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Sustainable construction and quality of improved columns with three types of water-cement ratios on deep mixing method in Saga Lowland, Kyushu, Japan

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Abstract

In this study, we investigated the application of the deep mixing method (DMM) to cohesive soil in the Saga Lowland of Kyushu, Japan. The study focused on examining three types of water-cement ratio (W/C) conditions, with a constant addition of cement-based binder (C). Due to the soft clay nature of the Saga Lowland, frequent ground settlement and deformation occur, necessitating measures to prevent adverse effects on the surrounding environment. The objective of this research is to provide a valuable approach to optimizing the quality of the improved columns while minimizing ground displacement in an environmentally considerate manner. In Saga Lowland, it is common to fix the W/C ratio at 1.0 and vary the cement content. Through experimental construction for improved columns on the field, the study confirmed that W/C values of 0.5, 1.0, and 1.5 influence the quality of the improved structure. A higher W/C value of 1.5 resulted in a more fluid cement slurry due to a higher injection rate (IR = 23.9%), as evidenced by statistical analysis revealing higher average unconfined compressive strength (\bar{q}_{ud}), and a lower coefficient of variation (CV). The defective rate of 10% (q_{ud}) from the design standard strength shows that values are lowest for Case 2, followed by Case 3 and then Case 1. Comparing the values of Case 2 and Case 3, it is observed that in Case 3, with a higher W/C, the CV is lower. Regarding horizontal ground displacement (Sh), Case 3 exhibited a Sh value of 2.0 to 6.5 mm, significantly lower than Saga prefecture standards (20 mm). This outcome is attributed to reduced viscosity during mixing, leading to improved fluidity and minimal lateral displacement of the soil–cement columns (which often results in lateral ground uplift). Even though with a higher W/C = 1.5, the implementation cost remains the same, but the constructed structure would be of higher quality and smaller displacement, with the overall structure corresponding to the standard quality. The study includes the specific geotechnical conditions of the Saga Lowland and the scope of experimentation. Nonetheless, in terms of the applicability and optimization of DMM in Saga Lowland, the findings provide practical guidance for engineers in selecting W/C ratio and IR during construction for future DMM implementations, thereby contributing to the development of long-lasting infrastructure and sustainable societal development.

Keywords Ground improvement, Water-cement ratio, Injection rate, Unconfined compressive strength, Lateral displacement

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1 Introduction

Construction of the Ariake Sea Coastal Road in Saga lowland, characterized by a substantial layer of soft ground ranging from 10 to 25 m deep, is currently underway. The ground in this region is comprised of three layers: the lower member of the Hasuike Formation (non-marine deposit) at the bottom, the Ariake Clay Formation (marine deposit) in the middle, and the upper member of the Hasuike Formation (non-marine deposit) on top. The cohesive soil in the Ariake clay layer is known as Ariake clay, while the cohesive soil in the upper and lower portions of the Hasuike layer is referred to as Hasuike clay [1, 2].

The state parameters of Ariake clay exhibit significant sensitivity and compressibility, akin to those of Hasuike clay. Consequently, ground improvement techniques, such as the deep mixing method (DMM), become imperative [3, 4]. For reasons of demographic growth and its corollary of urbanization, we need to build modern, sustainable cities and roads. So, we need new, intelligent urban planning that creates safe, affordable, and resilient cities with green and culturally inspiring living conditions. Soil treatment and stabilization by mixing, an economic and eco-friendly method, is a technique that is increasingly being used worldwide to improve soft soils [5]. DMM involves injecting a cement-based binder slurry into the ground and mechanically mixing it on-site, to improve its geotechnical properties [6].

In Saga Lowland, the DMM has been widely applied as one of the ground improvement techniques. However, on June 23, 2016, due to the impact of the Kumamoto earthquake and heavy rainfall, deformations occurred in improved columns constructed using DMM. This led to the collapse of the road at the Ashikari Minami Interchange (IC) on the Saga-Fukudomi Road. This road collapse is also considered to be associated with incomplete solidification of the improved columns [1]. DMM, commonly used for embankment stability, is expected to withstand vertical compressive forces. However, considering the occurrence of bending tensile forces due to arc sliding during the collapse, the presence or absence of strength variations, known as variability, in the improved columns is believed to be an important factor in the quality assurance [7, 8]. Furthermore, the larger bending moments on the columns might cause tensile cracks in the columns and induce large lateral displacement.

In Japan's DMM, various shapes and mixing methods of mixing blades have been developed. However, in indoor mixing tests conducted to determine the formulation specifications in the Saga lowland, it is common to fix the water-cement ratio at 1.0 and vary the amount of cement. Our research team has found that differences in water-cement ratio affect the mixing state. The challenge

is to select the appropriate W/C and amount of cement binder to produce improved columns of the desired quality [7].

In the design and construction of roads using DMM in the Saga lowland, common conditions include design standard strength (q_{uck}) of 500 to 1000 kN/m² and field standard strength (q_{uf}) of 750 to 1500 kN/m². Typically, to meet the q_{uf} requirement, a water-cement ratio of one (W/C=1.0) and a cement-based binder addition of C=100 to 150 kg/m³ are employed. Notably, our research explores the conditions of W/C=1.5 during actual DMM construction.

In this study, construction was carried out using three types of water-cement ratios (W/C): W/C=0.5 with reduced water content, W/C=1.0 as the baseline, and W/C=1.5 with increased water content. The quality of the improved columns and the horizontal displacement of the ground were examined through the DMM. To minimize ground displacement, it is common to reduce the amount of cement slurry injected into the ground [9–11].

Therefore, W/C=0.5 was chosen, and a dispersant agent developed specifically for DMM was added to ensure fluidity. In addition, the experiment aimed to assess the viability of W/C=1.5, which introduces additional water compared to the standard W/C=1.0, by comparing its effectiveness alongside the other ratios. Through on-site construction experiment, W/C=1.5 emerged as the most effective, thereby establishing its superiority.

This study emphasizes the importance of providing engineers with flexibility in future implementations of DMM by considering a wider range of water-cement ratios (W/C) to create better quality of improved columns and emphasize the impact of injection rate (IR) to minimize ground displacement. Creating improved columns with less variation through the optimal W/C and resulting IR contributes to the development of high-quality infrastructure capable of resisting lateral loads in earthquake-prone Japan, ultimately contributing to sustainable societal development. This paper delves into the quality of improved columns obtained through such strategic choices.

