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Research Paper

Lateral displacement of boundary wall of residential building due to timber piles installation in soft ground

S. Shrestha[1], N. Miura[2], and Y. Matsumoto[3]

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ABSTRACT

Numerous investigations on piles' behavior in soft ground have been concerned with piles' bearing capacity and settlement behavior. Relatively, little is known about the lateral displacement of the boundary wall caused by driving group piles into soft ground. The mechanism of lateral displacement of the ground and the boundary wall (BW) of residential buildings due to the timber pile installation in the soft ground was investigated by a series of three-dimensional finite element modelling (3D-FEM) and field measurements. Based on the numerical analyses, the magnitude of the lateral displacement of the ground has been quantified at first after investigating the mechanism in terms of installation patterns, machine movement, auger drilling, type of the pile, the distance of the nearest row of the pile to the BW, and stiffness of the fill material. Then the construction methods to minimize lateral displacement of the boundary wall have been proposed.

1. Introduction

Timber piles were used as the foundation of the small-scale buildings in the Saga lowland, the coastal area of the Ariake sea, Japan. In the field, the pile-driving machine (Pulsonic 4B, pushing force 10~16 tonnes, 20~60Hz) is used to drive the timber pile deep into the ground. **Figure 1 (a)** depicts the auger drilling at the location of the timber pile and **(b)** describes the installation of timber pile in that location later with a pile-driving machine. To reduce the settlement of the building, it is necessary to use the jointed-timber piles (JTP) to reach the supporting strata at greater depth with a higher Standard penetration test, SPT (*N*) values layer in the Saga lowland **(Fig. 1c)**. **Figure 2** shows the configuration in which the timber stake is joined with short concrete or preservative-treated timber above the groundwater level.

During the immediate installation of the timber pile, the problem of lateral displacement of the ground is arising, affecting the nearby boundary wall (BW), causing cracks in the joint of the BW and bulging of BW. It is because pile driving displaces soil and previously driven piles laterally and vertically (Hagerty & Peck, 1997). Rainer et al (1991) suggests that significant soil displacement occurs during pile driving in a cohesive soil, and the volume of displaced soil is equal to the volume of the inserted piles. **Figure 3 (a)** depicts the picture of boundary wall of the residential buildings in Saga lowlad, Japan, L-shaped type. **Figure 3 (b)** shows the magnitude of laterally displaced BW after constructing the piles.

[1] Researcher & IALT member, Kyushu Piling Co. Ltd., Yanagawa City, Fukuoka 832-0082, JAPAN, shresthasailesh@gmail.com
[2] President & IALT member, Laboratory of Soft Ground, Saga 840-0811, JAPAN, miuran@viola.ocn.ne.jp
[3] Managing director, Kyushu Piling Co. Ltd., Yanagawa City, Fukuoka 832-0082, JAPAN, office@qp-pile.com
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Most investigations on piles' are done on bearing capacity and settlement behavior (shreshta et al., 2021). Relatively, little

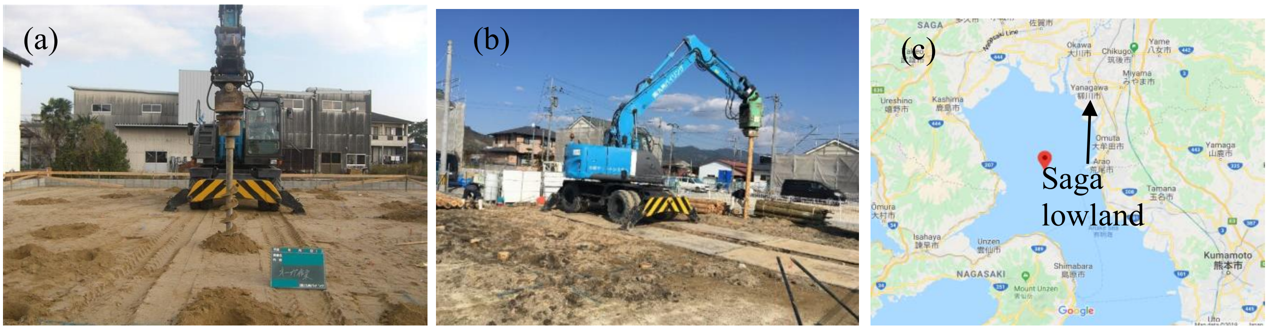


Fig. 1. **(a)** Auger drilling, **(b)** Installation of timber pile, **(c)** Saga lowland

