NUMERICAL PREDICTION OF LONG-TERM DISPLACEMENTS OF PILE FOUNDATION IN CLAYED GROUND CONSIDERING CONSTRUCTION PROCESS

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Abstract

In this paper, soil-water coupling analyses with FEM-FDM method are conducted to investigate the long-term displacements of pile foundation installed in soft clayed ground. The analytical target is the pile foundation of road viaduct now under construction at Niigata Prefecture, Japan. As constitutive model for ground, subloading tij model is considered, which is a simple elastoplastic model for normally and over consolidated soils. The influence of following factors are considered carefully; 1) drainage condition at side boundaries; 2) stiffness of bearing layer; and 3) space between piles. As conclusion of a series of analyses, followings are clarified; 1) the long-term behavior of pile foundation; 2) the influence of the drainage condition and the thickness of bearing layer; 3) the mechanism of how the space between piles affects the long-term displacements.

Introduction

In today's design standard, it is not necessary to consider the settlement of pile foundation. In very soft clayed ground, however, even if the bearing capacity of a pile foundation is sufficient enough to resist vertical load, the long-term settlement of the pile foundation due to vertical static load cannot be neglected. Sometimes this causes big problems, especially in those structures like railway bridges whose deformation is strictly restricted. For performance based design, it is necessary to check the vertical displacement not only in short-term, but also in long-term. Many prediction methods can be found in literature for the settlement in soft ground. But for pile foundation, due to the difficulty in evaluating the interaction of pile-soil-pile system, quantitative prediction method for long-term settlement in soft ground is still need to be developed. Therefore, in design of pile foundation in soft ground, we need to adopt high safety factor to bearing capacity for safety. But this method leads to an uneconomical design, e.g. increase in number of pile.

The analytical target in this paper, the pile foundation of road viaduct under construction in Niigata Prefecture Japan, has very soft clayed ground under its bearing layer, it is necessary to adopt high safety factor to bearing capacity. But in making an examination of long-term displacements in situ beforehand and deciding the allowable displacements occurred during construction, it is possible to design pile foundation with low safety factor,

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and it leads to economical design (e.g. decreasing number of piles or length of piles). The pile foundation designed in this concept is named 'Rationalized Pile Foundation'.

In design of Rationalized Pile Foundation, it is required to forecast the long-term displacements with accuracy. To check the long-term displacements, we need to solve the problem as the soil-water coupling problem. In this paper, a numerical prediction method with three-dimensional (3D) finite element analysis based on two-phase theory is proposed and a series of numerical calculations are conducted to clarify the mechanism of long-term behavior of pile foundation. For solving the two-phase problem, a soil-water coupling scheme by finite element and finite difference methods is adopted in which a backward finite difference scheme is adopted for continuum equation, while a finite element scheme is used for the spatial discretization of the equilibrium equation.

Some factors may affect the long-term settlement of pile foundation. In this paper, the influence of following factors is examined; 1) drainage condition at side boundaries; 2) stiffness of bearing layer; and 3) space between piles. The purposes of the research are following; 1) to propose a simple and practical method for prediction of long-term displacements in pile foundation not only qualitatively but also quantitatively based on simple constitutive models for soft clay and sandy ground; 2) to evaluate the influence of those factors above-mentioned. The calculations are all conducted with a 3D FEM code named DGPILE-3D (Zhang & Kimura, 2002).

Constitutive models of soils and numerical procedures

As mentioned in previous section, in order to properly evaluate the long-term displacements of pile foundation, constitutive models for soil skeleton play a very important role in numerical analyses. In present research, subloading tij model (Nakai and Hinokio, 2004) were used in finite element analyses, in which the influence of the intermediate principal stress can be properly evaluated. The model has been verified through many triaxial tests on normally consolidated clay, over consolidated clay, and sand in generalized stress paths. The parameters involved in tij models are almost the same as those in Cam-clay model. Therefore, it is rather easy to determine the values of these parameters with triaxial compression tests and consolidation tests.

In the formulation of soil-water coupling analysis, a FEM-FDM scheme proposed by Oka et al (1994), is adopted, in which finite element method is used for spatial discretization of equilibrium equation, and finite difference method is used for the spatial discretization of excess pore water pressure in the continuity equation. The mathematical formulation of 3D soil-water coupling analysis is also the same as the one proposed by Oka et al (1994). Detailed description about the constitutive models and the numerical procedure can be found in relevant references.

Numerical conditions in finite element analyses

In order to predict the long-term displacements of pile foundation and to evaluate the influence of drainage condition, thickness of bearing layer, and space between piles, a series of numerical analysis are conducted. In the first, the long-term displacements of actual pile foundation are predicted in Case-1 at undrained condition (Case-1-UC) and at drained condition (Case-1-DC). The influence of drainage condition at side boundaries is also evaluated in comparison with Case-1-DC and Case-1-UC. Secondary, the influence of thickness of bearing layer is evaluated in comparison with Case-1-DC and Case-2 (only the case at drained condition is conducted as Case-2). Finally, the influence of space between piles is evaluated in Case-3 at drained condition. More details about analytical cases are described in Table 1.

Case-1 and Case-2 are modeled for actual pile foundation of road viaduct now under construction at Niigata Prefecture, Japan. The pile foundation is designed as end bearing pile, and the thickness of bearing layer is 4.9 m in Case-1 and 3.0 m in Case-2. The soil layers except the bearing layer are the same in both cases. The soil properties are determined through triaxial compression tests and consolidation tests except sand layer, because of the difficulty in conducting triaxial compression tests on undisturbed sample. The value of Rf is assumed based on experience. More details of properties are shown in Table 2. All soil layers are modeled by subloading tij model.

The configuration of pile foundation is 3×4, and the pile is steel pipe pile filled with soil cement. The actual pile consists of three parts according to its position as shown in Table 3 and Figure 1(a), and the composition of the pile is considered carefully in the analyses. The pile is modeled by hybrid element composed with elastic beam element and solid element, and the volume of pile is considered carefully. The concrete footing above pile heads is modeled as rigid elastic element.

