IMPROVEMENT OF HORIZONTAL BEARING CAPACITY BY COMPOSITE GROUND FOUNDATION METHOD IN SOFT GROUND

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Abstract

The composite ground foundation is a new type of foundation that remarkably improves the horizontal bearing capacity by considering the mechanical interaction effect of the improved ground and pile which are installed as one body. This paper discusses the evaluation of bearing capacity of pile foundation (Type I) in a relatively shallow bearing layer where all layers of soft ground are improved. Primarily, the basics of design concept and the study of loading test in-situ and analysis by FEM are discussed. Next, the pile foundation (Type II) in a deep bearing layer where only the soft ground near the surface is improved is also described. The basic characteristics of its bearing capacity with respect to behavior of the pile and improved ground as one body are studied. This paper suggests that the bearing capacity is improved in both types of composite ground foundation.

Introduction

Traditionally, the ground and foundation structure are considered as independent models, for example, in the case of pile foundation, the load resistance characteristics of soft ground and pile are considered independently in the analysis. Therefore, in the case of bridge foundation constructed on a thickly accumulated soft ground or ground that is likely to cause liquefaction, large number of piles is usually necessary in order to satisfy the required performances, such as displacement and proof strength of pile, since the resistance of ground in-situ is small. In compensation for insufficiency of ground resistance in soft grounds and liquefaction grounds, new construction methods are being studied in order to restrain horizontal displacement and lessen the number of piles, and consequently, reduce the construction's total cost, using Deep-Mixing-Method (DMM) which reinforces ground resistance by pouring cement in peripheral ground. The "composite ground foundation method," that is defined herein, is a foundation practice which expects positive effect of interaction between the improved ground in-situ and the existing pile.

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The actual application of composite ground foundation method is being investigated in road constructions such as Ariake Sea Coastal Road (national highway) and Tokyo-Gaikan Expressway, through laboratory model tests and loading tests in-situ (Maeda, et al., 2001-2007). However, since this is a new construction method, its design method is not established. In regards to the scope of ground improvement and the evaluation of its strength and deformation characteristics, design method varies in different construction sites.

In this paper, the authors provide an additional study on the technical uniqueness and horizontal bearing capacity characteristics of composite ground foundation based on some loading tests which the authors participated in, and examine its practical design method.

Soil improvement by composite ground foundation and its technical characteristic

Presently, the composite ground foundation that is under development in Japan can be sorted in two types according to load/resistance characteristics as illustrated in Fig.-1 and Fig.-2. Figure-1 is the most basic type, where all layers of soft ground are improved as part of pile foundation. The whole block of improved ground is considered as a mass that does not move or deform and the increase of its stiffness and strength contributes to the betterment of pile's resistance and restoring force characteristics. The study of its practical use is already pushed forward by the authors (Maeda, et al., 2007).

On the other hand, Fig.-2 illustrates the foundation structure with deep bearing layer where only the soft ground near the surface that dominates most of foundation's horizontal resistance is improved in order to increase the horizontal bearing capacity characteristic of foundation (Maeda, et al., 2001, 2006). In this case, since it is assumed that the improved ground resists load with the pile foundation as one body, its deformation and movements is allowed. According to conventional studies, the evaluation of bearing capacity characteristics of Type II foundation, such as the load allotment and deformation due to mechanical interaction of pile and improved ground as well as the improvement of horizontal bearing capacity, is in considerable progress.

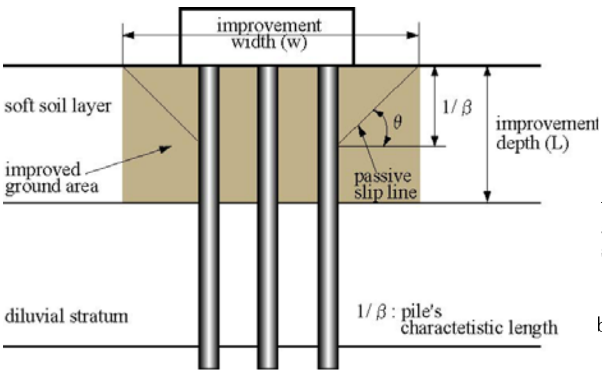


FIG.-1. TYPE I: BASIC TYPE
(Maeda, et al., 2007)

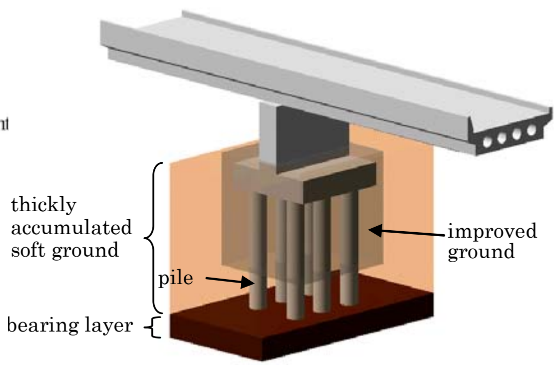


FIG.-2. TYPE II: FLOATING TYPE
(Maeda, et al., 2001, 2006)

Evaluation and characteristics of horizontal bearing capacity of composite ground foundation (Type I) （Maeda, et al., 2007）

A. Basic concept of design

This study is conducted in abutment foundation of Ariake Sea Coastal Road's Yabegawa Bridge that is constructed on a soft ground. In order to attain cost reduction of abutment foundation, the peripherals of pile is solidified by DMM which improved the horizontal bearing capacity and passive earth pressure. Comparing the composite ground foundation method to conventional method reveals that the required number of piles is decreased from 56 to 14 and the cost is drastically reduced to approximately 55%.

The design concept applied in practice is described as follows.

1) The foundation secures safety essential to earthquake Level 1 and Level 2 (JRA, 2002).

