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Improvements in Realtime Construction Control System and Its Application to Excavation Work

Masanari Tominaga, Tateshi Koseki, Masakazu Fukuwaka, Hideo Uchiyama, Isao Ichihara, Hiromi Shikata

Synopsis :
The Realtime Construction Control System was developed by Kawasaki Steel Corp. to safely carry out the construction of a huge foundation for No.6 blast furnace at Kawasaki Steel's Chiba Works. The outline of the RCC System was reported in Vol.9 No.3 & 4 of "Kawasaki Steel Technical Report" (1977, in Japanese). After the successful construction of the blast furnace foundation, this system was improved in terms of expansion of its functions, improvement in precision and reduction of computation time, and has been applied to various civil engineering works not only inside Kawasaki Steel but also outside of the company and has obtained excellent results. Major items of improvements in this system and an excellent example of its application are discussed.

The body can be viewed from the next page.

Improvements in Realtime Construction Control System and Its Application to Excavation Work*

Masanari TOMINAGA** Tateshi KOSEKI** Masakazu FUKUWAKA**
Hideo UCHIYAMA*** Isao ICHIHARA*** Hiromi SHIKATA***

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1 Introduction

RCC (Realtime Construction Control) system first came to prove its usefulness in 1975 during the construction of No. 6 blast furnace foundation at Chiba Works[1]. Using on-site measurements and soil condition analysis data, RCC demonstrated its speedy performance in processing some 2 000 on-site measurement data in the excavation of a soft ground over 30m deep.[2-4]

Subsequently, improvements were made to RCC in analysis model, parameter selecting method, and analysis algorithm all aiming at an expansion of analytical function, an improvement in accuracy and a reduction in computing time. RCC has been found useful not only in many in-company civil engineering works, but also in various outside projects to gain customers' high reputation. One example is the construction of a pumping room (treating capacity: sewage 6 m^3/s, rain water 52 m^3/s) in Sewage Treatment Station downtown Tokyo. RCC again performed its important role with information processed in it effectively used in a large-scale deep excavation in soft soil, completing the work successfully with only 4-stage struts instead of five original planned.

In this paper, main improvements of RCC and its applications are described, with some technical features explained.

2 New RCC System

The need of revision to an initial stage of RCC system came about with an aim of making it suitable to a commercial-scale assignment outside the company, such as general braced excavation works to be performed under a variety of soil condition, structural and environmental conditions. The RCC needed expansion in its scope of application and its function. To this end, the system configuration needed greater versatility, and it caused an increased calculating workload. In an effort to mitigate the workload, effort was made to bring structure analysis more efficient so as to solve two contradictory subjects: one to expand program versatility, the other to reduce calculating time. The following chapters will explain major improvements of the new RCC system.

2.1 Elasto-plastic Analysis

Figure 1 shows a basic structure model of the new RCC system. This is an elasto-plastic analysis model with reaction limit provided on passive side soil. Earth pressure on passive side soil increases with displacement of retaining walls, moving from earth pressure at rest to passive area, to attain passive earth pressure which is a critical value. This passive earth pressure is to be considered as reaction limit. In

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** Engineering Division
*** Chiba Works

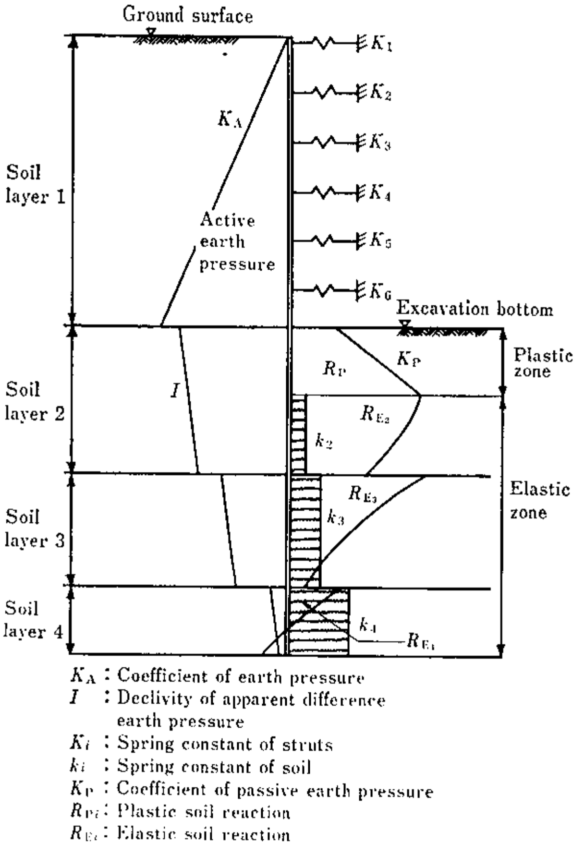


Fig. 1 A model for structural analysis

structural calculation of retaining walls, composed earth pressure and water pressure are taken as load, which is called "active lateral pressure". As active lateral pressure at a level deeper than excavation bottom, the authors have adopted an active earth pressure less earth pressure at rest at a level deeper than the excavation bottom. Consequently, the aforesaid reaction limit is the passive earth pressure minus earth pressure at rest. This value is represented by soil parameter, K_P.

In recent years, design of large-scale retaining walls is conducted through sequential elasto-plastic calculation method[5]. As is the case with the new RCC system, this is a designing method in which passive earth pressure is used as reaction limit on passive side. The fact that conceptual structure model used in RCC system and the one used in designing retaining walls are fundamentally the same not only facilitates comparison between analyzed value by RCC system and original design, but also brings analysis results by RCC system to an efficient use in similar structure designs of large-scale retaining walls in future.