Figure 1(a) also shows the configuration and composition of the pile foundation and the loading points in the numerical calculation. In the calculation, the load is applied evenly at all points of footing. It is known that initial stress condition greatly affects the behavior of soils. For simplicity, however, the disturbance of the surrounding ground due to the installation of piles is neglected and the initial stress field is assumed as a gravitational field of layered ground without the existence of piles. The construction process of footing, the pier and the superstructures are considered carefully as shown in Figure 2.

Figure 1(b) shows the finite element mesh for Case-1 and Case-2. Because of the symmetric condition of geometry and loading, only one fourth of the area considered is used in the calculation. In soil-water coupling analysis, drainage condition plays very important role, especially in the long-term problem. Though the loading area, the footing, is small compared with its surrounding ground, the drainage condition at far field, that is usually thought to be indifferent to the settlement of pile foundation, should be considered carefully. Therefore, in Case-1, two kind of drainage condition at side boundaries are considered, that is, completely drained (Case-1-DC) and completely undrained condition (Case-1-UC). In all cases, the ground surface is drained and the bottom of the ground is undrained. The boundary condition of displacement is as following: fixed at the bottom, free at the surface and roller at the side boundaries.

Figure 2 shows the loading process in the numerical simulation. The construction is finished in 306 days, and the analysis is continued up to 50 years.

Table 1 Cases of calculations

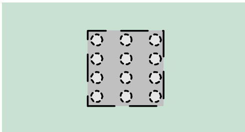
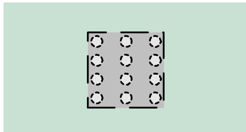
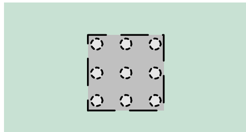
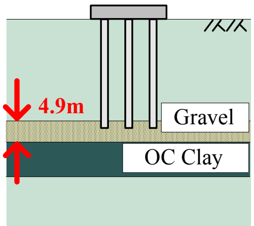
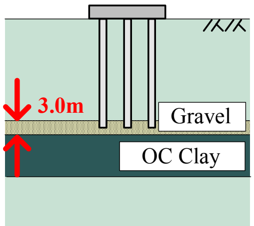
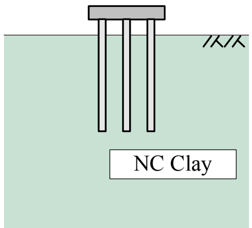
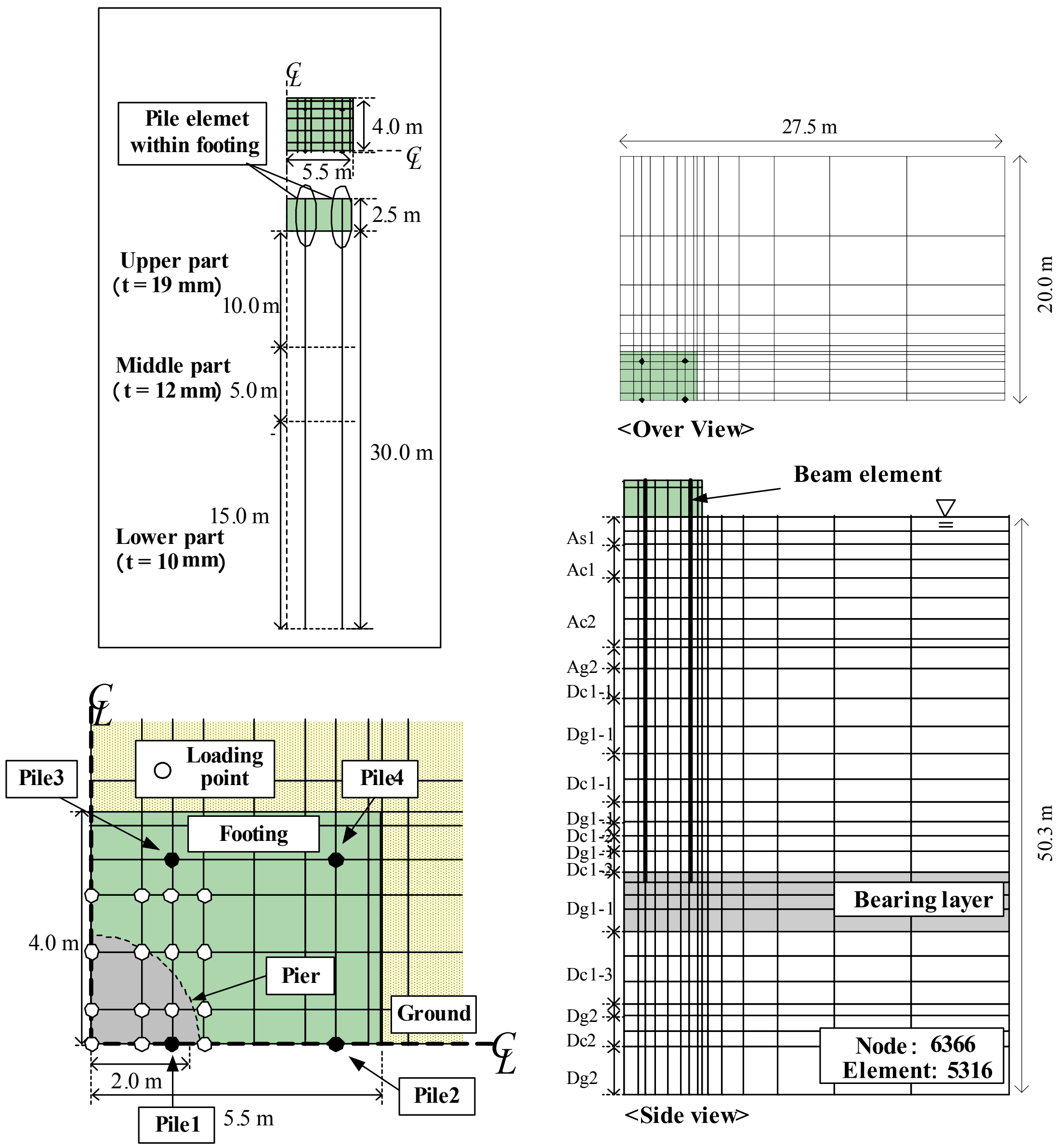
	Case-1	Case-2	Case-3
Length of pile [m]	30.0		20.0
Diameter of pile [m]	1.2		1.0
Pile Arrangement	3×4		3×3
Pile type	Steel tube pile with soil cement		Steel tube pile
Supporting type	End Bearing Pile		Frictional Pile
Thickness of Bearing layer [m]	4.9 (Gravel layer)	3.0 (Gravel layer)	— (NC Diluvial clay)
Drainage Condition at Side Boundaries	Drained (Case-1-DC) / Undrained (Case-1-UC)	Drained (Case-2)	Drained (Case-3)
Over View			
Side View			
Examined Parameter	Drainage Condition		
	Thickness of Bearing layer	Thickness of Bearing layer	
			Space between piles

