e.g., a rubber cylinder), observing the dynamic cyclic response, and then selecting suitable values for each fixed gain term. This process results in excellent system performance when testing soil specimens that have similar initial stiffness to that of the tuning specimen, yet as already discussed the initial stiffness of a granular specimen tested as part of a liquefaction study may fall across a wide range. To account for this variability, a user-defined specimen stiffness estimate, K_s, needs to be selected on a specimen-by-specimen basis, which is then used to factor the fixed gain values (i.e., PID) that were obtained during the apparatus tuning process (larger $\mathrm{K_s}$ values correspond to lower factored gains). Although this additional parameter does enable the loading system performance to be optimised for each test specimen, it does require a significant degree of user experience to accurately quantify the parameter.

Initial specimen stiffness is not however the only consideration when using PID feedback control. In the case of liquefaction tests performed in a dynamic triaxial apparatus, the specimen stiffness reduces as the soil approaches a liquefied state, at which point the PID values initially set at the beginning of shearing become sub-optimal. This results in the applied axial loading amplitude reducing, with the liquefaction resistance potentially being overestimated (i.e., the test specimen may require more cycles to liquefy). This problem has been the focus of development at GDS Instruments carried out to improve control systems used within dynamic test apparatuses such as the DYNTTS. The primary solution has been to implement a form of an adaptive control system, which can assess specimen stiffness as a soil test progresses and ultimately adjust gain values as required.

Solution – Adaptive Control

The previous section discussing control systems highlighted the importance of test specimen stiffness when controlling dynamic cyclic apparatuses, with two limitations in particular being pointed out when PID feedback is used:

(1) The requirement for specimen-specific tuning before each test.

(2) The inability of the initial tuning parameters to remain optimal as the specimen stiffness changes.

These limitations have previously been recognised when controlling dynamic materials testing apparatuses (Hinton, 1997), with an adaptive control system instead being suggested as a suitable method for improving apparatus performance. Although an adaptive control system is not straightforward to define, general consensus states that a fixed gain system (such as the PID feedback) is not adaptive (Åström and Wittenmark, 1989). This importantly means adaptive systems should be able to adjust their gain values based on specimen response, which in the case of liquefaction testing in a triaxial apparatus means adapting gains based on variations in soil stiffness.

Given the recognised improvement an adaptive control system may offer, development was carried out at GDS Instruments to implement a form of adaptive control for use in dynamic triaxial, hollow cylinder and direct simple shear apparatuses. A schematic of this adaptive control system is displayed in Figure 3, where FF = feed-forward.

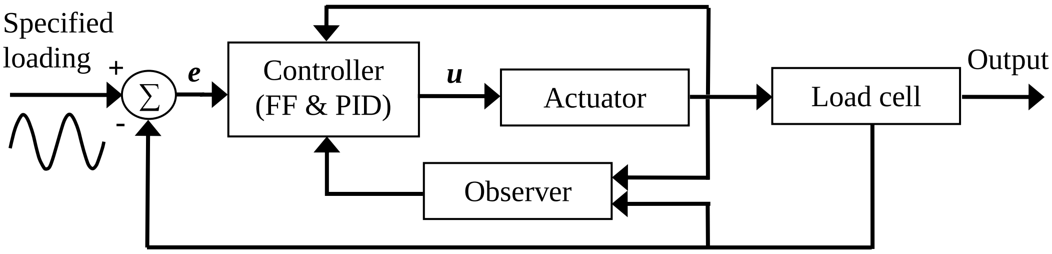

Figure 3 - Block component schematic of adaptive control developed for the GDS DYNTTS.

As shown in Figure 3, the adaptive control system contains two additions to the previously employed PID feedback: these are feed-forward and observer terms. Here the feed-forward control term primarily drives the loading actuator, based on a system calculation of the actuator driving signal required for the specified loading. Note this signal is adjusted through monitoring the actuator movement, allowing loading adjustments to be made before errors are recorded by the load cell. The observer term is used to calculate the specimen stiffness during the course of a test, which in turn factors the FF and PID terms. It is this inclusion which importantly transforms the control system to one with variable gains, enabling the apparatus to maintain its performance as the specimen stiffness changes.

Results – Dummy and LBFD Sand Tests

The newly developed adaptive control system was implemented within the firmware of a GDS DYNTTS, and initially assessed by testing 70 mm diameter triaxial specimens of rubber and saturated Leighton Buzzard Fraction D (LBFD) sand. Here the rubber specimen tests were conducted to investigate the sensitivity of the control system to the user-defined specimen stiffness estimate, while the saturated sand tests were used to assess the performance of the control system as the specimen stiffness varied.