2.2 Utilization of Analytic Solution

Assuming that a retaining wall consists of structural members whose loading and supporting conditions are of a linear type, thus permitting the application of the differential equation of beam, an analytic solution may be obtained for each constituting member. By combining these solutions under dynamic continuity conditions, a solution for overall retaining walls can be obtained. This is the structure calculation method which uses the analytic solution adopted in the new RCC system.

In the finite element method adopted in the old RCC system, efforts were made to solve simultaneous linear equations taking, as unknown, all the degrees of freedom at positions where solutions were to be obtained, in addition to the positions where structural conditions were changed, so as to obtain solution for an overall retaining walls. In the finite element method, such structural model as shown in **Fig. 1** will be such that simultaneous equations with 120 elements with about 60 nodes must be solved if the length of a retaining walls is 50 m. On the other hand, in the method using the analytic solution, solution for the overall retaining walls can be obtained by only taking, as unknown, the degree of freedom at positions where structural conditions change, and even in the case of the structure model shown in **Fig. 1**, it would be sufficient to solve simultaneous linear equations with only 24 elements and 12 nodes. In consequence, the scale of simultaneous linear solutions is about 1/5 of those of the finite element method, with resultant reduction in calculation time to about 1/25 on the same basis.

2.3 Equilibrium Equation with Initial Displacement taken into Consideration

Excavation progresses as struts advance in sequence supporting the growing active lateral pressure. In RCC system, structural calculation is performed along with such execution process.

The displacement of the retaining walls at the position where struts are installed is called initial displacement of struts. In the event that a structural system changes by the installation of struts and that an overall displacement, including initial displacement, is to be solved by a new structural system, the initial displacement must somehow be taken into consideration and how to do it is a problem. In the old RCC system, calculation was limited to elastic solution, and in the new structural system, calculation was made on the increment of working load, and the result thereof was superposed on the state of the initial displacement, thereby coping with the above problem. Though this method is so clear from the theoretical viewpoint, there arise the following problems, because soil parameters chosen through simulation concern the difference:

(1) To evaluate the change of soil nature using such soil parameters, it is required to consider both the relationship between the difference and soil parameters as well as the transition of such relationship, and further more, quantitative evaluation is difficult.
(2) When excavation is not much advanced, it sometimes happens that the retaining walls are almost free from any displacement. This is considered to be a temporary phenomenon caused by the maintenance of a preexcavation stress condition of the soil on passive side or the rigidity of the soil. Under such conditions, prediction is likely to be underestimated because attention is focused only on the variation.

The new RCC system adopted a method by which these problems can be solved in one breath by way of the equilibrium equation which takes the initial displacement into account.

Rigidity equation as against the increase after installation of struts may be expressed as follows:

$$\boldsymbol{f}^{(1)} - \boldsymbol{f}^{(0)} + \boldsymbol{f}_{eq}^{(1)} - \boldsymbol{f}_{eq}^{(0)} = \boldsymbol{K}^{(1)}(\boldsymbol{u}^{(1)} - \boldsymbol{u}^{(0)}) \quad \cdots\cdots (1)$$

$\boldsymbol{f}^{(0)}, \boldsymbol{f}_{eq}^{(0)}, \boldsymbol{u}^{(0)}$: Member's internal force at the time of initial displacement; Equivalent panel point load; Displacement, respectively

$\boldsymbol{f}^{(1)}, \boldsymbol{f}_{eq}^{(1)}, \boldsymbol{u}^{(1)}$: Member's internal force after installation of struts; Equivalent panel point load; Displacement, respectively

$\boldsymbol{K}^{(1)}$: Rigidity matrix including rigidity of struts

Further, rigidity equation before installation of struts may be expressed as follows:

$$\boldsymbol{f}^{(0)} + \boldsymbol{f}_{eq}^{(0)} = \boldsymbol{K}^{(0)}\boldsymbol{u}^{(0)} \quad \cdots\cdots (2)$$

$\boldsymbol{K}^{(0)}$: Rigidity matrix excluding rigidity of struts

From the formulas **(1)** and **(2)** described above, the following can be obtained;

$$\boldsymbol{f}^{(1)} + \boldsymbol{f}_{eq}^{(1)} + (\boldsymbol{K}^{(1)} - \boldsymbol{K}^{(0)})\cdot\boldsymbol{u}^{(0)} = \boldsymbol{K}^{(1)}\boldsymbol{u}^{(1)} \quad \cdots\cdots (3)$$

Thus an ordinary equilibrium equation can be formed for overall displacement. Since the soil parameter included in this equation concerns the overall displacement, $\boldsymbol{u}^{(1)}$, the problematical point arising from the increment method can be solved.

2.4 How to search for Soil Parameters

Regression analysis[6] by simulation has been adopted as an efficient method of searching for soil parameters. This method gives statistic calculation of the effect by each of inter-related parameters on evaluation function (total sum of residual square of measured displacement and calculated displacement), thus narrowing down the area that contains the real value.

Orthogonal table (see **Table 1**) is used to separate the related parameters. Here soil parameters are attributed to Cols. 1 to 13, and residual variation calculation is carried out according to each level for Nos. 1 to 36. Three levels of parameters are to be decided as follows: Two are taken respectively as the first and the third levels, with the intermediate value taken as the second level. In determining a new level, residual variation for each parameter must be added to its respective level, and significant difference between levels is to be examined by the formula **(4)**.

$$F_O = |S_{i,j} - S_{i,j+1}|/12\cdot V_e \quad \cdots\cdots (4)$$

$S_{i,j}, S_{i,j+1}$: Residual square-sum
i: Parameter No. (1 to 13)
j: Level (1, 2)
V_e: Predicted error variance

Then three new levels are to be determined by the pattern shown in **Table 2.** This method is repeated until convergence, thus deciding soil parameters.

