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DESIGN AND EVALUATION OF A NEW COMPOSITE FOUNDATION OF PILE WITH DMM TO CONTROL THE LATERAL DEFORMATION DURING EARTHQUAKE

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ABSTRACT

In order to improve earthquake performance of foundation structure in soft ground, it is necessary to increase horizontal resistance of the foundation. 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 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. 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 the composite ground foundation. Furthermore, it is expected that the proposed foundation method brings cost reduction effect.

Keywords: ground improvement, pile foundation, soft ground, horizontal bearing capacity, in-situ loading test

INTRODUCTION

From the viewpoint of cost reduction in provision of social overhead capital and environmental load reduction, various kinds of new foundation method have been proposed. Composite ground foundation proposed in this study is one of them and the practical use is expected.

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

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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.

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.

EVALUATION AND CHARACTERISTICS OF HORIZONTAL BEARING CAPACITY OF COMPOSITE GROUND FOUNDATION

Presently, the composite ground foundation is under development in Japan. 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).

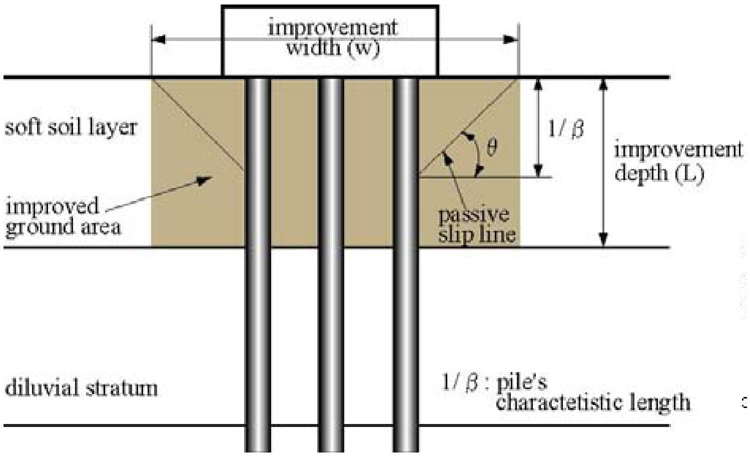

Figure 1. Soil improvement by composite ground foundation

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=150qu (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.

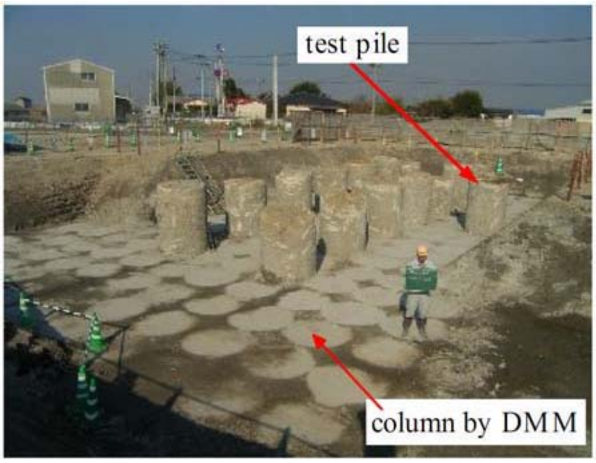

Photo 1. Cast-inplace piles in a composite ground foundation

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. 2.

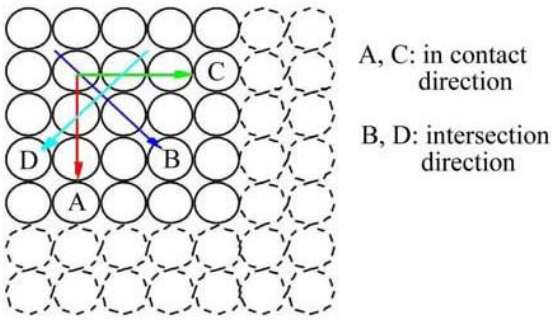

Figure 2. Measurement of shear wave velocities

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.3. 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 the following equations.