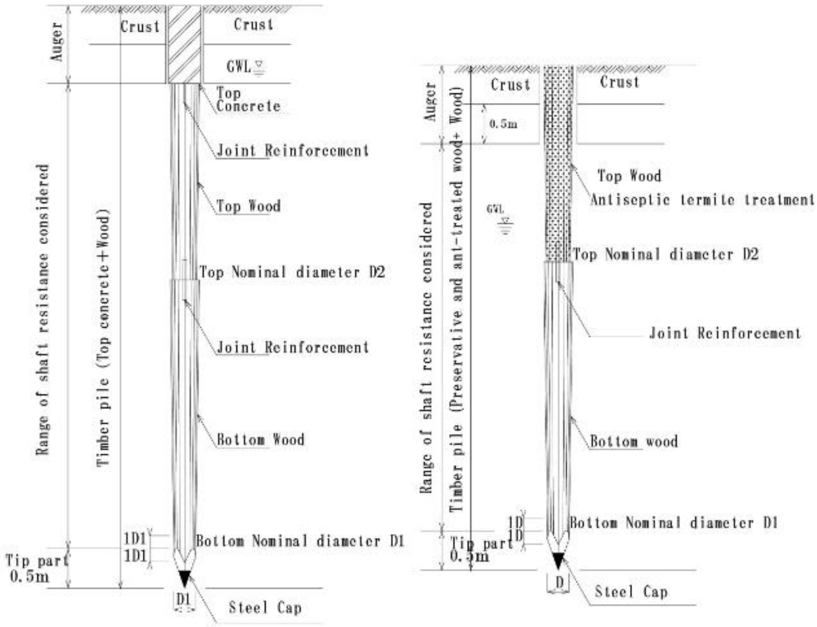


Fig. 2. Schematic of the Jointed-timber piles **[3]**

research is conducted about the consequences of installing piles, such as the lateral displacement caused by driving piles into cohesive soils. The driving of piles close to existing retaining structures affects the lateral stress distribution on the structure and the soil's stress-strain properties. The decrease of the adjacent soil's shear strength due to pile driving is reported in the literature (Hagerty & Peck, 1997; Rainer 1991) . Various factors can influence the lateral displacement of the ground, such as a sequence of pile driving, area improvement ratio of the pile, machine movement during the pile installation, type of the piles (a) floating type (b) end bearing type, stiffness of the fill material, and several other factors.

In this paper, an attempt has been made to understand the mechanism of the lateral displacement of the boundary wall, and quantifying the factors affecting the lateral displacement by two methods: (1) field investigations of the displacement of boundary wall before and after construction (2) finite element modelling of the lateral displacement of the boundary wall. The simulated results were analyzed with respect to the lateral displacement, heave, and excess pore water pressure of the ground at nearpoint the boundary wall. Based on the field investigation and simulated (numerical analyses) results, the construction methods to reduce the lateral displacement of the residential building's boundary wall have been proposed in this study.

2. Field investigations of the lateral displacement of the boundary wall (BW)

Lateral displacement of the residential buildings' boundary wall (BW) is a challenge during the timber pile multirow installation. It was not possible to directly measure the continuous lateral displacement of the boundary wall in the field. Therefore several points were marked at the top of the BW one or two days before the

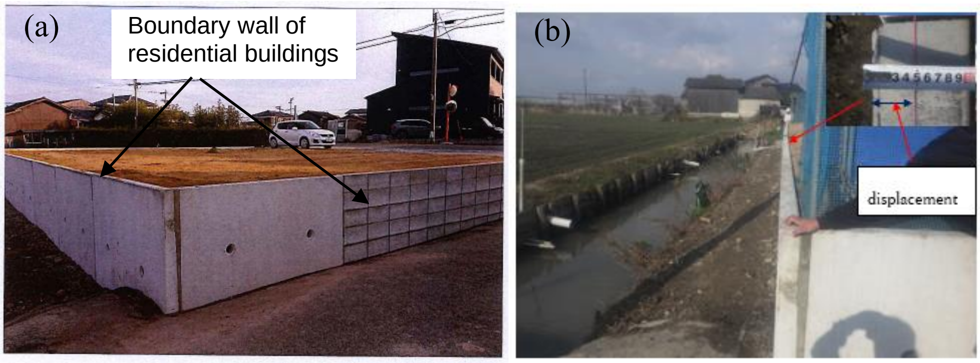


Fig. 3. (a) Boundary wall (BW) of the residential building **(b)** Lateral displacement of the BW (50 mm displaced at the center).

Table 1. Measured lateral displacement and construction details at different locations.

Site	Location details	**Lateral displacement (mm)**	Length of pile (m)	Distance of nearest pile from BW (m)	Depth of auger (m)	Top dia. (mm)	Bottom dia(mm).
A	Saga city	**20**	7.5	4.05	4.5	250	120
B	Okawa city	**36**	11	1.5	2.25	250	140
C	Saga pref., Kohoku town, Kishima district, Siroshi	**24**	17.5	1.3	2	250	130
D	Saga city, Yamato town	**12**	6.5	1.6	2	180	160
E	Saga city, Nishiyokamachi, Oaza	**53**	14.5	2	4	150	120
F	Fukuoka pref., Kurume city, kamitsu machi town	**17**	4	1.5	2	180	
G	Saga shi, Otakara	**27**	14	1.8	1	160	140
H	Saga pref,, Omachi cho, Kishima district	**16**	21.5	1.075	1	190	160
I	Kumamoto prefecture, Uto city	**20**	10	3	2	180	140
J	Saga pref., Kanzaki city	**12**	11.5	2.95	1.5	140	120
K	Fukuoka pref., Okimachi city	**25**	8.5	1.55	1.5	140	130
L	Saga pref., Oomachi city)	**16**	14	1.7	7.5	160	120

construction date, i.e., before pile installation, and then their coordinates were recorded. After the end of construction, the coordinates were measured at the same point. Then the difference between the coordinates was the lateral displacement of the BW. The maximum value has been evaluated to investigate the lateral displacement mechanism without considering their local directions. The field data were taken at 12 different sites in 3 prefectures in Kyushu island, Japan, i.e., Kumamoto prefecture, Saga prefecture, and Fukuoka prefecture. **Table 1** illustrates the construction details, location, measured lateral displacement of the BW at the end of construction of all the sites. The details of the field's measurement procedures have not been discussed in this study since it is a simple procedure. The measured lateral displacement was compared in terms of various influencing factors such as (1) distance of the nearest row of the pile from the BW, (2) depth of auger drilling, (3) length of the pile, (4) depth of soft soil. It was seen from the field data, that there was a tendency of decreasing lateral displacement of the BW, when BW distance was far from the nearest row of pile. While there was no clear picture obtained from the effect of depth of auger drilling. Auger drilling is a process to loosen the top crust, which is very hard and is done to reduce the soil displacement during the pile installation.