Condition for convergence is that there be no significant difference between three levels for any parameter. In the so-called All Possible Method adopted in the old system, trial number required in the cases where, for example, 8 parameters are divided into 5 levels, is $5^8 = 390\,625$, which gives too large a load to computer, making this method impracticable. In general, trial number in the regression method by simulation is of the order of 360, not much affected by the number of parameters.

The new RCC system permits 13 soil parameters maximum (hereinafter the new RCC system to be referred to simply as "RCC system")

3 Application Examples

3.1 Generality

As a typical case of achievement of RCC system in its full function, a large-scale deep excavation work in construction of pumping room for Sunamachi Sewage Treatment Station, Sewage Bureau of Tokyo can be introduced[7]. The project itself was assigned to Kajima Corporation, with Kawasaki Steel for analysis, by RCC system, of on-site measurement data

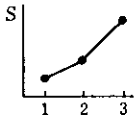
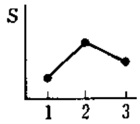
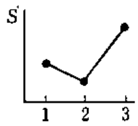
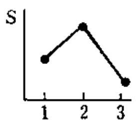
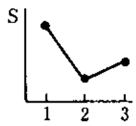
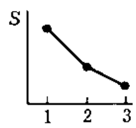
Table 1 Orthogonal table L36 (3^{13}) and sum of residual squares, *S*

No \ Col	1	2	3	4	5	6	7	8	9	10	11	12	13	*S*
1	1	1	1	1	1	1	1	1	1	1	1	1	1	*S* 1
2	2	2	2	2	2	2	2	2	2	2	2	2	1	*S* 2
3	3	3	3	3	3	3	3	3	3	3	3	3	1	*S* 3
4	1	1	1	1	2	2	2	2	3	3	3	3	1	*S* 4
5	2	2	2	2	3	3	3	3	1	1	1	1	1	*S* 5
6	3	3	3	3	1	1	1	1	2	2	2	2	1	*S* 6
7	1	1	2	3	1	2	3	3	1	2	2	3	1	*S* 7
8	2	2	3	1	2	3	1	1	2	3	3	1	1	*S* 8
9	3	3	1	2	3	1	2	2	3	1	1	2	1	*S* 9
10	1	1	3	2	1	3	2	3	2	1	3	2	1	*S*10
11	2	2	1	3	2	1	3	1	3	2	1	3	1	*S*11
12	3	3	2	1	3	2	1	2	1	3	2	1	1	*S*12
13	1	2	3	1	3	2	1	3	3	2	1	2	2	*S*13
14	2	3	1	2	1	3	2	1	1	3	2	3	2	*S*14
15	3	1	2	3	2	1	3	2	2	1	3	1	2	*S*15
16	1	2	3	2	1	1	3	2	3	3	2	1	2	*S*16
17	2	3	1	3	2	2	1	3	1	1	3	2	2	*S*17
18	3	1	2	1	3	3	2	1	2	2	1	3	2	*S*18
19	1	2	1	3	3	3	1	2	2	1	2	3	2	*S*19
20	2	3	2	1	1	1	2	3	3	2	3	1	2	*S*20
21	3	1	3	2	2	2	3	1	1	3	1	2	2	*S*21
22	1	2	2	3	3	1	2	1	1	3	3	2	2	*S*22
23	2	3	3	1	1	2	3	2	2	1	1	3	2	*S*23
24	3	1	1	2	2	3	1	3	3	2	2	1	2	*S*24
25	1	3	2	1	2	3	3	1	3	1	2	2	3	*S*25
26	2	1	3	2	3	1	1	2	1	2	3	3	3	*S*26
27	3	2	1	3	1	2	2	3	2	3	1	1	3	*S*27
28	1	3	2	2	2	1	1	3	2	3	1	3	3	*S*28
29	2	1	3	3	3	2	2	1	3	1	2	1	3	*S*29
30	3	2	1	1	1	3	3	2	1	2	3	2	3	*S*30
31	1	3	3	3	2	3	2	2	1	2	1	1	3	*S*31
32	2	1	1	1	3	1	3	3	2	3	2	2	3	*S*32
33	3	2	2	2	1	2	1	1	3	1	3	3	3	*S*33
34	1	3	1	2	3	2	3	1	2	2	3	1	3	*S*34
35	2	1	2	3	1	3	1	2	3	3	1	2	3	*S*35
36	3	2	3	1	2	1	2	3	1	1	2	3	3	*S*36

$S=\sum_{i}^{n}(\varepsilon_i)^2$: Sum of residual squares

ε_i : Residual = Calculated value − Measured value

Table 2 New level determination criteria

Pattern	Type of variation	Significant condition	New level		
			1	2	3
I		① There is no significant difference between 3 levels. ② There is no significant difference between the 1st level and the 2nd level. ③ There is a significant difference between the 1st level and the 2nd level. (Note)	1 1 0.5 (2)	2 1.5 1 (1.5)	3 2 1.5 (2)
II		Regardless of any significant difference	1	2	3
III		① There is no significant difference between the 3 levels. ② There is no significant difference between the 1st level and the 2nd level. ③ There is a significant difference between the 1st level and the 2nd level.	1 1 1.5	2 1.5 2	3 2 2.5
IV		Regardless of any significant difference	1	2	3
V		① There is no significant difference between the 3 levels. ② There is no significant difference between the 2nd level and the 3rd level. ③ There is a significant difference between the 2nd level and the 3rd level.	1 2 1.5	2 2.5 2	3 3 2.5
VI		① There is no significant difference between the 3 levels. ② There is no significant difference between the 2nd level and the 3rd level. ③ There is a significant difference between the 2nd level and the 3rd level. (Note)	1 2 2.5 (2)	2 2.5 3 (2.5)	3 3 3.5 (3)

(Note) For the 1st time, the level value shown in ( ) is used.
For the 2nd time onward also, when the new level value exceeds, the setting range, the level value shown in ( ) is adopted.