Table 2 Soil properties and parameters (common in Case-1 and Case-2)

	N	Thickness [m]	Density [g/cm^3]	ν	λ (C_t)	κ (C_e)	Rf	Permability [m/sec]	K_0	e_0
As1-1	10	3.0	1.73	0.30	(0.052)	(0.0024)	2.66	1.00e-6	0.50	1.08
Ac1	1	2.7	1.72	0.30	0.304	0.0334	3.69	4.76e-10	0.50	1.52
Ac2	3	5.7	1.72	0.30	0.260	0.0367	3.69	8.65e-10	0.50	1.43
Ag2	43	1.8	1.94	0.30	(0.0042)	(0.0032)	4.60	1.00e-4	0.50	0.65
Dc1-1	6	2.4	1.69	0.30	0.378	0.0420	3.69	1.76e-10	0.50	1.71
Dg1-1	45	4.6	1.94	0.30	(0.0042)	(0.0032)	4.60	1.00e-4	0.50	0.65
Dc1-2	6	3.9	1.69	0.30	0.191	0.0292	3.69	4.84e-10	0.50	1.13
Dg1-1	45	1.7	1.94	0.30	(0.0042)	(0.0032)	4.60	1.00e-4	0.50	0.65
Dc1-2	7	1.1	1.69	0.30	0.195	0.0313	3.69	1.14e-10	0.50	1.00
Dg1-1	45	1.3	1.94	0.30	(0.0042)	(0.0032)	4.60	1.00e-4	0.50	0.65
Dc1-2	11	1.7	1.69	0.30	0.195	0.0313	3.69	1.14e-10	0.50	1.00
Dg1-1 (Bearing Layer)	45	4.9	1.94	0.30	(0.0042)	(0.0032)	4.60	1.00e-4	0.50	0.65
Dc1-3	11	5.9	1.69	0.30	0.221	0.0314	3.69	3.42e-10	0.50	1.20
Dg2	49	1.0	1.94	0.30	(0.0042)	(0.0032)	4.60	1.00e-4	0.50	0.65
Dc2	14	2.5	1.84	0.30	0.239	0.0276	3.69	4.40e-11	0.50	1.10
Dg2	49	3.9	1.94	0.30	(0.0042)	(0.0032)	4.60	1.00e-4	0.50	0.65

Table 3 Parameters of steel pipe pile with soil cement (common in Case-1 and Case-2)

	Upper part	Middle part	Lower part
Thickness of steel pipe pile [mm]	19	12	10
Stiffness ***EA*** [kN]	1.42e7	9.95e7	8.69e7
Area ***A*** [m^2]	5.86e-2	3.73e-2	3.11e-2
Equivalent Young's modulus ***E*** [kPa]	2.55e8	2.67e8	2.79e8
Equivalent second moment ***I*** [m^4]	7.05e-3	4.55e-3	3.81e-3



(a) (b)

Fig. 1 Composition and configuration of pile foundation and finite element mesh (common in Case-1 and Case-2)

