Trends in the Standardization of PMT in Japan and Current Utilization

Yasuaki Kawai[1#], Susumu Yamabe[1], Shiro Ohta[1], Keita Mikami[1]
[1]Kawasaki Geological Engineering, 2-11-15 Mita, Minato-ku, Tokyo, Japan
#Corresponding author: kawaiy@kge.co.jp

Abstract

The application of the pressuremeter test (PMT) in Japan has a long history, dating back to the 1950s, primarily for measuring the deformation modulus of the ground. In particular, the lateral subgrade reaction coefficient (K_{ho}) in pile foundation design for buildings is derived from the deformation modulus obtained through the test. In Japan, the PMT is classified as a method that applies uniform load. In contrast, the borehole jack test (BHJ), which applies uniform deformation, has independently evolved to produce similar test results. Both have been standardized as loading tests in Japan. This article presents the characteristics and results of each method, along with comparisons to various ground parameters and proposed conversion methods. In the 2010s, the Japanese Geotechnical Society (JGS) revised its testing method standards in accordance with international standards set by International Organization for Standardization (ISO). In 2025, further revisions are planned to integrate and reorganize these standards, considering the latest domestic application trends, with a focus on drilling methods and repeated loading. This paper summarizes these developments.

RESUME

L'application du test pressiométrique (PMT) au Japon a une longue histoire, qui remonte aux années 1950, principalement pour mesurer le module de déformation du sol.En particulier, le coefficient de réaction latérale de la fondation (K_{ho}) dans la conception des fondations sur pieux pour les bâtiments est dérivé du module de déformation obtenu par le test. Au Japon, le PMT est classé comme une méthode qui applique une charge uniforme. En revanche, le test de déformabilité des forages (BHJ), qui applique une déformation uniforme, a évolué indépendamment pour produire des résultats d'essai similaires. Les deux ont été normalisés en tant qu'essais de chargement au Japon. Cet article présente les caractéristiques et les résultats de chaque méthode, ainsi que des comparaisons avec divers paramètres du sol et des méthodes de conversion proposées.Dans les années 2010, la Société géotechnique japonaise (JGS) a révisé ses normes de méthodes d'essai conformément aux normes internationales établies par l'Organisation internationale de normalisation (ISO). En 2025, de nouvelles révisions sont prévues pour intégrer et réorganiser ces normes, en tenant compte des dernières tendances nationales en matière d'application, en mettant l'accent sur les méthodes de forage et les charges répétées. Cet article résume ces évolutions.

Keywords: PMT, BHJ, lateral subgrade reaction coefficient, deformation modulus, ISO

1. Introduction

The history of pressuremeter tests (PMT) in Japan began in 1959 with the 'Public Works Research Institute-type *K*-value measuring device,' which utilized a 2-meter-long rubber tube and incompressible water as the fluid instead of air (Fukuoka et al. 1959). Later, in 1962, the three-chamber pre-boring pressuremeter (PB-PMT) developed by Ménard was introduced (Mori 1964). At the same time, the one-chamber pressuremeter, an improved version of the 'Token-type K-value measuring device,' was developed by Suyama et al (Suzuya et al. 1964).

The borehole jack test (BHJ) using the constant displacement loading method was developed by Miki in 1963 (Miki 1966) as a high-pressure and ultra-high pressure loading device (KKT) for bedrock, and it continued to evolve through the 1970s and 1980s. In addition, various loading devices were developed for different purposes and applications, such as those for determining the deformation characteristics of soil and ground under repeated stress, and self-boring type loading devices. Later, in the 1990s, a self-boring pressuremeter (SB-PMT) was developed for high-precision deformation measurement due to the deformation characteristics of repeated stress of gravel ground and soft rock, as well as for the deformation and strength characteristics of bedrock (Yoshida et al. 1990, Tani, Nishi and Yoshida 1995, Tani 1995).

2. History of PMT Standards in Japan

The borehole load test, a type of pre-boring test conducted by inserting a measuring tube into a pre-drilled test hole, was first standardized in the JGS standards in 1995 including the single-chamber and three-chamber types with a uniform loading method, as well as the constant deformation load method (JSCE of Japan 1959).