2) Ground parameters are determined according to existing technical standards (JRA, 2002) such as unconfined compression test, lateral loading test in bore, conversion formula using the N-value, etc., and the deformation modulus of improved ground is empirically calculated using the formula E=150q_u (kN/m^2) from unconfined compression strength.

3) The improvement rate of soil is set to 78.5% of the arrangement in contact.

4) The area of soil improvement is set from pile's characteristic length 1/β, which is the ground area that largely contributes to the horizontal resistance of pile, to the area of influence of passive slip line.

5) The interactive effect of pile and ground considers the increase in horizontal/vertical bearing capacity and passive earth pressure of ground.

6) The improvement depth determines the range where the improved ground block will not slide during Level 2 earthquake.

Based on these conditions, improvement width and depth becomes w=16.8m and L=10.5m, respectively, as shown in Fig.-1.

Photo-1 shows the construction work of ground improvement and pile.

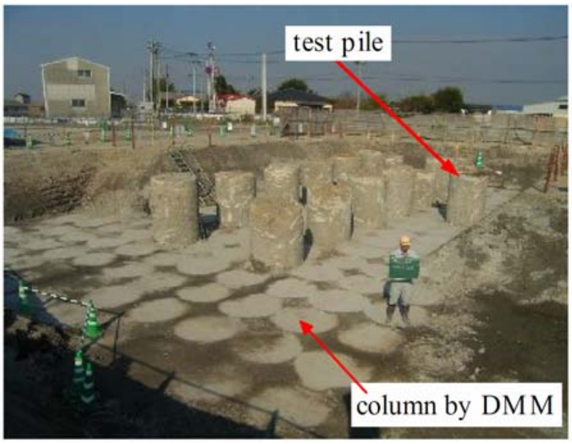


PHOTO-1. CAST-IN-PLACE PILES IN A COMPOSITE GROUND FOUNDATION

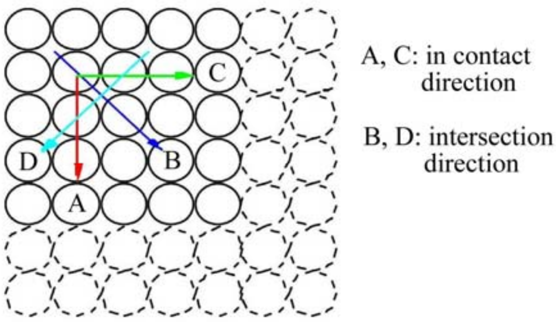


FIG.-3. MEASUREMENT OF SHEAR WAVE VELOCITIES

B. Evaluation of improved ground column

In general, the average strength of improved ground becomes considerably greater than the design strength since there is unevenness in strength.

Herein, the strength of improved ground is studied using the following methods.

1) Using the core boring sample, unconfined compression stress is studied by performing unconfined compression test and pin penetration test of 10 cm interval.

2) The strength and deformation characteristics are investigated in details through triaxial CU test that measures minute strain using LDT.

3) Deformation modulus in the order of minute strain is studied using seismic velocity logging of improved ground.

4) The stiffness of improved ground in the order of minute strain is studied by measuring the shear wave velocities in the directions described in Fig.-3.

Among the information provided from the series of measured items mentioned above, a summary on modulus of deformation is discussed herein.

The depth distribution of deformation modulus in minute strain based on seismic velocity logging is shown in Fig.-4. This suggests that deformation modulus is approximately E=1500 to 2000 MN/m^2, which is similar to other measurements such as LDT, etc. Modulus of deformation is estimated according to equations Eq.-3 and Eq.-4 shown in later section.

The variation of shear wave velocity measurements according to directions are shown in Table-1. The modulus of deformation along direction of intersection is found to be E=1100MN/m^2 which is less than half of E=2900 MN/m^2 in direction of contact. This result might suggest that the distance of transmission is far since the wave path is indefinite. Although this matter cannot be considered directly in the study of composite foundation, it is interesting to note that difference occur in relevance to the existence of unimproved ground.

TABLE.-1. SHEAR WAVE VELOCITY MEASUREMENTS

Measurement directions		S wave velocity (m/s)		dynamic poison raio	dynamic modulus of deformation (kN/m^2)
		measurements	average		
Direction of contact	A line	966	833	0.32	2,931,000
	C line	700			
Direction of intersection	B line	727	614	0.41	1,134,000
	D line	501			

C. Horizontal loading test of full-scale test pile

In order to confirm the propriety of ground reaction coefficient based on the assumed design improvement area described earlier, horizontal loading test of full-scale pile is conducted.