2 Materials and methods

2.1 Basic soil properties

As indicated in Fig. 1, the construction site is situated in Saga City, which is part of Saga prefecture in Kyushu region, the most southern island of Japan, as shown in Fig. 1. Approximately 2.3 km southwest of the Honjo Campus of Saga University. Figure 2 illustrates a columnar diagram and the required depth for ground improvement. As detailed in the previous section, the subsurface

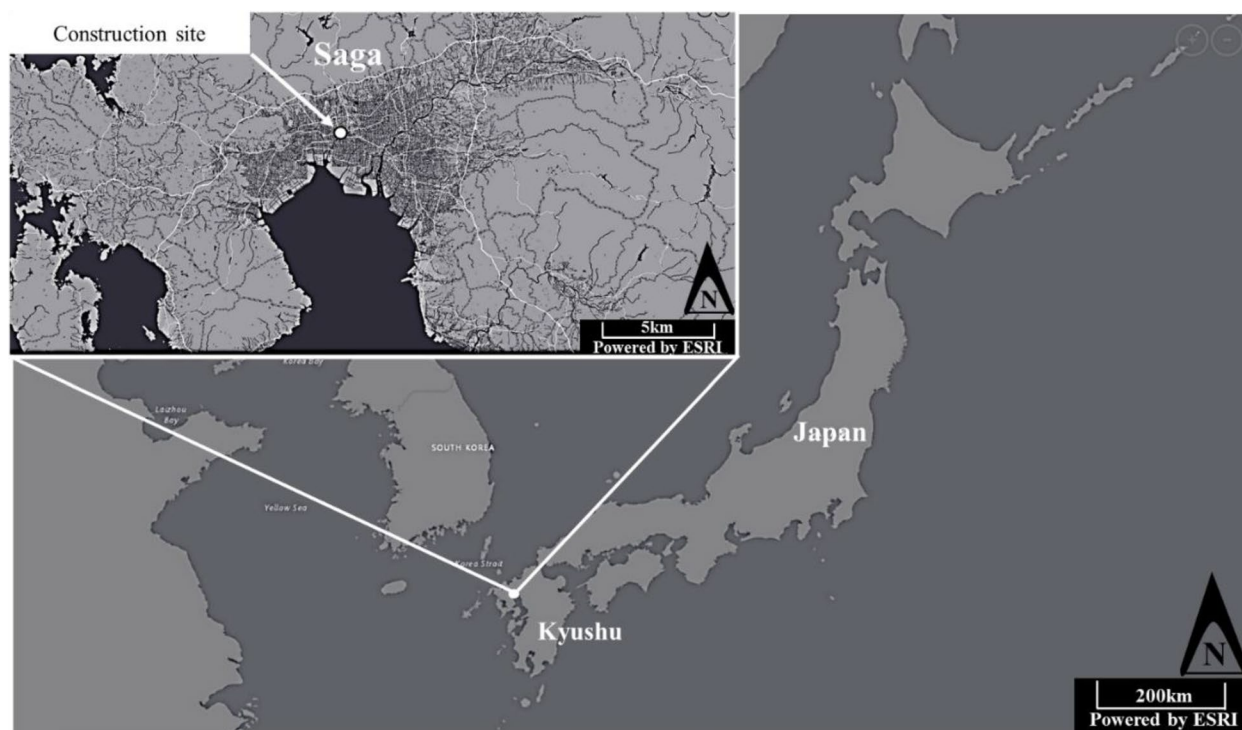


Fig. 1 Saga lowland in Kyushu, the southern island of Japan

conditions at this construction site are characterized by soft ground deposits with a distinct stacking pattern. This pattern includes the lower member of the Hasuike Formation (non-marine) at the bottom, followed by the Ariake clay Formation (marine), and finally, the upper member of the Hasuike Formation (non-marine) at the top.

Table 1 presents the geotechnical properties of cohesive soils within each stratum, categorizing them as Hasuike clay lower (H_{cl}) for the cohesive soil in the lower member of the Hasuike Formation, Ariake clay (A_c) for the cohesive soil in the Ariake Clay Formation, and Hasuike clay upper (H_{cu}) for the cohesive soil in the upper member of the Hasuike Formation. The arrangement of test results follows Mikasa's classification of soil's geotechnical engineering properties [12]. The particle density (ρ_s) for all three clays ranges from 2.58 to 2.60 g/cm³, indicating similar mineralogical properties.

Concerning the liquid limit (LL), a characteristic bow-shaped distribution is observed. LL values decrease from $LL(H_{cl})=93.5\%$ to $LL(A_c)=71.3\%$, then increase to $LL(H_{cu})=77.6\%$. A similar trend is noted for the plastic limit (PL). As for the natural water content (W_n), values increase steadily: $W_n(H_{cl})=84.1\%$, $W_n(A_c)=85.3\%$, and $W_n(H_{cu})=111.6\%$. The current state of the soil structure is reflected in the liquidity index (LI), with relatively high values: $LI(H_{cl})=0.9$, $LI(A_c)=1.2$, and $LI(H_{cu})=1.4$. The

unconfined compressive strength (UCS) (q_u) exhibits a decrease corresponding to the variation in W_n . Values decrease to $q_u(H_{cl})=55.5$ kN/m², $q_u(A_c)=55.5$ kN/m², and $q_u(H_{cu})=35.2$ kN/m².

2.2 Type of binder

We used a cement-based binder called Ustabilizer 10 (US10) suitable for the cohesive soil of the Saga Lowland. The US10 was developed to address soil types and site conditions that are difficult to solidify with conventional cement (Ordinary Portland Cement), as depicted in Fig. 3 with the categorization of the cement-based binder within a framework. It likely indicates where this material stands in relation to other materials in terms of its application, properties, or effectiveness.

Table 2 shows the chemical composition of ordinary Portland Cement and the cement-based binder US10. US10 is particularly favored for its promotion of flash setting, contributing to early strength development in cement slurry. This characteristic is attributed to its elevated Sulfur trioxide (SO₃) content, a principal component of gypsum (Calcium Sulfate Dihydrate CaSO₄·2H₂O) [14]. Gypsum, an additive raw material in the clinker grinding process, contains water within its molecular structure and comprises approximately 23.3% calcium (Ca) and 18.5% sulfur (S) [15]. US10 has less SiO₂ and more SO₃ compared to ordinary Portland cement.

