Special edition paper

# Development of a Method of Analyzing Behavior of Cast-in-place Pile Bore Walls Using the Shear Strength Reduction FEM



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When constructing cast-in-place piles near tracks or existing structures, work must be limited to within the track closure time, and careful deformation prevention work must be done almost every time construction is performed. Those are needed because a method of assessing safety factors such as train running stability and track deformation at pile construction has not yet been established. Work time limitation and deformation prevention increase the construction period and costs, resulting in greater overall time and expenses required for the project. In light of that, deregulating work time and limiting deformation prevention work to only what is really needed by being able to confirm safety at pile construction are urgent issues.

To enable quantitative assessment of safety at pile construction, we studied and improved an analysis method by the three-dimensional elasto-plasticity finite element method that incorporated the shear strength reduction method (SSR-FEM). We were able to confirm effectiveness of this analysis method, and we completed development of analysis software. This article reports the overview of those.

●Keywords: Cast-in-place pile, Stability of bore wall, Finite element method (FEM)

## 1 Introduction

When structures are constructed in over-track spaces, new foundations including cast-in-place piles are often installed near foundations of existing tracks, viaducts and buildings. But methods of assessing stability of pile bore walls and their impact on surrounding ground and adjacent foundations have not yet been put in place. It is thus difficult to formulate an appropriate plan for work to control the impact. Under these circumstances, foundation construction can only be done at night when the track is closed and is thus often accompanied by excess impact control work. This leads to an increase of the construction period and costs. Impact control work can even cause ground deformation and other adverse effects.

To overcome those problems, more appropriate impact control work is needed based on more appropriate assessment of drilling effects. Methods of making such assessment, however, have not been sufficiently put in place. We only have experiment results which show that securing a distance to the existing foundation approximately equal to the diameter of the new pile can reduce the impact[1]. It is therefore a matter of urgency to establish an assessment method that can be applied to actual design and construction planning.

We thus developed and confirmed effectiveness of FEM analysis software that incorporated the shear strength reduction method as a simplified impact analysis method for planning. An overview and considerations of the development are as follows.

## 2 Study on Analysis Method

### 2.1 Overview

When constructing cast-in-place piles at sites adjacent to lines in service, it is necessary to ensure stability of the adjacent tracks, roadbed and the ground underneath them. While drilling, collapse of bore walls must be prevented by using slurry (muddy water). However, there is little information on the mechanisms and boundary conditions of bore wall collapse, so currently we prevent collapse by setting the slurry level high to a certain degree.

In light of that situation, we have developed a method of clarifying the stability and collapse behavior of a bore wall by applying the three-dimensional elasto-plasticity finite element method that incorporates the shear strength reduction method (SSR-FEM). Unlike conventional FEM, SSR-FEM is an analysis method that can automatically calculate the shape of the slip surface and the total safety factor (the minimum safety factor that the "system" to be considered has as a whole) without predicting and assuming the slip surface[2), 3)]. This method has been already introduced in the manual of JR East for design and construction of trench wall stability for continuous underground walls.

### 2.2 Software Overview

The SSR-FEM analysis software developed along with the manual for design and construction of trench wall stability for continuous underground walls uses FEM mesh that models two-dimensional cross section including the trench cross-section as the cross section to analyze. Thanks to the characteristics of SSR-FEM, that software can automatically calculate the assumed slip surface shape (shown as a contour diagram) and the safety factor of the total system. However, it cannot be applied to three-dimensional mesh such as the cylinder of a pile bore because it has an analysis function just for two-dimensional models.

We thus decided to develop a new pre- and post-processor that can handle three-dimensional mesh to enable three-dimensional analysis of the behavior of the surrounding natural ground against a cylindrical bore. The computing engine, however, was used for the most part as-is. Fig. 1 shows a software screen image and Fig. 2 an example of results display using a third-party application ("assumed slip surface" added for explanatory purposes).