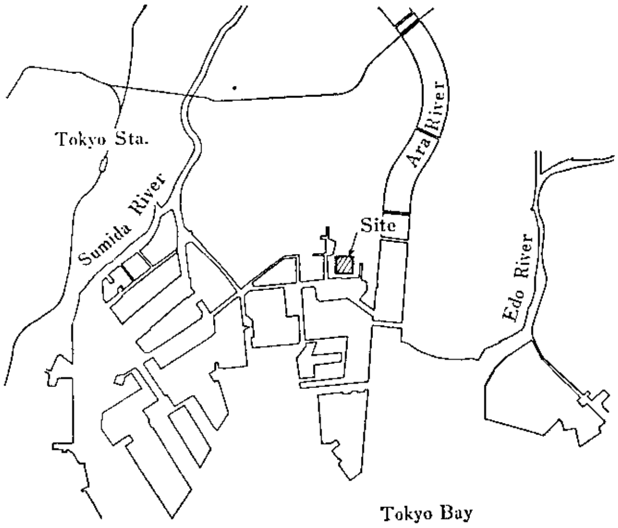
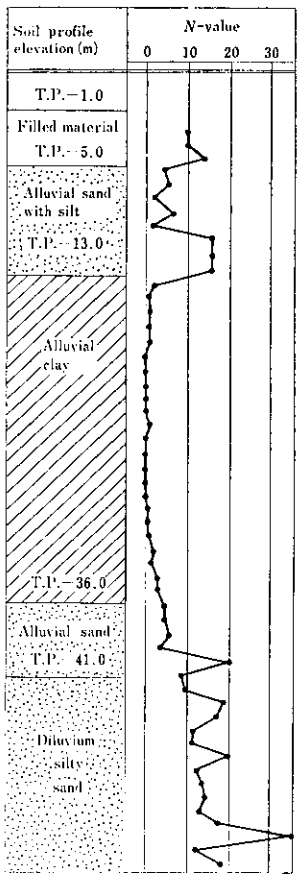


Fig. 2 Site location



T.P.: Standard mean sea level of Tokyo Bay

Fig. 3 Soil profile

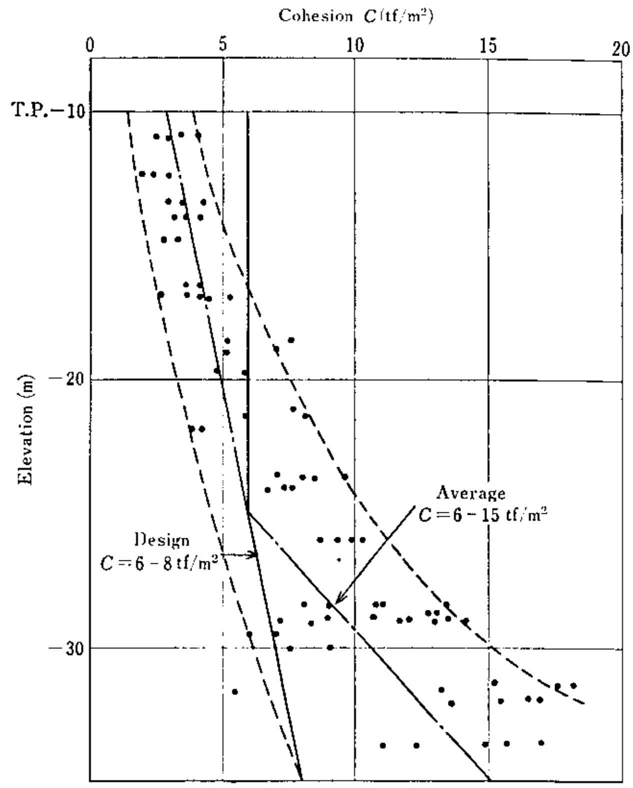


Fig. 4 Distribution of cohesion

on the retaining walls.

Figures 2 and **3** show respectively construction site and boring log, while **Fig. 4** cohesion distribution of alluvial silt deposit. From T.P. −13 m to −36 m, there exists a soft alluvial silt deposit with very high sensitivity ratio (*N*-value: 0 to 2, natural moisture content: 85% or more). Underneath it exists a stable diluvium sandy layer with *N*-value of 20 to 50, with loose alluvial sandy layer (*N*-value: less than 10) inbetween. Cohesion of alluvial silt deposit, which increases with depth, is 3 tf/m², but much dispersed underneath. In particular, the south and west sides of excavation portion, is a reclaimed land of the reservoir of Sunamachi canal, which is very poor subsoil, being not consolidated as on the north and east sides.

Figures 5 and **6** show structural sectional drawing and plan, respectively. The retaining wall utilizes interlocked steel pipe piles of ϕ1 500 mm (t = 19–22 mm on the west side, t = 19 mm on the east, south and north sides), and lower tips of steel pipe piles are embedded down to diluvial deposit of T.P. −45 to −49 m. Subsoil inside the retaining walls, from T.P. −10 m down to −25 m, has been improved by chemico piles, and in order to support superstructure, cast-in-place piles (ϕ2 500 mm) are installed over all area on excavation portion. Pumping room was to