The interpretation of the results based on the latest studies, the range of applicable ground including bedrock, and the appropriateness of the load retention time have been added in. the “Pressuremeter test for bedrock (JGS3531-2004)” was standardized in 2004 (JSCE of Japan 2006). In the standard, two approaches are presented for interpreting the test results of bedrock deformation characteristics: one as an "index-type" and the other as a "mechanical property-type". Most tests conducted in Japan before 2004 were the "index-type", whereas the "mechanical property-type" requires special procedures as self-boring, interpretation of results through theoretical analysis, and specific assumptions.

In the 2011 revision, the test was classified into “Rock pressuremeter test (JGS3531-2004)” and “Borehole lateral load test (JGS1421-2003)”, and from the 2012 revision onwards, considering the alignment with international standards and trends, the "constant displacement loading method" and the "uniform loading method" were consolidated into the "index-type" and the "mechanical property-type", resulting in a classification of three types. From 2025 onwards, the “mechanical property-type” is planned to be subdivided into a pre-boring type and a self-boring type as shown in Figure 1.

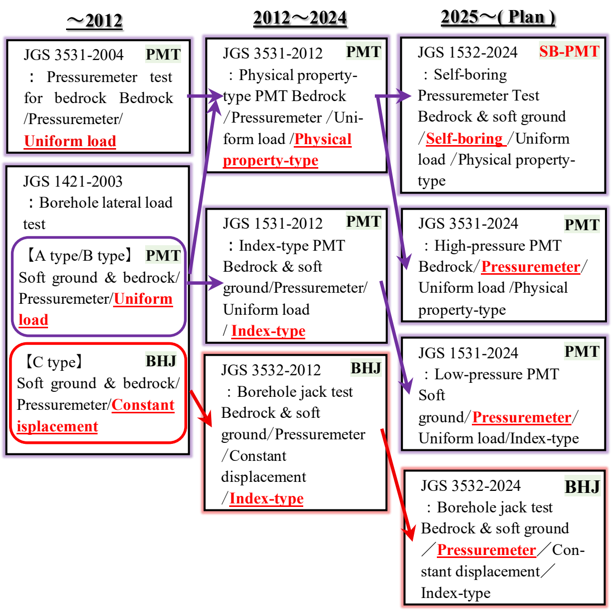

Figure 1. Flow of JGS Standard Revisions

3. Types and characteristics of borehole load tests

In Japan, borehole load tests are classified into pressuremeter tests (PMT), which apply a uniform loading method, and borehole jack tests (BHJ), which apply a constant displacement loading method, based on the difference of loading methods.

3.1 Types of borehole load tests

The main purpose of the borehole load test is to determine the lateral soil reaction coefficient K_{h0} in foundation structure design in Japan. Based on coherence and trends of ISO in this text, the standards were revised to include as “Pressuremeter test to evaluate index values of the ground (JGS1531)” corresponding to “ISO22476-4: Prebored pressuremeter test by Ménard procedure”, “Pressuremeter test to evaluate mechanical properties (JGS3531)” corresponding to “ISO22476-5: Prebored pressuremeter test”, and “Borehole Jack Test (JGS3532)” corresponding to “ISO22476-7:Borehole jack test”.

3.2. Characteristics of uniform loading method and constant displacement loading method

The “PMT for obtaining index values for the ground (index-type)” and the “pressure meter test for evaluating the mechanical physical properties of the ground (mechanical property-type)” are classified as the uniform load loading method, which applies uniform pressure to the borehole wall to obtain the deformation characteristics of the ground.

The “BHJ” is classified as the uniform displacement loading method, which applies a rigid loading plate to the borehole wall to obtain the deformation characteristics of the ground.

3.2.1. Uniform loading method

The test equipment is relatively easy to use, and it has been widely used in Japan. However, there have been many cases of the rubber tube at the loading section bursting due to the bore wall conditions and the loading pressure. The PMT (single-chamber type) is used as the test equipment as shown in Figure 2.

