







An Attempt to Evaluate In Situ Dynamic Soil Property by Cyclic Loading Pressuremeter Test

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Abstract. Laboratory experiments, such as cyclic triaxial tests, are generally conducted to evaluate the dynamic behavior of soil for earthquake-proof design. The disturbance and stress release of soil specimens caused by sampling considerably affect the testing results. To avoid sampling disturbance effect, the authors attempted to measure the dynamic soil properties under cyclic loading by directly implementing an in situ pressuremeter test in the borehole. In the feasibility test on loose sand, it was confirmed that cyclic loading was achieved in situ successfully. Besides, in the tests on medium dense sand, hardening behaviors of surrounding soil were observed.

Keywords: Liquefaction · Pressuremeter · In situ testing · Cyclic loading

1 Introduction

Assessing the dynamic behavior of the ground during earthquake is important in the design of foundation ground against liquefaction. In general, laboratory soil tests are performed to evaluate the dynamic behavior of soil. However, many researchers are confronted with the problem of disturbance during sampling and transportation of sand and gravel. Freeze sampling [1], which can minimize the effects of disturbance, is costly and cannot be applied to all investigations. Even less disturbed samples sustain the adverse effect of stress release. Therefore, even if the number of test results is increased, these results do not reach their true values. As a result, ground improvements are sometimes over-constructed especially in liquefaction countermeasures. Accordingly, the authors believe that the development of a technique for evaluating the in situ dynamic soil property is required.

To avoid the effects of sample disturbance, conducting in situ tests is efficient. The standard penetration test (SPT) has been widely researched for liquefaction assessment. The current liquefaction assessment is based on the relationship between undrained cyclic shear strength and N-value that has been derived by Seed (1979) [2] and Seed et al. (1983) [3]. However, the SPT cannot be applied to gravel because of the overestimation problem caused by gravel strike. The cone penetration test (CPT) has also been widely

studied because it is more convenient than the SPT. Seed and Alba (1986) [4] and Shibata and Teparaksa (1988) [5] showed the relationship between undrained cyclic shear strength and cone penetration resistance. The piezocone penetration test (CPTu) can measure pore water pressure in addition to cone penetration. Juang et al. (2008) [6] related the CPTu results to liquefaction history through artificial neural network learning, and Ching and Juang (2011) [7] showed the relationship between the probability of liquefaction occurrence and safety factor. The piezo drive cone test (PDC) [8, 9], which measures the pore water pressure generated by the cone tip in the ground during dynamic penetration, can evaluate the liquefaction safety factor, F_L , and settlement from the measured values. However, CPT, CPTu, and PDC cannot penetrate the hard ground with N-value ≥ 20 . Although the in situ tests are the most promising method, currently, no investigation method can evaluate the dynamic soil properties, such as stiffness degradations whether liquefaction will occur, regardless of soil type.

This study focuses on the pressuremeter test, which has no problems in testing both hard ground and soft ground. The pressuremeter test [10] is an in situ test method to determine the initial pressure (horizontal stress) and shear modulus of the ground from the relationship between the pressure and displacement of the borehole wall by loading the hole with a probe. Many researchers utilize the pressuremeter test to assess the static properties of the ground. Therefore, we have advanced this technique by modifying the conventional monotonic loading test to the cyclic loading test to enable the pressuremeter test to assess the dynamic soil properties. Thus far, few studies have been conducted on pressuremeter tests with cyclic loading. Reiffsteck et al. (2016) [11] endeavored to implement pressuremeter tests with cyclic loading on sandy to clayey soils at approximately 15 sites. Although Reiffsteck et al. (2016) observed strain increase due to cyclic loading in some sections of the ground where liquefaction is a concern, the study did not reach liquefaction assessment. In addition, Kamura and Kazama (2021) [12] conducted the displacement-controlled cyclic pressuremeter test on loose sand where liquefaction is a concern and obtained the softening behavior and cyclic mobility of soil.

Although a study on cyclic loading pressuremeter tests has been conducted, evidence regarding the dynamic behavior of soil using these tests is insufficient. Accordingly, this paper presents the possibility of assessing in situ dynamic soil property using cyclic pressuremeter tests in relation to the potential for judgment of liquefaction occurrence.