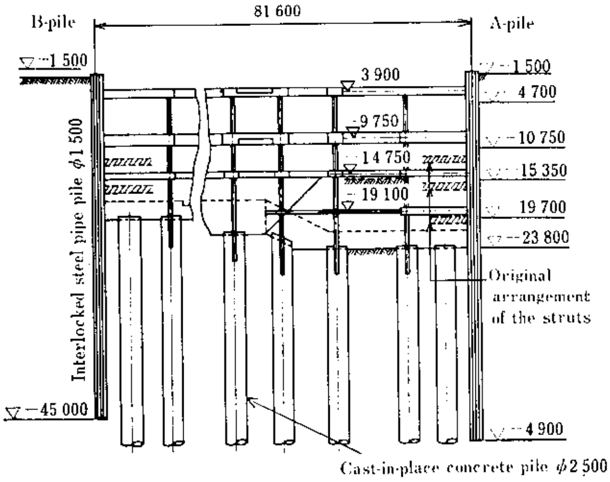


Fig. 5 Section of excavation site

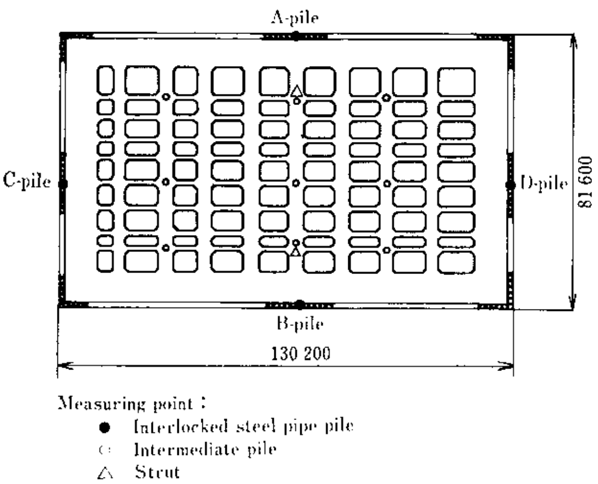


Fig. 6 Plan of excavation site

be constructed in internal space 130 m × 82 m in plan with steel pipe piles at the outer circumference. For the purpose of confirming safety and security of the retaining walls for such a large-scale deep excavation work, measurement monitoring and RCC analysis were carried out with the progress of the excavation performance.

The final excavated depth was T.P. −19.8 m on the south side, and T.P. −23.8 m on the north side. The struts installed are called the first strut, the second strut, and so on from the ground level down, and corresponding excavation down to respective positions of struts installed are called the primary excavation, the secondary excavation, and so on.

The retaining wall structure was designed based on the elasto-plastic sequential analysis method. The fundamental idea of this method is quite the same with RCC system; that is, structural analysis of braced excavation work is performed by sequentially calculating stress and displacement caused by excavation at each stage in the retaining walls and struts. For lateral pressure coefficient K_a, 0.75 was adopted, and as cohesion of alluvial silt deposit, the value C of 6tf/m^2 was taken as obtained from a soil test after soil improvement. The calculated maximum stress of the steel pipe material at the final excavation stage was about 90% of allowable stress 2 850 kgf/cm^2; namely 2 850 × 0.9 = 2 565 kgf/cm^2.

Table 3 shows measuring items and instruments used, and **Fig. 6**, installation locations of respective instruments. These data were processed by automatic processing system where microcomputers were utilized. Data obtained using the insertion-type sliding inclinometer on the displacement of the retaining walls, the strain to the retaining walls and the struts were used for daily control purposes.

Among these, data used in RCC system were the displacement of the retaining walls measured by the insertion-type sliding inclinometer, and based on this, analyses were made by RCC system on the actual state and the prediction.

3.2 Excavation Planning

Construction site for the pumping room falls on a very poor soil, and further deep excavation is required on a large plane. There existed therefore a variety of uncertain elements and excavation procedure was studied most elaborately.

After having placed steel pipe piles, chemico piles were executed covering the overall area on excavation portion to improve the passive resistance of excavation portion soil. Excavation was planned to be done with struts in five stages in all (four stages partially). The first and second stage struts were also used as part of the floor of the main structure, and all the struts were of reinforced concrete, except for the steel-structured fifth one. Preceding to the primary excavation which was executed before installing struts, an excavation was made down to T.P. −2 to −4 m within the range of about 30 m at the back of the retaining walls, thus reducing the lateral pressure acting on the retaining walls and decreasing the horizontal displacement and stress. In the excavation thereafter, priority was given to the east side where the soil was relatively good, in order to minimize displacement and stress increase on the west side where soil was poor. But notwithstanding such consideration, the head of retaining walls after the primary excavation showed about 10 cm of displacement, to the recognition of the difficulty of this excavation work.

Table 3 Measuring apparatus and items

Item	Measuring apparatus		Number of apparatus
	Device	Kind · Type	
Stress of pile	Strain gage	L. V. D. T. type	62
Lateral displacement of pile	Vertical inclinometer	L. V. D. T. type	6
Strut load	Reinforcing bar stress transducer	L. V. D. T. type	52
	Concrete stress transducer	Strain gage	19
	Thermometer	L. V. D. T. type	5
Earth-pressure	Earth-pressure meter	L. V. D. T. type	18
Pore-pressure	Pore-pressure meter	L. V. D. T. type	10
Underground water level	Underground water level meter	L. V. D. T. type	4
Displacement and settlement of pile	Transit	—	6
	Level	—	6
Movement of intermediate pile	Transit	—	9
	Level	—	9
Movement of struts	Transit	—	60
	Level	—	48
Settlement of the ground	Level	—	16