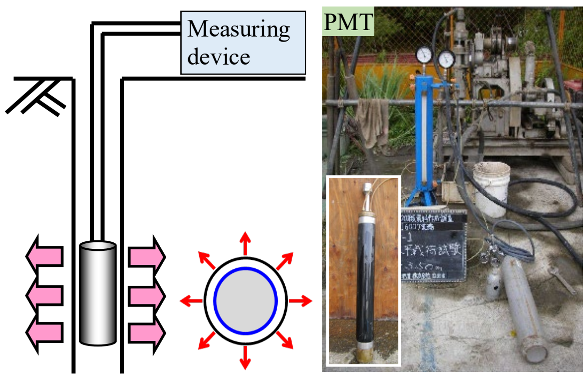

Figure 2. Diagram of the uniform loading method

The “mechanical property-type” is a method of evaluation based on a model that interprets the test results as a boundary value problem and assumes that the test borehole is a perfect circle with no disturbance to the hole wall and that the plane strain and axisymmetric conditions are satisfied. The SB-PMT is mainly used to minimize the effects of loose or disturbed borehole walls in Japan. In recent years, many research cases have been reported on this method. The pressuremeter (three-chamber type) is used for the test.

3.2.2. Constant displacement loading method

BHJ is a method of applying pressure to the ground surface in constant displacement using a rigid loading plate refer to Figure 3. In reality, the pressure applied to the borehole wall is not uniform due to the condition of the borehole wall, and the loading pressure is set to the average pressure applied to the borehole wall surface due to the complex boundary conditions. Additionally, as shown in Figure 3, the non-uniform loading direction allows for the evaluation of ground anisotropy. Furthermore, the high maximum loading pressure enables its application to stiff ground. However, although the reason remains unclear, its usage has been notably limited in recent years.

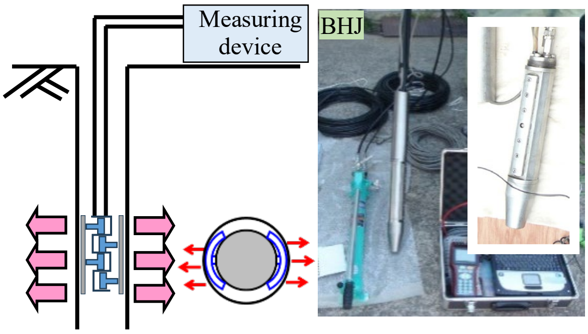

Figure 3. Diagram of the constant displacement loading method

4. Comparison of the results of measuring the deformation modulus, E

4.1. Comparison of deformation modulus, E based on differences in testing equipment

The deformation modulus, *E* obtained from the index-type can be calculated from the intermediate radius of the interval used to determine the linear slope of the relationship between the effective borehole wall pressure and the displacement of the borehole plane. Figure 4 shows the curves representing the relationship between the effective borehole wall pressure *P* and the displacement r of the main cell (*P-r* curve), as well as the relationship between the effective borehole wall pressure *P* and the creep displacement Δr (*P*-Δr curve). A comparative experiment between single-chamber and three-chamber PMTs was reported by Suyama et al (1964) and Tayama et al. (1966), and the results showed a difference of about 7%. However, considering the errors under conditions such as the heterogeneity of the strata observed in soft ground, local irregularities in the test hole, and disturbances to the borehole wall, as well as the precision required for design, it can be concluded that both methods yield approximately the consistent deformation modulus.

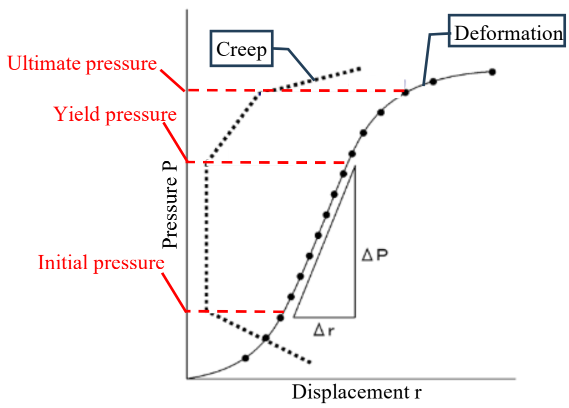

Figure 4. Relationship between effective cavity pressure and displacement of cavity plane, and the relationship between effective cavity pressure and creep amount (Translated from the original figure into English with some additions) (JSCE 2013)

The difference between the two test devices lies in the approach used to calculate the displacement of the loading cell. The single-chamber type calculates the displacement from the entire surface area of the loading cell. The three-chamber type divides the loading section into three chambers (upper, middle, and lower), and those are expanded at the same pressure. Then the displacement of the mail cell in the middle chamber is determined.