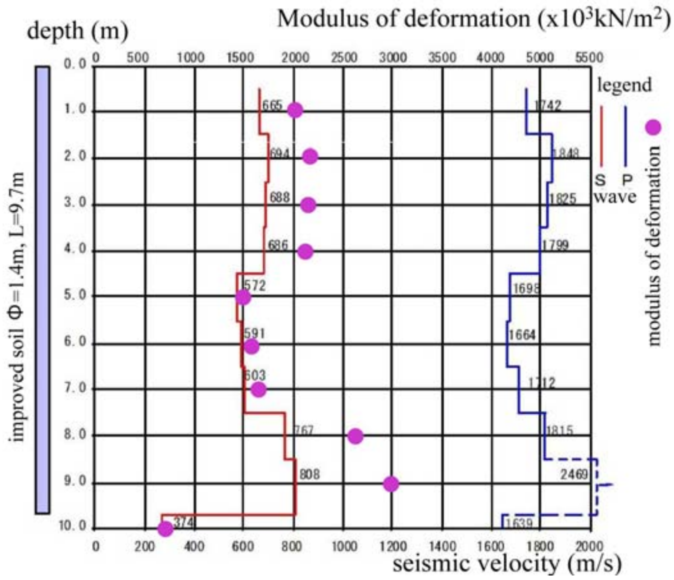


FIG.-4. SEISMIC VELOCITY LOGGING RESULT

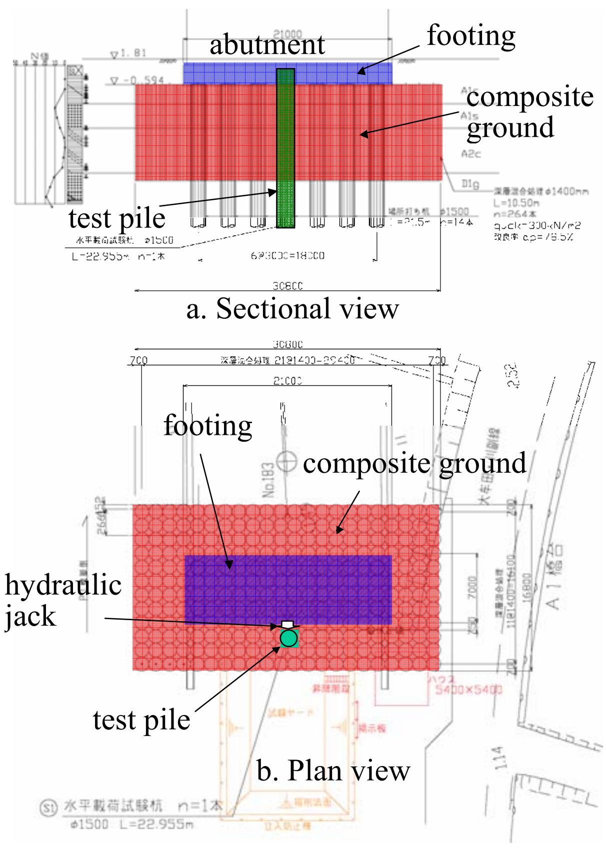


FIG.-5. LOADING TEST LOCATION

Load reaction is applied using the footing and the test pile having the same dimensions with that of the actual piles is installed as illustrated in Fig.-5. The piles are cast-in-place piles with a diameter of 1.5m and length of 21.5m which are installed by all casing method.

The result of loading test is shown in Fig.-6. This result reveals that the horizontal resistance of pile is extremely large. Although design calculation requires only 54% of the improvement area, the displacements due to design horizontal force were 1/3 that of design displacement for normal and Level 1 earthquake loads, and 1/10 that of Level 2 earthquake load.

This result suggests that the assumed design values for ground reaction coefficient and shear strength are extremely small and safe values. The actual strength of improved ground is about three to four times that of design values. This suggests future studies on the effect of improved ground's strain level, strength and improvement area with respect to ground reaction coefficient. Moreover, the mass of improved ground did not move or incline because it was anchored in the bearing layer.

D. Analyses by three-dimensional finite element method

The bearing capacity was considerably improved compared to initial design value as revealed in loading test. In this section, the characteristic of this bearing capacity are investigated by elastoplastic analysis of the loading test condition using three-dimensional finite element method. Three-dimensional model used in the analysis is shown in Fig.-7.

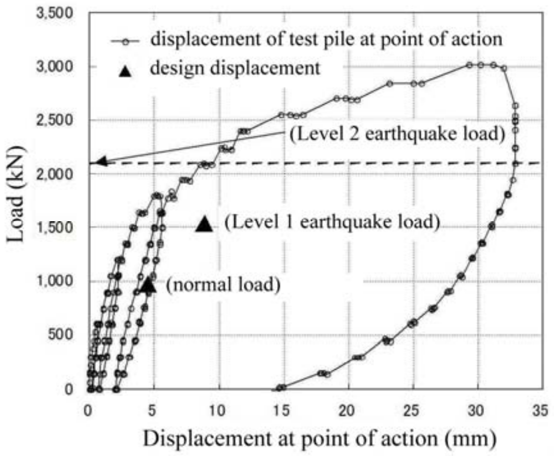


FIG.-6. LOAD-DISPLACEMENT RELATIONSHIP

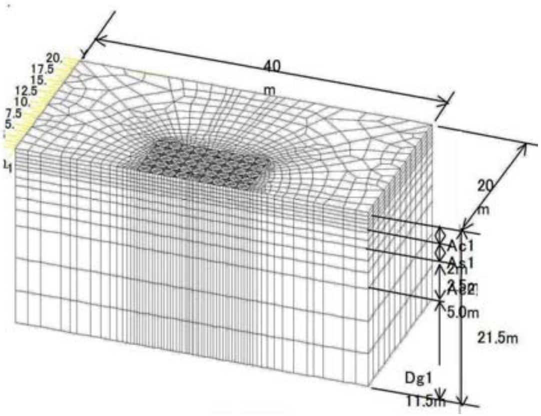


FIG.-7. FINITE ELEMENT ANALYSIS MODEL

Moreover, the difference in behavior of composite ground model and DMM model is studied. In the equivalent composite ground model, the average strength and deformation characteristic of improved ground is used in the entire improved part of the model. On the other hand, the improved and unimproved parts are modeled as is in the DMM model. Both models are illustrated in Fig.-8.