The rubber specimen was initially set up in the DYNTTS and isotropically confined via a cell pressure of 100 kPa. Note the specimen was placed within a rubber membrane, allowing the GDS extension top-cap arrangement to be used, and extension stresses to be applied during cyclic shearing (i.e., symmetrical two-way loading was applied). The specimen height and diameter following application of confinement were determined to be 140.52 mm and 69.33 mm respectively. Cyclic shearing was conducted by applying an axial load amplitude equal to 0.096 kN, or 25 kPa deviator stress, for five cycles. This was performed for various combinations of loading frequency (0.1, 0.2, 0.5, 1 and 2 Hz), user-defined stiffness estimate (0.1, 0.2, 0.5, 1, 2, 5 and 10), and control system (PID feedback and adaptive control). Note only stiffness estimate values of 0.1, 1 and 10 were selected for the adaptive control system tests.

To compare performance of the apparatus using PID feedback and adaptive control systems, the percentage error of the applied double amplitude axial load with respect to the target double amplitude axial load (i.e., 0.192 kN) was calculated from the test data. Equation 1 defines this percentage error, which is based on loading uniformity calculations given in the ASTM test standard for determining the cyclic triaxial strength of soil under load control (ASTM D5311-11). Note ΔP_t = target double amplitude axial load (i.e., 0.192 kN), ΔP_c = applied single amplitude axial load in compression, and ΔP_e = applied single amplitude axial load in extension.

$$Error(\%) = \frac{\Delta P_t - (\Delta P_c - \Delta P_e)}{\Delta P_t} 100 \tag{1}$$

The percentage error defined in Equation 1 was calculated for the first load cycle of each loading combination, as well as the average of all five load cycles. In this latter case the absolute value of Equation 1 is reported in this publication. Figure 4 displays the percentage errors calculated following testing of the rubber specimen in the DYNTTS using PID feedback and adaptive control. From observation of the error plots three main conclusions can be drawn:

(1) The apparatus performance is relatively insensitive to variations in the stiffness estimate and control system when loading is conducted at 0.2 Hz and below, with the percentage error not exceeding 1 %.

(2) When using PID feedback at loading frequencies greater than 0.2 Hz, the apparatus performance is reduced as (i) loading frequency increases, and (ii) as the stiffness estimate decreases. These observations highlight the greater importance specimen-specific tuning plays as loading frequency increases.

(3) When using adaptive control, the apparatus performance is relatively insensitive to variations in the stiffness estimate and loading frequency, with the percentage error not exceeding 1.2 % at loading frequencies of 1 Hz and below. Caveats to this statement include (i) the apparatus was unstable when using a stiffness estimate equal to 0.1, and (ii) the maximum percentage error when loading at 2 Hz was equal to 5.7 % for the average of five load cycles. Overall however these observations strongly suggest the adaptive control system provides a significant improvement in apparatus response and reduced sensitivity to the selected stiffness estimate, particularly at loading frequencies of 1 Hz and below.