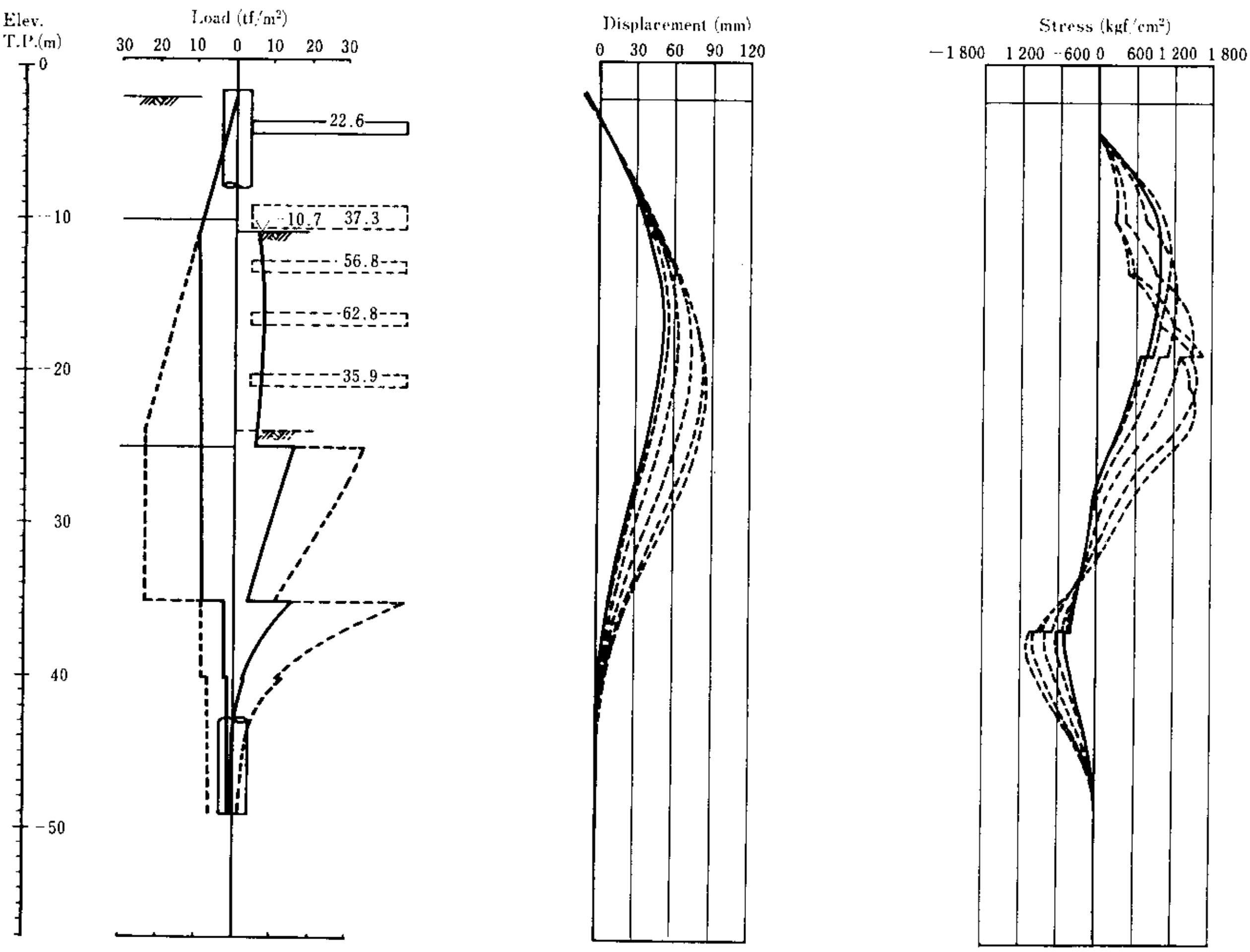


Fig. 7 Analysis at 2nd excavation stage (A-pile)

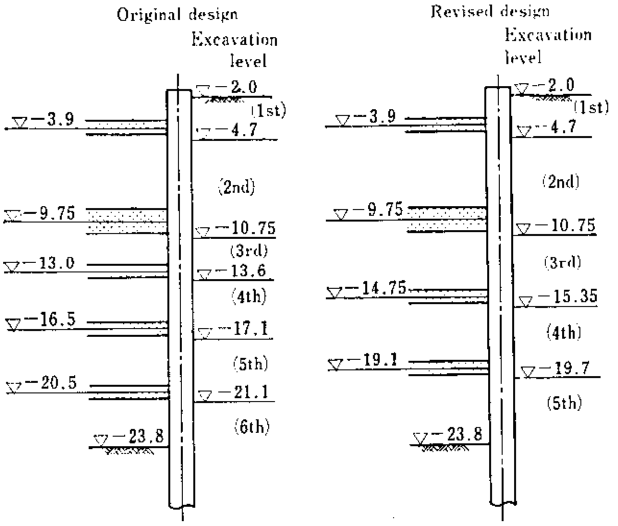


Fig. 8 Design change with the number of struts reduced from 5 to 4

3.3 Saving One-Stage Strut

3.3.1 Discovery of a possibility

When the secondary excavation was ended, displacement of pile A situated on west side was found noticeable. **Figure 7** represents the results of analysis made by RCC system at that time. In the figure, actual state analysis value is indicated by full line, and prediction value, by broken line. The final predicted maximum stress at the secondary excavation was σ = 1 590 kgf/cm^2, namely about 62% of design value. The final predicted stress for other piles measured was equal to or less than that value, and it was at this time that a discovery was made on the possibility of four-stage struts eliminating one stage, as shown in **Fig. 8**. Then, prediction analysis in the four-stage struts was made. Concerning lateral pressure coefficient, the value selected by RCC system was less than the design value at the time of termination of the secondary exacavation. Since, however, the said value was almost identical with the value measured by the