Further, when the pile's length was increased and their tip lay at the soft ground layer, lateral displacement of the BW was not reduced significantly according to the field measurement. The field measurement comparison results in the graph form in terms of the above factors are not included in this paper—however, the final measured lateral displacement after the end of the construction is shown in **Table 1** in third column in bold characters. From the discussions above, there was still need for an accurate method for understanding lateral displacement of the BW considering the above factors. To understand in more details, further analysis was conducted through 3D-finite element modelling (3D-FEM).

3. Numerical investigations of the lateral displacement of the boundary wall (BW)

3.1 Background

Although there can be many possible patterns, there are probably two common patterns practiced in the field **[4]**, and at first, those two sequences of pile installation were investigated. One was the first row of piles constructed parallel to the wall first, and then the other row of piles subsequently away from the boundary wall (BW). Another was later row of piles towards the BW are constructed first, and finally, the first row of piles nearest to the BW was constructed at last. **Figures 4 (a)-(b)** depicts the two standard patterns. Further, another method of installation to counteract the lateral displacement, as illustrated in **Fig. 4 (c)**, was investigated. A quantitative understanding of factors that affect the lateral displacement of boundary wall listed below was done with 3D-finite element modelling:

(1) Effect of installation sequence/pattern of the piles and machine movement in the field.

(2) Effect of depth of the auger hole near the BW.

(3) Effect of types of the piles: (a) floating type (b) end-bearing type.

(4) Effect of the distance of the nearest row of piles to the BW, stiffness of the fill material.

Table 2 depicts the different case studies done on this research incorporating the above influencing factors.

3.2 Constitutive model and parameters

The full-scale numerical investigation was conducted with a plane strain type 3D full-scale embankment (**Fig. 5**). The structure mode view, 3D view, and the numerical model's plan view are shown in **Figs. 5 (a)-(c)**. Plane strain displacement boundary condition contains five rows of explicitly modeled columns, i.e., the behavior of columns in 3D. The soft clay was modeled by the soft soil model, and the fill material and the sand layer were modeled by the linear elastic model obeying the Mohr-Coulomb failure criterion. For soft soil model, the value of the slope of rebound line in *e-ln(p')* plot (*e* is voids ratio and *p'* is effective mean stress), κ, was assumed as 1/10 of the value of the slope of virgin compression line in *e-ln(p')* plot, λ. The timber piles, joint and boundary wall (BW) were treated as a linear elastic material. The permeability of the timber piles was the same as that of the corresponding soil layers, while the BW was non-porous. A plastic calculation was used to carry out an elastic-plastic deformation analysis in which it was not necessary to take the change of pore pressure with time into account.

Further, each pile was constructed in a separate stage construction mode. Ten-node tetrahedron elements were used to model the whole model. The total number of nodes (vertex plus side nodes) was approximately 85,981 and the total number of elements was about 61,289. The boundary conditions were, at the left and the right (x-direction) and the front and the back (y-direction) boundaries. The horizontal displacement was fixed, but the vertical displacement was allowed. At the bottom boundary, both the horizontal and vertical displacements were fixed. Both the ground surface and the bottom boundary (sand layer) were defined as drained and other boundaries were defined as undrained.

The height of the fill material was 1.5m, the diameter of the piles was 0.25m, the length of the piles floating-type was 15m, and the end-bearing type was 17.5m. The spacing of the piles was 2m. The value of the poison's ratio (ν) was assumed. The adopted values of model parameters are shown in **Tables 3-4.** The values for the ground were determined in reference to the soil properties at a test embankment site in Saga, Japan, reported by Chai (Chai et al., 2015) The clayey soil modeled in this study is called Ariake clay, which is a marine clay with a natural water content that is usually more than 100%. The value of the slope of the compression line (λ) is approximately 0.4–1.3 (compression index, C_c, of roughly 1.0–3.0). The model parameters for the structural elements, timber piles, were based on the QP code 2 2018, the manual of Kyushu Piling Company limited, certified by the General Building research corporation of Japan. **Figure 5 (a)** shows the detail of the geometry of the structures simulated in numerical modeling. In **Fig. 5 (b)**, 3D view shows the depth at which all the FEM results (lateral displacement, heave, and excess pore water pressure) were measured with an arrow mark. Similarly, **Fig. 5 (c)** plan view also shows the location at which all the FEM results were measured. Since this is a plane-strain model, only the depth of the measurement (which is at the edge of the BW or the ground surface) is essential. And since the measured point is 2m inside the outer boundary surface, it is not affected by the boundary constraints. The machine's weight was 16 tones, and since the external dimension of the machine legs was 4.5m by 3.5m, the uniformly distributed load of the machine was 10.15 kN/m^2.