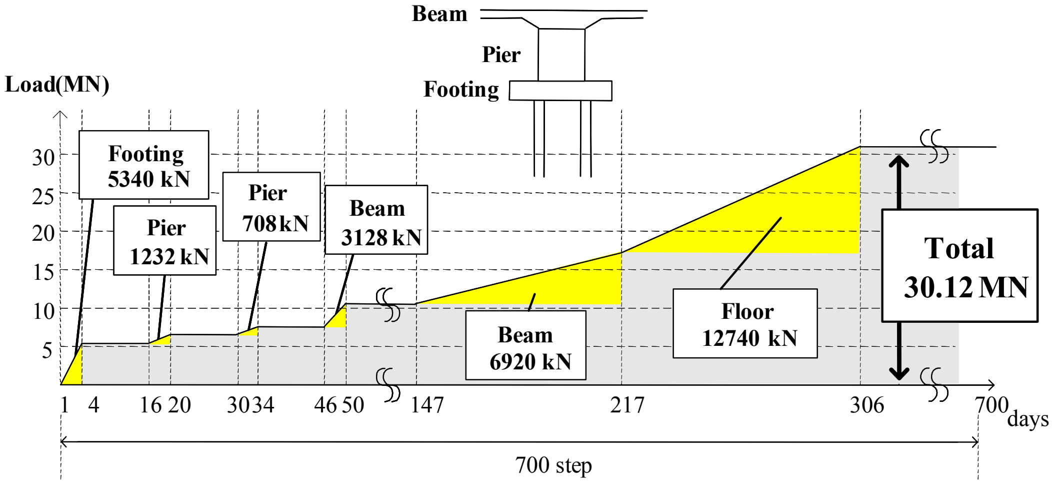


Fig 2 Construction process and its numerical simulation in loading step

Table. 4 Soil properties

Rf	3.69
λ	0.20
κ	0.030
ν	0.30
e_0	1.20
k	4.00e-10

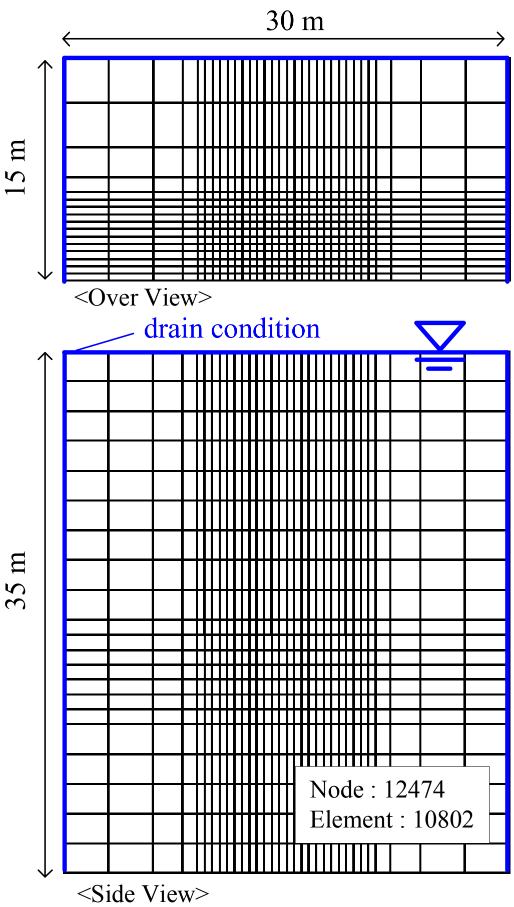


Fig. 3 Finite element mesh in Case-3

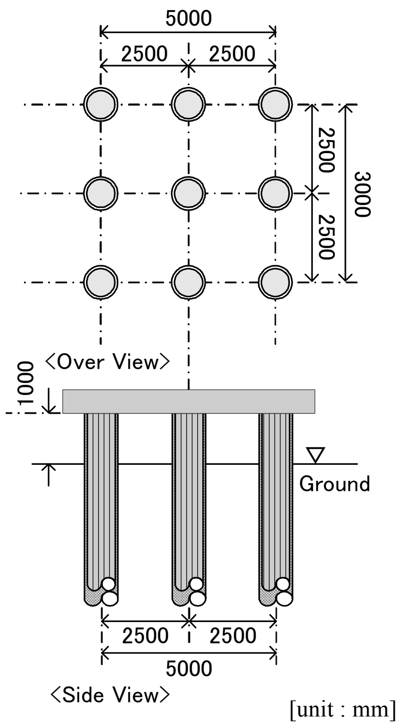
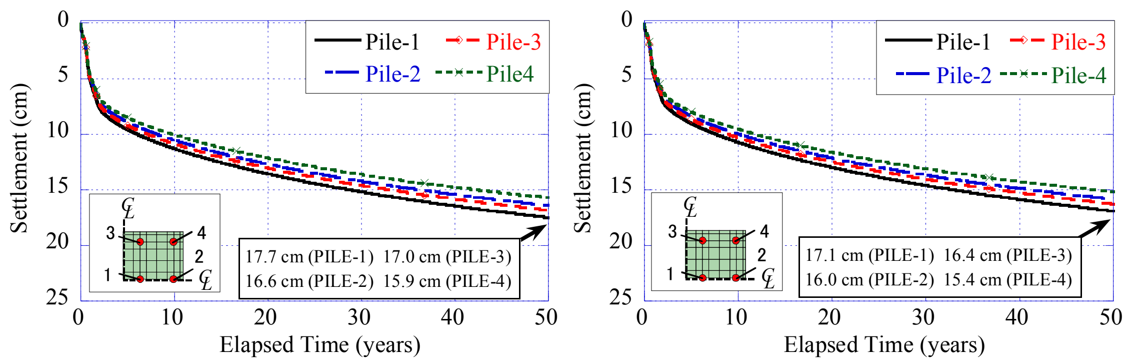


Fig. 4 Configuration of piles in Case-3

Case-3 is modeled as virtual pile foundation in order to evaluate the influence of space of piles by simple numeric experiment. Figure 3 shows finite element mesh used in Case-3. The ground is assumed to be filled with soft diluvial clay, those N value is about 5, and the soil properties are also assumed as the common value in soft diluvial clay, shown in Table 4. The soil is modeled as subloading tij model. The ground surface and side boundaries are drained condition. The pile is assumed to be just steel pipe pile with 1.0 m diameter and 20.0m length, and the configuration of pile foundation is 3×3 as shown in Figure 4. The pile is modeled as hybrid element composed with elastic beam element and solid element, and the volume of pile is considered carefully. The load is assumed by load test simulation. To focus pile-soil-pile system, the footing is assumed to be not-grounding.

Prediction of long-term displacements of actual pile foundation

Figure 5 shows the settlement of Pile-1 to Pile-4 due to the vertical load of the superstructure from the beginning of the construction. The difference between the vertical settlement at pile head and pile end is almost in the same order in all piles and is about 5 mm which stands for the compression of the piles. The maximum settlement occurred at Pile-1, followed by Pile-2 and Pile-3, and the minimum settlement occurred at Pile-4. The difference of the settlement between Pile-1 and Pile-4 is about 18 mm, showing that even if the stiffness of footing is large enough, there still exists some bending deformation within the footing. There exists a sharp turning point in the settlement curve around 2 years (=700 days). Before that time, the settlement developed very quickly and then it changed to a slow pace in its development.