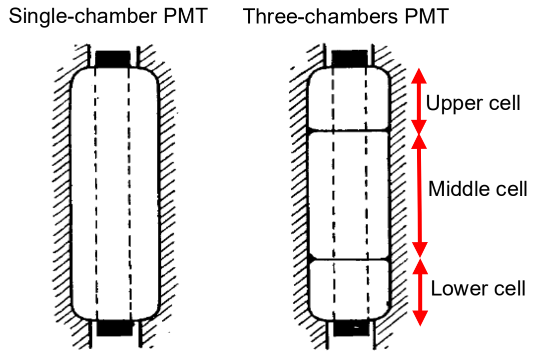

Figure 5. Diagrams of the loading section for the single-chamber PMT and three-chamber types PMT (Translated from the original figure into English)

4.2. Comparison of test results by PMT and BHJ

Yahagi et al. (1972) examined the validity of measurement results from various borehole load tests. The target ground is a soft alluvial silt layer, and a comparison between the results of the PMT (single-chamber type) and BHJ showed almost identical in the test results. Figure 6 shows the relationship between the test results of the PMT (single-chamber type) and BHJ. In this report, 10 additional data points comparing the results of the PMT (single-chamber type) and the BHJ were included. As a result, while the deformation modulus, *E* obtained from the BHJ was higher in some cases, it was generally confirmed that there was no significant difference in the values.

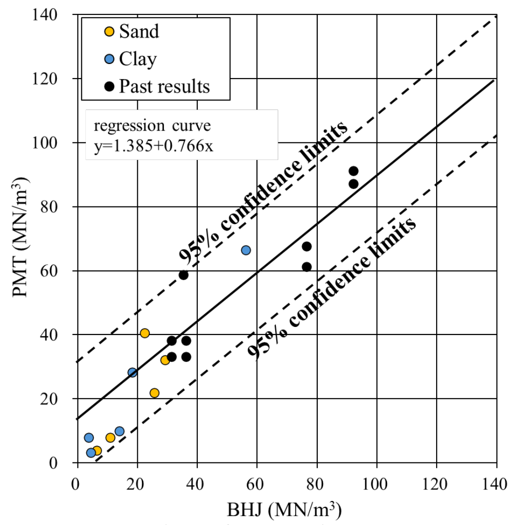

Figure 6. Comparison of PMT and BHJ measurement results (Translated from the original figure into English with some additional data)

5. Comparison with geotechnical mechanical properties obtained from other survey and testing methods

5.1. Relationship with the standard penetration test (SPT)

There are many examples of comparisons between the deformation modulus, *E* obtained from the borehole load test and the *N*-value of the SPT, and Figure 7 is one example (Yoshinaka 1968). Regardless of the ground material, the relationship E=700N (kN/m^2) is approximately valid (Tsuchiya 1980). The N-value obtained from the SPT is defined as the number of blows required to penetrate 30cm into the ground using a cylindrical sampler with 81.0 cm in total length and 5.1 cm in outer diameter setting at the measurement location, and a 63.5 kg steel hammer dropped freely from a height of 75 cm (JIS A 1219:2023).

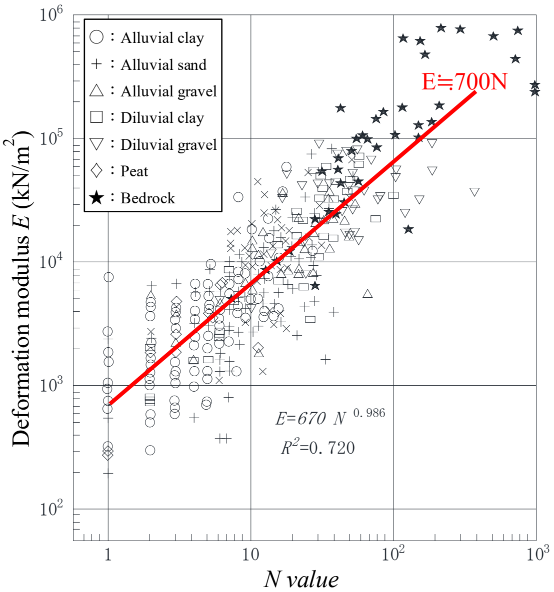

Figure 7. Relationship between deformation modulus and *N*-value obtained from borehole load test (Translated from the original figure into English. Approximate straight-line is added)