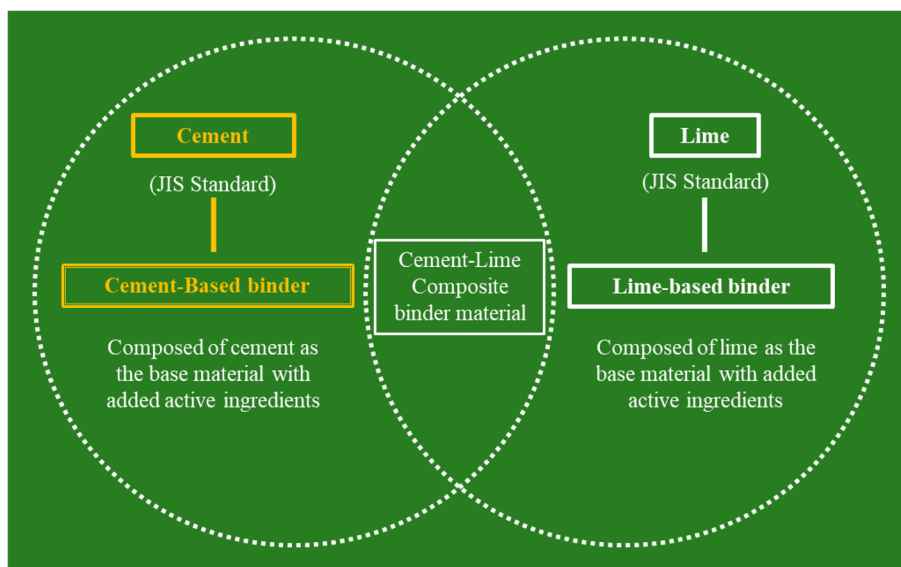


Fig. 3 Categorization of the cement-based binder in JIS (Japanese Industrial Standards) [13]

Table 2 Chemical Composition of Ordinary Portland Cement and Cement-based Binder

Ordinary Portland Cement (%)		Cement and Cement-based Binder(US-10) (%)
SiO ₂	21.4~22.6	18.04
Al ₂ O ₃	4.3~5.7	4.99
Fe ₂ O ₃	2.5~3.3	2.74
CaO	63.0~64.7	61.14
MgO	0.8~2.7	0.98
SO ₃	1.7~2.4	6.88

This cement-based binder produces a lot of ettringite and takes up soil moisture as crystalline water. As a result, the grown crystals entangle in a net-like structure, restraining the movement of soil particles and increasing the strength of the improved soil by reducing the water content. The application of US10 significantly enhances the strength, stiffness, and durability of soil, rendering it suitable for diverse engineering applications and its versatility, coupled with its cost-effectiveness, positions US10 as a compelling choice for projects with budget constraints, contributing to its widespread use in soil stabilization and ground improvement initiatives in Saga prefecture. For Case 1 with W/C=0.5, a dispersant agent developed specifically for DMM was added to ensure fluidity, as shown in Table 3.

2.3 DMM implementation method

The DMM is primarily executed using a specialized single or twin mixing shaft machine designed to implement

Table 3 Characteristics of dispersing agent

Main component	Naphthalene sulfonate compounds
Appearance	Brown liquid
Density(g/cm ³)	1.19~1.23
pH	8.0~10.0

single or two columns simultaneously for improved ground conditions [16]. Thanks to its variety of setting and specialty, this machine is commonly used in Japan based on the needs, the purpose, and the location of implementation. However, as shown in Figs. 4 and 5, for this study, a single mixing shaft machine with a free blade, facilitating the execution of one column at a time, was utilized. This specific investigation was done based on real-world conditions, following Saga prefecture standard work process in implementing DMM (use of W/C=1) [1]. The construction was carried out using three types of water-cement ratios (W/C): W/C=0.5 with reduced water content in the cement slurry, W/C=1.0 as the baseline, and W/C=1.5 with increased water content in the cement slurry. To address the cohesive soil conditions in the Saga Lowland and prevent excessive rotation with accurate mixing, the mixing shaft machine is equipped with two free blades. The fixed mixing blades, as illustrated in Fig. 4, rotate clockwise for digging and mixing at depth and counterclockwise for withdrawal. The achieved improvement depth is approximately 23 m from the ground surface, with a limit of 20 blows for the ground's N-value (number of blows). The construction



Fig. 4 Construction Machine: single mixing shaft machine for DMM

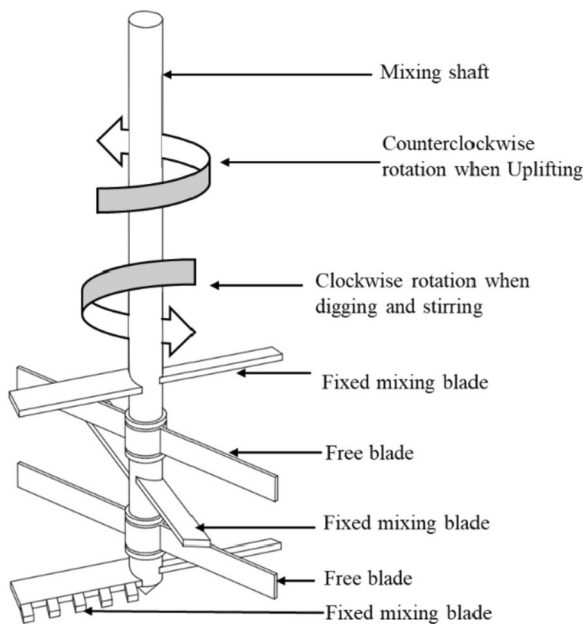


Fig. 5 Type of blades and rotation direction of DMM machine

of a single improved column takes approximately 60 to 90 min, depending on its length. In the current experimental construction, columns with a diameter of 1.2 m and a length of 13.5 m (as shown in Fig. 2) were constructed. The excavation speed was set at 0.5 m per minute, the withdrawal speed at 1.0 m per minute, and a shaft rotation speed of at least 25 rotations per minute were ensured for all W/C ratios, completing the construction of a single improved column in approximately 60 min [17].

2.4 Water-to-cement ratio (W/C) conditions

The amount of cement-based binder added on the construction sites in Japan is determined by the following Eq. (1) [18].

$$q_{uck} = \gamma \overline{q_{uf}} = \gamma \lambda \overline{q_{ul}}, \tag{1}$$

where:

q_{uck} = Design standard strength.

$\overline{q_{ul}}$ = Average value of unconfined compressive strength (UCS) of improved soil in laboratory mixing test.

$\overline{q_{uf}}$ = Average value of unconfined compressive strength (UCS) of improved soil.

γ : Correction factor for scattered strength.

$$\lambda : \overline{q_{uf}} / \overline{q_{ul}}$$

$$\gamma \lambda = 1/3 \sim 1/4$$

The determination of the amount of cement (C) on construction sites follows a specific procedure. Initially, a water-cement ratio (W/C) of 1.0 is considered [19], and laboratory mixing tests are performed with three different C values. The objective is to identify the C value that meets the design standard strength (q_{uck}).

In adherence to [20], laboratory mixing tests were carried out with varying C values specifically, 100 kg/m³, 130 kg/m³, and 150 kg/m³. The lab mixing test conducted with C=130 kg/m³ yielded an average strength $\overline{q_{ul}}$ =2400kN/m². We adopted C=130 kg/m³ to meet q_{uck} =800 kN/m². The required field standard strength (q_{uf}) is 1200 kN/m² on site.