2 Pressuremeter Devices

There are two types of cyclic loading paths for pressuremeter tests: the pressure-controlled and displacement-controlled methods. The former can be widely applied to various soil properties. In contrast, the latter cannot be employed because it may not provide adequate pressure to generate sufficient strain in stiff soil. This section describes the test devices for pressure control.

The schematic of pressuremeter devices for cyclic loading is shown in Fig. 1. This device expands a probe with a membrane by supplying water from a controlled automatic pressurizer. The change in the volume of the probe is measured from the water level change in the standpipe. Other than the automatic pressure device, the other instruments utilized are the same as those in a standard pressuremeter test.

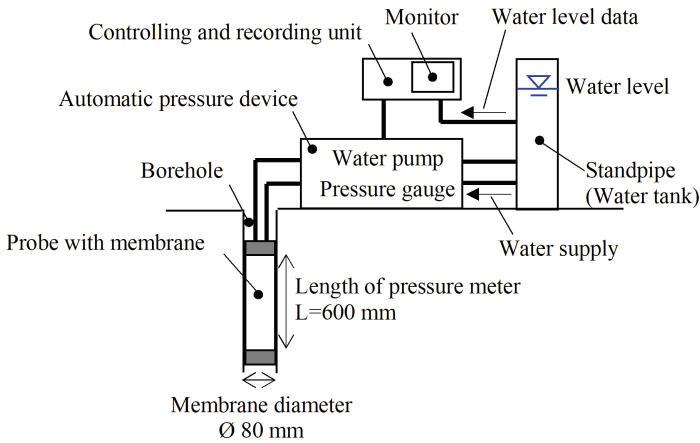


Fig. 1. Schematic of pressuremeter devices for cyclic loading.

3 Feasibility Test in an Outdoor Pit

3.1 Installation and Field Conditions

The authors conducted the feasibility test in a large soil tank made of reinforced concrete. The tank was approximately 2.5 m in height, 9.0 m in width, and 10.0 m in length. It was filled with Ube silica sand No. 6 (relative density: about 60%; permeability coefficient: 7.4×10^{-5} m/s). The probe was installed with pre-burying means into the soil tank. Earth pressure sensors, water pressure sensors, and inclinometers are placed around the probe.

3.2 Result of Cyclic Loading Test Using Pressuremeter

Representative results of the relationship between pressure and radial displacement are shown in Fig. 2, the time history of earth pressure is shown in Fig. 3. The calibrated plot in Fig. 2 indicates the results except for the probe membrane tension. The earth pressure sensor corresponding to the Fig. 3 was located at the center depth as the probe and distance of 30 cm in the horizontal direction. By cyclic loading, the relationship in Fig. 2 exhibits a virtually constant loop shape. As the number of loading increases, the cavity is gradually expanded; the radial displacement is more significant with higher pressure. The earth pressure reacts linearly with the cyclic loading in Fig. 3. The earth pressure only measured less than 1/10 of the loading probe pressure. Accordingly, the authors could confirm that the pressure-controlled cyclic loading had been achieved by using the pressuremeter equipment. In addition, it was found that the spatial extent of influence observed via the cyclic pressuremeter test was very small and limited.

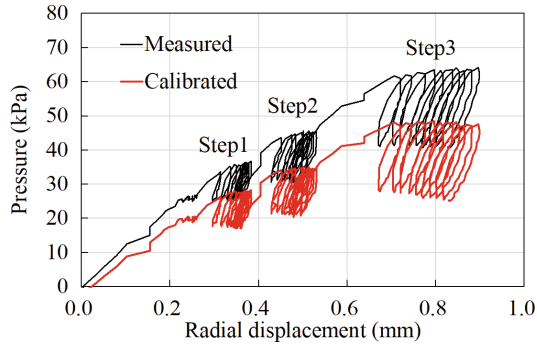


Fig. 2. Relationship between pressure and radial displacement in an outdoor pit.

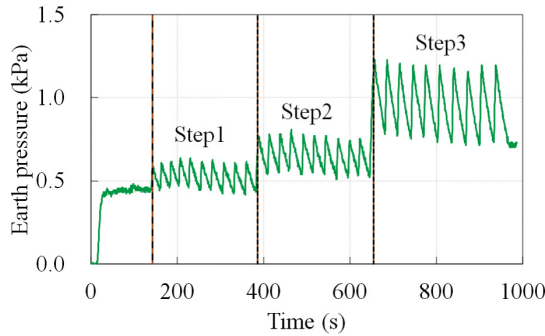


Fig. 3. Time history of earth pressure located at the center depth as the probe.

