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Quality assessment of in-situ cement stabilized soil by using inserting-type needle penetration apparatus

Évaluation de la qualité du sol stabilisé au ciment in situ à l'aide d'un appareil de pénétration d'aiguille de type à insertion

Hiroyasu Ishii[1)] Makiko Kobayashi[1)] & Kiyonobu Kasama[2)]
1) *Advanced Center of Technology, Taisei Cooperation, Yokohama, Japan*
2) *School of Environmental and Society, Tokyo Institute of Technology, Tokyo, Japan*

ABSTRACT: Apart from conventional quality assessment methods for cement stabilized soils typically basing on unconfined compressive strength (q_u), we have room to invent new methods by taking advantage of recent advancements on mechanical/electronic components and data processing technology. The present research includes the development of an "inserting-type" needle penetration apparatus to semi-automatically measure needle penetration load and penetration length in boreholes. This can identify the penetration rates (N_p) quickly and accurately at multiple points in practice. In this paper, we firstly present trial measurement results conducted at 675 points in three boreholes. we have examined the relationships between penetration load and penetration length, as well as the variations in N_p through the boreholes. We then examine the applicability of two conversion formulae to estimate 27 q_us based on the obtained N_ps. Both formulae, respectively offered by another researcher and proposed by the authors, reasonably reproduce estimated q_us, with better versatility by the latter.

RÉSUMÉ : Outre les méthodes conventionnelles d'évaluation de la qualité des sols stabilisés au ciment, basées généralement sur la résistance à la compression non confinée (q_u), nous avons la possibilité d'inventer de nouvelles méthodes en tirant parti des avancées récentes sur les composants mécaniques/électroniques et la technologie de traitement des données. La présente recherche comprend le développement d'un appareil de pénétration d'aiguille de « type à insertion » pour mesurer semi-automatiquement la charge de pénétration de l'aiguille et la longueur de pénétration dans les trous de forage. Cela peut identifier les taux de pénétration (N_p) rapidement et avec précision à plusieurs points dans la pratique. Dans cet article, nous présentons dans un premier temps les résultats de mesures d'essais réalisés en 675 points dans trois forages. nous avons examiné les relations entre la charge de pénétration et la longueur de pénétration, ainsi que les variations de N_p à travers les forages. Nous examinons ensuite l'applicabilité de deux formules de conversion pour estimer 27 q_us sur la base des N_p obtenus. Les deux formules, respectivement proposées par un autre chercheur et proposées par les auteurs, reproduisent raisonnablement les q_u estimés, avec une meilleure polyvalence par ces derniers..

KEYWORDS: cement stabilized soil; needle penetration test; unconfined compressive strength.

1 INTRODUCTION

In-situ ground stirring with stabilizing agents such as cement and lime is a typical ground improvement method which has been and will be widely used as an effective measure against ground damages. Recently, practical works are significantly advanced by introducing information and communication technologies in terms of machine operation as well as data acquisitions of operational records.

The present work by the authors deals with quality assessment of the cement stabilized soils using inserting-type of needle penetration tests. By utilizing the assessment method proposed, we can obtain needle penetration resistance at a number of points; the authors believe that quality assessment can be conducted more effectively and quickly than that by employing conventional unconfined compressive strength (q_u) tests.

In this paper, a case study of the new assessment on cement stabilized soil is presented. Firstly, the methodology of the study as well as an inserting-type needle penetration apparatus is introduced. Secondly, obtained data are shown to clarify how the method works for detailed assessments. Finally discussed are the conversion formulae to estimate q_u based on the obtained needle penetration resistance.

2 METHODOLOGY

2.1 *Preparation of cement stabilized soil*

A stabilized soil column with 1.2 m in diameter and 1.0 m in height was created by a mechanically stirring method on site (see Figure 1). The stirring method developed by the authors has a unique collapsible stirring blade which contributes to obstacle avoidance and inclined operation (Fujiwara et al. 2016). In preparation of the experimental ground, after digging the ground in a pit shape to a depth of 1.2 m, purchased mountain sand was backfilled and lightly compacted with a backhoe in layers. After fully backfilled to the ground surface, the area was covered by a 0.5 m thick banking.