Furthermore, there are currently no established criteria regarding the injection volume of the slurry. As outlined by the Public Works Research Center [18], low cement addition amounts may lead to pulsation issues during slurry transportation from the plant to the stirring blades, posing challenges in maintaining a stable supply. A higher IR is believed to lead to a more uniform spread of the cement slurry throughout the soil. Conversely to [21] who obtained good performance with a lower IR for the case of sand. A minimum slurry volume of 90 L/m³ (with C=70 kg/m³ in the case of W/C=1.0) is recommended. It is essential to highlight that these recommendations are driven by mechanical limitations associated with slurry transport and are not directly linked to quality assurance. The IR is automatically set up from the plant based on the slurry (water + cement) as shown in Table 4. The formula for IR calculation is simply related to the percentage of the volume of the slurry injected in m³. If we have the volume (V) of slurry per 1m³, with a Cement density=2.98 t/m³, we have the following Eq. (2) as [20]:

$$IR = (V/1) \times 100\% \tag{2}$$

Table 4 Mixing conditions

Cases	C(Kg/m ³)	W/C	Admixtures	Volume (V) of slurry per (1m ³)	Injection rate IR(%)
1	130	0.5	Dispersing agent	0.109	10.9
2	130	1.0	-	0.174	17.4
3	130	1.5	-	0.239	23.9

Here V: Volume of water + Volume of cement [19]

Volume of water = C × W/C [19]

Volume of cement = (1 m³ × C) / Cement density [19]

Based on a C value of 130 kg/m³, three distinct sets of conditions outlined in Table 4 were established, and on-site construction tests were subsequently conducted. In Table 4, IR denotes the slurry injection amount represented as a percentage of the target soil volume.

2.5 Measurement of ground displacement

The mechanism underlying ground displacement involves a myriad of parameters, including the geotechnical properties of the soil, groundwater conditions, soil-structure interaction, seismic activity, construction activities, and rheological properties. Soil density and compaction influence displacement. Loose or poorly compacted soil is more susceptible to settling and deformation under load compared to densely packed soil. Changes in groundwater levels can lead to soil expansion or contraction, resulting in heave or settlement. Soil shear strength is crucial. Weak soils are more prone to deformation under stress, while soils with higher shear strength offer more stability. The clay prevalent in the Saga lowland, as discussed in Sect. 2.1 and Table 1, exhibits notable sensitivity and compressibility, highlighting the necessity of employing DMM as a countermeasure against soft ground. The clay prevalent in the Saga lowland, as discussed in Sect. 2.1 and Table 1, exhibits notable sensitivity and

compressibility, highlighting the necessity of employing DMM as a countermeasure against soft ground. Given these soil characteristics, occurrences of ground displacement pose daily challenges for engineers in the Saga lowland.

The rheological behavior of the soil encompasses its viscosity [21], shear strength, and deformability, which dictate the flow and deformation of soil under stress, thereby influencing the rate and magnitude of ground displacement. Through cone penetration tests conducted at the construction site surrounding the DMM construction area, the behavior of ground displacement was assessed by [10]. On average, the test results revealed a decrease in the water content of the surrounding clay, coupled with an increase in the concentration of cations as sampling locations approached the columns. Additionally, the shear strength of the surrounding clay exhibited a notable enhancement, with an approximately 23% increase after 40 days and a 50% increase after 70 days compared to the original strength [10].

In this specific study, we measured the ground displacement (Sh) during the construction of Cases 1 to 3. Figure 6 shows the arrangement of the improved columns and the installation positions of inclinometers. The improved columns had a diameter of 1.2 m, and the ground displacement meters were installed 2 m away from the center of the improved columns. Data were collected up to a reference point set at a depth of 22 m in the gravel layer. Four improved columns were constructed to the west of the ground displacement meters, and the subsequent ground displacement was measured. Figure 7 illustrates the DMM construction status, while Fig. 8 shows the displacement measurement conditions.

2.6 Boring sample for quality confirmation

Figures 9, 10, 11 depict specimens for quality assurance confirmation through boring. Boring activities were executed seven days after the installation of

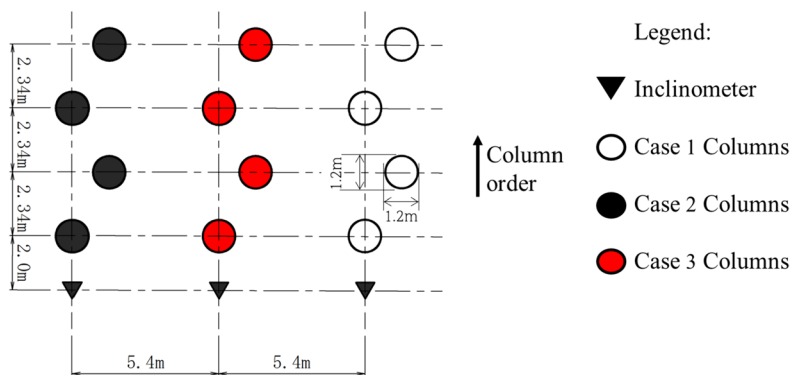


Fig. 6 Arrangement of the improved columns and ground displacement meter



Fig. 7 DMM implementation



Fig. 8 Ground displacement measurement using inclinometer

the improved columns, and samples were gathered for quality confirmation and subsequent unconfined compression tests (UCT). These figures provide a comprehensive overview of the samples for quality confirmation.

Although the samples exhibit horizontal cracks, believed to be induced by the boring process and the tension force exerted on the samples during the extraction of the boring rod, the overall quality remains satisfactory. The sampling rate is 100%, and no unconsolidated or discontinuous sections were identified. Among the cases, the number of horizontal cracks is observed to be highest in Case 1, followed by Case 2 and then Case 3.

2.7 UCS of specimens dominated by cohesive soil in quality confirmation samples

To ensure the quality of the improved columns, horizontal cracks in the quality assurance specimens were carefully avoided, and UCS (q_u) tests were conducted using as many UCT specimens as possible. Figure 12 illustrates