The model shown is a cutout of a quarter of the analyzed area (with the center angle at 90°) with the pile center as the reference point for symmetry. The numbers of nodal points and



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elements of the model are reduced to an extent that does not cause engineering problems so as to allow more efficient analysis calculation[3].

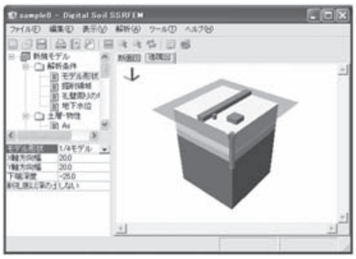

Fig. 1 Software Screen (image)

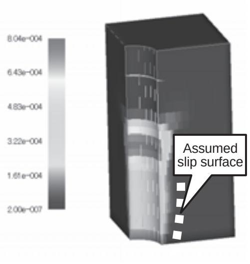


Fig. 2 Example of Results Display

## 3 Parameter Study

### *3.1 Overview*

We carried out a parameter study as follows to check to what extent each of the parameters "ground conditions," "difference between slurry level in bore and groundwater level" and "slurry specific gravity" contributes to the total safety factor. The analysis model was based on Fig. 3, and conditions were as shown in Tables 1 to 4. The analysis conditions were as follows.

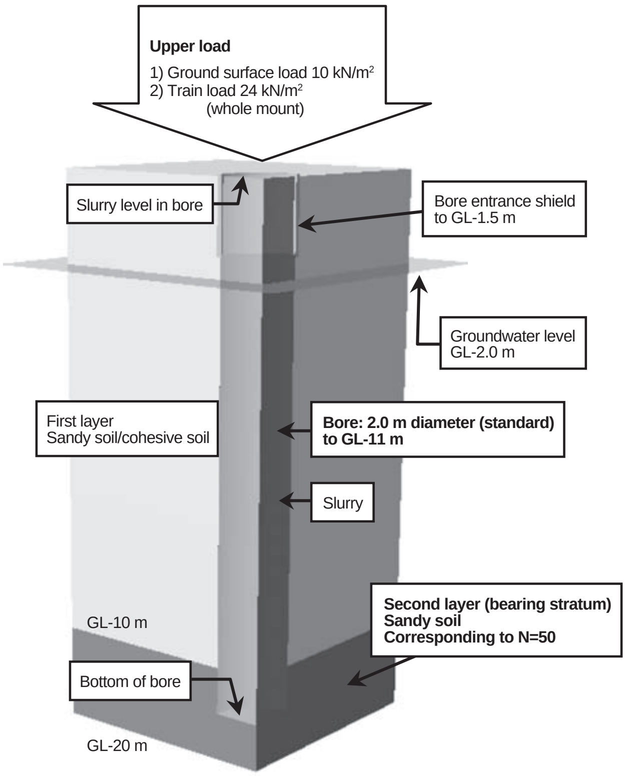


Fig. 3 Analysis Model (Quarter) Used in Parameter Study

1) Analysis model

The radius of the drilled bore was 1.0 m (pile diameter 2.0 m), and a "quarter model," —a 90° cutout of the pile circumference— was analyzed. The analyzed area was 5 m in horizontally from the pile center and 12 m in depth. The drilling depth was 11 m, so 1 m natural ground was left at the pile tip.

In the analysis cases where the pile diameter was used as a parameter, the ground conditions were fixed and the pile diameter varied from 0.6 m to 4.0 m.

2) Ground conditions

In the ground conditions, we assumed that there was a single sand or clay layer from ground level (GL) to GL -10 m ("the 1st layer" in Fig. 3). We set ground layer compositions with different standard penetration resistance N-values as shown in Tables 1 to 4. We also assumed that the ground deeper than GL -10 m was the bearing ground of the pile (bearing stratum) of sand of N = 50.

We figured out the soil constants of individual layers based on the design standards and placed a bore entrance shield (L = 1.5 m).