In the in-situ stirring work, pre-mixing was performed from the ground surface to a depth of 1 m with mixing water discharged horizontally from the base of the stirring blade. After that, in place of mixing water, cement slurry was discharged with a cement water ratio of 1:1 at 20 L/min. Stirring work was then conducted by pulling up/pushing down the stirring blade with a rotational speed of 30 rpm and a vertical movement speed of 1 min/m. The above procedure refers to the standard construction method aiming for the unconfined compressive strength of several hundred kN/m^2.

Immediately after the completion of the stirring work, the following tasks were carried out to provide a measurement hole for "inserting-type" needle penetration tests. First, the 0.5 m banking was removed to expose the upper surface of the stirred part, and three polyvinyl chloride pipes (PVC, outer diameter 114 mm) were vertically installed with a backhoe bucket into the middle positions in the radial direction. Prior to the installation, the tip of the PVC pipe was processed into a tapered shape, and the outer and inner surfaces were coated with a lubricant, so that the friction between the stirred soil and the pipe surfaces was reduced. As a result, the inside of the pipe was fully filled with the stirred soil, whereas the inside soil surface reached almost the same height as the outside.

After conducting the above preparation work, each PVC pipe was rotated and edge cutting was performed for a few days so that the PVC pipes and the stirred soil would not adhere to each other (see Figure 2(a)). After that the curing period was secured for 28 days to allow the stirred soil to be stabilized in place. Subsequent to the field preparation, in consideration of ensuring the efficiency of the measurement work and utilizing the stabilized body in a separate study, the whole stabilized body was dug up and moved to a room controlled at 20°C. There, the PVC pipes were pulled out from the stabilized body, and the remaining holes were filled with a wet waste cloth until the measurement experiment at the age of 56 days.

From the stabilized soil left in the PVC pipes, specimens with a diameter of 50 mm and a height of 100 mm were secured for a series of unconfined compression tests. Each PVC pipe was divided into nine pieces of a length of approximately 110 mm each, and a total of 27 specimens were obtained (see Figure 2(b)).

2.2 *Use of inserting-type needle penetration device*

For the assessment, we used an "inserting-type" needle penetration apparatus (see Figures 3 and 4) developed by the authors (Kobayashi et al. 2019). Needle penetration resistance is measured in investigation holes with an inner diameter of approximately 120 mm. It is known that needle penetration rate N_p (N/mm), which can be calculated from needle penetration resistance and penetration length, has a good correlation with strength characteristics (Ngan 2011); the measurement data representing the strength characteristics can be more quickly obtained with the needle penetration apparatus developed than that by q_u, since the measurement work is easy.

On the other hand, "portable type" and "desktop type" are indicated in the standards of the Japanese Geotechnical Society (2014) as conventional methods to obtain needle penetration resistance. The "portable type" is superior due to its quickness of measurement data acquisition, but it has the disadvantage of containing many measurement errors included in manual operations. In the "inserting-type", the device is fixed by pressing it to the inner wall of the investigation hole with a reaction force arm, and the measurement is performed at a specified penetration speed (20 mm/min), so the measurement error can be minimized according to the "desktop type" method. Consequently, the inserting-type can be considered as a method that achieves both quickness and accuracy.

3 RESULTS AND DISCUSSION

3.1 *Needle penetration resistance*

In the measurement of the inserting-type needle penetration resistance, 5 depths in 5 directions were grouped as 1 unit, referring to one q_u specimen, with 20 mm intervals in depth and 72° in direction. Accordingly, 9 units per hole counted 9 × 3 = 27 units for total consisting of 5 × 5 × 27 = 675 points of needle penetration resistance measurements. Here, 25 points per unit are considered enough to calculate coefficients of variations in consideration of the examination in terms of the conversion formula described later.

