# Adaptive control implementation for the dynamic cyclic testing of soil specimens

## Mise en œuvre d'une régulation adaptative pour essais cycliques dynamiques de specimens de sol

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**ABSTRACT**  This paper presents the implementation and assessment of an adaptive control system used to improve performance of an electro-mechanical dynamic cyclic triaxial apparatus. Implemented within the loading actuator control system firmware, adaptive control rapidly adapts to variations in soil specimen compliance as a dynamic cyclic test progresses. Performance of the new adaptive control system is assessed through testing of polyurethane and saturated sand specimens, and is compared with that of traditional fixed gain PID control. Observed results show adaptive control enables an undrained sand specimen to be loaded until the double amplitude axial strain exceeds 20 %, with a maximum error of 2 % recorded between the specified and measured loading amplitudes. The system also produces actuator performance that is relatively insensitive to initial tuning parameters, reducing the requirement for specimen-specific tuning and potential for operator error.

**RÉSUMÉ**  La présente communication présente la mise en œuvre et l'évaluation d'un système de commande adaptif utilisé pour améliorer les performances d'un appareil triaxial électromécanique lors d'essais triaxiaux cycliques dynamiques. Installé au niveau du micro logiciel de la commande de chargement, ce régulateur adaptif s'ajuste rapidement aux variations de la structure des éprouvettes de sol au fur et à mesure du déroulement de l'essai cyclique dynamique. Les performances de ce nouveau système ont été évaluées en réalisant des essais sur des éprouvettes de polyuréthane et de sable saturé et comparées aux résultats obtenus avec un système de régulation traditionnel PID à gain fixe. Les résultats observés montrent que le système adaptif peut contrôler un chargement sur un échantillon de sable non drainé jusqu'à dépasser les 20 % de la double amplitude de déformation axiale, avec une erreur maximum de 2 % entre les amplitudes spécifiées et mesurées. Les performances du système de pilotage sont relativement insensibles au réglage initial des paramètres, réduisant ainsi le besoin d'un réglage spécifique pour chaque échantillon et les risques d'erreur dus à l'opérateur.

## 1  INTRODUCTION

The dynamic cyclic response of soil is integral to many geotechnical engineering projects, including those in which critical structures and/or soil deposits may be subjected to seismic, 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 & Brown 1991), which may not be captured during traditional static geotechnical analyses. Recognising this fact, laboratories have evolved to perform dynamic cyclic tests on soil specimens using

a wide range of testing apparatuses, enabling 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 (liquefaction resistance), and is typically determined at strain levels in the order of 1 % double amplitude axial strain and above from triaxial test data (ASTM 2013; JGS 1999).

Performing cyclic tests on materials at dynamic frequencies, which in this paper covers a frequency range from 0.1 Hz to 2.0 Hz, does however present challenges for the apparatus being used. In particular, the system and tuning employed to control the load-

ing actuator has a significant effect on the uniformity of load amplitude that can be maintained throughout a test, especially as material stiffness changes (Hinton 1997). Given that laboratory test standards such as ASTM D5311/D5311M and JGS 0541 require uniform application of load until large strains or soil specimen failure is reached, the system controlling 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 an electro-mechanical dynamic cyclic triaxial apparatus produced by GDS Instruments. This development, a form of adaptive control, reduces the need for operators to provide specimen-specific tuning, and improves actuator response as soil specimens soften, each when compared with traditional fixed gain proportional-integral-derivative (PID) control. Description and assessment of the adaptive control system is performed within the context of undrained cyclic triaxial strength testing of sand (i.e., load-controlled) to determine liquefaction resistance.