$$G = \gamma \, Vs^2 / g \tag{1}$$

$$E = 2\,(1+\nu)\, G\, n \tag{2}$$

Here, γ is unit weight, Vs 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 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			

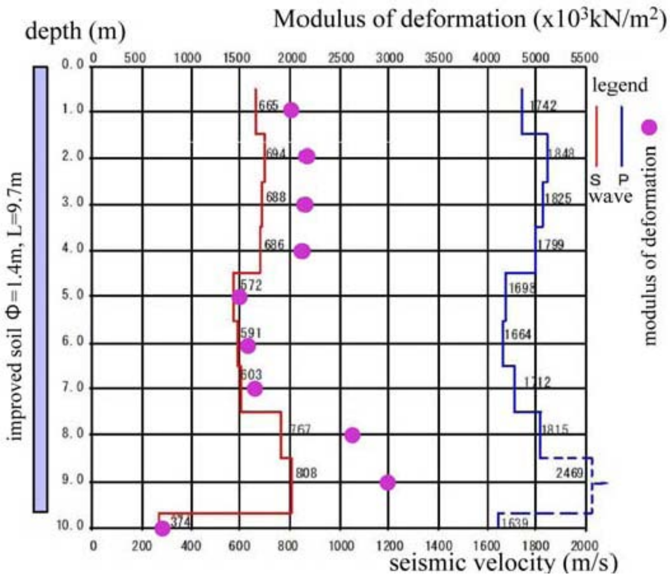

Figure 3. Seismic velocity logging result

Evaluation of improved ground column
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.

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.4. 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.

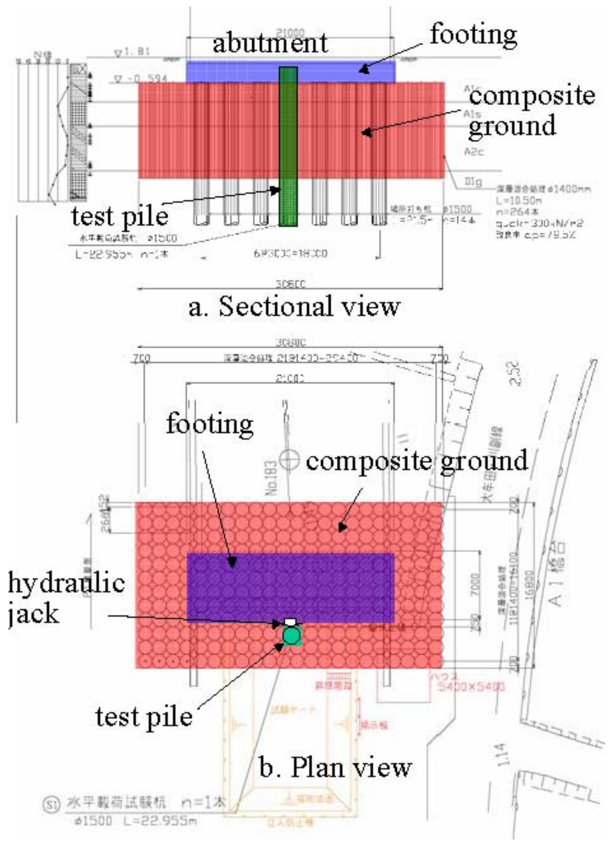

Figure 4. Loading test loaction

The result of loading test is shown in Fig.5. 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.

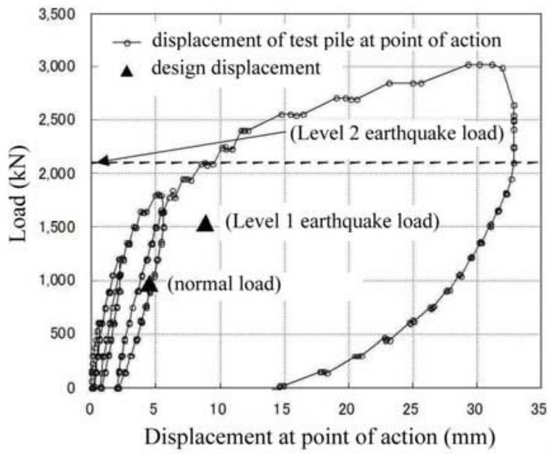

Figure 5. Load-displacement relationship

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 FIG.-5. LOADING TEST LOCATION elastoplastic analysis of the loading test condition using three-dimensional finite element method. Three-dimensional model used in the analysis is shown in Fig.6.