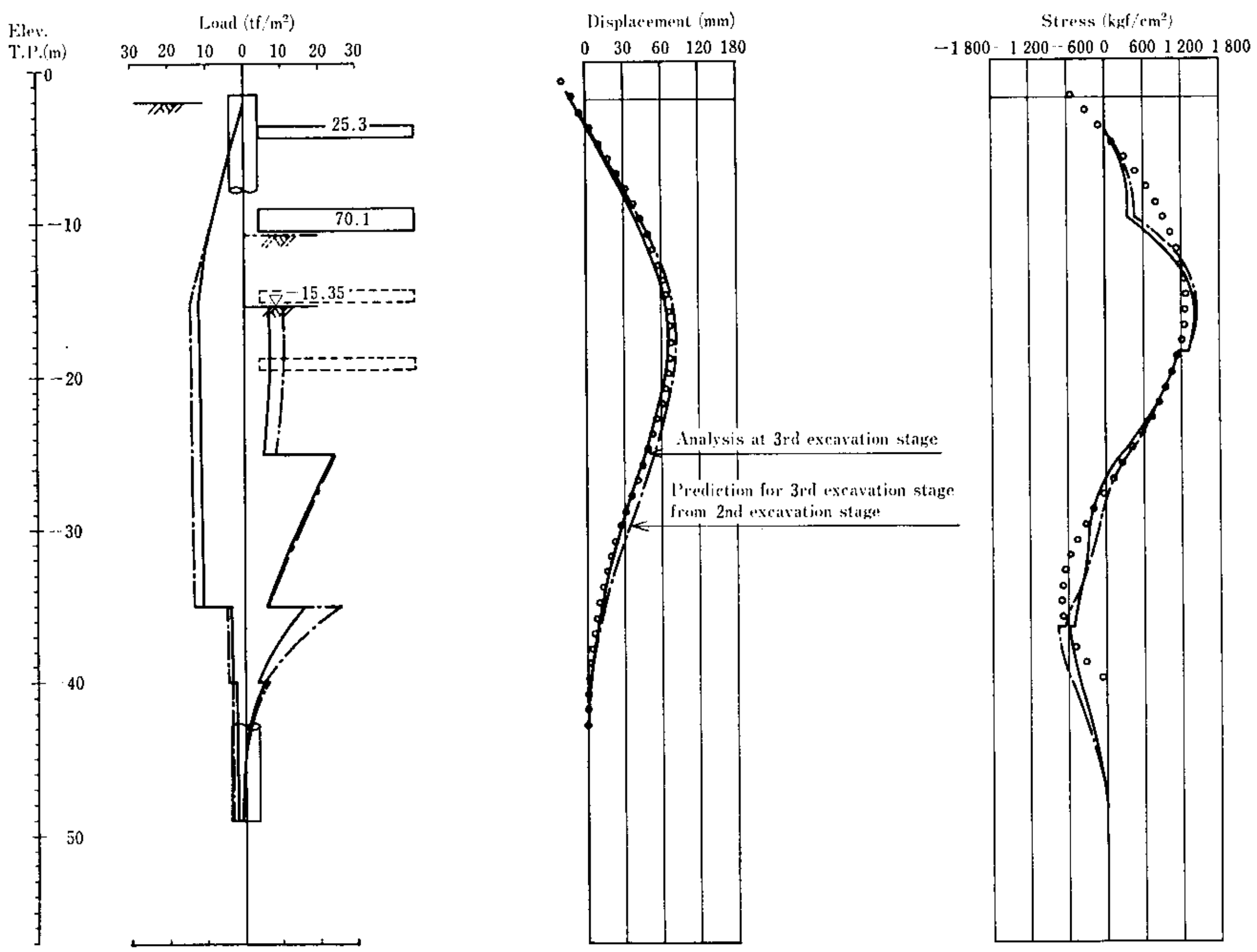


Fig. 9 Analysis of 3rd excavation stage (A-pile)

earth pressure cell, the authors considered that the selected value was appropriate, and used the said lateral pressure coefficient. As for passive earth pressure, the authors have limited the passive earth pressure in controlling to the lower limit $C = 6$ to 8 tf/m^2 the cohesion of this soil because of some apprehensions about overestimating the soil of alluvial silt deposit at a level of T.P. −25 to −35 m in particular. As a result, it was found that even in the case of four-stage struts, the final maximum stress was 91% of the design value, implying the full possibility of one stage reduction.

3.3.2 Search for possibility

In order to make doubly sure the possibility to reduce by one stage the number of struts stages, a test pit excavation in approximately 30 m × 30 m was made around the pile B. On this occasion, check points were provided on two steps: one at the third excavation level (T.P. −13.6 m) in the original design, and the other at the third excavation level (T.P. −15.35 m) in the modified design concept. Analyses by RCC system were made along with actual behavior of the retaining walls using measured values, thereby confirming the precision of the values by prediction analysis made at the time of the secondary excavation. **Figure 9** compares the value of actual state analysis made at exacvation of T.P. −15.35 m with the values predicted at the time of termination of the secondary excavation (T.P. −10.7 m). The predicted values at the termination of the secondary excavation coincide relatively well with the actual values, with their difference between the maximum stress of steel pipe piles is only on the order of 20 to 50 kgf/cm^2, showing high precision of the predicted value at the termination of the secondary excavation.

Figure 10 shows the result of prediction analysis for pile A at the third stage excavation down to T.P. −15.35 m. The predicted value at the final stage was about 55% of the design value, and the value of stress measured by strain gage coincided well with the predicted value. Moreover, the predicted values for