## 2 FIXED GAIN PID FEEDBACK CONTROL

Figure 1 displays a schematic of the closed-loop PID feedback control system traditionally used to conduct load-controlled tests within a GDS Dynamic Triaxial Testing Apparatus (DYNTTS). Here $e_T$ corresponds to the total error between measured and specified loading waveforms (e.g., a uniform sinusoidal waveform), while $u_T$ represents the voltage signal used to drive the velocity-controlled electro-mechanical loading actuator. This signal is a function of the individual PID gain values and total error, and is updated every 0.2 ms. Note the PID gain values remain fixed throughout loading, with base values optimised during apparatus production via a tuning process using a 100 mm diameter polyurethane test specimen (Shore A 70 hardness).
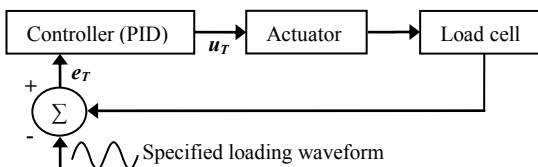


**Figure 1.** Closed-loop fixed gain PID feedback control system schematic traditionally used within the DYNTTS firmware.

Although the closed-loop fixed gain PID system shown in Figure 1 produces a significant improvement in loading actuator performance when compared with open-loop control systems (Higuchi et al. 2000), it is recognised two limitations exist.

Firstly, optimal values for the fixed PID gains are highly dependent on the soil specimen stiffness, as has been discussed following strain-controlled clay testing in a true triaxial apparatus (Mandeville & Penumadu 2004). This requires specimen-specific tuning to be provided by the apparatus operator whenever specimen stiffness varies, which is achieved for the DYNTTS by adjusting a non-dimensional initial specimen compliance estimate parameter, $K_{SI}$. Note this parameter simply scales each of the fixed base PID values, where $K_{SI} < 1$ increases each of the PID values, while $K_{SI} > 1$ decreases each of the PID values. Here operator experience is critical; if an unsuitable $K_{SI}$ value is chosen the loading actuator may not reach the specified load amplitude ($K_{SI}$ too great), or conversely become unstable due to P, I and/or D being too great ($K_{SI}$ too low).

Secondly, changes in soil stiffness during loading may render the initially optimal fixed PID gain values inappropriate as a test specimen is strained, again noted by Mandeville and Penumadu. In the case of cyclic strength testing of sand in a dynamic triaxial apparatus, progressive specimen softening results in the initial fixed PID gain values becoming suboptimal (i.e., P, I and/or D too low), leading to reduction of the measured load below the specified amplitude. This then may result in overestimations of the cyclic strength and/or non-compliance with laboratory test standards.

## 3 IMPLEMENTATION OF THE ADAPTIVE CONTROL SYSTEM

Adaptive control systems, which may loosely be characterised as special types of non-linear feedback control that do not retain fixed gains (Åström & Wittenmark 1989), offer a means to mitigate the issues associated with fixed gain PID control (FGC) summarised in Section 2. Such systems have previously been employed in materials-testing apparatuses to different degrees, from the simple reduction of PID gain values by a factor of ten at a specified strain limit (Mandeville & Penumadu 2004), to estimating the

specimen and apparatus compliance in real-time with continual updating of the individual PID gain values (Hinton 1997).

Figure 2 displays a schematic of the adaptive control system (AC) recently developed for the DYNTTS. Implemented within the loading actuator control system (LACS) firmware, primary additions to the system described in Figure 1 include a feedforward (FF) controller to calculate the required actuator drive signal, and compliance observer to estimate the specimen compliance in real-time.
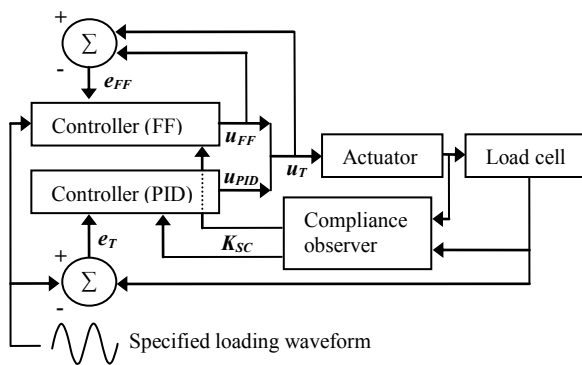


**Figure 2.** Adaptive control system schematic recently developed for the DYNTTS.

The FF controller directly relates the specified loading waveform to the required voltage signal used to drive the loading actuator, rather than relying on a non-zero value of $e_T$ to produce a drive signal. This is carried out by converting the specified loading waveform to actuator displacement via a compliance estimate, and then calculating drive velocity from displacement. Finally, a voltage signal is derived from the calculated drive velocity. The signal output from the FF controller, $u_{FF}$, is also compared with the total drive signal, $u_T$, to produce a FF error, $e_{FF}$. This error is subsequently used to correct $u_{FF}$, a process that enables the FF controller to provide the majority of drive signal to the actuator.