4 Cyclic Pressuremeter Tests in the Actual Field

4.1 Field Conditions

The authors conducted the cyclic pressuremeter tests to observe the in situ dynamic behavior on the non-liquefiable ground. The authors selected the alluvial lowland site in Sendai, Miyagi, Japan. The site is located on a flooded plain called Sendai Plain, the N -values are relatively large in Fig. 4. The F_C and CSR mean fine grain content and cyclic stress ratio respectively, which were carried out with the specimens sampled from the same borehole.

The cyclic pressuremeter tests were carried out at three depths with different densities and soil types: medium dense sand with $N = 14$, dense sand with $N = 29$, and clay with $N = 3$. These layers have a low potential for liquefaction.

4.2 Testing Procedure

The probe was installed a pre-formed hole means with mud water. The initial probe pressure was corresponding to 1.5 times the effective horizontal stress, which was calculated from the unit weight of soils and the coefficient of earth pressure at rest K_0 ($K_0 = 0.5$),

was applied. This was done to prevent the disturbance and fracture of the borehole and to make initial stress condition. The water injection rate to the probe was set to 1.2 L/min with the loading rate of 0.2–0.5 Hz. The number of cyclic loading was 29 cycles, and the pressure amplitude was set to three cases to obtain the shear modulus in the different stress levels. The loading conditions for each depth are shown in Fig. 5.

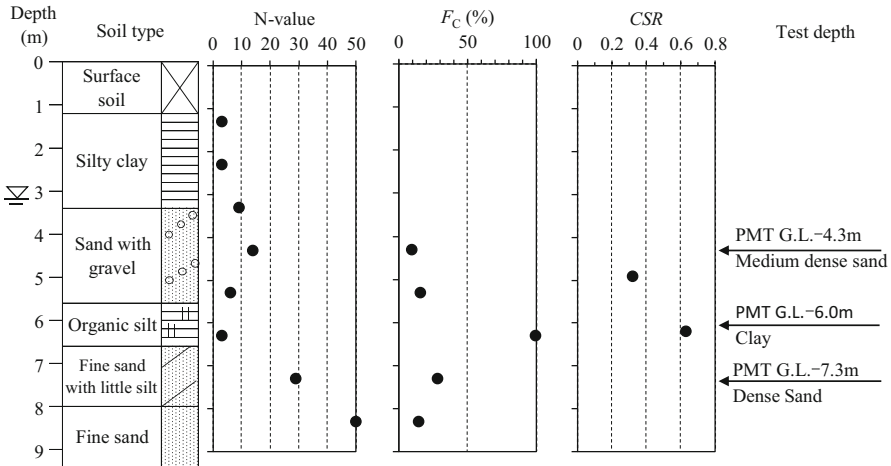


Fig. 4. Field conditions and test depths at the target site in Sendai, Miyagi, Japan.

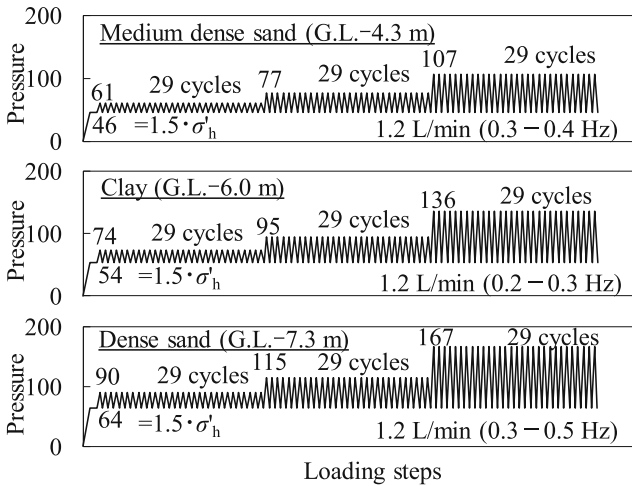


Fig. 5. Loading conditions for each depth.