3) Slurry specific gravity

To be on the safe side, we set the specific gravity of the slurry slightly low at 1.02 (weight per unit volume ≈ 10 kN/m$^3$) and the water head difference in 0.5 m increments to a maximum of 2.0 m with relation to the groundwater level. In the analysis cases where slurry specific gravity was used as a parameter, the ground conditions were fixed and the slurry specific gravity varied from 1.0 to 1.14.

Table 1 Analysis Conditions and Total Safety Factor (variable: sand ground/N)

| | N | Slurry level in bore | Total safety factor |
|---|---|---|---|
| [Sand]<br>Pile diameter 2.0 m<br>Groundwater level GL -2.0 m<br>Slurry specific gravity 1.02 | 2 | +0.0 | 0.22 |
| | | +0.5 | 0.77 |
| | | +1.0 | 1.17 |
| | | +1.5 | 1.49 |
| | | +2.0 | 1.77 |
| | 4 | +0.0 | 0.23 |
| | | +0.5 | 0.83 |
| | | +1.0 | 1.25 |
| | | +1.5 | 1.58 |
| | | +2.0 | 1.87 |
| | 7 | +0.0 | 0.27 |
| | | +0.5 | 0.89 |
| | | +1.0 | 1.33 |
| | | +1.5 | 1.69 |
| | | +2.0 | 2.00 |
| | 10 | +0.0 | 0.26 |
| | | +0.5 | 0.88 |
| | | +1.0 | 1.34 |
| | | +1.5 | 1.71 |
| | | +2.0 | 2.01 |
| | 15 | +0.0 | 0.28 |
| | | +0.5 | 0.97 |
| | | +1.0 | 1.44 |
| | | +1.5 | 1.83 |
| | | +2.0 | 2.16 |
| | 20 | +0.0 | 0.30 |
| | | +0.5 | 1.04 |
| | | +1.0 | 1.54 |
| | | +1.5 | 1.95 |
| | | +2.0 | 2.29 |

4) Load

For the load, we applied on the whole ground surface a ground surface load including the track structure (10 kN/m²) and the load of the train on the track adjacent to the pile bore (24 kN/m²). As the width of the plane model area was 5 m, this train load was almost equal to the train load on a track.

Table 2 Analysis Conditions and Total Safety Factor (variable: clay ground/N)

| | N | Slurry level in bore | Total safety factor |
|---|---|---|---|
| [Clay] Pile diameter 2.0 m Groundwater level GL -2.0 m Slurry specific gravity 1.02 | 1 | +0.0 | 0.32 |
| | | +0.5 | 0.34 |
| | | +1.0 | 0.36 |
| | | +1.5 | 0.39 |
| | | +2.0 | 0.42 |
| | 2 | +0.0 | 0.64 |
| | | +0.5 | 0.68 |
| | | +1.0 | 0.73 |
| | | +1.5 | 0.78 |
| | | +2.0 | 0.84 |
| | 3 | +0.0 | 0.95 |
| | | +0.5 | 1.02 |
| | | +1.0 | 1.09 |
| | | +1.5 | 1.17 |
| | | +2.0 | 1.26 |
| | 4 | +0.0 | 1.22 |
| | | +0.5 | 1.26 |
| | | +1.0 | 1.44 |
| | | +1.5 | 1.49 |
| | | +2.0 | 1.68 |
| | 5 | +0.0 | 0.89 |
| | | +0.5 | 1.31 |
| | | +1.0 | 1.39 |
| | | +1.5 | 1.79 |
| | | +2.0 | 2.06 |
| | 7 | +0.0 | 0.83 |
| | | +0.5 | 1.21 |
| | | +1.0 | 1.48 |
| | | +1.5 | 1.93 |
| | | +2.0 | 2.26 |