The compliance observer is added to estimate current specimen compliance in real-time, $K_{SC}$, using feedback from actuator movement and the internal submersible load cell. $K_{SC}$ is then used to continually scale the FF compliance estimate and individual PID controller gain values, enabling the AC system to account for non-linear soil response by varying the previously fixed gain values.

LACS tuning is again carried out during apparatus production through testing a 100 mm diameter polyurethane specimen. It is also noted the initial specimen compliance estimate parameter, $K_{SI}$, remains available to the operator, allowing the initial FF compliance estimate and individual base PID gain values to be manually factored if required.

## 4 ASSESSMENT OF THE ADAPTIVE CONTROL SYSTEM

Performance of the AC system was assessed and compared with the FGC system through testing of two materials in the DYNTTS. The first, a 70 mm diameter polyurethane specimen (Shore A 70 hardness), was used to assess the sensitivity of each control system to the initial LACS tuning. This was designed to highlight the degree of specimen-specific tuning required by the operator when using each control system. The second material, Leighton Buzzard Fraction D (LBFD) sand, was used to perform two saturated undrained cyclic strength tests, one test using each control system. This testing was designed to quantify the performance of each control system as the specimens softened.

### 4.1 Sensitivity to initial tuning parameters

The polyurethane specimen was placed in the DYNTTS and isotropically confined via 100 kPa cell pressure. Note a top-cap extension device was used to apply two-way symmetrical loading to the specimen. Following application of confining pressure, the specimen diameter and height were calculated to be 69.3 mm and 140.5 mm respectively. The specimen was then cyclically loaded with a specified amplitude equal to 0.096 kN (25 kPa deviator stress) for five load cycles, using various combinations of loading frequency ($f$ = 0.1, 0.2, 0.5, 1 and 2 Hz), initial specimen compliance estimate ($K_{SI}$ = 0.1, 0.2, 0.5, 1, 5 and 10) and control system (FGC and AC). Note only $K_{SI}$ = 0.1, 1 and 10 were used for AC.

Sensitivity to initial tuning was assessed by calculating the percentage drift error, $Error_{AP}$, in measured double amplitude load for each load cycle. Equation 1 defines this percentage error, based on uniformity guidelines given by ASTM. Note $\Delta P_T$ = specified

double amplitude load (0.192 kN), $\Delta P_c$ = measured single amplitude load in compression, and $\Delta P_e$ = measured single amplitude load in extension (note $P$ = zero under isotropic conditions).

$$Error_{\Delta P}(\%) = \frac{\Delta P_T - (\Delta P_c - \Delta P_e)}{\Delta P_T} 100 \qquad (1)$$

Figure 3 displays $Error_{\Delta P}$ during the first and fifth load cycles with respect to $f$ for each loading combination. Note data from testing performed using AC when $K_{SI}$ = 0.1 is not shown as the actuator became unstable prior to completion of one load cycle.

The overall rise in error observed in Figure 3 as $K_{SI}$ and $f$ were increased shows the sensitivity of FGC to the initial LACS tuning. This trend is however expected, firstly given greater $K_{SI}$ values correspond to lower P, I and D gains, and hence reduced $u_T$ for similar total error. Secondly, increased $f$ inherently requires greater drive velocity, which can only be provided by increased $e_T$ in a fixed gain system.
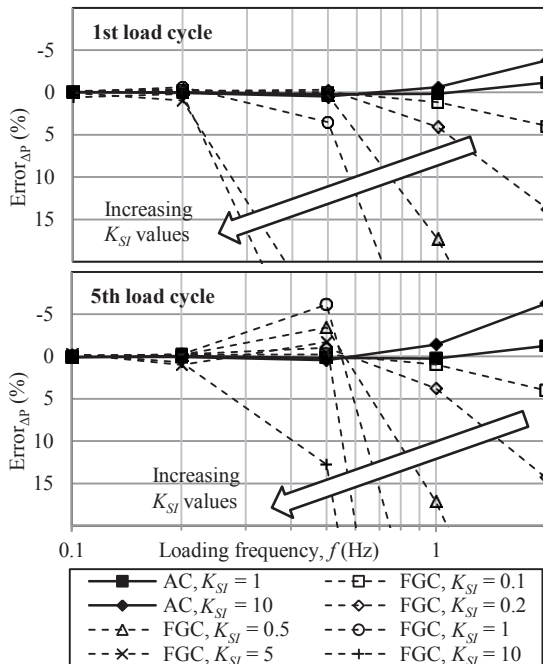