The first figure from the left in Figure 5 shows the distribution of N_p with depth obtained in the three holes (BH-A, B, C) with

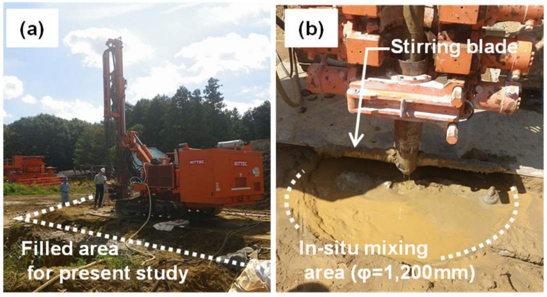

Figure 1. In-situ cement mixing in the field: (a) overview, (b) stirring blade and mixing area.

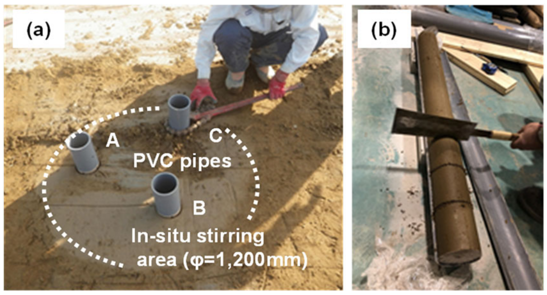

Figure 2. Use of PVC pipes to create investigation holes and to obtain q_u specimen: (a) PVC pipes vertically set in a stirring area, (b) sample collection from a PVC pipe.

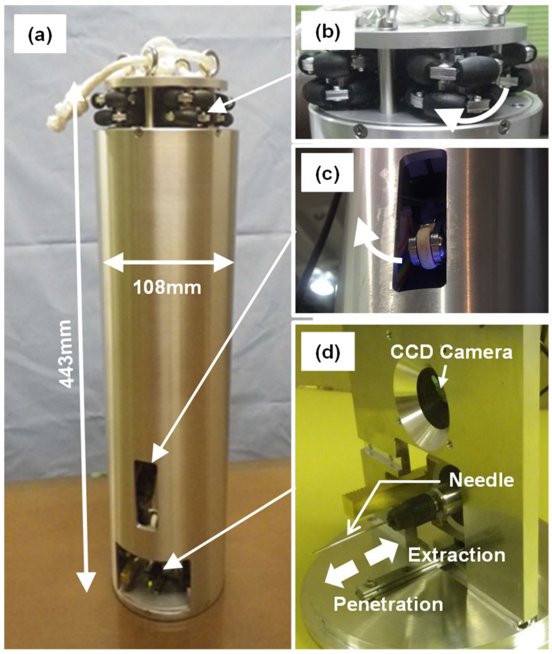

Figure 3. Inserting-type needle penetration apparatus: (a) the front view, (b) orientation wheels, (c) reaction force arm (d) penetration and monitoring device.

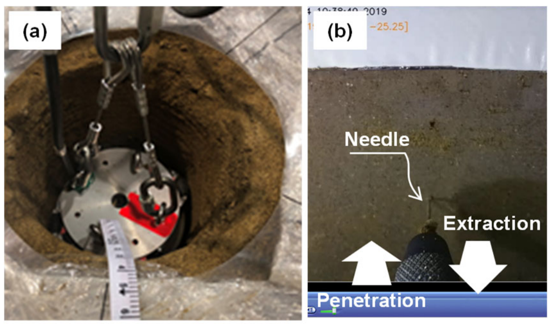

Figure 4. Insertion-type needle penetration testing: (a) view over measuring hole, (b) captured image during penetration and extraction.

the N_p ranging from 0 to 40 N/mm, which is covering all measurement results. The other three in Figure 5 respectively show the same results from the three holes, but magnified for N_p ranging from 0 to 4 N/mm. From these results, the following observations may be made:

i) N_p is dominant at values about 0 to 3 N/mm for all holes.
ii) Measured values appear prominent in the lower layer G.L.-900 to 1,000 mm and the upper layer G.L.0 to -200 mm.
iii) From the magnified distribution, it can be seen that the N_p near G.L.-200 to 300 mm tends to be larger than those near the upper and lower ends.