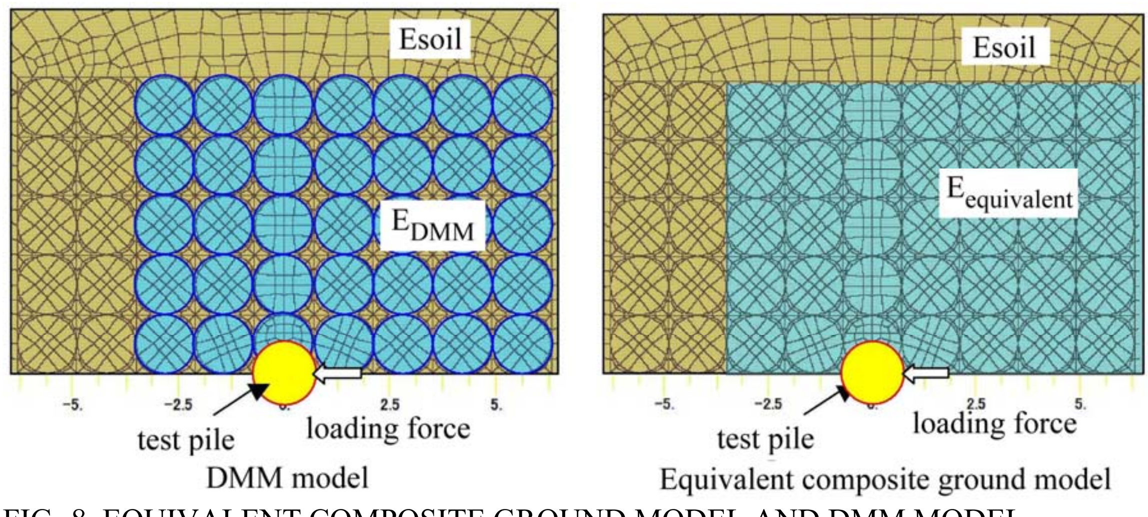


FIG.-8. EQUIVALENT COMPOSITE GROUND MODEL AND DMM MODEL

Ground coefficients used in the analysis is shown in Table-2. Although the improved ground’s deformation modulus depends strongly on strain, in this analysis, strain level of approximately 0.1% is considered.

TABLE.-2. GROUND COEFFICIENTS OF COMPOSITE GROUND FOUNDATION

Cases	Improved ground's *E* (MN/m²)	Improved ground's *c* (kN/m²)	Pile's *E* (MN/m²) 3)	Pile's *c* (MN/m²)
Equivalent ground composite-E	788 2)	Elastic	20,000	Elastic
Equivalent ground composite-EP	788 2)	390 2)	20,000	18.0 4)
Equivalent ground composite-EPL	788 2)	390 2)	20,000	1.8 5)
DMM-E	1,000 1)	Elastic	20,000	Elastic
DMM-EP	1,000 1)	500 1)	20,000	18.0 4)
DMM-EPL	1,000 1)	500 1)	20,000	1.8 5)

1) Strain level of improved soil is assumed to be less than 0.1%,
2) Average improvement rate is 78.5%, 3) Concrete's modulus of deformation,
4) $\sigma_c/2$, 5) Decreased to 1/10 from $\sigma_c/2$ (sensitivity analysis)

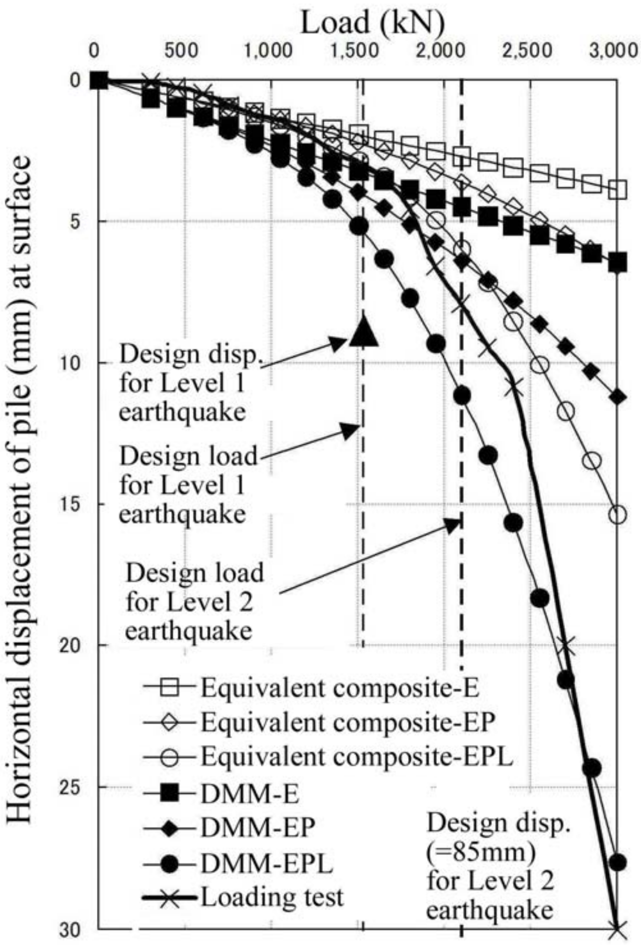


FIG.-9. LOAD-DISPLACEMENT CURVES

The load-displacement curves are shown in Fig.-9.

Analytic results imply that existing design methods for Level 1 and Level 2 earthquakes, that is, elastic design method and ductility design method, respectively, provide safety design values.

In equivalent composite ground model, displacement is slightly underestimated in both elastic and elastoplastic models except in the where pile strength is reduced to 1/10. In DMM model, displacement is considered to be slightly large. Here, there was no remarkable difference between the two models because the improvement rate in contact arrangement was 78.5%. However, if the improvement rate is varied, it is necessary to reconsider the analytic model carefully

Evaluation and characteristics of horizontal bearing capacity of composite ground foundation (Type II)

A. Horizontal loading test in-situ (Maeda, et al., 2001)

In the vicinity of Misato JCT of Tokyo-Gaikan Expressway, the ground under TP-40m is composed of alluvial deposit of silt fine sand and sand silt with N-value of about 0 to 10. Good bearing layer lies below TP-47m. Thus, the Type II floating-type composite ground foundation is adopted. Horizontal loading test is performed to study the bearing capacity characteristics of this new foundation.

The list of specifications and arrangement of test samples are presented in Table-3 and Fig.-10, respectively. Two test samples were prepared to be used in two cases of loading direction that is along strong load and weak load. The improvement depth, L=8.4m, is approximately equal to the characteristic length of pile.