5.2. Relationship with the plate load test

Comparative tests between the plate loading test and the borehole load test were conducted on sandy ground and Kanto loam (volcanic cohesive soil) at the same depth and loading direction (Tsuchiya 1980). It was confirmed that the deformation modulus obtained from the plate loading test was approximately three times that of the borehole load test. Similar comparisons have been made with other deformation modules, and it has been reported that the deformation modulus obtained from the BHJ is often smaller than those obtained from plate loading tests. On the other hand, Figure 8 shows an example of a comparison between the deformation modulus obtained from the BHJ and that obtained from the plate loading test for bedrock. As the rigidity of the bedrock increases, the deformation modulus obtained from the plate load test tends to decrease relatively. Therefore, when estimating the deformation modulus of the plate loading test from the BHJ results, it is necessary to make corrections based on the rigidity of the target ground, as shown in Figure 8.

As an evaluation of the deformation characteristics of foundation bedrock for large structures, which are generally evaluated based on the results of plate loading tests, and the design values are obtained from the conversion relationship shown in Figure 8. On the other hand, the BHJ, which can be easily conducted even at greater depths, is positioned as an "index-type test" that complements and supplements the results of the plate load test (JSCE of Japan 2001,Matsumoto et al. 1983, Tokumaru et al.2000, Nagatsu et al. 1987, Saito et al. 1976, Takeuchi et al. 1976).

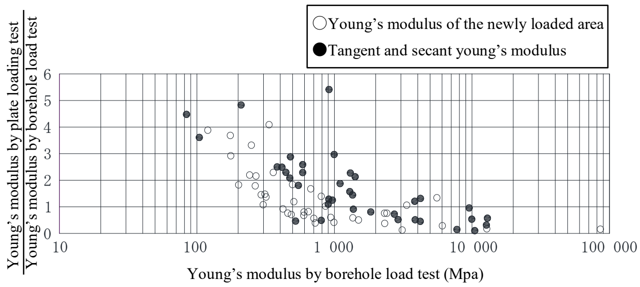

Figure 8. Relationship between deformation modulus from borehole load test and deformation modulus from plate load test (Translated from the original figure into English with some additions)

5.3. Comparison with *E* obtained from laboratory element tests

In order to evaluate the deformation modulus, *E* obtained from the BHJ, a comparative study has been conducted with the deformation modulus, *E* obtained from triaxial compression tests and uniaxial compression tests. Figure 9 shows the relationship between the deformation modulus E obtained from triaxial compression tests and unconfined compression tests conducted on samples taken from the same depth as the borehole load test. (Yoshinaka 1968). The triaxial compression tests were conducted under lateral pressure condition corresponding to the sampling depth of the specimen, perhaps without local guage instrument, and elastic modulus were obtained from ordinary method at that time. Moreover, as shown in Figure 9, the results of borehole load tests and laboratory element tests are nearly consistent, regardless of the type of soil material.

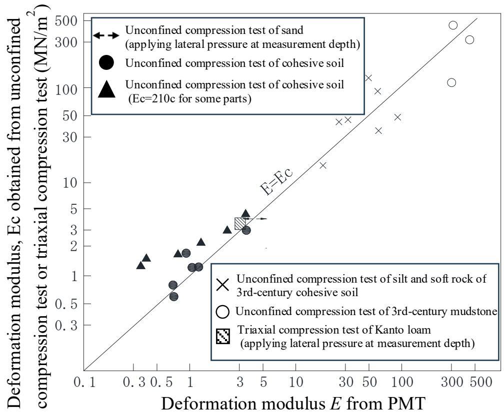

Figure 9. Relationship between deformation moduli obtained from borehole load tests and laboratory tests (Translated from the original figure into English)

6. Comparison of shear modulus dependency on strain levels

In the cyclic borehole load test, the shear modulus *G* at different strain levels can be obtained at each level, showing the strain dependency of shear modulus (Sugawara et al. 1991). Figure 10 shows a case study where the strain dependency of the shear modulus G_{UR} soils to moderately hard rock was measured using the PMT (Sakurai et al. 2006.).