**Figure 3.** Sensitivity of control system to initial tuning parameters.

Figure 3 additionally highlights two important points relating to initial tuning sensitivity:

- The actuator performance was relatively insensitive to variations in $K_{SI}$ and control system when $f \leq 0.2$ Hz. In these cases the absolute error did not exceed 1 %.
- Improved performance was observed when AC was used. Here the absolute error did not exceed 1.5 % when $f \leq 1$ Hz and $1 \leq K_{SI} \leq 10$. For the same $K_{SI}$ and $f$ range FGC produced a maximum absolute error greater than 80 %.

These observations suggest AC produces actuator performance that is relatively insensitive to initial LACS tuning, and as such should reduce the potential for operator error that exists when carrying out specimen-specific tuning. However the actuator instability observed when using AC with $K_{SI}$ = 0.1 highlights the fact that gains increased significantly above base values may still produce unstable response.

### 4.2  Performance as test specimen softens

Two LBFD sand specimens were reconstituted in the DYNTTS via a moist-tamping preparation method previously used by the authors (Rees 2010), targeting a post-consolidation void ratio, $e_c$, of 0.865. This target provided a relative density, $D_{rc}$, approximately equal to 50 %, based on reported maximum and minimum void ratios $e_{max}$ = 1.01 and $e_{min}$ = 0.72 respectively (Klotz 2000). Note the specimens were nominally 70 mm in diameter and 144 mm in height.

Each specimen was saturated by percolating de-aired water through the sand, with 500 kPa back pressure then applied to complete saturation. Following saturation confirmation (B-value $\geq$ 0.95), isotropic consolidation was carried out at a mean effective stress, $p'$, of 100 kPa. Shear wave bender element (BE) tests were conducted after consolidation to enable estimation of the initial shear modulus, $G_0$, with sinusoidal input frequencies ranging between 5 kHz to 17.5 kHz.

Post-consolidation properties of each LBFD specimen are given in Table 1. Here void ratios were determined from post-test sand and pore water masses, while $G_0$ values were estimated from an average tip-to-tip cross-correlation travel time. The cross-correlation calculation was performed using the GDS BEAT add-in for Microsoft Excel (Rees et al. 2013). The values in Table 1 suggest relative consistency between the two specimens, with LBFD-1 slightly looser and softer than LBFD-2.

**Table 1.** Post-consolidation properties of LBFD sand specimens.

| Test specimen | Void ratio, $e_c$ | Relative density, $D_{rc}$ (%) | Shear modulus, $G_0$ (MPa) |
|---|---|---|---|
| LBFD-1 | 0.876 | 46 | 89 |
| LBFD-2 | 0.871 | 48 | 91 |

Undrained cyclic loading was performed using each control system (FGC for LBFD-1, AC for LBFD-2) at $f$ = 0.1 Hz with the specified loading amplitude equal to 0.096 kN (25 kPa deviator stress). This corresponded to a cyclic stress ratio, CSR, of 0.125. Note $K_{SI}$ = 1 for each test.