TABLE.-3. SPECIFICATIONS OF TEST SAMPLES FOR COMPOSITE PILE

Improved ground			Soil cement steel pipe pile (2piles)			
Width, B	Width, D	Improvement length, L_1	Pile length, L_2	Pile dia., D_p	Thickness, t	Soil dia., D_s
3.2 m	1.4 m	8.4 m	30.0 m	0.6 m	0.016 m	0.8 m

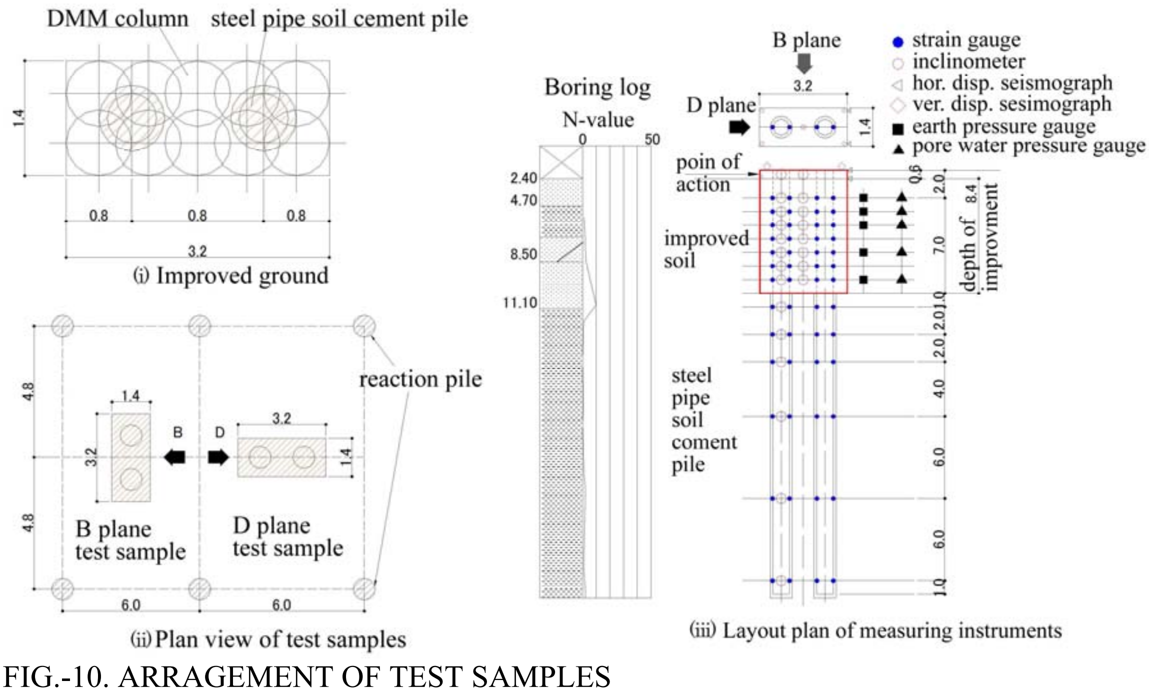


FIG.-10. ARRAGEMENT OF TEST SAMPLES

B. Horizontal loading test results and simulation analysis

Relationships of load, H, and displacement, δ, according to horizontal loading test and analysis by finite element method is shown in Fig.-11. Also, the results of three-dimensional analysis by finite element method are presented in the same figure. Comparing the results for D-plane loading test, i.e. in the direction of strong load, analytic results of Case 1 and Case 2 almost agree with test values when δ/B'=2.5% (δ=35mm); beyond this condition, Case 2 showed close values with test results. This is because, improved ground's stiffness decreases with increase of displacement due to elasticity; although, the improved ground and pile, as one body, showed high stiffness when displacement is small.

In the case of B-plane loading in the direction of weak load, analytic results and test results agree with each other within δ/B'=0.3% (δ=10mm). However, analytic values become larger than test values when displacement is beyond this condition. This implies that it is necessary to study the influence of decrease in improved ground's stiffness when displacement is large.