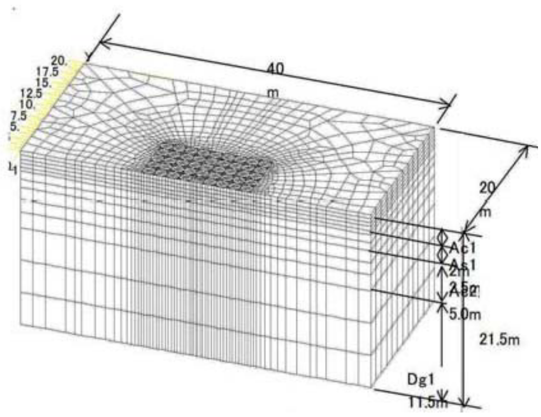

Figure 6. Finite element analysis model

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 shown in the DMM model. Both models are illustrated in Fig.7.

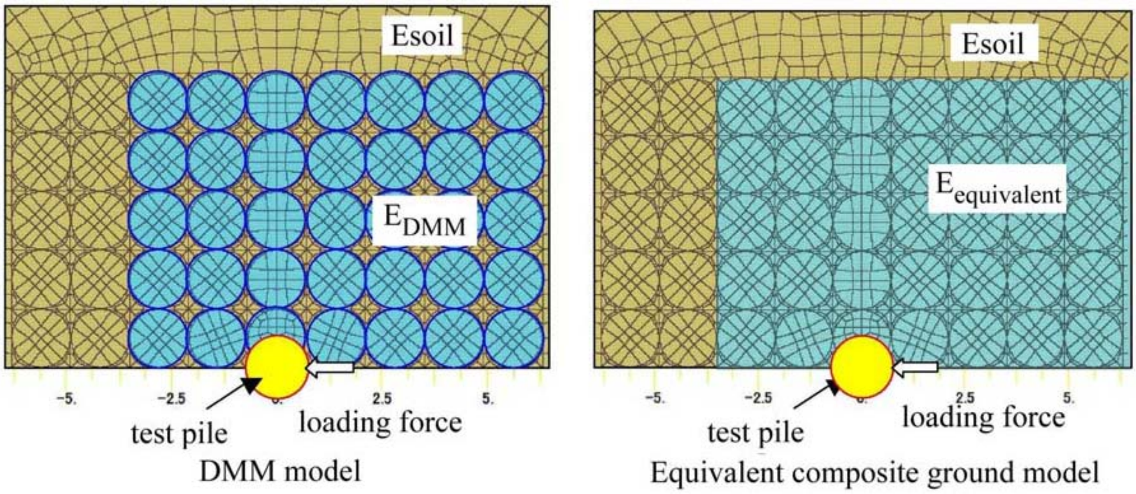

Figure 7. Equivalent composite ground model and DMM model

Geologic stratum and soil parameters are shown in Table 2. Ground coefficients used in the analysis is shown in Table 3. Although the improved ground's deformation modulus depends strongly on strain, in this analysis, strain level of approximately 0.1% is considered.