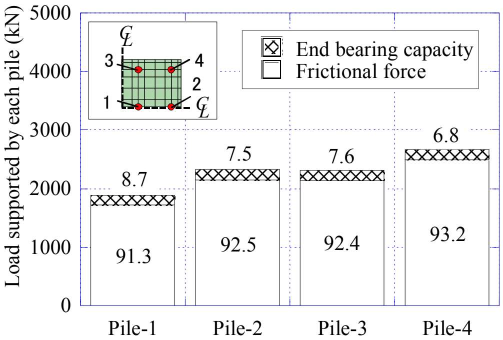


(a) Pile head (b) Pile end

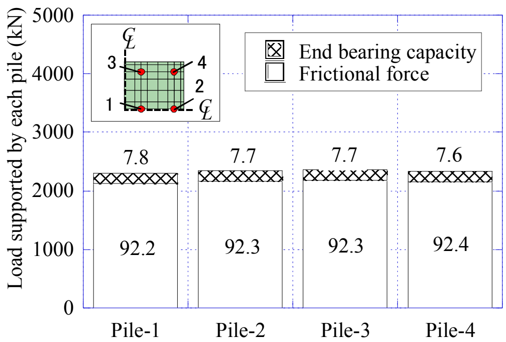
Fig. 5 Settlements of pile foundation due to its construction
(Case-1, undrained at side boundaries)

Figure 6 shows the bearing capacity of each pile from frictional force of surrounding ground and point bearing capacity from bearing layer at 306 days, 700 days, and 50 years. Figure 7 shows the change of bearing capacity in all piles in the spans of 700days and 50years. Both figures show the same fact; Just after the construction (=

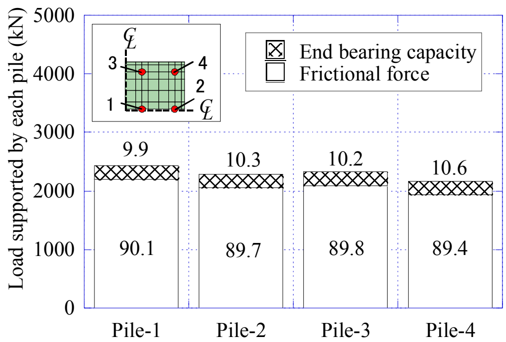
306days), point bearing capacity of Pile-1 is 8.7 % of bearing capacity, while that of Pile-4 is 6.8 %. Maximum bearing capacity occurred at Pile-4, and minimum at Pile-1. At 700 days, end bearing capacities and bearing capacities are almost same in all piles. At 50 years, end bearing capacity of Pile-1 is 9.9 % of bearing capacity, while that of Pile-4 is 10.6 %. Maximum bearing capacity occurred at Pile-1, and minimum at Pile-4.



(a) 306 days (just completion of construction)

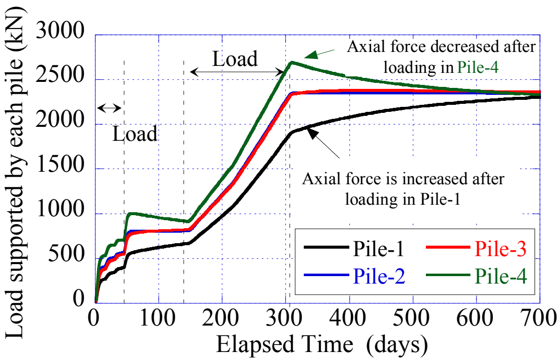


(b) 700 days

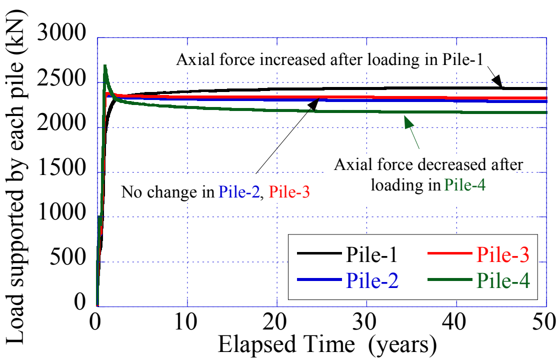


(c) 50 years

Fig. 6 Bearing capacity of pile and ratio of end bearing capacity to frictional force (Case-1, undrained at side boundaries)



(a) 700 days

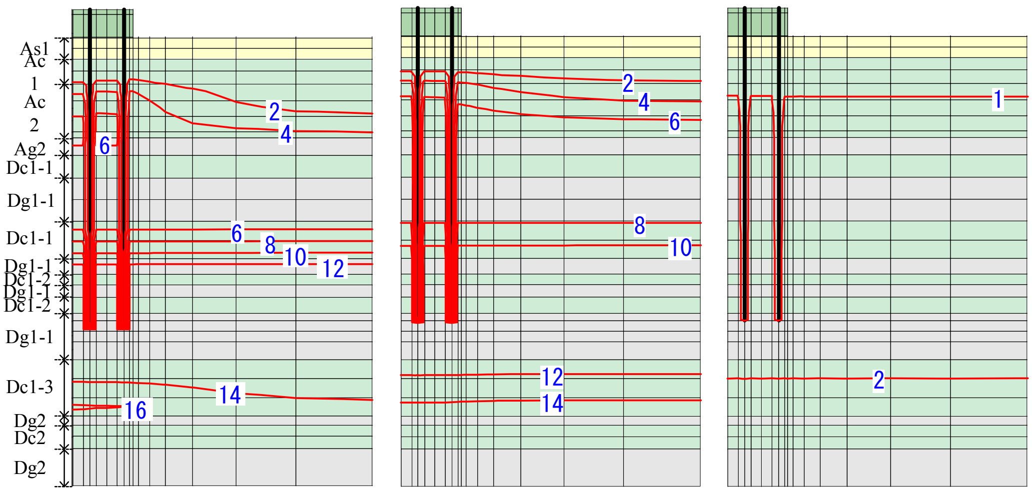


(b) 50 years

Fig. 7 Change of bearing capacity (Case-1, undrained at side boundaries)

From these results, it is known that just after the construction the inner pile (Pile-1) cannot obtain enough frictional force and the outer pile (Pile-4) support larger load, and according to the progress of the settlement, the load is evenly shared and finally the inner pile (Pile-1) support the largest load in all piles (Pile-1 to -4).