3.3 Simulation of the installation of the timber pile

Timber pile installation in the FEM was done based on the cavity expansion theory from Vesic (Vesic, 1972). The finite element software used in the analysis is Plaxis 3D (2018). In reality, timber piles are installed in the field by creating a deep hole and displacing the soil as the timber pile's tip progresses downwards. Alternatively, the pressure created during the timber pile tip downward movement as it occupies its volume equals the pressure needed to expand the same volume's cavity. A small circle representing a small cavity should be extended until its size becomes the bigger outer circle. It is difficult to simulate in this manner in the FEM due to its limitations. Therefore, at first, a rectangular part of 0.02m thickness was created. It was expanded to the left direction and right direction and finally formed a bigger square representing the actual timber pile. The rectangular part is defined as a fragile material at first, and then after its

Table 2. Case studies for numerical analysis

No.	**Description of pile installation**
Case A1	Towards the wall **(Fig. 4a).**
Case A2	Away from the wall (AW)**(Fig. 4b).**
Case A3	AW, piles alternate installation (**Fig. 4c**)
Case A4	AW(Machine load (ML) at 2 positions)
Case A5	Auger hole with depth 2.5 m **(Case A51)**, 3.5m**(Case A52)**, and 5m**(Case A53)**.
Case A6	AW (Length of the pile 17.5m**(Case A61)**, 1-row end bearing type and other rows-floating type **(Case A62)**).
Case A7	AW (Fill material E= 10000, v = 0.3(**Case A71**)); (Fill material E= 1000,v = 0.3(**Case A72**))

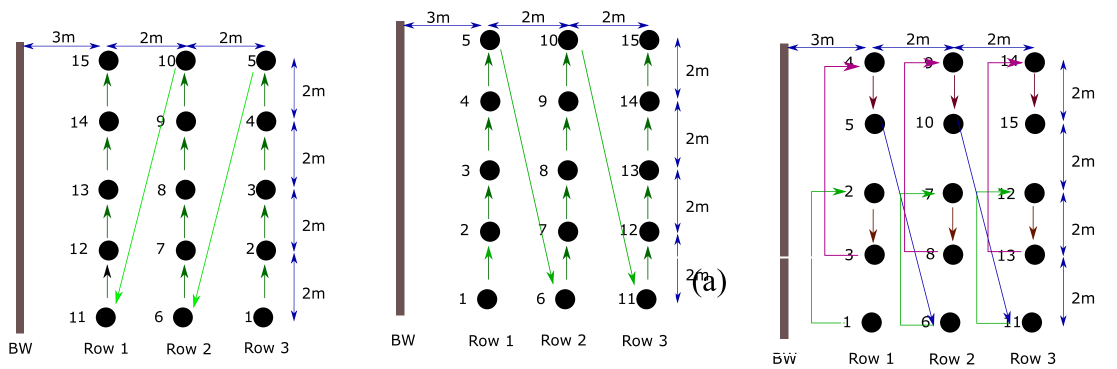


Fig. 4. (a) Piles installation towards the wall, **(b)** Pile installation away from the wall, **(c)** Pile installation in alternate pattern **[4]**

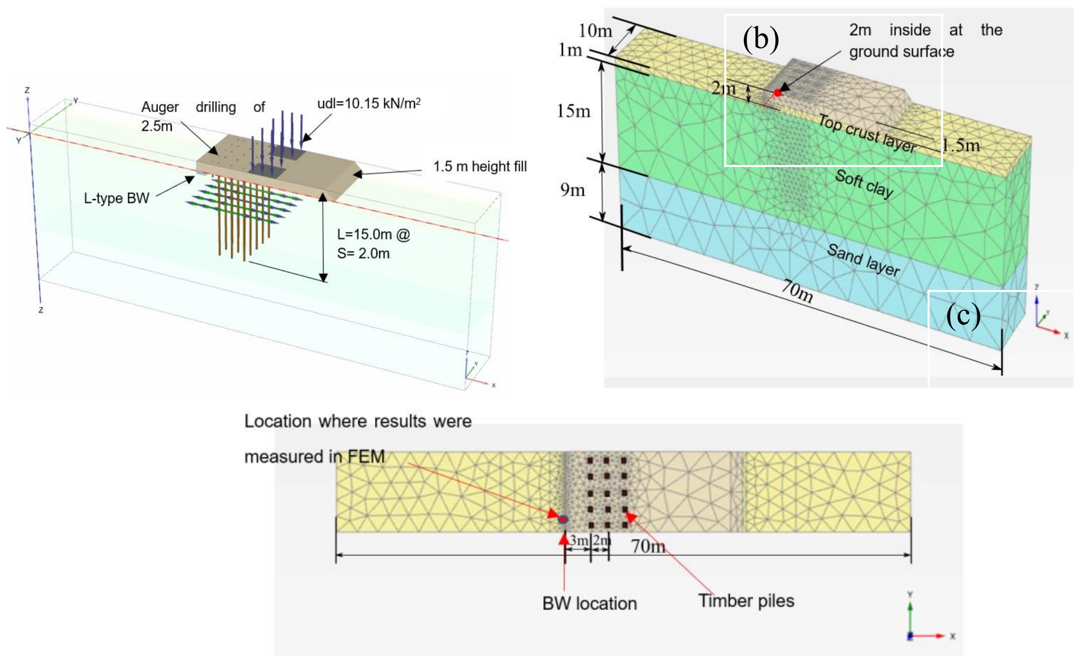


Fig. 5. FEM 3D model mesh view of the fill material with timber pile installation (a)Structure mode view (b) 3D mesh view (c) Plan mesh view

expansion to the bigger square shape, it is given the properties of the actual timber pile. When converting the circular area to the square area, the bending stiffness (*EI*) was equal. And the dimension of the circular shape in square shape was 0.22 m. Likewise, all the timber piles were created in the FEM, and then simulation was progressed.