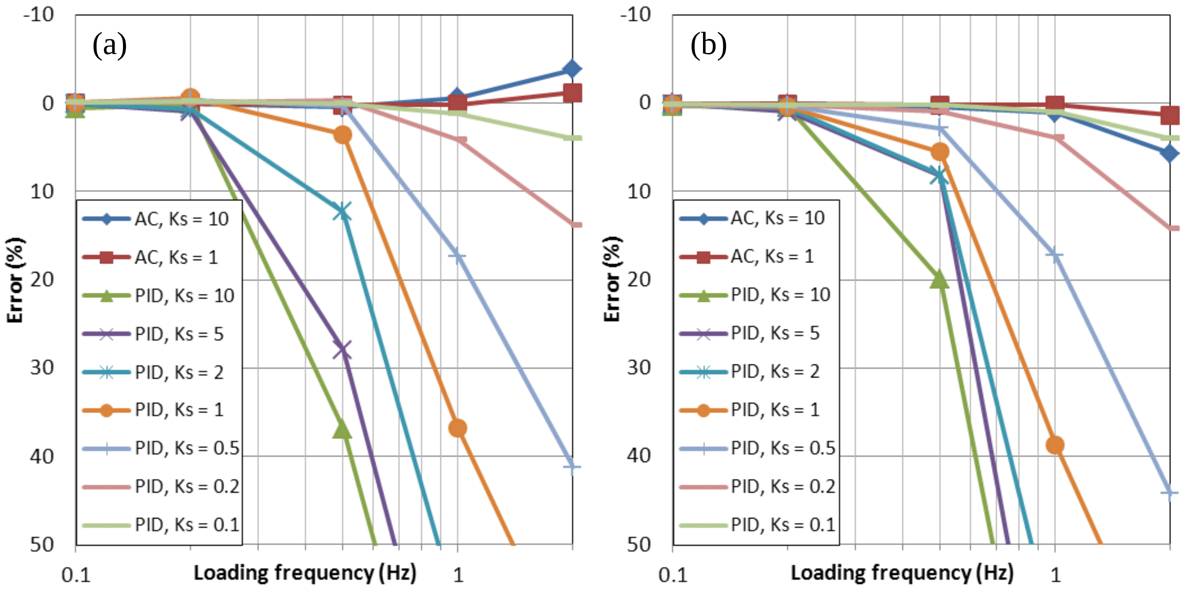

Figure 4 – Percentage error of double amplitude axial load applied to the rubber test specimen following (a) one load cycle, and (b) absolute average error across five load cycles. Note AC = adaptive control and PID = PID feedback.

Two LBFD sand specimens were reconstituted in the DYNTTS using a moist-tamping preparation method, targeting a void ratio of 0.865 (relative density approximately equal to 50 %). Each specimen was saturated by firstly percolating de-aired water through the sand, with raised back pressures (500 kPa) then applied to complete saturation. Following confirmation that Skempton's B-value was greater than 0.95 for each specimen, isotropic consolidation was carried out to an effective confining stress of 100 kPa. After consolidation had completed, bender element tests were conducted to enable initial stiffness comparisons between each test specimen, with undrained cyclic shearing subsequently performed using a loading frequency of 0.1 Hz and an axial loading amplitude equal to 0.096 kN (25 kPa). The user-defined stiffness estimate was held at a value of 1.0 for each test.

Post-consolidation properties of each tested LBFD specimen are given in Table 1, along with the control system used for loading each specimen, and the number of cycles required to reach a double amplitude axial strain of 5 % (a common failure criterion for liquefaction tests). Note void ratios were determined based on post-test masses taken of the specimen sand and pore water, while shear modulus values were estimated from an average tip-to-tip cross-correlation travel time obtained from S-wave bender elements tests conducted at input frequencies ranging between 5 kHz to 17.5 kHz.

Table 1 – Post-consolidation properties of the LBFD specimens tested in the DYNTTS.

Test Specimen	Void ratio e_c	Height H_c (mm)	Diameter D_c (mm)	Shear modulus G_0 (MPa)	Cycles to 5 % DA axial strain N_c	Control system
LBFD-1	0.876	143.66	69.64	89.0	23	PID feedback
LBFD-2	0.871	143.67	69.66	91.3	19	Adaptive

Figure 5 presents the stress-strain response of the tested LBFD specimens when (a) PID feedback was used, and (b) adaptive control was used. Here the PID feedback control system maintains the target loading amplitude in the small strain range (below 1 % double amplitude), but as the specimen begins to liquefy the applied load significantly reduces, with the percentage error as defined in Equation 1 increasing above 80 %. Conversely the adaptive control system maintains the target loading amplitude across a very large strain range (above 15 % double amplitude), with the percentage error reaching an approximate maximum of 5 % before the shearing was halted.

To further explore the difference in specimen response between each control system, Figure 6 displays the recorded axial strains with respect to load cycle number. Here it can be observed that PID feedback results in a relatively slower build-up of applied strain as the specimen liquefies, with a maximum double amplitude strain of approximately 5 % to 6 % able to be reached. In contrast the adaptive control system allows for rapid straining of the test specimen as a state of liquefaction is reached, with the applied double amplitude strain increasing from 5 % to 20 % in the space of one load cycle. Also note the specimen tested using PID feedback required 23 load cycles to liquefy based on the 5 % double amplitude strain failure criterion, even though the specimen was estimated to be slightly looser and softer post-consolidation than the specimen tested using adaptive control. The latter specimen liquefied in only 19 cycles.