Table 3 Analysis Conditions and Total Safety Factor (variable: pile diameter)

| | N | Pile diameter (m) | Total safety factor |
|---|---|---|---|
| [Sand] Groundwater level GL -2.0 m Slurry specific gravity 1.02 Slurry level +1.0 m | 10 | 0.6 | 1.72 |
| | | 0.8 | 1.62 |
| | | 1.0 | 1.57 |
| | | 1.2 | 1.51 |
| | | 1.5 | 1.45 |
| | | 2.0 | 1.34 |
| | | 2.5 | 1.26 |
| | | 3.0 | 1.20 |
| | | 3.5 | 1.13 |
| | | 4.0 | 1.08 |
| [Clay] Groundwater level GL -2.0 m Slurry specific gravity 1.02 Slurry level +1.0 m | 3 | 0.6 | 1.59 |
| | | 0.8 | 1.48 |
| | | 1.0 | 1.39 |
| | | 1.2 | 1.31 |
| | | 1.5 | 1.22 |
| | | 2.0 | 1.09 |
| | | 2.5 | 0.99 |
| | | 3.0 | 0.91 |
| | | 3.5 | 0.84 |
| | | 4.0 | 0.78 |

Table 4 Analysis Conditions and Total Safety Factor (variable: slurry specific gravity)

| | N | Slurry specific gravity | Total safety factor |
|---|---|---|---|
| [Sand] Pile diameter 2.0 m Groundwater level GL -2.0 m Slurry level +1.0 m | 10 | 1.00 | 1.22 |
| | | 1.02 | 1.34 |
| | | 1.04 | 1.44 |
| | | 1.06 | 1.53 |
| | | 1.08 | 1.61 |
| | | 1.10 | 1.68 |
| | | 1.12 | 1.74 |
| | | 1.14 | 1.79 |
| [Clay] Pile diameter 2.0 m Groundwater level GL -2.0 m Slurry level +1.0 m | 3 | 1.00 | 1.07 |
| | | 1.02 | 1.09 |
| | | 1.04 | 1.12 |
| | | 1.06 | 1.14 |
| | | 1.08 | 1.16 |
| | | 1.10 | 1.18 |
| | | 1.12 | 1.21 |
| | | 1.14 | 1.23 |

*3.2 Analysis Results*

Fig. 4–7 show the relations between the total safety factor and variables shown in Tables 1–4.

Fig. 8–11 show the increment distribution (in contour diagrams) of the octahedral shear strain (dimensionless) in the typical analysis cases. Those confirm the following trends.

(1) With the loose sand model (Fig. 8), instability of the bore wall is distributed over a wide area. It occurs before formation of the slip surface in the natural ground and deteriorates stability of the whole system. The safety factor of the whole system is therefore quite low at 0.22.

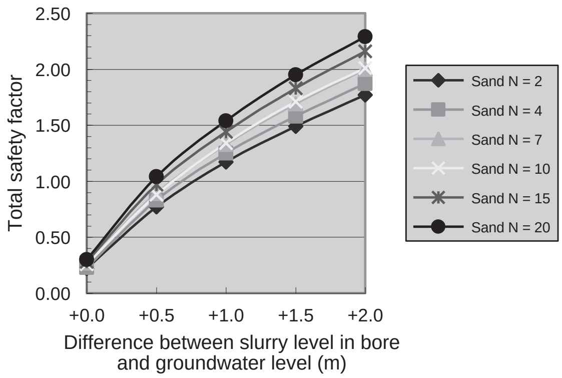


Fig. 4 Total Safety Factor Distribution (slurry level in bore/sand)

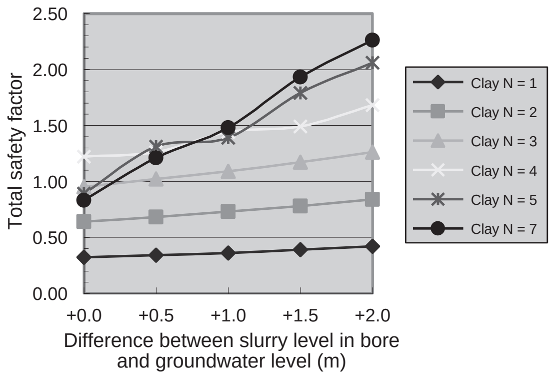


Fig. 5 Total Safety Factor Distribution (slurry level difference/clay)