When the relationships between the penetration resistance and the penetration lengths were confirmed with respect to observation i) above, they usually showed an increasing tendency as shown in the left figure in Figure 6 (BH-A, Unit3, SN12). On the other hand, with the prominent values, the penetration resistances decreased significantly after the peak value, as shown in the right figure in Figure 6 (BH-A, Unit3, SN19). This suggests that the needle tip came into contact with solid materials; it is possible that gravel was mixed from the foundation ground to the mountain sand near the lower end, and that insufficiently stirred cement slurry remained at the upper end. From the results of all 675 points, it was confirmed that the penetration resistance tends to increase with the penetration length when N_p is approximately 2 N/mm or below. Noteworthy is the fact that such confirmation and analysis cannot be made in assessment using the portable needle penetration apparatus, in which the penetration resistance is specified only from the maximum contraction amount. Contrarily, in case of assessment using the desktop type, cutting out of the specimen and measurement with the loading device would have to be repeated in laboratory that requires heavy effort. It is therefore clear that the in-situ inserting type is advantageous in the acquisition of the measured values.

Based on the above discussion, results with N_p exceeding 2N/mm were set aside for further estimation, and the results of the remaining 622 points were summarized as a frequency distribution for each unit. The results of BH-A thus evaluated are shown in Figure 7. The coefficients of variation are below 30% in the middle depth of A-4 to 7, whereas the degree of variation is large in the upper and lower ends.

3.2 *Conversion formula*

Used often in practice and research is the method to estimate the unconfined compressive strength q_u of soft rocks and cement-improved soil by utilizing the correlation with the needle penetration resistance N_p on both logarithmic axes (Kitazume 2003, Ngan 2011). It is common to associate q_u with one N_p measurement, but the authors propose here a method for evaluating q_u with 25 N_p measurements. This was inspired by the theoretical interpretation that the unconfined compressive strength decreases according to the variation in the strength of the evaluation element in the cylindrical specimen and the size of the specimen as shown in the study by Omine et al. (2005). In this paper, the following two formulae for q^u (kN/m^2) are used for the examination:

$$\log(q_u) = 1.043\log(Q_N) - 1.158 \quad (1)$$

$$\log(q_u) = 0.896\log(N_{p_{ave}}) + 2.557 - 2.230(N_{pcov})^{1.934} \quad (2)$$

Eq. 1 is based on the previous study (Kitazume 2003), in which Q_N is calculated based on the penetration resistance (N) at the 5 mm penetration. The two coefficients are set based on the cement stabilized soil for Kawasaki clay. On the other hand, Eq. 2 is the formula proposed by the authors; N_{pave} and N_{pCOV} are the average values, taking into account the variation in coefficient N_p (N/mm) based on 25 points measurements per unit. The

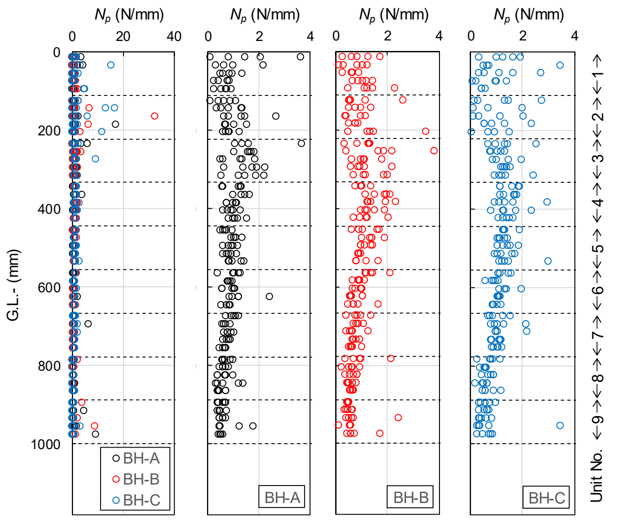

Figure 5. Vertical distributions of needle penetration resistance: overall borehole results with 0 ~ 40 in N_p range (first from the left) and individual borehole results with 0 ~ 4 in magnified N_p range