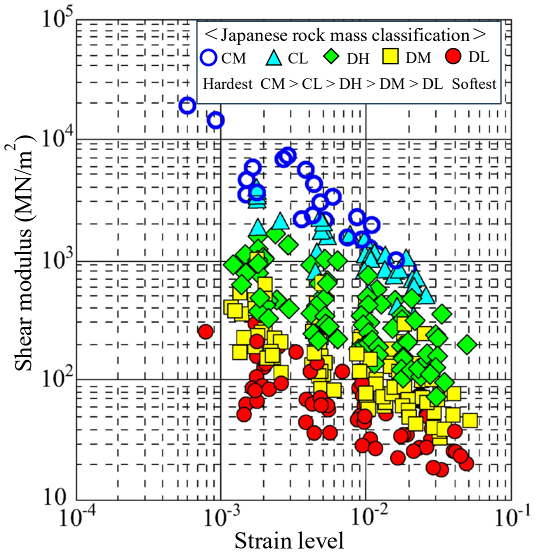

Figure 10. Relationship between strain dependency of shear modulus G_{UR} in cyclic loading section by PMT (Translated from the original figure into English with some additions)

In addition, the shear modulus G_{UR} of the cyclic loading section obtained from the PMT is compared with the shear modulus *G* obtained from laboratory tests, PS logging, etc., and the evaluation was done considering strain levels. Figure 11 is a typical example. The shear modulus *G* obtained from the PMT is located in the strain range around 10-3, but it is consistent with the shear modulus *G* obtained from the laboratory test results (Tani et al. 1994).

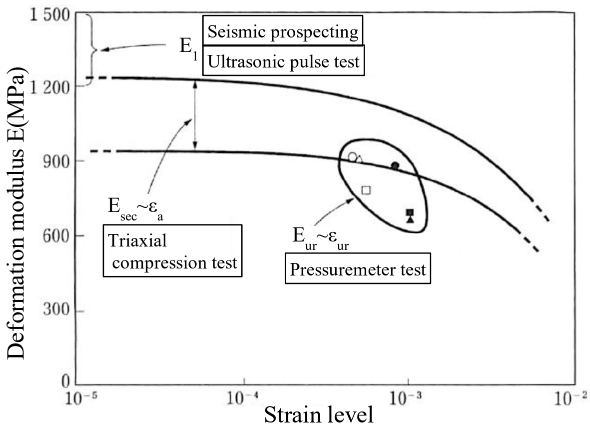

Figure 11. Relationship between deformation moduli obtained from laboratory tests for borehole load tests and various in-situ tests (Translated from the original figure into English)

Figure 12 presents the secant Young's moduli, determined from the slopes of stress–strain curves obtained through various in-situ tests conducted on the Kazusa Group (consolidated silt) in Japan, along with the corresponding results from triaxial compression tests (Tatsuoka et al. 1997). The deformation modulus depends on the strain level, so the value of the deformation modulus differs depending on the magnitude of the strain level that occurs in the bedrock during testing, but this figure shows that it can be interpreted in a unified manner if the strain level dependence of the rigidity is taken into account. This type of examination requires "mechanical property-type" testing and the results of the PMT correspond to the strain level in the order of 10^{-4} to 10^{-3}.