Table 2. Geologic stratum and soil parameters

Layers	Depth from bottom of footing (m)	γ_t (kN/m^3)	ν 1)	E 2) (MN/m^2)	c (kN/m^2)	ϕ ($^\circ$)
Ac1	0~2.0	15	0.45	28.5	20 5)	15 4)
As1	2.0~4.5	18	0.33	31.5	0	30 6)
Ac2	4.5~9.0	16	0.45	28.5	20 5)	15 4)
Dg1	9.0~	18	0.33	370.0 3)	0	35 6)

1) 0.45 for Cohesive soil and 0.33 for sandy soil, 2) $(E)_{PS}$ /2, 3) $(E)_{PS}$, 4) CU test, 5) two times of c=10kN/m^2 (CU test), 6) 30° for sandy soil and 35° for sandy gravel

Table 3. Ground coefficients of composite ground foundation

Cases	Improved ground's *E* (MN/m^2)	Improved ground's *c* (kN/m^2)	Pile's *E* (MN/m^2) 3)	Pile's *c* (MN/m^2)
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) σ_c /2, 5) Decreased to 1/10 from σ_c /2 (sensitivity analysis)

Analytical result is compared with design value and in-situ loading test results in Table 4. Measured value of horizontal displacement at pile head is approximately 3 mm at the loading condition of Level 1 earthquake and is one third of the design value. Measured value at the loading condition of Level 2 earthquake is approximately 9 mm and is considerably smaller than the design value. The result of FEM analysis is almost same level with the measured value by the loading test.

Table 4. Comparison among design values, loading test and analytical results

Loading condition	Horizontal load at pile head in design (kN)	Horizontal displacement at pile head (mm)		
		Design	Loading test	FEM
Level 1 earthquake	1,500	9	3	2~5
Level 2 earthquake	2,100	85	9	3~11

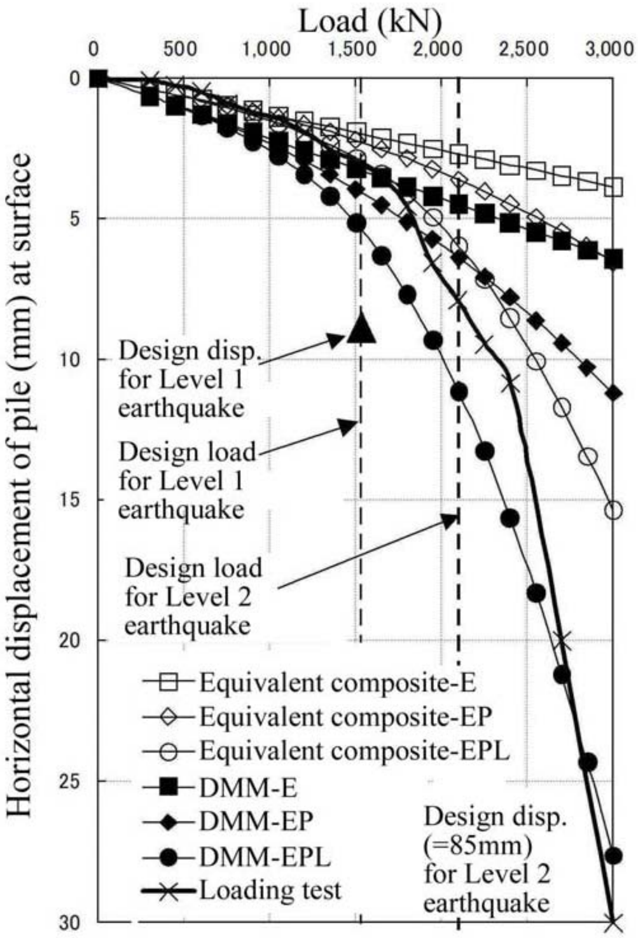

Figure 8. Load-displacement curves

The load-displacement curves are shown in Fig.8. 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.

CONCLUSIONS

The load-displacement characteristics of composite ground foundation are studied in order to improve its horizontal bearing capacity by performing horizontal loading tests. 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) The crosswise improvement area of the composite ground foundation 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) The composite ground foundation is a new pile foundation method with high performance for restraint of deformation and reduction of construction cost.

For further study, it is necessary to bring up a rational determination method of design parameters for the composite ground foundation, and a new design method for performance-based design is also required.

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