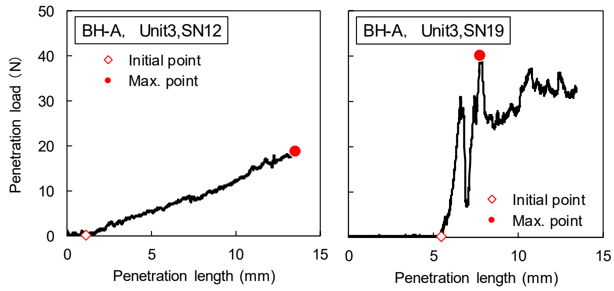

Figure 6. Examples of penetration length and penetration load curve: a result showing increment tendency(left) and significant decrease (right).

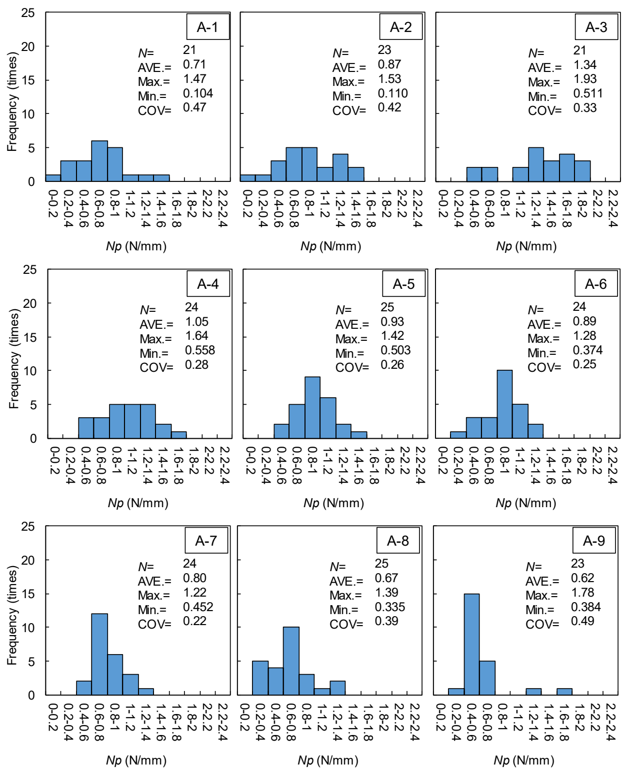

Figure 7. Histograms of N_p as per estimation units of BH-A

coefficients are determined by a wide variety of data including in-situ stirring and compaction stabilization treatment of loam, clay, and sandy soil (Kobayashi 2019). The first and second terms on the right side in Eq. 2 have the same format as Eq.1; the proposed formula is characterized by adding the third term. After identifying the correlation only for data with negligible variation (with N_{pCOV} less than 10%), the third term is fixed to gradually correct the estimated values according to the N_{pCOV}.

Table 1 shows the estimated strength values by each conversion formula together with those measured and confirmed by the specimens collected from the PVC pipes. At the same time, Figure 8 compares the distribution of the measured and estimated values with depth. It may be seen that at the same level the results by Eq.2 are closer to the measured values than by Eq.1. It may also be seen that the results obtained from Eq.1 previously evaluated for a specific soil type (Kawasaki clay) are in a similar consistency as those with Eq.2. The main difference is that Eq.2 provides relatively good estimation accuracy without specifying type of soil to be evaluated, and that it is more versatile and advantageous as a conversion formula.