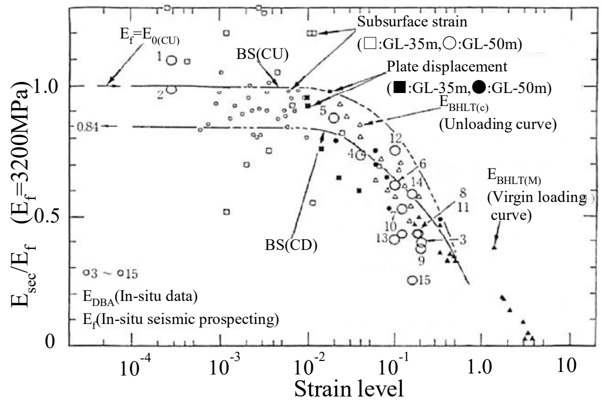

Figure 12. Relationship between deformation modulus and strain level obtained from various deformation tests (Translated from the original figure into English)

The value of the deformation module obtained from the initial gradient of the pressuremeter curve is extremely sensitive to disturbances in the borehole wall, and it is said to underestimate the actual deformation modulus of the ground (Mori et al. 1981.). In contrast, the shear modulus G_{UR} in the cyclic loading section during unloading and reloading is less affected by borehole wall disturbances and stress release, it is considered a more reliable indicator. Additionally, it has been pointed out that the shear modulus G_{UR} in the cyclic loading section depends on the magnitude of the strain during the unloading and reloading loop.

Research on the relationship between strain levels and the shear modulus G_{UR} in the cyclic loading section has also been actively conducted. One approach involves performing multiple cycles of unloading and reloading with different strain amplitudes during a single borehole load test. This aims to comprehensively understand the relationship between strain levels and the shear modulus G_{UR} in the cyclic loading section.

7. Future trends in loading tests in Japan

7.1. Application of the PMT

In seismic countries like Japan, understanding the dynamic deformation characteristics of the foundation ground is critical. In recent years, research on the dynamic deformation characteristics of ground during earthquakes and the potential for liquefaction has been advancing through repeated loading tests using the PMT, as studied by Kazama et al. (Azuno et al. 2024, Kamura and Kazama 2021).

Additionally, with future revisions of the JGS standards, the widespread use of SB-PMT is anticipated. Particularly, in the case of geotechnical surveys for offshore wind power generation projects, the deformation modulus, *E* obtained using the "index-type" may be affected by the loosening and disturbance of the borehole wall, which may affect the test results. Therefore, SB-PMT, which minimizes these effects, is expected to provide a more accurate understanding of deformation characteristics.

7.2. Application for BHJ

In order to understand the deformation characteristics of bedrock, it is necessary to take into account the anisotropy of the bedding, foliation, and jointing. Therefore, Kawakubo et al. (2022) proposed a method for evaluating the anisotropy of bedrock using BHJ, in which a formula for calculating the displacement of the borehole wall is derived from the exact solution of elasticity, and Young's modulus is calculated by inverse analysis, taking anisotropy into account. Additionally, in measurements on reclaimed land, where the soil layers are mixed with sand and waste materials in a disorganized manner, using the PMT may result in damage to the loading section (rubber tube). Therefore, BHJ with a larger loading plate is utilized to prevent such issues.

7.3. Application of other borehole load tests

In Japan, several borehole load tests are not yet standardized, including the borehole local load test (GoTEN), shear friction tests, and push-in borehole load tests.

The GoTEN is a kind of borehole load test using BHJ apparatus. The test method involves applying point loading to the borehole wall after core drilling to measure the mechanical properties at different depths of the target object. In Japan, it has a solid track record, primarily in the deterioration diagnosis of concrete structures, and it can be used to estimate the compressive strength and static elasticity modulus of concrete. Currently, research is being conducted on its applicability for evaluating the mechanical properties of bedrock and for assessing the deterioration of concrete damaged by fire.

The shear friction test is a method used to determine the shear strength and deformation characteristics of in-situ soils using a borehole. This test has been standardized by the Japan Highway Public Corporation as the In-situ Shear Friction Test (SBIFT) in Japan. SBIFT is conducted by self-boring the ground without loosening it, and it involves probing with expansion and shear to determine the shear strength and deformation characteristics of the ground.

8. Conclusions and Remarks

In Japan, PMT has been used since the 1950s to measure the deformation modulus of the ground. In addition, BHJ has evolved uniquely in Japan as a test that produces results in consistent with PMT.

Currently, two types of PMT, index-type and mechanical property-type, and BHJ are standardized in Japan. In the future, further revisions are planned to integrate and reorganize these standards, considering the latest domestic application trends, with a focus on drilling methods and repeated loading.

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