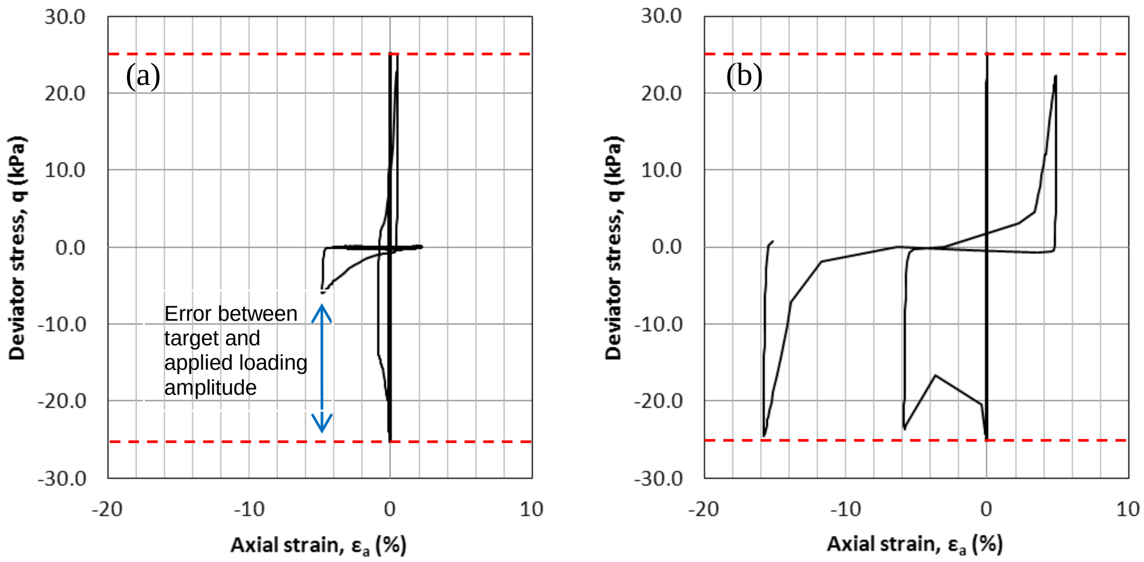

Figure 5 – Stress-strain response of LBFD specimens cyclically loaded under undrained conditions using (a) PID feedback, and (b) adaptive control. Note the target load amplitudes are shown by the horizontal dashed red lines.

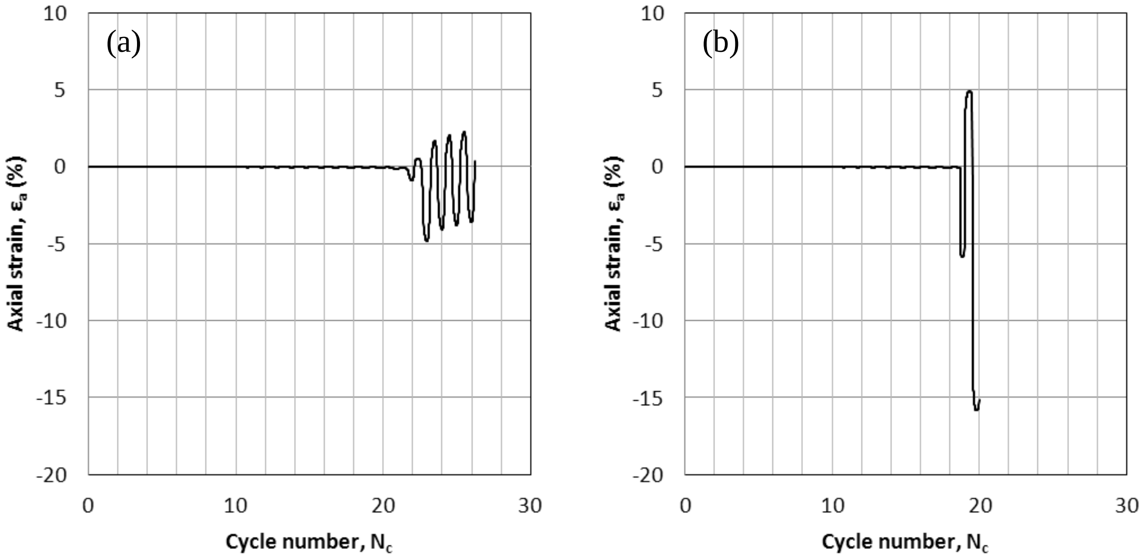

Figure 6 – Axial strain of LBFD specimens cyclically loaded under undrained conditions using (a) PID feedback, and (b) adaptive control.

The observed performance of the DYNTTS when cyclically shearing undrained LBFD specimens with similar post-consolidation properties initially suggests the adaptive control system noticeably outperforms the PID feedback system. It should however be emphasised that this statement is purely based on the testing of two granular specimens prepared to the same initial state, and that additional testing on different soil types (e.g., cohesive soils) is scheduled to further assess the performance of the newly developed adaptive control system.

Conclusions

References

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