Fig. 9 Case 1, improved column for quality confirmation



Fig. 10 Case 2, improved column for quality confirmation

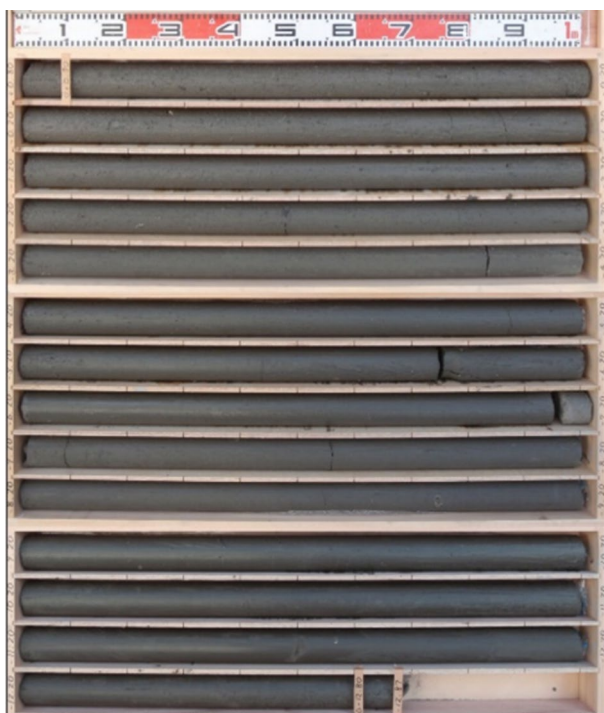


Fig. 11 Case3, improved column for quality confirmation

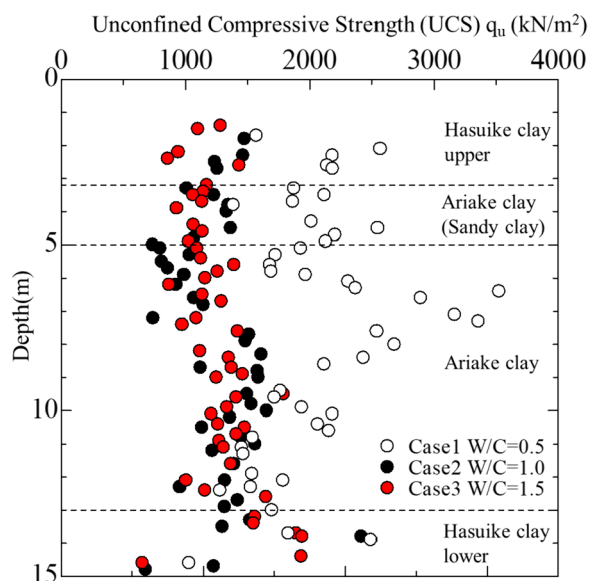


Fig. 12 Overall UCS of specimens

the vertical distribution of UCS (q_u) from Case 1 to Case 3, and the results of UCS (q_u) are summarized in Table 5.

Figure 13 provides an illustrative example of construction management records, showcasing the two-step mixing process executed during construction at the deepest part (depth

Table 5 Trend of overall UCS (\bar{q}_u)

Case	1	2	3
W/C	0.5	1.0	1.5
Number of samples (pieces)	46	45	48
\bar{q}_u (kN/m ²)	2,051	1,270	1,266
$q_{u\max}$ (kN/m ²)	3,523	2,417	1,939
$q_{u\min}$ (kN/m ²)	1,385	682	655

≈ 14.5 m to 15.0 m). This involved repeated stirring movements to achieve a uniform mixed consistency, aiming for the desired mixture at the bottom of the improved column.

For the specimens composed mainly of cohesive clay only, the analysis was concentrated by excluding the values for the Ariake clay (sandy clay) portion and the lower part of the lotus pond clay shown in Fig. 12. Table 6 outlines the trend of UCS (q_u) for specimens dominated by cohesive soil, considering average, maximum, minimum, standard deviation, and coefficient of variation.

Further statistical processing results are presented in Table 7, offering a comprehensive understanding of the UCS (q_u) data used in this study. The Chi-square test is used to assess the nature of data distribution and examine the differences between categorical variables from a random sample to judge the goodness of fit between expected (χ^2) and observed results (χ_0^2). And CV_0 is the coefficient of variation of the unbiased variance of our data. The null hypothesis is that "the results of q_u follow a normal distribution," and the alternative hypothesis is that "the results of q_u do not follow a normal distribution." Since χ_0^2 is less than χ^2 in each case, no significant difference is observed, allowing the results of q_u to be considered normally distributed in all cases. Furthermore, the coefficient of variation (CV) for q_u ranges from 20 to 25%, which is relatively low when compared to the experience of ground improvement techniques using slurry.

Table 8 shows the results of the reliability confirmation through the F-test regarding CV [22]. The F-test as a statistical method for comparing the variances of two populations, is used to assess the spread of data distribution. The null hypothesis is that "there is no difference in the variance between CV_0 and CV," and the alternative hypothesis is that "there is a difference in the variance between CV_0 and CV." Since CV_0^2 is less than $CV^2 \cdot F$ in each case, no significant difference is observed between CV_0 and CV, confirming the reliability of CV. This allows for a simple comparison and consideration of each value.

3 Discussion and results

3.1 UCS for quality confirmation of overall samples

The average value of UCS \bar{q}_u was highest in Case 1, followed by Case 2, and then Case 3. It is common for q_u to decrease as the water-cement ratio (W/C) increases, however, despite

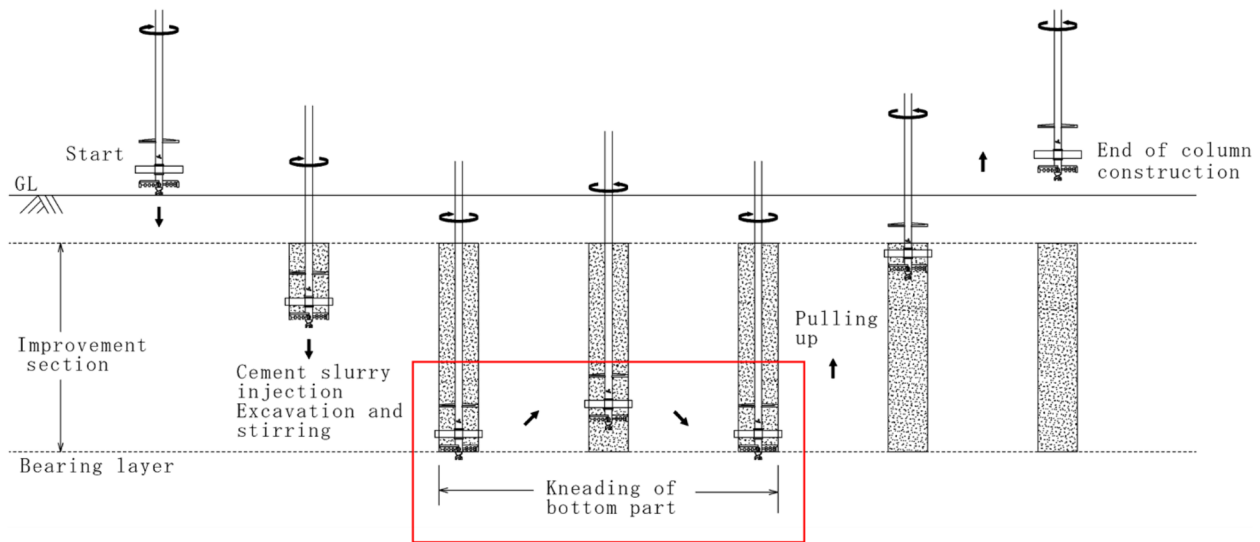


Fig. 13 Construction management of DMM's bottom part

Table 6 Trend of UCS based on cohesive part (Hasuike clay upper and Ariake clay)UCS (q_u)

Case	1	2	3
W/C	0.5	1.0	1.5
Number of samples (pieces)	39	38	40
\bar{q}_u (kN/m ²)	2,091	1,288	1,312
$q_{u\max}$ (kN/m ²)	3,523	2,417	1,939
$q_{u\min}$ (kN/m ²)	1,277	739	860
Range of q_u (kN/m ²)	2,246	1,678	1,079