Figure 8 shows the distribution of excess pore water pressure of ground at 306 days, 700 days, and 50 years. It is known from the figure that excess pore water pressure (EPWP) not only exists in the ground near pile foundation, but also in the far field in the same order. And in Figure 8-(a), it is found that bigger EPWP remains around inner pile end than outer pile end. This is the mechanism of the change in load sharing rate among piles. That is, because of the remaining of EPWP, consolidation of soft clay around inner pile end delays from that around outer pile end. Just after construction, deformation of soft clay around outer pile end advances compared with that around inner pile end, so that outer pile support larger load than inner pile. According to the progress of consolidation, the load is evenly shared. The consolidation is finished earlier around outer pile end than inner pile end, and inner pile supports largest load among piles at last.



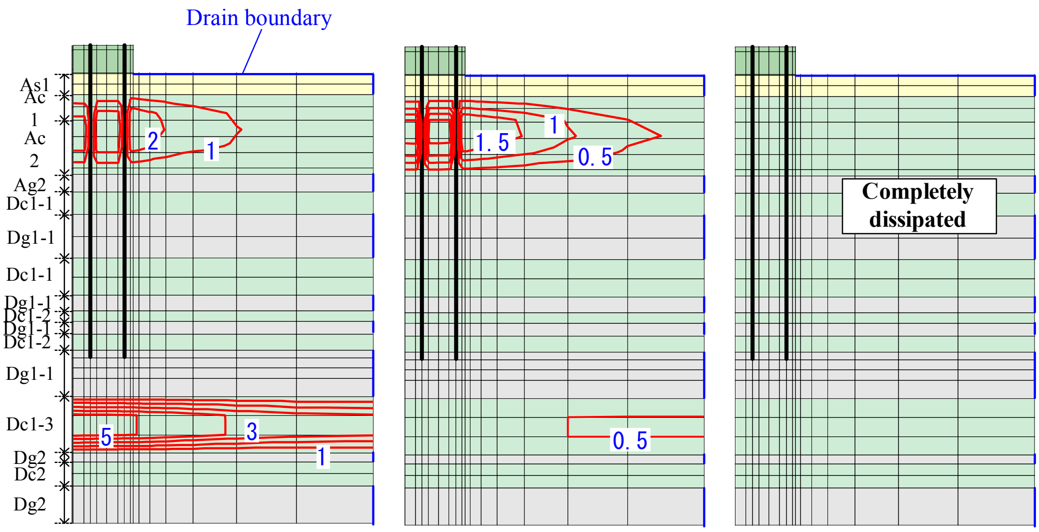
(a) 306 days (b) 700 days (c) 50 years

Fig. 8 Distribution of excess pore water pressure (Case-1, undrained at side boundaries)

<u>Evaluation of the influence of drainage condition at side boundaries</u>

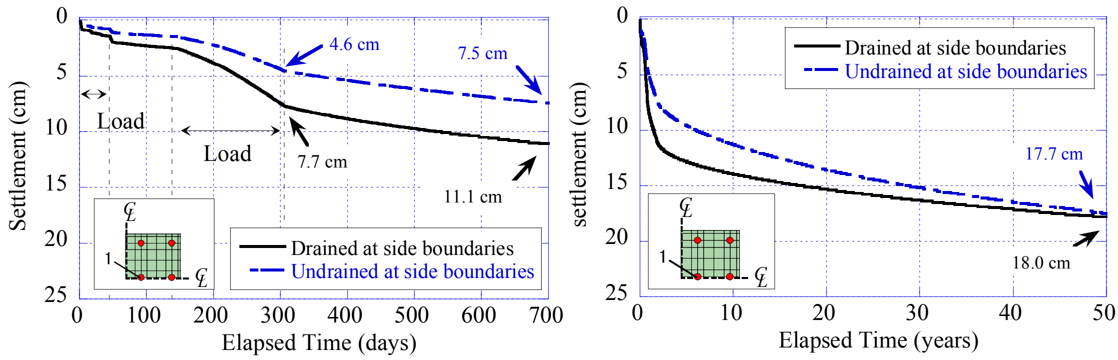
Figure 9 shows the distribution of EPWP of ground at 306 days, 700 days, and 50 years in Case-1-DC. Under drained condition at side boundaries, EPWP in the ground is dissipated earlier than the case under undrained condition. After 50 years, EPWP dissipated completely, and it is totally different from the pattern in the case of drained condition.

Figure 10 shows the comparison of the settlements at the head of Pile-1 for different drainage conditions at side boundaries, Case-1-UC and Case-1-DC. From the figure, it is known that drainage condition affects just long-term behavior of settlement, and not affect the amount of settlement. Therefore, the drainage condition is very important to predict the long-term behavior of pile foundation. In real case, management of the settlement occurred after construction is very important, so that improvement of drainage condition is very helpful to manage long-term settlement of pile foundation. That is, making the side boundaries be permeable may fasten the dissipation of EPWP in the ground, the total settlement due to a vertical load is remained the same.



(a) 306 days (b) 700 days (c) 50 years

Fig. 9 Distribution of excess pore water pressure
(Case-1, drained at side boundaries)



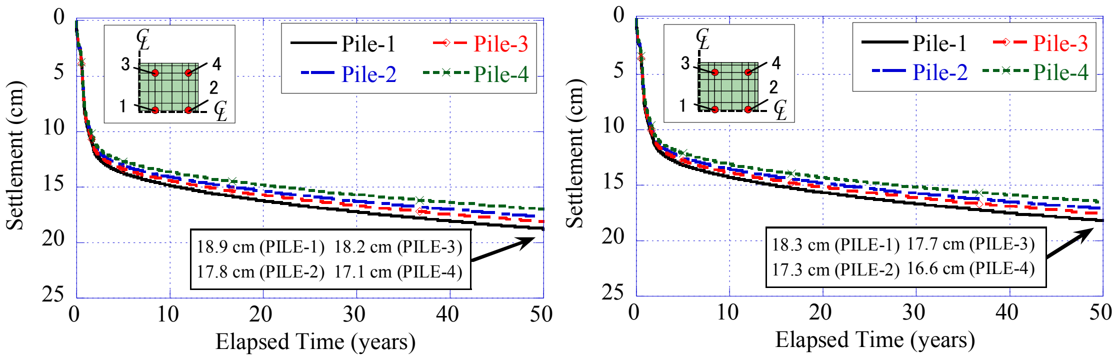
(a) 700 days (b) 50 years

Fig. 10 Comparison of settlements at head of Pile-1
for different drainage condition of side boundaries (Case-1)