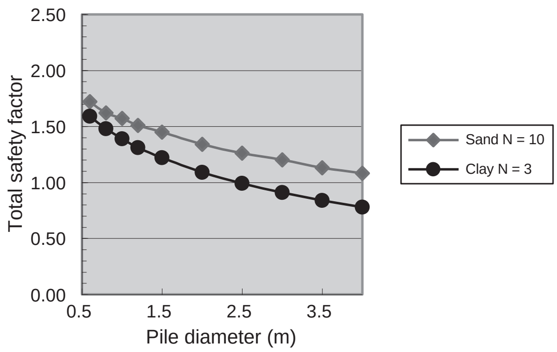


Fig. 6 Total Safety Factor Distribution (pile diameter)

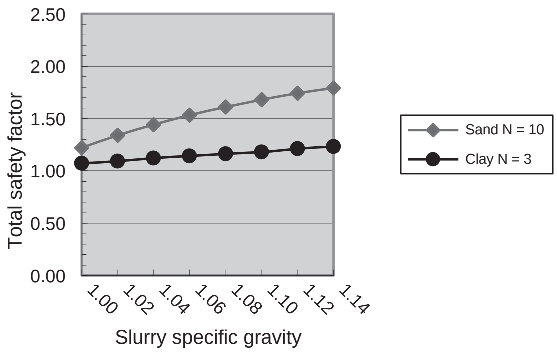


Fig. 7 Total Safety Factor Distribution (slurry specific gravity)

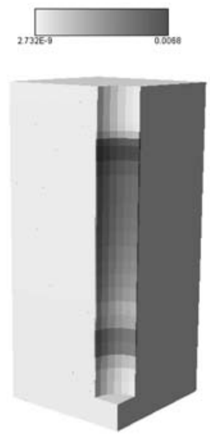

Fig. 8 Loose Sand (N = 2)

Fig. 9 Medium Sand (N = 20)

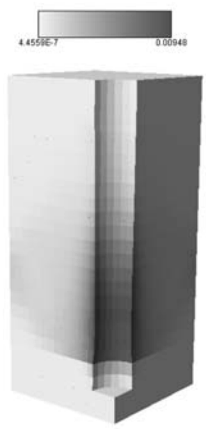

Fig. 10 Soft Clay (N = 2)

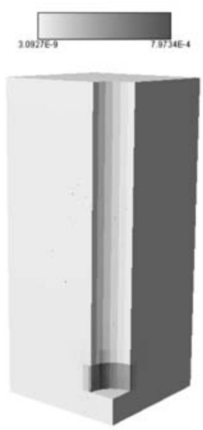

Fig. 11 Medium Clay (N = 15)

(2) With the medium sand model (Fig. 9), stability of the bore wall is improved compared to the case with the loose sand model. Complex and parallel progress of formation of the slip surface and instability of the bore wall in the sand layer are observed and so is instability of the bore wall surface in the bearing stratum. However, the safety factor of the whole system is as high as 1.54.

(3) With the soft clay model (Fig. 10), instability of the bore wall does not deteriorate stability of the whole system thanks to the adhesion of clay, even though some instability of the bore wall is found. As a result, creation of the slip surface of the natural ground occurs slightly earlier. The safety factor of the whole system is 0.77, which is significantly higher than that of the loose sand model. Still, we have to use caution as deformation of the bore wall surface is quite advanced, and values other than safety factor can decide the limit conditions.

(4) With the medium clay model (Fig. 11), adhesion of clay contributes greatly to stability. Therefore, no effect is found on the bore wall and the natural ground in the layer. Instability of the bore wall surface in the bearing ground (regarded as sand) thus occurs first. The safety factor of the whole system is high at 1.40.

Total safety factor, stability of the bore wall and location where the slip surface occurs with natural ground are determined by complex combination of the natural ground physical properties and the ground layer composition. We believe that the developed software can clearly elucidate their behavior, and it could thus be sufficiently useful. So, it would be appropriate to put it into practical use as a reference tool upon confirming that the analysis results have a level of reliability that would not cause problems in practical use.