4 CONCLUSIONS

In this paper, through the inserting-type needle penetration apparatus proposed by the authors, the distribution of strength characteristics with depth in the cement stabilized soil was verified by measurement of needle penetration resistance. The suitability of measured values and the applicability of conversion formulae to estimate q_u were also examined for both existing conversion formula and that proposed by the authors. It became clear that the proposed formula in this paper is more advantageous and versatile, since the application is not restricted within a specific type of soil.

Regarding the verification of cement improved soil strength in practice, the authors believe that the use of needle penetration tests is more practical in terms of acquiring and evaluating large amounts of data, as well as automating these tasks. We would like to promote its utilization as a quality evaluation method along with the conventional unconfined compressive strength tests.

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Table 1. Histograms of N_p as per estimation units of BH-A

BH & Unit.	$N_{pAve.}$ (N/mm)	N_{pCOV}	Q_N※ (N/5mm)	Estimated q_u (kN/m²) Eq.1	Estimated q_u (kN/m²) Eq.2	q_u (kN/m²)
A-1	0.71	0.47	3.54	259.7	80.5	139.4
A-2	0.87	0.42	4.35	321.9	121.1	215.4
A-3	1.34	0.33	6.68	504.1	245.6	240.7
A-4	1.05	0.28	5.26	392.7	234.8	204.2
A-5	0.93	0.26	4.63	344.0	223.5	146.9
A-6	0.89	0.25	4.44	329.0	218.1	161.1
A-7	0.80	0.22	3.98	293.2	211.4	152.0
A-8	0.67	0.39	3.37	246.5	108.8	134.6
A-9	0.62	0.49	3.10	226.3	66.8	105.4
B-1	0.85	0.48	4.27	316.0	92.6	97.2
B-2	0.83	0.41	4.13	305.0	119.5	210.8
B-3	1.12	0.42	5.60	419.0	154.9	191.1
B-4	1.28	0.28	6.39	480.7	278.2	216.9
B-5	1.13	0.29	5.67	424.3	245.2	170.6
B-6	0.92	0.31	4.60	341.1	186.5	167.7
B-7	0.76	0.31	3.82	280.9	160.3	100.0
B-8	0.63	0.30	3.14	229.1	138.2	126.6
B-9	0.56	0.50	2.81	204.1	57.3	167.1
C-1	0.82	0.63	4.11	303.3	43.7	77.5
C-2	0.76	0.74	3.79	278.7	21.9	162.4
C-3	1.17	0.25	5.85	438.7	280.4	227.0
C-4	1.39	0.22	6.94	524.3	355.7	207.1
C-5	1.31	0.19	6.55	493.9	360.0	196.5
C-6	1.11	0.24	5.54	414.8	272.3	178.1
C-7	0.99	0.20	4.96	369.0	275.7	97.2
C-8	0.63	0.37	3.17	231.9	109.7	131.3
C-9	0.53	0.39	2.67	193.4	88.0	120.7

※$Q_N = 5 \times N_{pave}$

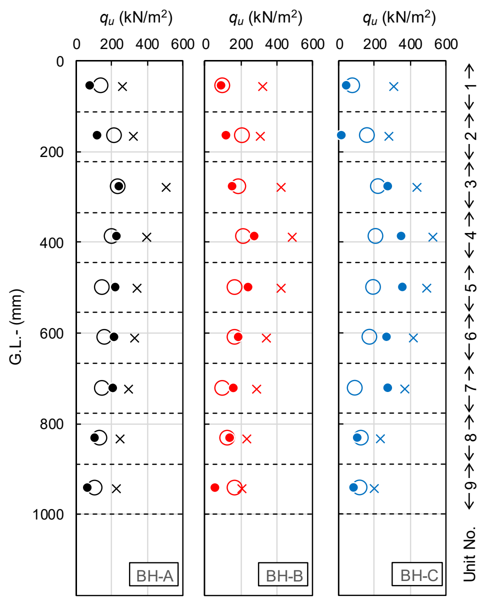

Figure 8. The depth distributions of measured values (○), estimated values by Eq-1 (×) and those by Eq-2 (●).

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