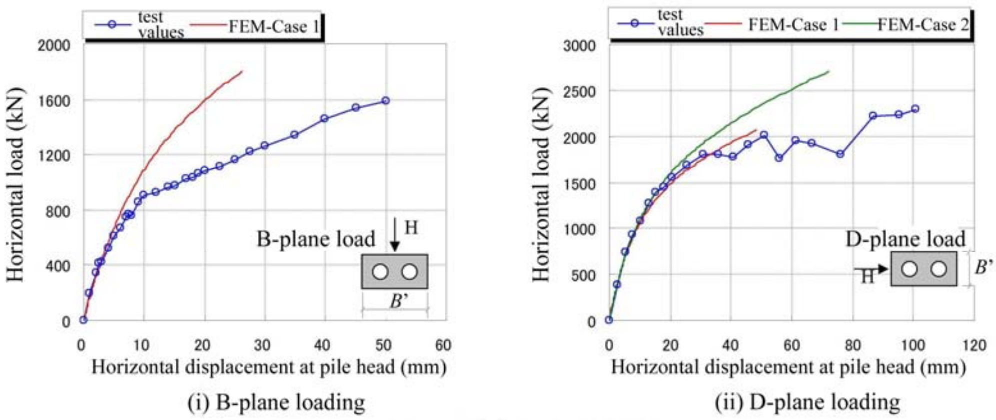


FIG.-11. LOAD-DISPLACEMENT RELATIONSHIPS

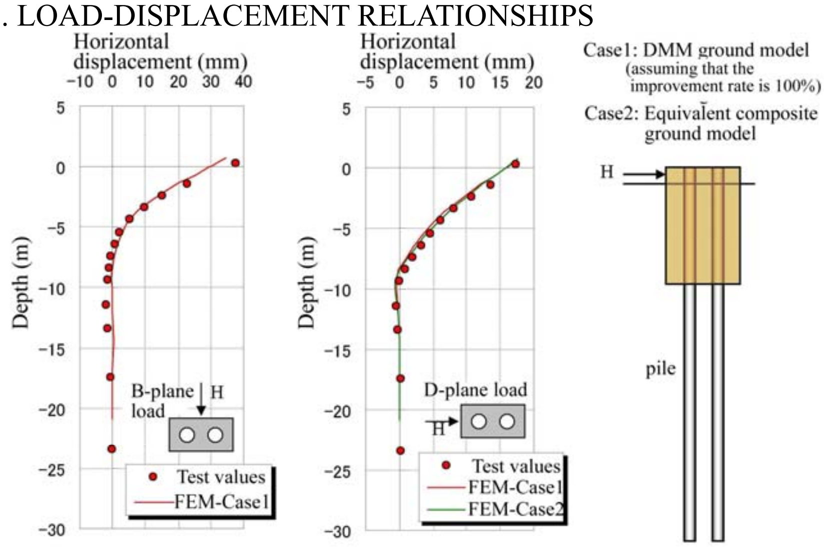


FIG.-12. HORIZONTAL DISPLACEMENT DISTRIBUTION (WHEN δ/B'=1.0%)

Fig.-12 show the distribution of horizontal displacement, δ, at pile head with respect to depth, z, according to horizontal loading test and analysis by finite element method, considering allowable displacement, δ/B'=1%, for Level 1 earthquake. These figures show that test results and analytic results agree with each other for loading tests in B-plane and D-plane.

C. Laboratory model test and its bearing capacity characteristics (Maeda, et al., 2006)

a. Outline of laboratory model test

Laboratory loading test of Type II composite ground foundation's model is conducted to investigate in details its bearing capacity characteristics. A large shear earth tank (Ichikawa, et al., 2006) is used in the test as shown in Fig.-13 and Photo-2. It consists of a shear earth tank (depth of 8m and inside measurement of 2.5m at the side) filled with soil, a jig set installed in the pile head for loading and five actuators used for moving the earth tank or footing in horizontal direction.

Loads and displacements in the vertical and horizontal directions can be voluntarily applied through the jig while the rotation of footing remains fixed. In this study, horizontal load is applied to the footing using only the actuator connected to jig of pile head.

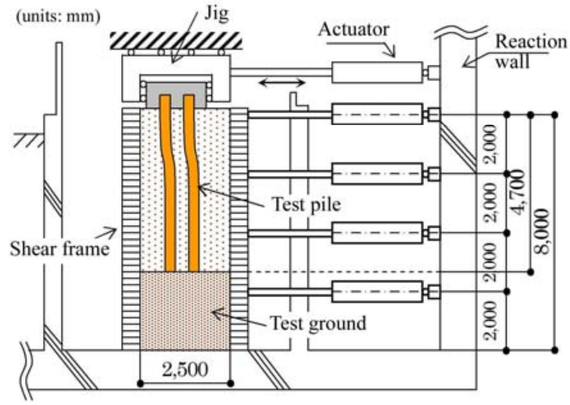


FIG.-13. SET-UP OF LARGE SHEAR EARTH TANK

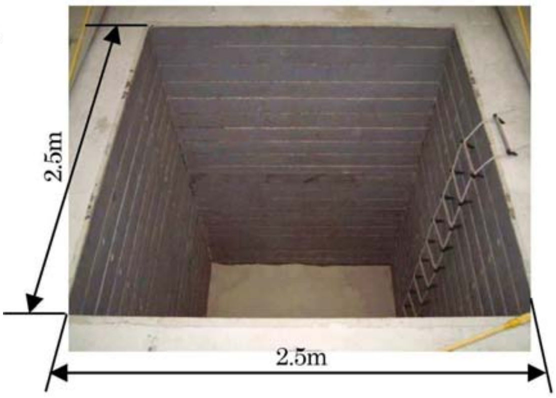


PHOTO-2. APPEARANCE OF LARGE SHEAR EARTH TANK

Moreover, 19 strain gauges are installed in piles at the front and back rows as shown in Fig.-14. Here, improvement depth is L=1.2m which is approximately equal to 1/β of pile

b. Summary of ground

Test ground is made by filling the tank with sand (free-fall) after test pile is packed. Ground materials are made from air-dried Iide quartz sand No.6 (D50=0.2mm, ρ_{dmax}=1.73g/cm^3, ρ_{dmin}=1.41g/cm^3). The relative density, D_r, of material from level crown of tank to 4.7m deep is set to 20% to 80%, while D_r=20% in the surface layer. In addition, the bearing layer's relative density is more than 90%.

Test results are shown in Fig.-15.The deformation modulus of soil presented in

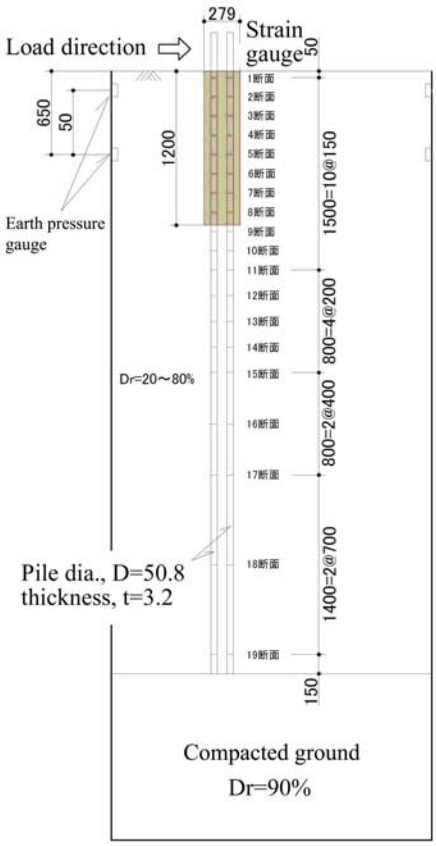


FIG.-14.SET-UP TEST SAMPLE

Fig.-15(iv) are values estimated based on Dutch cone penetrometer test result, E_1, and seismic velocity logging result (before loading of composite ground pile), E_2. The following equations are used to calculate deformation modulus, E_1 and E_2.