4.3 Calculation of Shear Strain and Shear Modulus in Assuming an Elastic Material

The shear modulus near the borehole surface is calculated by $G = 1/2 \cdot (\delta p / \delta \varepsilon_c)$, and the radial strain is calculated by $\varepsilon_c = y_c / \rho_0$, based on the thick-walled cylinder theory for elastic materials by Mair et al. (1987) [10]; where G is shear modulus, p is probe pressure, ε_c is radial strain, y_c is radial displacement, ρ_0 is initial radius respectively. In this study, to evaluate the strain level of the obtained shear modulus, the shear strain near the borehole surface is required. Since the circumferential and radial strain are equal and opposite at the borehole wall, probe pressure equals circumferential shear stress [10]. Therefore, the shear strain is calculated from $G = 1/2 \cdot (\delta p / \delta \varepsilon_c)$ and Hooke's law [13] as $\gamma = 2 \cdot \varepsilon_c$, where γ is shear strain.

4.4 Results of Cyclic Loading Test Using Pressuremeter

The relationship between pressure and radial displacement is shown in Fig. 6. The calibrated values mean except for probe membrane tension results. The radial displacement is defined as the relative displacement from the initial step. The set values are the pressure amplitude of the cyclic loading shown in Fig. 5.

The pressure and displacement relationship in Fig. 6 exhibited an almost constant loop shape by cyclic loading in each constant pressure loading step. In the case of clay, as the pressure amplitude in a step increases, the cavity is gradually expanded; the increase of radial displacement is more significant with higher pressure. On the other hand, dense sand showed no significant displacement with increasing pressure amplitude.

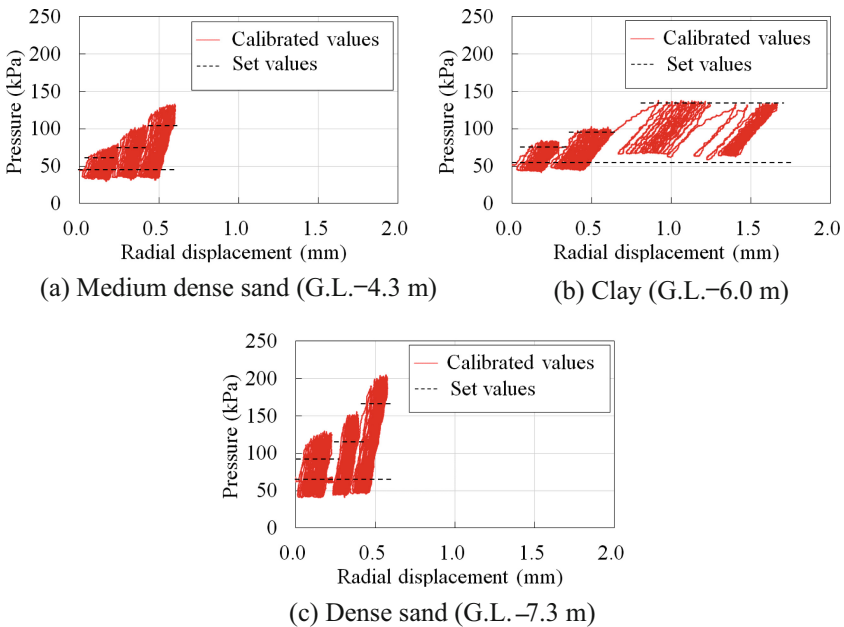


Fig. 6. Relationship between pressure and radial displacement in the actual field.

The relationships between shear modulus and shear strain at certain loading cycles are shown in Fig. 7. The largest shear modulus is obtained on dense sand, followed by medium dense sand, clay, and depends on the N-value and soil type. In addition, as the pressure amplitude increases, the shear strain is expanded in order. The shear strains were obtained in the range of 0.2 to 1.3%, and the shear modulus was obtained at the strain magnitude corresponding to liquefaction occurrence level.

The results of clay showed slight softening behaviors in which the shear modulus decreased with increasing pressure amplitude. On the contrary to this, medium dense sand showed hardening behaviors in which the shear strain and shear modulus increased with increasing pressure amplitude and loading cycles. Furthermore, the shear modulus of dense sand did not change significantly with increasing pressure amplitude. The hardening behaviors indicate that the surrounding soil may have become denser due to cyclic loading under partial drainage condition.