4. Simulated results from Finite element Modelling

The direction and the depth of the point at which FEM results were measured are shown in **Fig. 5 (b)**. There was no big difference in the outcome when the measurement point was either 2m, 4m, 6m, or 8 m inside from the edge of the model for Case A1 at the same depth. In this study, all the measurements were chosen at 2 m inside the modelled boundary on the ground surface point adjacent to the boundary wall. Since, the lateral displacement of the boundary wall is equal to the lateral displacement of the ground at which it rests, the measured point was common for both the ground and the boundary wall. Therefore, the following sections discusses the results in terms of the lateral displacement of the ground as the lateral displacement of the boundary wall.

The summarized results in terms of various factors affecting lateral displacement of the boundary wall (a) installation sequence of the piles and machine movement during the pile installation (b) depth of the auger drilling near the BW (c) Type of the piles: (i) floating type piles (ii) end-bearing type piles (d) distance of the nearest row of piles to the BW, stiffness of the fill material are discussed below.

4.1 Effect of installation pattern and the machine movement on the displacement of the boundary wall

When the piles are installed in the ground, it will create heave, lateral displacement of ground, and rise in pore water pressure at the ground simultaneously. Heave is defined as the upward vertical displacement of the soil. Therefore, all the affecting parameters are studied to understand the lateral displacement, heave, and excess pore water pressure of the ground.

4.1.1 Lateral displacement:

Case A2, a construction practice as discussed in the **Fig. 6** yields a smaller lateral displacement than Case A1. This can be the first row of the piles constructed in Case A2 that become a stiffer area preventing further displacements. Case A3, which is a similar pattern to Case A2 in which the sequence of the pile installation is altered, shows a slight improvement than the Case A2 by slightly reducing the ground's initial displacement. In Case A2 and Case A3 construction, roughly 80% of the lateral displacement occurred during the first row of the pile installation. Cases A2, A3 seem to be effective in reducing the lateral displacement of the boundary wall. Similar kind of results were obtained in the condition of Case A1 and Case A2 pattern as reported by the Public Works Research Center: Manual on design and execution of deep mixing method, p.183, 2005 (In Japanese language) (Public Works Research Centre, 2005). Therefore, the results from the numerical simulation are verified based on the existing report on deep mixing method. The lateral displacement of the boundary wall obtained from the simulation result was nearly five times higher than the average of the lateral displacement obtained from the field. According to the field measurement and construction experience, 30mm was the maximum lateral displacement in the field on average. It may be because, in the field the auger drilling was performed at every locations of the timber pile which reduced the overall displacement.

4.1.2 Heave and excess pore water pressure of the ground

The effect of installation patterns on the heave of ground is investigated. **Figure 7 (a)** shows that Case A3 has the lowest heave, and Case A1 has the highest heave of the ground. This result justifies the higher lateral displacement in Case A1. While there is a significant difference in the magnitude of heave between Case A2 and Case A3, and a more negligible difference in the lateral displacement between the two, the possible reason for the difference in heave is the installation order. The excess pore water pressure of the ground is higher when the pile installation is near the BW (**Fig. 7b**). In contrast, there is no significant difference in terms of peak excess pore water pressure for all the cases. However, in Case A3, the final excess pore pressure is two times higher than Case A1 and Case A2. These results suggest that because of the generation of excess pore water pressure, the shear strength of the ground was reduced, and simultaneously, the lateral displacements and heave occurred.

The cross-section was taken from point (0,2) to (70,2) for the simulated model, and the horizontal displacements of soils were confirmed in the true scale. From these results, it can be seen that Case A1 (**Fig. 8a**) has greater lateral displacements and heave than Case A2 (**Fig. 8b**), as indicated by the red vector arrows. Even though several analyses were carried out to understand the effect of machine movement on the lateral displacement of the ground, the results were not clear. There was a 5.27% increase (in Case A4) of lateral displacement of the boundary wall when the machine load was considered in the L-shaped type boundary wall design. The distance from the machine to the boundary wall was 8.0 m in the case of L-shaped type BW.

the size of the auger holes was the same as the size of the pile volume as depicted in the top right corner in **Fig. 9**. The auger drilling was done next to the nearest row of piles and in 5 locations. In the field, the auger drilling can be done, and the soil can be removed to another place nearby to implement. This way of construction seems to

Table 3. Model parameters for soil

Depth (m)	Soil strata	*E* (kN/m²)	*c`( ϕ`)*	*ν*	*κ*	*λ*	*M*	e_0	γ_t (kN/m³)	k_v(10-³m/day)	k_h(10-³m/day)
0-1	Surface soil	-	10 (30)	0.15	0.034	0.34	1.6	1.8	16	1	1.5
1-16	Soft clay	-	10 (30)	0.15	0.058	0.58	1.6	2.85	14.1	1.44	2.15
16-25	Sand	40,000	20(35)	0.1	-	-		0.76	19	250	250
	Fill material	20,000	20(35)	0.2	-	-		0.76	19	250	250

Table 4. Model parameters for structure

Material	*E* kN/m²)	*ν*	e_0	γ_t(kN/m³)
Wall	40,000	0.1	0.5	24
Joint	700,000	0.1	0.5	24
Timber	7,320,000	0.2	0.5	8

Note: Where *E*= modulus of elasticity; *c`*= effective cohesion; *ϕ`*= effective friction angle; *λ*, *κ* = value of the slope of virgin compression line in *e-ln*(*p'*) plot; *M*= slope of critical state line in SSM; e_0=void ratio; γ_t=total unit weight; k_v, k_h = vertical and horizontal permeability of the soil.