We therefore carried out verification tests on actual ground to confirm its reliability. The next section will outline the tests.

## 4 Collapse Tests of Actual Ground for Software Verification

### 4.1 Overview

The software introduced in the previous sections was developed new in this study. We therefore need to verify whether it correctly reflects actual phenomena. We observed the behavior of bore walls in bore wall collapse tests to compare the actual behavior with the software analysis results.

In the bore wall collapse tests, we drilled bores of 1,000 to 2,500 mm diameters as is done for actual cast-in-place piles. Then we induced bore wall collapse by gradually lowering the level of the slurry in the bores after completion of drilling. Fig. 12 shows the test flow and Table 5 describes the details of the test cases.

Concerning the ground conditions of the site, the surface layer was embankment assumed to be improved soil, the layer at GL -1.5–3.5 m was soft silt clay including humus, and the layer deeper than GL -3.5 m was loose or medium fine sand. The groundwater level was GL -0.81 m. Fig. 13 shows the soil boring log.

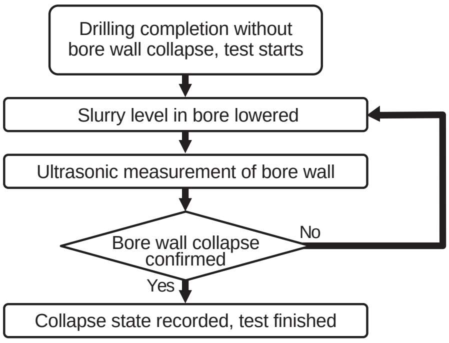


Fig. 12 Bore Wall Collapse Test Flow

Table 5 Bore Wall Collapse Test Cases and Results

| (Slurry and groundwater level are in relation to GL.) | | No.1 | No.2 | No.3 | No.4 |
|---|---|---|---|---|---|
| Pile diameter (mm) | | Ø1000 | Ø1500 | Ø2000 | Ø2500 |
| Groundwater level (m) | | -0.50 | -0.60 | -0.60 | -0.60 |
| Slurry level (m) | (a) [Analysis] at Fs ≈ 1.0 | -0.55 | -0.60 | -0.55 | -0.50 |
| | (b) [Test] when collapse confirmed | -1.10 | -1.20 | -1.30 | -1.20 |
| | (c) [Test] at sign of collapse (estimation) | -0.90 | -0.80 | -0.60 | -0.80 |
| (a)–(b) | | 0.55 | 0.60 | 0.75 | 0.70 |
| (a)–(c) | | 0.35 | 0.20 | 0.05 | 0.30 |

### *4.2 Advance Analysis Using Software*

To predict the water level at which collapse occurs in the bore wall collapse tests, we carried out advance analysis using slurry level as the parameter under conditions applicable to the test. By graphing the obtained total safety factor values (Fig. 14), we estimated the slurry level at which collapse occurs.

The results showed that the slurry level was roughly proportional to the pile diameter and the total safety factor became lower than 1 at a slurry level of +0.2–0.4 m in relation to the groundwater level. We therefore predicted that bore wall collapse would occur at around this slurry level in the collapse tests.