$N = q_c / 400$ *Equation-1*

$E_1 = 2800\, N$ *Equation-2*

Equation-1 expresses the relationship of cone penetration resistance and N-value for fine sand with particle size of 0.1 to 0.2mm (MLIT's Railway Bureau, 2001).

$G = \gamma\, V_s^2 / g$ *Equation-3*

$E_2 = 2\,(1+\nu)\, G\, n$ *Equation-4*

Here, q_c is cone penetration resistance, N is N-value, γ is unit weight, V_s is shear seismic velocity, g is gravity acceleration, G is shear deformation coefficient, ν is Poisson's ratio and n is reduction coefficient equal to 0.125 (MLIT's Railway Bureau, 2001). The relevance of Dutch cone penetrometer and shear seismic velocity is confirmed according to the correspondence of deformation modulus E_1 and E_2.

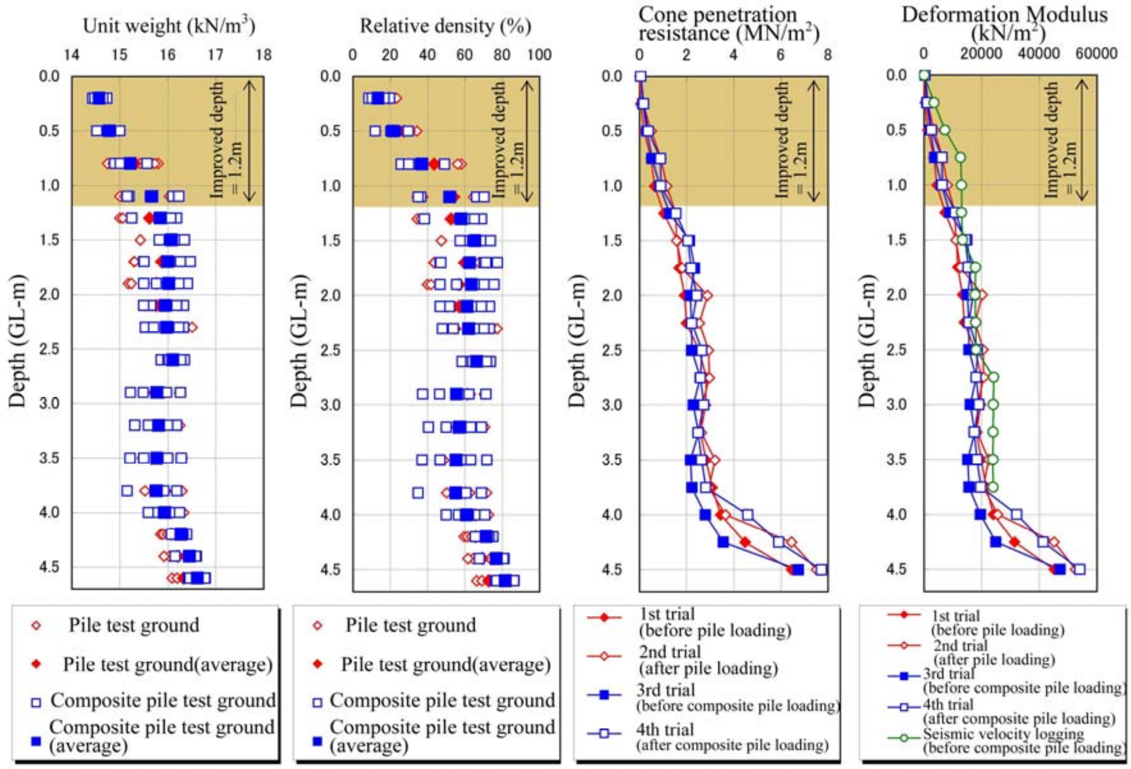
The strength and deformation modulus of improved ground taken from test results are shown in Table-4.

TABLE-4. PYSICAL PROPERTIES OF IMPROVED GROUND

Sample No.	Unconfined compression strength q_u (kN/m^2)		Deformation modulus E_{50} (MN/m^2)	
1	2246	Average=2393	1958	Average=2390
2	2323		2762	
3	2611		2450	

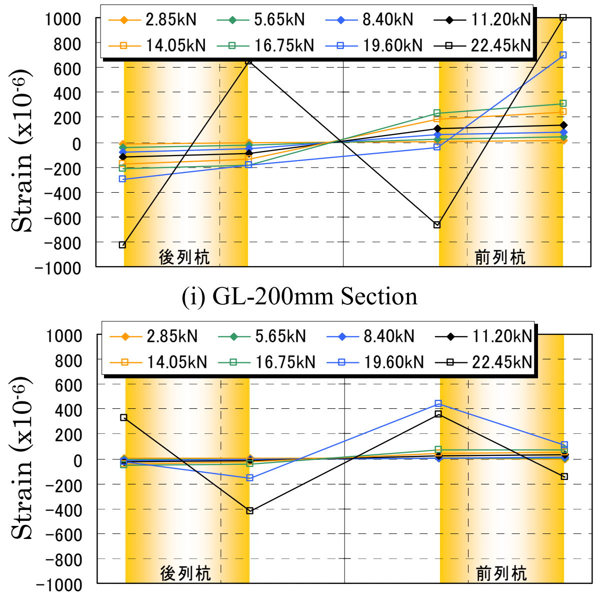
c. Horizontal loading test results

Load-displacement curves are presented in Fig.-17 in later section. Test results of composite ground pile according to Fig.-17 shows elastic behavior when displacement is approximately less than 3.2% of width *B* (9.12mm) and may not able to support load when load force is 16.75kN and displacement is 9.12mm (maximum load of sixth cycle). The next point of measurement shows that load continues to decrease even though the displacement increases. However, horizontal resistance tends to increase after the seventh cycle. Furthermore, the yield strengths when horizontal displacement is equal to 1% of width *B*, is 7.75kN for composite ground pile and 3.03kN for ordinary pile.