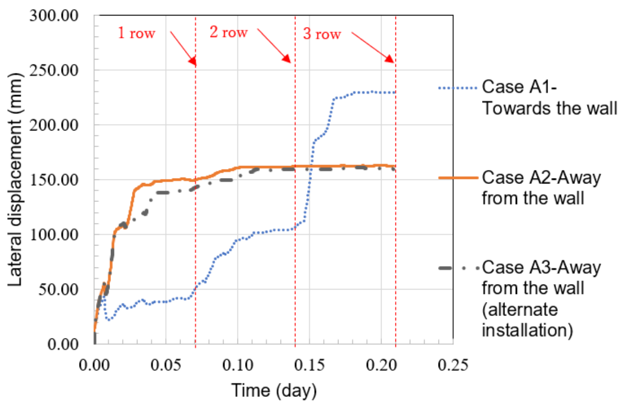


Fig. 6. Effect of installation pattern on the lateral displacement of the boundary wall.

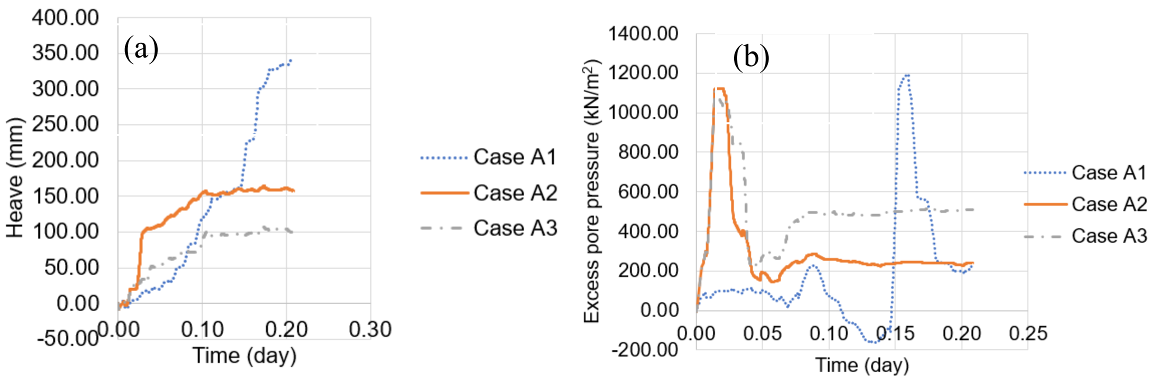


Fig. 7. Effect of installation pattern on (a) Heave (b) Excess pore water pressure.

4.2 Effect of auger drilling on the lateral displacements of the boundary wall

The auger drilling was simulated between the boundary wall (BW) and the nearest row of the pile and

be effective as it can reduce the lateral displacement considerably. The drilled-out soil can be filled again after the completion of the construction. The depth of the drilling should be up to the depth of the hard crust layer. In this study, only the auger drilling in one direction (at 5 locations) between BW and the nearest row of the pile is studied. However, in the field, at all the timber column's locations since there is 1 ~ 2 m crust, auger drilling can be done which can considerably reduce the lateral displacements of the boundary wall.

From the simulated results, the heave at the ground was also reduced considerably from roughly 100 mm in the case of Case A4 to 25 mm in the Case A5 (1), when the auger drilling was simulated between the BW and the nearest row of pile. In **Fig. 9 (a)** since there was the machine load, the notation ML is included in the parentheses. In terms of excess pore water pressure, it is considerably reduced at the measured point, i.e., 90% reduction of the Case A4 to Case A5 (1). This was due to the dissipation of pore water pressure in the simulated auger drilled hole. From **Fig. 9 (b)**, it can be confirmed that due to the simulated 2.5 m auger drilling, lateral displacement and heave of the ground reduced considerably in the ground surface near the BW. The lateral displacement obtained from the simulation in the case of auger drilling was nearly 2.0 times higher than the average of the lateral displacement obtained from the field of 30 mm. This simulated result is closer to the field. Therefore, the simulated results agree with the field observations of lateral displacement and the conclusions and suggestions can be made based on the simulated results.

4.3 Effect of type of pile on the lateral displacements of the boundary wall

In Case A2, the length of all the piles were 15m (floating type). In the Case A6(1), they were increased to 17.5m (end-bearing type), and in the Case A6 (2), one row of piles had a length of 17.5m, and the other remaining two rows of piles have a length of 15 m as seen in **Fig. 10 (b)**. From the simulated results (**Fig. 10 (a)**), if the length of the piles was increased up to the stiff layer (end bearing type), the lateral displacement of the boundary wall was considerably reduced. Case A6 (2) further illustrates that only one row of the pile near the BW, if its length was increased, then the lateral displacement was considerably reduced similarly to Case A6 (1). Similarly, heave of the ground was also highly reduced from nearly 150 mm in Case A2 to 25 mm in Case A6 (1). The direct effect could be seen in the lateral displacement, where the heave was also reduced considerably. The positive excess pore water pressure of the ground was also reduced with the change in the type of the pile. **Figure 10 (b)** clearly illustrates the reduction of ground displacements when the model was simulated in Case A6 (2).