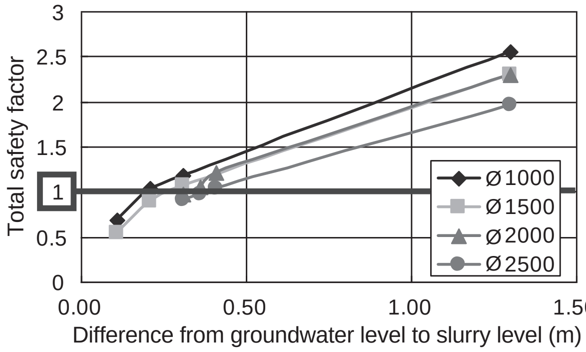


Fig. 14 Total Safety Factor Distribution in Advance Analysis

### *4.3 Bore Wall Collapse Test Results*

Lowering the slurry level in the bore in the bore wall collapse test, collapse occurred in the fine sand below the clay when the slurry level reached -0.6 to 0.7 m to the groundwater level. Almost the same results were seen in every case, regardless of pile diameter. The shape of the collapse was triangular or wedge-shaped, and the horizontal width of the collapse was estimated to be roughly 300–400 mm. Fig. 15 shows a conceptual diagram of the test state and collapse occurrence state. Table 5 lists the slurry level of each test case when the bore wall collapsed. Fig. 16 shows an example of the ultrasonic measurement records (No. 4, 2,500 mm diameter).

In comparison to the advance analysis results, the slurry level at the occurrence of collapse was lower by about 0.5–1.0 m, while the location of the occurrence of collapse was largely consistent with the analysis results.

### *4.4 Consideration of Test Results*

The slurry level in the pile bore at which the total safety factor became 1 in the analysis calculations differed by as much as 0.75 m from the level at which the collapse occurred in the tests (Table 5: (a)–(b)). The main reason would be that the point when the total safety factor became 1 in the analysis calculations

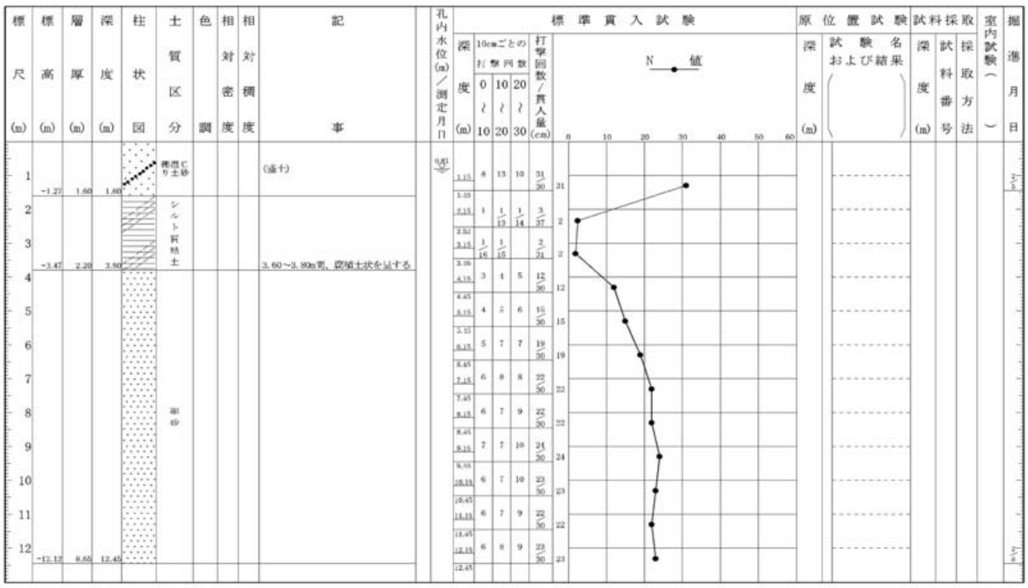

Fig. 13 Soil Boring Log of Test Ground

was the point where a part of the natural ground reached the collapse state. At the same time, that point was not necessarily equal to the point when a large collapse occurred.

Thus, we tried to read small collapses or signs of that from the measurement record. From that, we found turbidity of the slurry or signs of existence of free sand before the depth of final collapse in some cases (ex. Fig. 16 (2)). The slurry level at that time was higher than that at the final collapse by 0.2–0.7 m, with the difference from the slurry level where total safety factor was 1 in the analysis calculation being 0.05–0.35 m (Table 11: (a)–(c)). Taking into account the unevenness of the ground, those could be regarded as being largely equal to each other.

On the other hand, the location of collapse in the analysis was, as mentioned above, near the sand just under the clay. That is consistent to the actual location of the collapse (Fig. 15, 16).

Based on these results and considerations, we believe that the analysis results of the developed software have sufficiently accurate reproducibility of actual phenomena for practical use. And we believe that it delivers analysis results on the safe side.