Figure 4 presents the specified and measured loads applied to the LBFD specimens, along with the measured axial strains, with respect to load cycle. Included is the point at which a double amplitude axial strain, DA $\varepsilon_a$, of 5 % was exceeded.
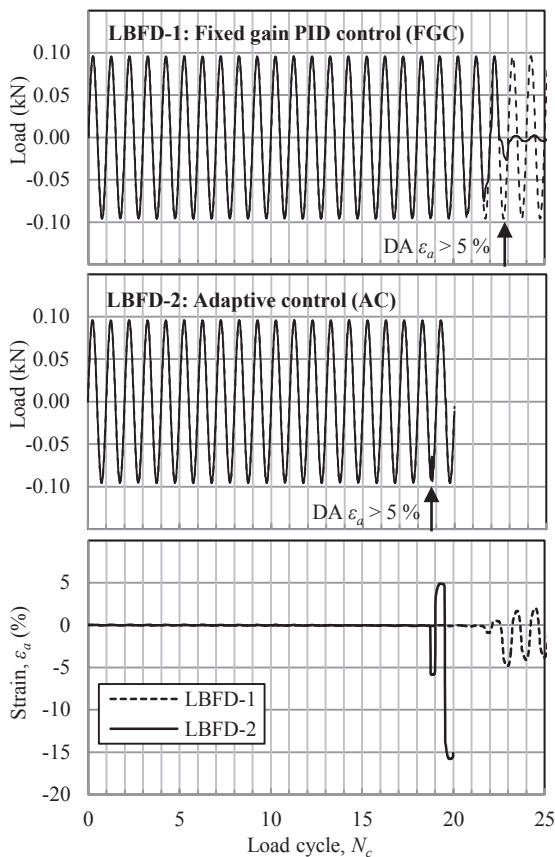


**Figure 4.** Specified and measured loads applied to the LBFD specimens, and measured axial strains. Note specified load is shown as a dashed line and measured load as a solid line.

Qualitatively it is observed that FGC led to a reduction in measured load below that specified before DA $\varepsilon_a$ = 5 %, while AC maintained the specified load amplitude when DA $\varepsilon_a$ > 20 %. Also note the first load cycle applied to LBFD-2 suggested the LBFD specimens were initially ten times less compliant than the polyurethane specimen.

A quantitative performance assessment was made by determining the percentage drift error and load ratio, $\Delta P_c / \Delta P_e$, for each load cycle. These were compared with limit values stated in the ASTM and JGS test standards referred to in Section 1. Note these limits are $Error_{\Delta P}$ < 5 % when $\varepsilon_a$ < ±5 % for ASTM, and $0.9 \leq \Delta P_c / \Delta P_e \leq 1.1$ when DA $\varepsilon_a \leq 2$ % for JGS.

Figure 5 displays $Error_{\Delta P}$ with respect to zones in which error would exceed the ASTM limit.
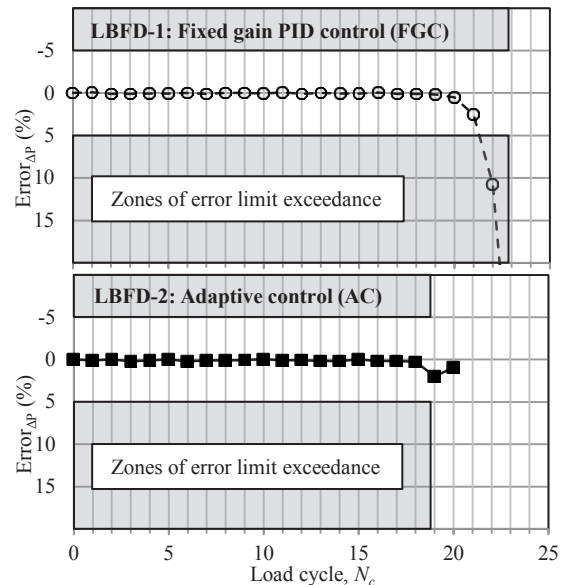


**Figure 5.** Percentage drift error of the tested LBFD specimens.

Observations noted from Figure 5 are:
- FGC with no operator tuning produced minimal error until the 22nd load cycle, during which the error exceeded the ASTM limit. This coincided with significant specimen softening, demonstrating the limitation of fixed gain control when specimen stiffness changes. Note the specimen had liquefied, based on a DA $\varepsilon_a$ > 5 % failure criterion, after completing the 23rd load cycle.