4.4 Effect of distance of the nearest row of piles to the boundary wall, stiffness of the fill material to the lateral displacement of the boundary wall

Some other cases of simulations were conducted for the boundary wall which were not L-shaped. When the boundary wall (BW) was far from the pile's nearest row, the lateral displacement of the boundary wall was considerably reduced. The lateral displacement was 240 mm when the BW was 1.5 m far , 137 mm when the BW was 3.0m far from , and 75.62 mm when the BW was 4.5m far. In the case of the stiffness of the fill material, there was increase of the lateral displacement of the boundary wall due to the strength reduction of the fill material, 162.36 mm in Case A2 (E=20000, v = 0.2), 172.41 mm in Case A71 (E=10000, v = 0.3), 201.85 mm in Case A72 (E=1000, v = 0.3).

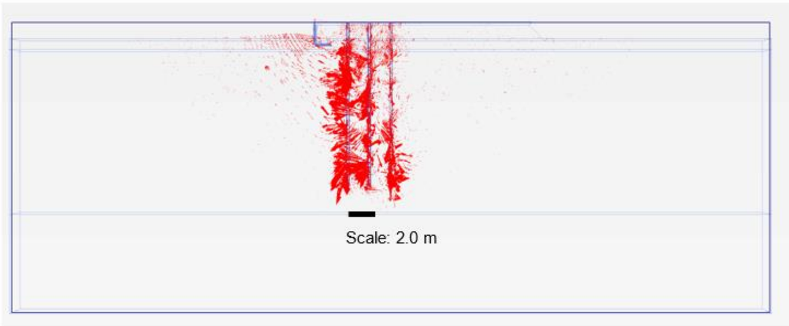
5. Proposed construction methods for the pile installation

5.1 Based on the numerical results

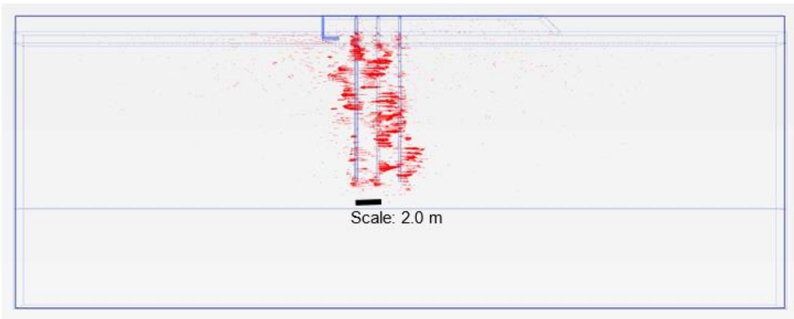
Since the same trend of results were reported by the Public Works Research Center: Manual on design and execution of deep mixing method, p.183, 2005 (In Japanese language) **[4]** in the case of the construction of deep mixing columns in two different patterns Case A1 and Case A2 as illustrated in this study, the results from the numerical simulation in this study is verified, and the construction methods can be proposed based on the numerical results for the field application. Based on the FEM results of **Fig. 6,** it is suggested to implement the Case A2 type of construction (pile installation). Case A1 type of installation sequence can create lateral displacement where the adjacent neighbor house's boundary wall (BW) is very nearby. From the result of heave of the ground attached to the boundary wall, it is seen that either Case A2 or Case A3 is the safe way to pile installation. It is suggested to construct the pile's row near the BW first and then the piles' inside row. The effect of machine movement could not be understood fully. Further analyses should be carried out to understand the mechanism clearly in the case of the machine movement effect. As per the result of **Fig. 9**, drilling auger holes before pile installation is the best way to install the timber piles. Here, the auger hole was drilled between the BW and the nearest row of the pile. Because of this drilled auger hole (the exact size of timber pile), both the lateral displacement and heave of the ground or the boundary wall was reduced. In the field construction, it is proposed to drill the holes with the auger at every location where the timber pile is to be installed.

The end-bearing type of timber pile installation has less lateral displacement and heave of the ground. Therefore, it is proposed to construct the row of piles nearest to the BW longer (end-bearing type) and the inside timber pile (floating type) as a countermeasure against the lateral displacement and heave and at the same time safe and economical design.

The stiffness of the fill material affects the lateral displacement of the ground and the boundary wall. The pile driving machine can become unstable in case of the lower stiffness of the fill material as a result of higher lateral displacement.Care should be taken in construction work when the fill material is not highly compacted and did not achieve its full strength. As the distance of the BW increases from the nearest row of the pile, the lateral displacement of the ground and the BW also reduces. Therefore, if the pile-installation is conducted as far as possible, the existing structure or BW is safe and needs to be considered in the design phase. However, in the case of unavoidable situation of maintaining far distance



(a) Case A1-Towards the wall



(b) Case A2-Away from the wall

Fig. 8 3D-FEM results in terms of lateral displacements and heave represented by vectors.