Evaluation of the influence of thickness of bearing layer

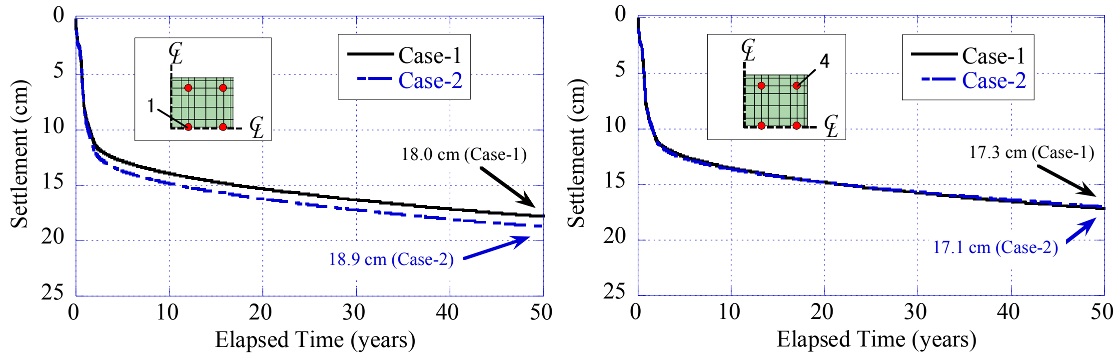
Figure 11 shows the settlements of all piles due to the construction of the bridge in Case-2-DC, under drained condition at side boundaries. The difference between Case-1-DC and Case-2-DC is only the thickness of the bearing layer; 3.0m in Case-2 instead of 4.9m in Case-1.

Figure 12 shows the comparison of the settlement at the head of Pile-1 and Pile-4. The pattern of the settlement in Case-2 is the same as that in Case-1. Due to the difference of the thickness of the bearing layer, the settlement in thin bearing layer is larger than that in thick bearing layer, and the difference is 9 mm at inner pile (Pile-1), 3 mm at outer pile (Pile-4). From these results, it is known that, in end bearing pile , thin bearing layer causes uneven settlement, and larger settlement occurs at the inner pile head than outer pile head.



(a) Pile head (b) Pile end

Fig. 11 Settlements of pile foundation due to its construction (Case-2, drained at side boundaries)



(a) Pile-1 (b) Pile-4

Fig. 12 Comparison of settlements at the head of piles (Case-1 and Case-2, drained at side boundaries)

Evaluation of the influence of the space between piles

In the current discussion, the long-term displacements of pile foundation is accompanied with the change of the load sharing rate, and the mechanism of this phenomenon is clarified as following; 1) inner pile cannot obtain enough frictional force because the soil around inner pile is restrained between piles; 2) EPWP remains around inner pile end and the consolidation of clay around inner pile end delays from that around outer pile end. This phenomenon cannot be found in the case of single pile, this problem is peculiar to the pile foundation (= Pile Group Effect). From the current research, it is well-known fact that the influence of pile group effect closely relates to the space between piles. In order to make clear the influence of space between piles in long-term displacements of pile foundation, numerical experiment with soil-water coupling FEM-FDM method is conducted. 6 cases of numerical experiment are considered, the space is; single pile, 1.5D, 2.0D, 2.5D, 3.0D, 4.0D, 5.0D (D is the diameter of pile)

Figure 13 shows the behaviors of long-term settlement of single pile, 1.5D, 2.5D, and 5.0D. It is shown that the amount of the settlement increases when the space between piles decreases, while the behaviors of long-term settlement are almost same.

Figure 14 shows the comparison of the amount of settlement at 50 year in each case, and the settlement of 1.5D is almost 2 times bigger than single pile, while the settlement of 5.0D is 1.5 times bigger than single pile.

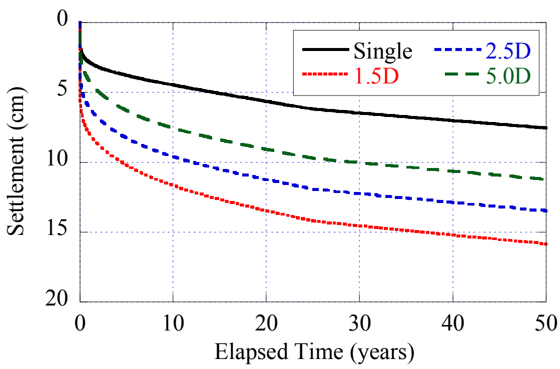


Fig. 13 Long-term settlement (Single pile, 1.5D, 2.5D, and 5.0D)