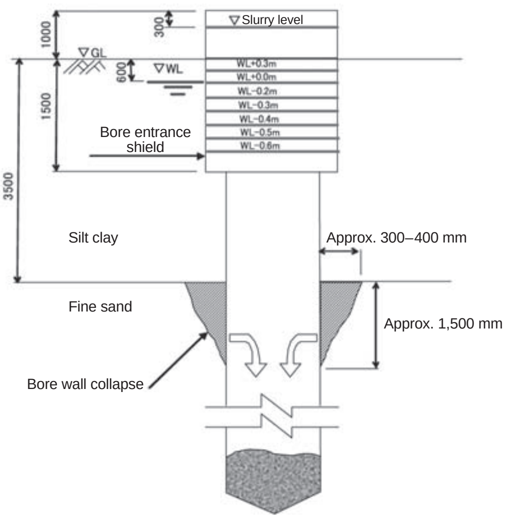


Fig. 15 Occurrence of Bore Wall Collapse (conceptual image)

## 5 Consideration of Software Characteristics

The developed software for the most part reproduced well the behavior of surrounding ground except ground of loose sand as shown in Fig. 9–11. It can thus calculate the safety factor of the whole system.

At the same time, it stopped calculating when partial collapse such as stripping of the bore wall occurred with loose sand like in Fig. 8. The computational total safety factor was thus considerably lower than the actual factor, not necessarily reproducing the actual situation. As shown in Table 5, however, the analysis results were all on a safer side than the test results. And variation of the results was not extremely large, not deviating from usual variation of actual ground.

Accordingly, we believe that the analysis results of the developed software can be applied to actual designing and safety checking work.

The actual ground drilling test results show that the slurry level at occurrence of obvious collapse was lower than the predicted level in the analysis, while the location of the occurrence of collapse agreed well with the analysis results. The reason could be that ultrasonic measurement of the bore wall in the slurry has limitations in accuracy, so "start of collapsing" could not be accurately identified in the tests. If we can identify the aforementioned signs, we will be able to more precisely verify the software.

## 6 Conclusion

Safely speeding up pile construction at sites near tracks contributes to cutting construction costs in development projects and to earlier return on investment. We expect that applying the developed software will bring about more appropriate control of the impact of pile construction at the worksite, resulting in shorter construction period and more appropriate costs.

The initial version of the software was released with the formulation of the manual of JR East for design and construction near structures during train operation time slots, and it has already been put to use for actual work.

By feeding back results of actual design and construction, we will further improve the software analysis accuracy and the method of evaluating analysis results.


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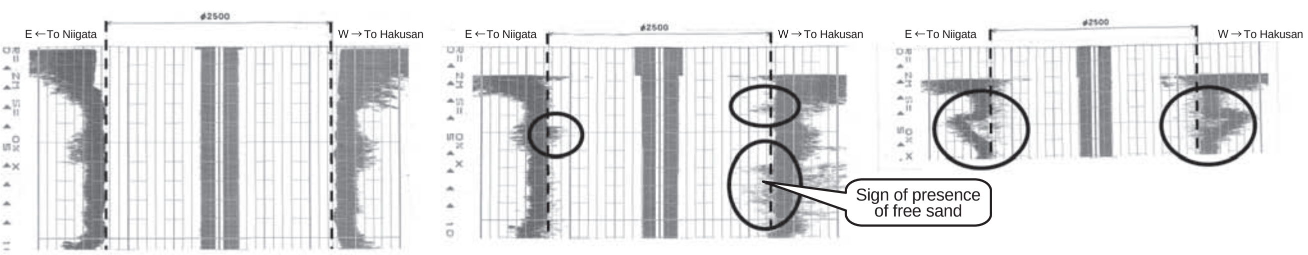


(1) At drilling completion (2) At sign of collapse (estimated) (3) When collapse confirmed

Fig. 16 Ultrasonic Measurement Results (Pile No. 4)