Table 7 Statistics and test result the χ^2 for q_u

Case	1	2	3
W/C	0.5	1.0	1.5
Number of sample (n)	39	38	40
\bar{q}_u (kN/m ²)	2091	1288	1312
Variance s^2	270,411	104791	70652
Standard deviation (S)	520	324	266
X_0^2	7.0	8.1	4.9
χ^2	11.1	11.1	11.1

Table 8 Results of statistical processing of coefficient of variation (CV) for q_u

Case	1	2	3
W/C	0.5	1.0	1.5
Number of sample (n)	39	38	40
CV(%)	25	25	20
Coefficient of variation Unbiased variance CV_0^2	0.063	0.065	0.042
$CV^2 \cdot F$	0.100	0.102	0.066

Case 3 having a higher W/C compared to Case 2, \bar{q}_u was minimized to the greatest extent relative to Case 2. The maximum UCS ($q_{u\max}$) tends to increase with a decrease in W/C. The minimum UCS ($q_{u\min}$) showed the highest value in Case 1, followed by Case 2, and then Case 3. Like \bar{q}_u was, the difference between Case 2 and Case 3 was minimized.

3.2 UCS of cohesive soil specimens

In terms of the average UCS (\bar{q}_u), Case 1 recorded the highest value, followed by Case 3, and then Case 2. It is noteworthy that all cases yielded results exceeding $q_{uf}=1200$ kN/m². As mentioned earlier, it is common for q_u to decrease as W/C increases. However, despite Case 3 having a higher W/C compared to Case 2, (\bar{q}_u) was higher in Case 2. Regarding $q_{u\max}$, Case 1 showed the highest value, followed by Case 2 and then Case 3. Typically, a decrease in W/C is associated with an increase in $q_{u\max}$. For $q_{u\min}$, Case 1 exhibited the highest value, followed by Case 3 and then Case 2.

3.3 Statistical processing of UCS

In the deep mixing method for the foundation of box culverts in Saga Prefecture, the lab mixing test strength (q_{ul}) is determined by selecting a high value between 3 times the design standard strength (q_{uck}) [$q_{ul}=3 \times q_{uck}$] and 2 times the on-site standard strength (q_{uf}) [$q_{ul}=2 \times q_{uf}$], as specified by the Saga Prefectural Government [21]. From these two values, $q_{uf}/q_{uck}=1.5$ is obtained. Under this condition, when calculating CV, it becomes as follows [16].

$$q_{uck} = \bar{q}_{uf} - K \times \sigma$$

$$= \bar{q}_{uf} - K \times \bar{q}_{uf} \times CV \tag{3}$$

$$= \bar{q}_{uf} (1 - K \times CV) \tag{4}$$

And then,

$$\bar{q}_{uf}/q_{uck} = 1/(1 - K \times CV) \tag{5}$$

$$1.5 = 1/(1 - 1.3 \times CV)$$

$$CV = 0.25$$

Here, σ represents the standard deviation of q_{uf} ($\sigma = q_{uf} \times CV$) [23], and K is a constant determined by the defect rate ($K = 1.3$ when the defect rate is 10%).

Figure 14 illustrates the relationship between q_{uck} , q_{uf} and q_{ul} and it can be inferred that in the deep mixing

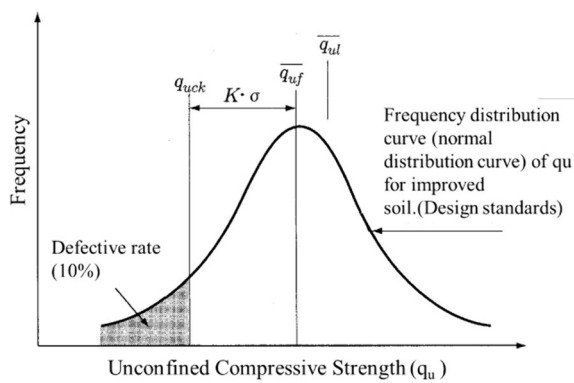


Fig. 14 Standard frequency distribution curve of q_u for improved soil and defective rate

Table 9 Comparison of CV of the \bar{q}_u for data accuracy confirmation

Case	1	2	3
W/C	0.5	1.0	1.5
Number of sample (n)	39	38	40
\bar{q}_u (kN/m ²)	2091	1288	1312
Standard deviation (S)	520	324	266
CV(%)	25	25	20

method for the box culvert foundation in Saga Prefecture, a condition of $CV \leq 0.25$ (25%) is required for standard quality [24, 25].

Table 9 shows comparison between CV of the \bar{q}_u , for data accuracy confirmation. On the one hand, starting with Case 3, which had the lowest CV of 20%, both Case 1 and Case 2 yielded equivalent values of $CV = 25\%$. On the other hand, regarding the average \bar{q}_u , while Cases 2 and 3 showed equivalent values, Case 3 exhibits a lower CV of 20% despite having a lower water-cement ratio (W/C), indicates that it maintains a higher quality. Even in Case 1, where W/C is the lowest, the \bar{q}_u value is the highest, and $CV \leq 25\%$, meeting the standards.

Based on the \bar{q}_u and CV mentioned above, we calculated the value of the unconfined compressive strength (q_{udr}) corresponding to a defective rate of 10%, as shown in Fig. 14 mentioned in the design standards [22]. The statistical trends are visualized in Fig. 15a, b, and c, and the summarized trends extracted from these figures are presented in Table 10. The q_{udr} values are lowest for Case 2, followed by Case 3 and then Case 1. Comparing the values of Case 2 and Case 3, it is observed that in Case 3, with a higher W/C, \bar{q}_u is higher and CV is lower, resulting in a higher q_{udr} . Increasing the W/C, even with the same amount of C, leads to higher q_{udr} and better-quality results. This is believed to be influenced by the higher injection rate (IR).