(i) unit weight (ii) Relative density (iii) Cone penetration resistance (iv) Deformation modulus

FIG.-15. SUMMARY OF GROUND



(i) GL-200mm Section

(ii) GL-650mm Section

FIG.-16. STRAIN MEASUREMENTS OF PILE

This implies that the horizontal yield strength of composite ground pile for Level 1 earthquake is nearly 2.5 times that of ordinary pile when both have the same number of piles and in similar arrangement.

Fig.-16 shows the vertical strain measurements of pile corresponding to each cycle's maximum load in horizontal loading test in order to check the behavior of improved ground and pile as one body. This figure suggests that strain distribution mode changes within 16.75kN (6th cycle) to 19.60kN (7th cycle). This means that improved ground and pile behave as one body (i.e. the composite structure of improved ground and pile satisfies the Bernoulli- Euler theory) until the 6th cycle. Beyond this, it act similar to ordinary pile (i.e. piles in the front and back rows resist bending) because the strain's positive and negative signs are reversed in front and back rows. Therefore, the authors consider that the behavior of composite structure of improved ground and pile as one body will not be true in this case.

d. Analyses by three-dimensional finite element method

Three-dimensional analyses using finite element method of horizontal loading tests for ordinary pile and composite ground pile are conducted. The analytic model and material's yield conditions are almost the same with that of simulation analysis of in-situ test, stated in early section (Maeda, et al., 2006).

Load-displacement relationships are shown in Fig.-17and Fig.-18. Analytic results of composite ground pile are close to test values when horizontal displacement is within 5%(14mm) of width *B*. It can be thought that when horizontal displacement is beyond 5% of *B*, displacements due to factors inexpressible in analysis such as elasticity and cracks become large which lead to collapse of improved ground. Similarly, analytic results of ordinary pile are almost the same with the test values.

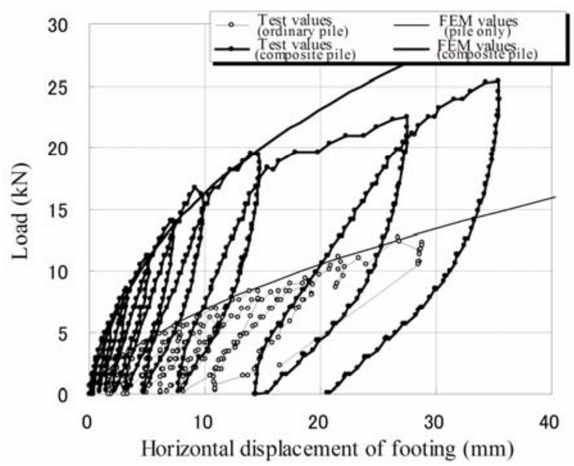


FIG.-17. LOAD-DISPLACEMENT CURVES

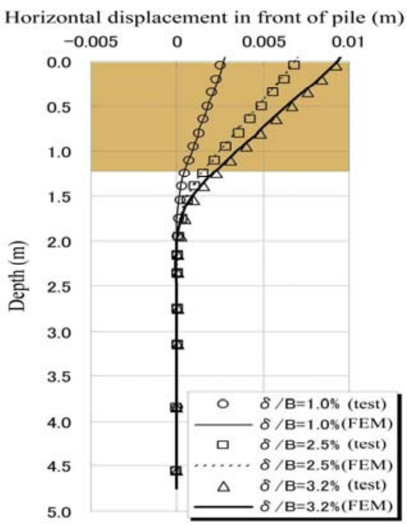


FIG.-18.HORIZONTAL DISPLACEMENT

Conclusions

The load-displacement characteristics of composite ground foundation is studied in order to improve its horizontal bearing capacity by performing horizontal loading tests of Type I and Type II foundations which have different bearing capacity mechanism. Based on these results, composite ground foundation has remarkably improved horizontal bearing capacity compared to ordinary pile. Furthermore, three-dimensional elastoplastic analysis by finite element method is primarily used to simulate and investigate in details the behavior observed in the loading test. The following matters are drawn from the results.

1) In the case of Type I composite ground foundation, the crosswise improvement area is

determined from the relationship of pile's characteristic length 1/β and passive slip area. Economic advantage is probable since displacements based on tests and analyses are sufficiently small and the improvement area can be reduced more.

2) Six cases of analysis by finite element method are conducted using DMM model and equivalent composite ground model with varied parameters. Results suggest that the displacement restraint effect of composite ground foundation is well represented.
3) According to in-situ and laboratory loading test results of Type II composite ground foundation, horizontal bearing capacity greater than ordinary pile can be expected because of improved ground's high stiffness as well as passive resistance in front and frictional resistance in the side. Sufficient composite effect is confirmed since improved ground and steel pipe pile behave as one body when displacement is small, approximately within 1% of foundation width.
4) On the other hand, when displacement starts to exceed 1% (in-situ) or 5% (laboratory) of foundation width, the behavior of improved ground and pile as one body fails and displacement increases, although, decrease in bearing capacity is not observed. These characteristics should be considered in stability calculation model for Level 2 earthquake. Also, in regards to unity of improved ground and pile when displacement is large, laboratory test and in-situ test showed similar results.

Acknowledgements

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