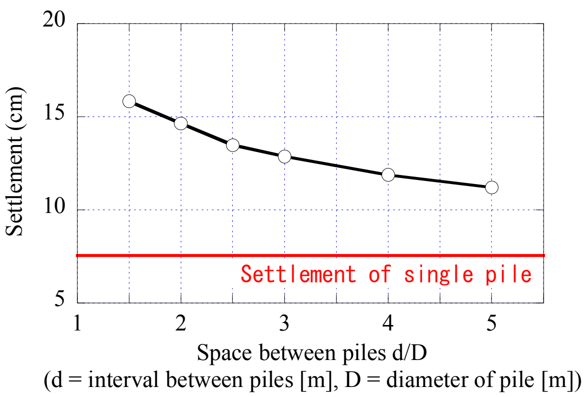
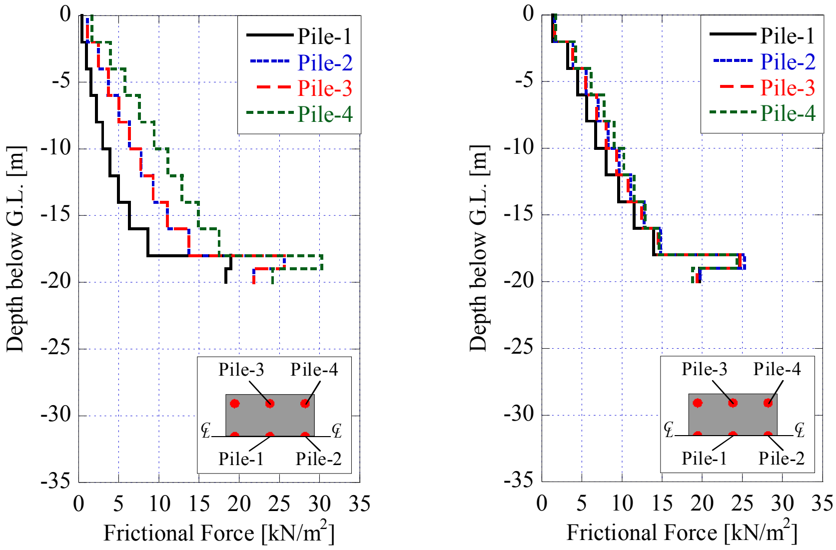


Fig. 14 Comparison of settlement at 50 years

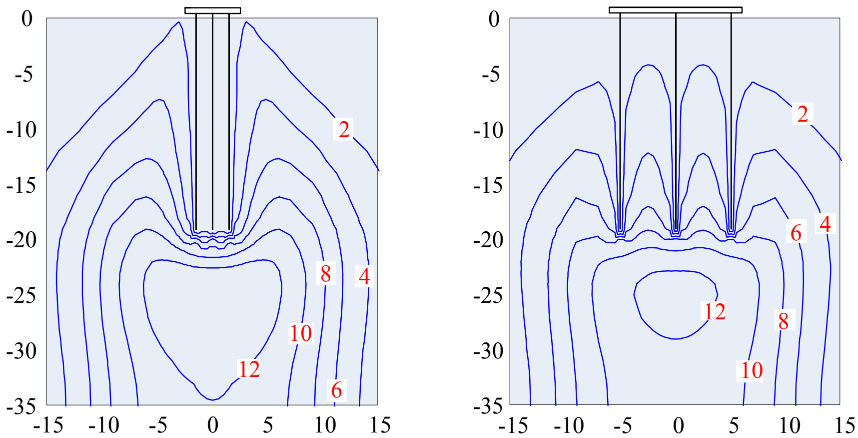
Figure 15 shows the distribution of frictional forces obtained by Pile-1 to Pile-4 at 1 year after completion of loading in the case of 1.5D and 5.0D. In the case of 1.5D, the frictional force obtained by Pile-1 (inner pile) is smaller than Pile-4 (outer pile), while the frictional forces obtained by each pile in the case of 5.0D are almost same. This is because when the space of piles decreases, the soil between piles is restrained, and inner pile cannot obtain enough frictional force. This is the one reason that just after construction the inner pile cannot be shared the load well in pile foundation.

Figure 16 shows the distribution of EPWP in the case of 1.5D and 5.0D at 1 year after completion of loading. It is found that in the case of 1.5D bigger EPWP remains not only around inner pile end but also deeper area under pile end than in the case of 5.0D. It is known that when the space between piles decreases, frictional force obtained from ground also decreases, and stress transmitted by pile end increases. It is also known that the interaction of pile-soil-pile system is emphasized by decreasing in the space between piles, and pile group behaves like single caisson when the space between piles is narrow. And the concentration of the stress transmitted by pile end is emphasized. This is the mechanism of the increase of the amount of settlement in pile foundation according to the decrease of the space of piles.



(a) 1.5 D (b) 5.0 D

Fig. 15 Distribution of frictional force (1 year after completion of loading)



(a) 1.5 D (b) 5.0 D

Fig. 16 Distribution of EPWP [unit: kPa] (1 year after completion of loading)

Conclusions

In this paper, soil-water coupling analyses with FEM-FDM method are conducted to investigate the long-term displacements of pile foundation installed in soft clayed ground.

The conclusions obtained in Case-1 and Case-2 are followings;

1) Uneven settlement occurs even under the evenly applied load condition. This is because the dispersal of EPWP around inner pile end delays from that around outer pile end, and it causes the time difference of consolidation depends on the position of clay. The consolidation of clay around inner pile end delays from that around outer pile end. And the settlement of inner pile becomes bigger than outer pile at last.
2) Just after construction, the outer pile supports the load mainly. This is because the soil around inner pile is restrained by piles and the inner pile cannot obtain enough frictional force. The load sharing rate of the inner pile increases with the passage of time. This is because the consolidation of clay around outer pile end finishes earlier than that around inner pile.
3) Drainage condition affects the dispersal process of EPWP, and causes the difference of the long-time behavior of settlement. But it is not related to the amount of the settlement.
4) Thickness of bearing layer doesn't affect the long-term behavior of settlement, but affect the amount of settlement. Thin bearing layer causes uneven settlement, and larger settlement occurs at inner pile head than outer pile head.

The conclusions obtained in Case-3 are followings;

5) The settlement of pile foundation is much affected by the space between piles, and decrease of space causes increase of amount of settlement. Even the space is 5.0D, the amount of settlement is still 1.5 times bigger than single pile.
6) When the space of piles becomes smaller, the soil around inner pile is restrained strictly, and inner pile cannot obtain enough friction, and it leads the stress transmitted from pile end to be increased. And pile group behaves like single caisson, the concentration of the stress transmitted by pile end is emphasized. This is because the amount of settlement increases according to the decrease of the space between piles.

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