3.4 Measurement of ground displacement during construction

Figure 16 presents the results of ground displacement. In the sandy clay layer at a depth of 3.2 to 5.0 m, the value of Sh is suppressed, but this layer also restrains the rise of the mixed soil in the lower clay layer. As a result, the displacement of the lower clay layer is expected to be higher. Table 11 shows the maximum ground displacement values for Cases 1 to 3. Generally, it is believed

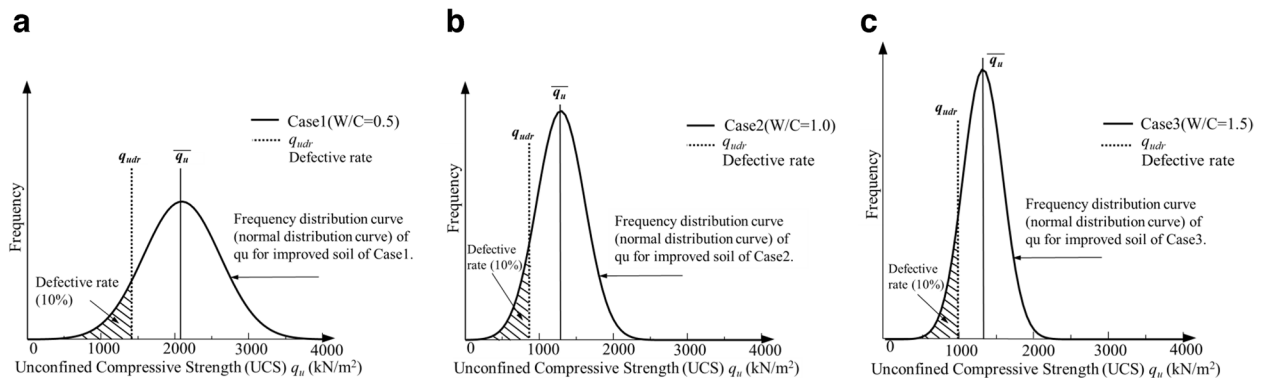


Fig. 15 a Case 1 Defective rate from design standard strength (q_{udr}). b Case 2 Defective rate from design standard strength (q_{udr}). c Case 3 Defective rate from design standard strength (q_{udr})

Table 10 Summarized trends of Fig. 15a to c

Case	1	2	3
W/C	0.5	1.0	1.5
Injection rate (IR)(%)	10.9	17.4	23.9
\bar{q}_U (kN/m ²)	2091	1288	1312
CV(%)	25	25	20
q_{udr} defective rate(kN/m ²)	1411	870	971

through engineers’ experience on the construction field, that reducing the slurry amount of C injected into the ground can control *Sh*. The results indicate that Case 3, with the highest W/C and the largest IR, shows the minimum value of *Sh*. Following this, Case 2 with a W/C value of 1.0, and Case 1 with the minimum W/C value and IR, exhibit higher values of *Sh*.

3.5 Impact on the surrounding environment

For the Ariake Sea Coastal Highway (Saga-Fukutomi Road), the vertical and horizontal displacement of

Table 11 Maximum ground displacement values

Case	1	2	3
W/C	0.5	1.0	1.5
Injection rate IR(%)	10.9	17.4	23.9
Maximum displacement (mm)	13.1	12.6	6.5

public–private boundaries is defined as approximately 50 mm for both field areas and 20 mm for residential areas. Figure 17 illustrates the primary purpose of DMM implementation, which is to mitigate ground settlement and prevent ground uplifting, thereby avoiding disruption to local habitats in the surrounding environments.

Control of ground settlement and lateral ground displacement for habitat preservation, include proper management of W/C and IR which can help prevent habitat disturbance in the surrounding environment promoting ecosystem stability and biodiversity conservation.

In this study the horizontal ground displacement exhibited a *Sh* value of 2.0 to 6.5 mm, significantly lower than the