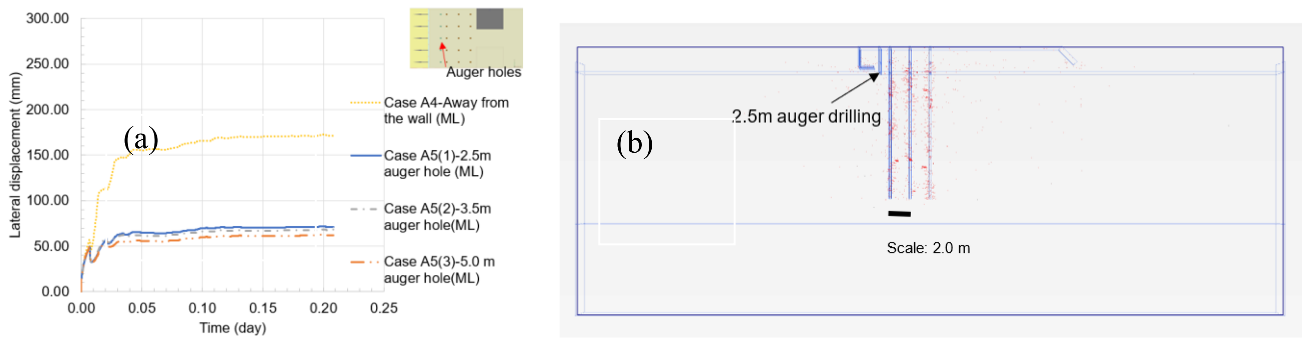


Fig. 9. Effect of auger drilling (a) on the lateral displacement of the boundary wall (b) 3D-FEM results in terms of lateral displacements and heave (Case A5 (1)) (ML in the parentheses means existing machine load).

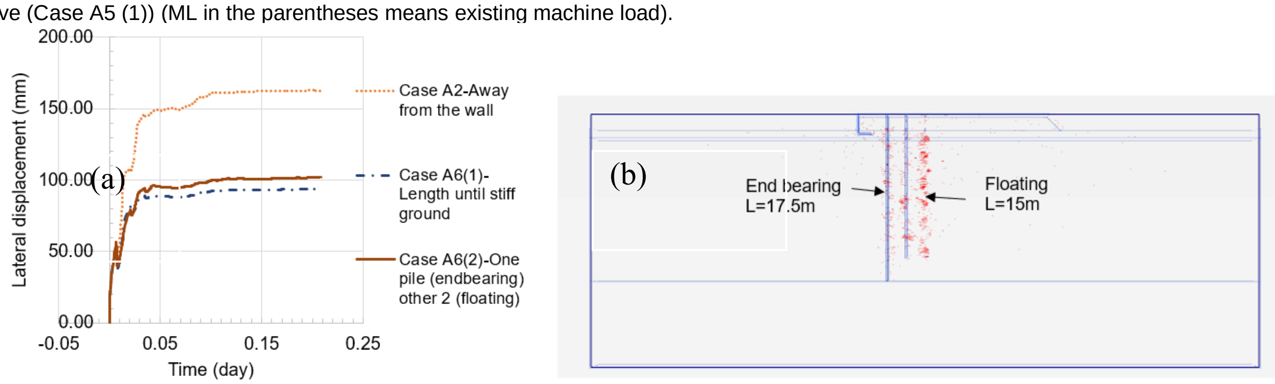


Fig. 10. Effect of type of pile (a) on the lateral displacement of the boundary wall (b) 3D-FEM results in terms of lateral displacements and heave (Case A5 (1)).

of pile location, if the construction activities followed the above proposed recommendations, then the lateral displacement of the boundary wall can be minimized to a negligible amount and can guarantee no disturbance to the existing boundary wall.

5.2 Based on the field investigated results

In the field investigation, when the distance between the boundary wall (BW) and the nearest row of pile increases, the lateral displacement of the BW decreased. In other cases, when the auger was drilled, when the length of the pile increased, when the thickness of the soft ground increased, some trend of the data can be presumed; however, the trend could not be understood clearly. Hence, the 3D-FEM helped the authors to understand the mechanism more clearly, and the construction methods are proposed more based on the results of numerical analyses. Further, field investigations is recommended in the future to compare the simulated and the field investigated results.

6. Conclusions

The lateral displacement mechanism of the boundary wall (BW) in the soft ground under the effect of timber pile-installation was investigated by a series of three-dimensional finite element modelling (3D-FEM) and field investigations quantitatively. The main factors influencing the value of the maximum lateral displacement of the boundary wall are as follows: (a) Installation pattern of the piles (b) depth of the auger drilling (c) distance between the BW and the nearest row of pile (d) type of the timber pile, end-bearing or floating condition (e) stiffness of the fill material. Based on the results of the FEM 3D investigations, the following findings can be suggested:

(1) Lateral displacement of the boundary wall can be reduced by adopting the below ways as construction methods (1) following the proper installation pattern (Case A2 or A3), (2) auger drilling of at least the crust layer or greater depth (Case A5(1)~A5 (3)), increasing the length of one row of pile nearest to the BW as end-bearing type and inside piles as floating type (Case A6 (2)), increasing stiffness of the embankment or fill material (Case A7 (1)-(2)).

(2) The ground's lateral displacement behavior agreed with respect to their heave and excess pore water pressure behavior which helped the mechanism to be understood clearly.

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