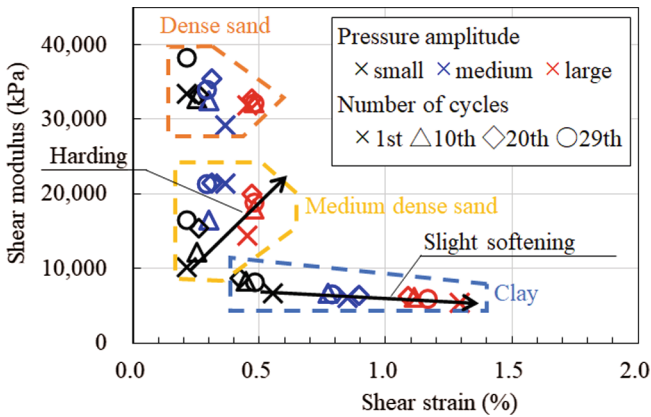


Fig. 7. Relationship between shear modulus and shear strain.

5 Conclusions

In this paper, we reported the results of an attempt to evaluate the in situ dynamic behaviors by cyclic pressuremeter tests. The results and conclusions are as follows.

- The pressure-controlled cyclic loading had been achieved by using the pressuremeter equipment.
- The spatial range of influence observed via the cyclic pressuremeter test was very small and limited, less than 30 cm from the surface of the pressuremeter probe.
- Clay showed slight softening behaviors with increasing pressure amplitude. On the other hand, medium dense sand showed hardening behaviors with increasing pressure amplitude. The latter indicates that the surrounding soil may have become denser due to cyclic loading under partial drainage condition.

In order to increase the applicability, there are the following technical issues:

- Theoretical interpretation of dynamic behavior of ground by cyclic pressuremeter test considering the soils as an elastoplastic material.
- Confirmation of the excess pore water pressure generated by cyclic loading on the liquefied ground.

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References

1. Yoshimi, Y., Hatanaka, M., Oh-oka, H.: Undisturbed sampling of saturated sands by freezing. *Soils Found.* **18**(3), 59–73 (1978)
2. Seed, H.B.: Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes. *ASCE J. Geotech. Eng. Div.* **105**(2), 201–255 (1979)
3. Seed, H.B., Idriss, I.M., Arango, I.: Evaluation of liquefaction potential using field performance data. *J. Geotech. Eng.* **109**(3), 458–482 (1983)
4. Seed, H.B., De Alba, P.: Use of SPT and CPT tests for evaluating the liquefaction resistance of sands. *Use In-Situ Tests Geotech. Eng. Geotech. Special Publ.* **6**, 281–302 (1986)
5. Shibata, T., Teparaksa, W.: Evaluation of liquefaction potentials of soils using cone penetration tests. *Soils Found.* **28**(2), 49–60 (1988)
6. Juang, C.H., Chen, C.-H., Mayne, P.W.: CPTu simplified stress-based model for evaluating soil liquefaction potential. *Soils Found.* **48**(6), 755–770 (2008)
7. Ching, J., Juang, C.H.: Selection among CPTu-based liquefaction models. *Procedia Eng.* **14**, 2576–2584 (2011)
8. Sawada, S., Tsukamoto, Y., Ishihara, K.: Method of dynamic penetration with pore pressure transducer Part 2 results of chamber test. *Japan Natl. Conf. Geotech. Eng.* **39**, 1927–1928 (2004)
9. Sawada, S., Yoshizawa, D., Hiruma, N., Sugano, T., Nakazawa, H.: Evaluation of differential settlement following liquefaction using Piezo Drive Cone. In: *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering: The Academia and Practice of Geotechnical Engineering*, vol. 2, pp. 1064–1067 (2009)
10. Mair, R.J., Wood, D.M.: *Pressuremeter Testing Methods and Interpretation* (1987)
11. Reiffsteck, P., Fanelli, S., Desanneaux, G.: Evolution of deformation parameters during cyclic expansion tests at several experimental test sites. In: *Proceedings of the 5th International Conference on Geotechnical and Geophysical Site Characterisation, ISC 2016*, pp. 791–796 (2016)
12. Kamura, A., Kazama, M.: Assessment of stiffness degradation of soil by in-situ cyclic loading using pressuremeter. In: *6th International Conference on Geotechnical and Geophysical Site Characterization, ISC2020-153* (2021)
13. Timoshenko, S.P., Goodier, J.N.: *Theory of Elasticity* (1934)