- AC with no operator tuning produced minimal error (maximum $Error_{\Delta P}$ = 2.0 %) throughout loading, with DA $\varepsilon_a$ > 20 % during the final (20th) load cycle. This demonstrates the improvement in performance when variations in specimen stiffness are accounted for. Note the specimen had liquefied (DA $\varepsilon_a$ > 5 %) after completing the 19th load cycle.

It is also noted $\Delta P_c / \Delta P_e$ fell outside the stated JGS limits during the 22nd load cycle applied to LBFD-1, while $\Delta P_c / \Delta P_e$ remained within limits during all load cycles applied to LBFD-2 (the maximum deviation from unity was $\Delta P_c / \Delta P_e$ = 1.04).

## 5 CONCLUSIONS

Adaptive control was implemented within the loading actuator control system firmware of an electro-mechanical dynamic cyclic triaxial apparatus produced by GDS Instruments. This was carried out to improve actuator performance beyond that of traditional fixed gain PID control, reducing the requirement for specimen-specific tuning and enabling specified loading amplitudes to be maintained during undrained cyclic strength testing.

Assessment of the adaptive control system was performed through dynamic cyclic triaxial testing of polyurethane and saturated sand specimens. The polyurethane tests suggested the adaptive control system produced actuator performance that was relatively insensitive to initial tuning, with the measured load deviating by 1.5 % from the specified amplitude at loading frequencies of 1 Hz and below. This reduces the potential for operator error that exists when specimen-specific tuning is required.

The saturated sand specimen tests demonstrated the adaptive control system enabled actuator performance that met apparatus requirements stated in the ASTM and JGS test standards for cyclic strength testing, with a maximum error of 2 % recorded as the double-amplitude axial strain exceeded 20 %. This was contrasted with observed performance when using fixed gain PID control, during which the measured load amplitude noticeably dropped below that specified as the sand specimen softened, briefly exceeding limit tolerances set out in ASTM and JGS.

Overall these observations suggest adaptive control provides an improved system for controlling electro-mechanical actuators within load-controlled dynamic cyclic soil testing apparatuses, although further testing on different geo-materials (e.g., clay) is required for additional verification.

## REFERENCES

ASTM. 2013. ASTM D5311/D5311M: Standard test method for load controlled cyclic triaxial strength of soil. ASTM International, West Conshohocken, PA, USA: ASTM International.

Åström, K. J. & Wittenmark, B. 1989. *Adaptive Control*, Addison-Wesley, Wokingham, UK.

Higuchi, T. Hyde, A. F. L. & Yasuhara, K. 2000. Liquefaction criteria for a non-plastic silt. *International Symposium on Coastal Geotechnical Engineering In Practice: Volume One* (Eds: Tsuchida, T.), 33-38. Taylor & Francis, Abingdon, UK.

Hinton, C. E. 1997. Adaptive PID control of dynamic materials-testing machines using remembered stiffness. *Applications of Automation Technology to Fatigue and Fracture Testing and Analysis: Third Volume, ASTM STP 1303* (Eds: Braun, A.A. & Gilbertson, L. N.), 111-119. American Society for Testing and Materials, West Conshohocken, PA, USA: ASTM International.

JGS. 1999. JGS 0541-2000: Method for cyclic undrained triaxial test on soils. The Japanese Geotechnical Society, Tokyo, Japan.

Klotz, U. 2000. *The influence of state on the capacity of driven piles in sands*, City University, London, UK.

Mandeville, D. & Penumadu, D. 2004. True triaxial testing system for clay with proportional-integral-differential (PID) control. *Geotechnical Testing Journal* **27**, 1-12.

O'Reilly, M.P. & Brown, S. F. 1991. *Cyclic Loading of Soils: from theory to design*, Blackie and Son Ltd, Glasgow, UK.

Rees, S. D. 2010. *Effects of fines on the undrained behavior of Christchurch sandy soils*, University of Canterbury, Christchurch, NZ.

Rees, S. D. Le Compte, A. & Snelling, K. 2013. A new tool for the automated travel time analyses of bender element tests. *Proceedings, 18th International Conference on Soil Mechanics and Geotechnical Engineering: Fourth Volume* (Eds: Delage, P., Desrues, J., Frank, R., Puech, A., Schlosser, F.), 2843-2846. Presses des Ponts, Paris, France.