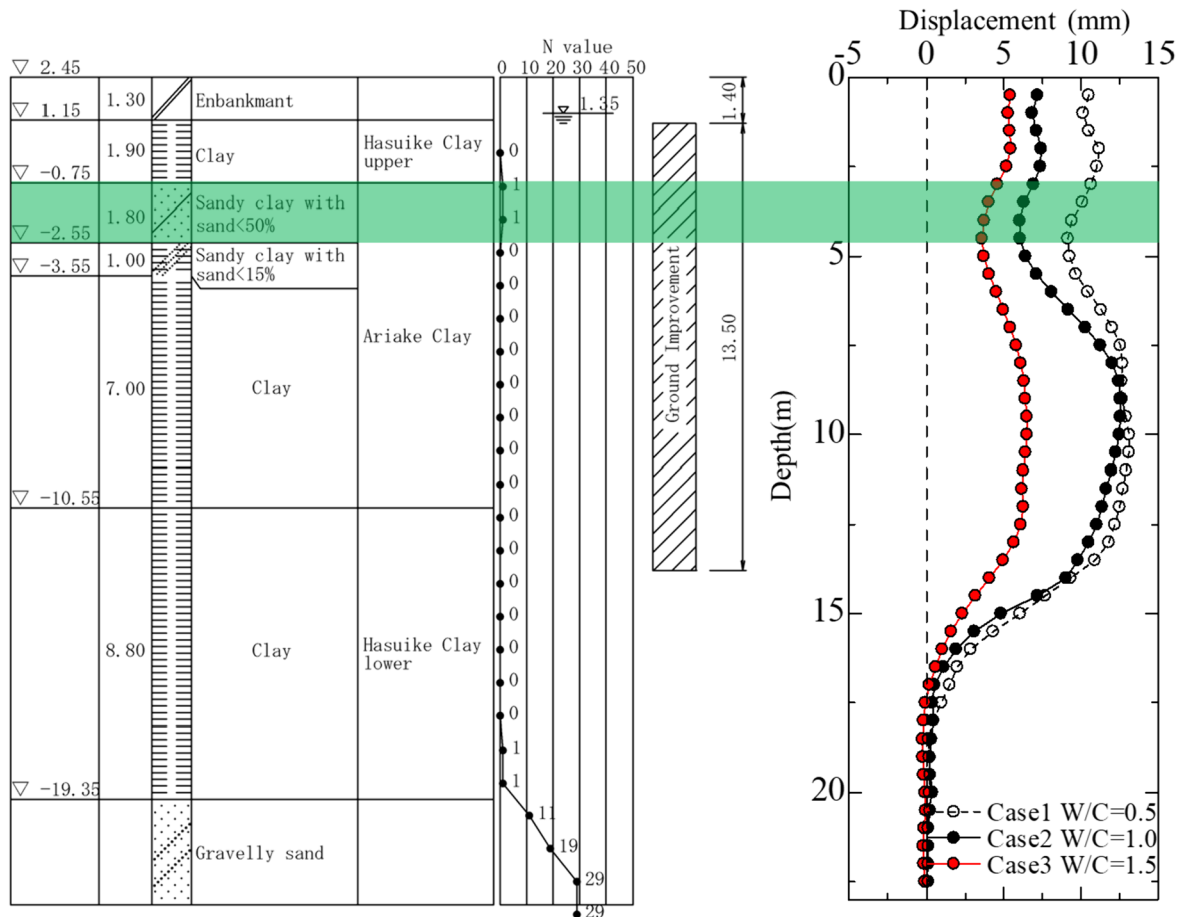


Fig. 16 Results of ground displacement

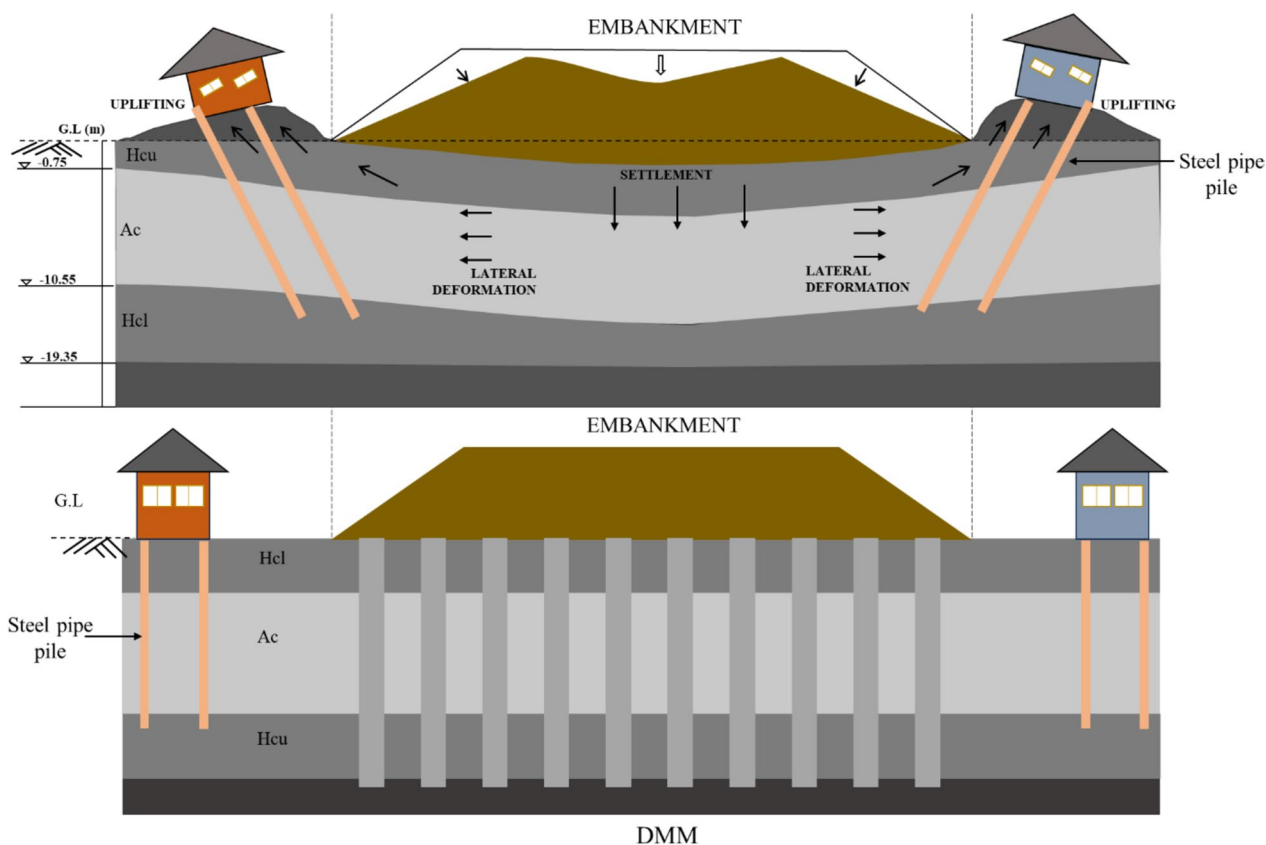


Fig. 17 Soft ground settlement, lateral deformations and DMM implementation in Saga lowland

Saga prefecture standards (20 mm). In terms of long-term stability and resilience, optimizing W/C values and injection rates contributes to the long-term stability and resilience of the improved ground, by conforming to the Saga prefecture construction design standards. A well-designed DMM application that considers environmental factors ensures that the enhanced soil remains structurally sound and capable of withstanding natural disturbances such as earthquakes and extreme weather events, thereby reducing the need for future interventions, minimizing environmental disturbances and ecological risks [26].

The study encompasses an investigation into the specific geotechnical conditions prevalent in the Saga Lowland, coupled with an experimental framework delineated within its scope. In elucidating the applicability and optimization of Deep Mixing Method (DMM) within the Saga Lowland, the study’s findings furnish engineers with actionable insights for discerning the optimal Water-to-Cement (W/C) ratio and Injection Rate (IR) parameters during construction for forthcoming DMM endeavors. This, in turn, fosters the advancement of enduring infrastructure and promotes sustainable societal development.

As part of future endeavors, the authors intend to conduct Micro-Induced Polarization (MIP) tests or Scanning

Electron Microscopy (SEM) analyses to elucidate the interaction mechanisms between IR and W/C. Additionally, the authors plan to execute a series of tests employing a consistent injection rate while varying the total cement content (held constant) and water content (adjusted in accordance with the W/C ratio).

4 Conclusion

In the context of applying DMM to cohesive soil in Saga lowland, the experimentation with three types of W/C conditions under the same C provided valuable insights into constructing in a sustainable manner. The key findings and conclusions drawn from the study are summarized as follows:

- 1 W/C=1.5 allowed for the achievement of higher quality improved columns. This improvement is attributed to the higher IR and the elevated W/C value to 1.5. These factors contribute to the creation of a more fluid cement-based slurry, thereby enhancing mixing conditions and resulting in a lower CV. The underlying mechanism might be associated with the increased fluidity of the cement-based slurry, facilitated by higher IR and selective W/C.

- 2 The analysis of ground displacement revealed that Case 3, characterized by a high W/C ratio (W/C=1.5), exhibited a Sh value of 2 mm, significantly lower than the government standards (20 mm). This underscores the crucial role of the interplay between W/C and IR values in influencing ground displacement.
- 3 Using the same amount of cement, the same equipment, the same construction period, and increasing the W/C will have the same implementation cost, but the constructed structure will be of higher quality with smaller displacement with an overall structure responding to the standard quality.
- 4 The investigation into different W/C conditions within the DMM demonstrated the possibility of providing more flexible W/C value selection for engineers involved in future DMM implementation.

Acknowledgements

We extend our sincere gratitude to the Saga Prefecture Civil Engineering Office and Mr. Nishiyama from Okamoto Construction for their invaluable support, both through the commissioning process and as the main contractor, providing essential resources for this study. We appreciate their commitment and collaboration.

Author contributions

Conceptualization: H., USUI; Methodology: H., USUI; Software: H., USUI; Validation: H., USUI, D.D., SOME, M. J., SINDETE; Formal analysis: H., USUI; Investigation: H., USUI, D.D., SOME, M. J., SINDETE; Resources: H., USUI; Data curation: H., USUI; Writing—original draft preparation: D.D., SOME, M.J., SINDETE; Writing—review and editing: H., USUI, T., HINO; Visualization: M. J., SINDETE; Supervision: T., HINO; Project administration: T., HINO.

Funding

No funding was received for conducting this study.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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Received: 10 January 2024 Revised: 28 February 2024 Accepted: 29 February 2024

Published online: 02 April 2024

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