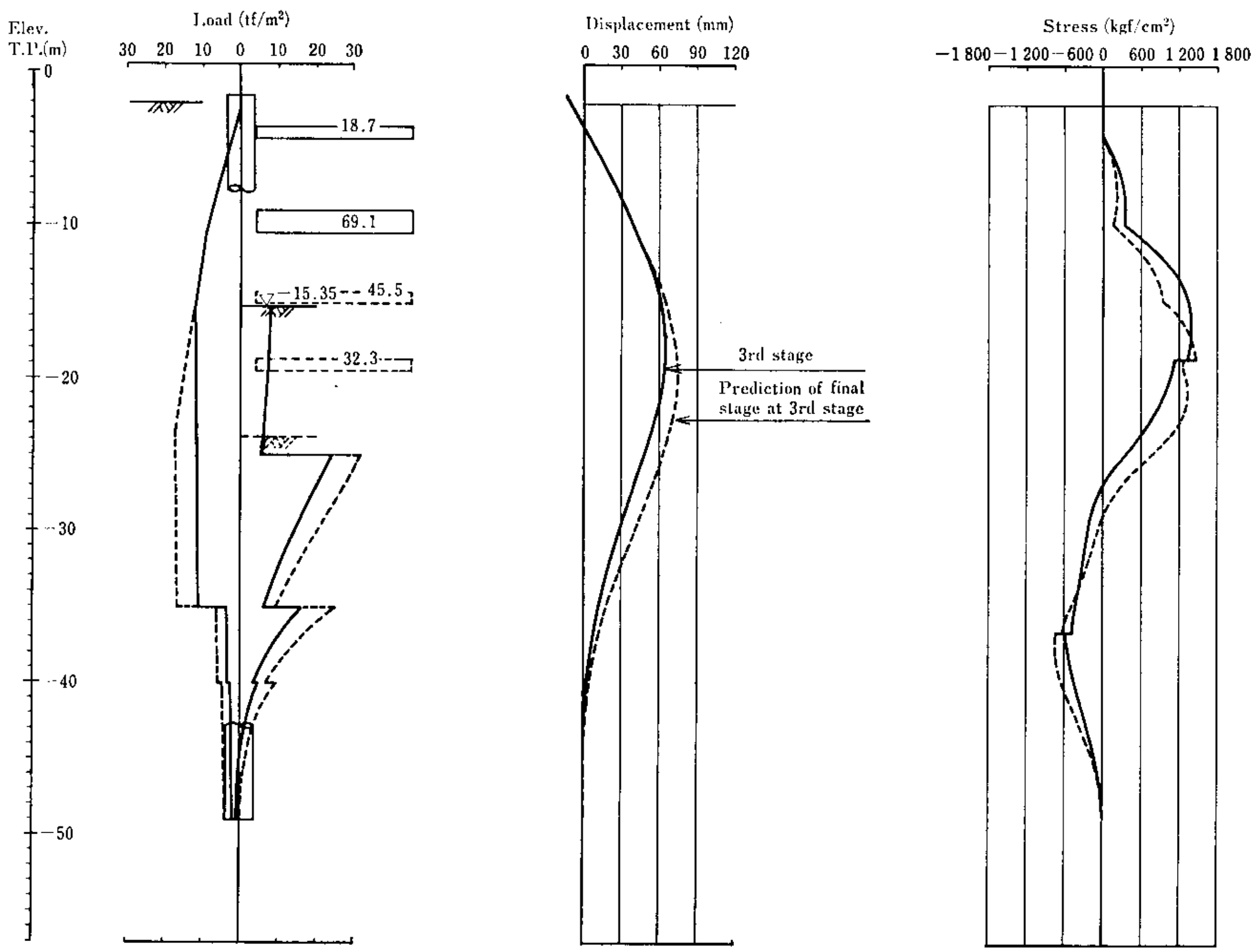


Fig. 10 Prediction of final stage with 4 struts (A-pile)

other piles were also about 50 to 70% of the design values. As a result, it was concluded possible to reduce one stage of struts. Therefore, design modification for four-stage struts was determined, thus proceeding with further excavation on the overall area.

3.3.3 Subsequent development

Figure 11 shows the development of stress of the retaining wall actually measured after the secondary excavation. For two piles both, the stress after the decision on the design modification for four-stage struts has been on the same tendency. Stress increment due to soil creep during the installation of the secondary strut is equal to the stress difference between Pile A and Pile B until the final excavation. It was possible to hold the stress increment below the maximum allowable stress set up at the time of designing.

Figure 12 shows the measurement of lateral pressure

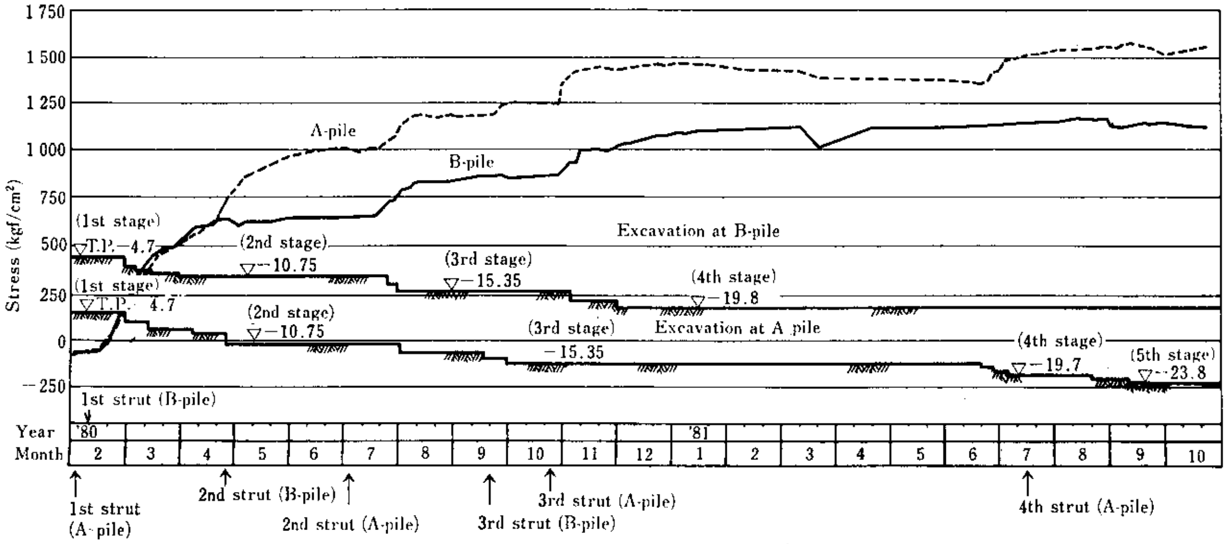


Fig. 11 Excavation schedule and stress of pile

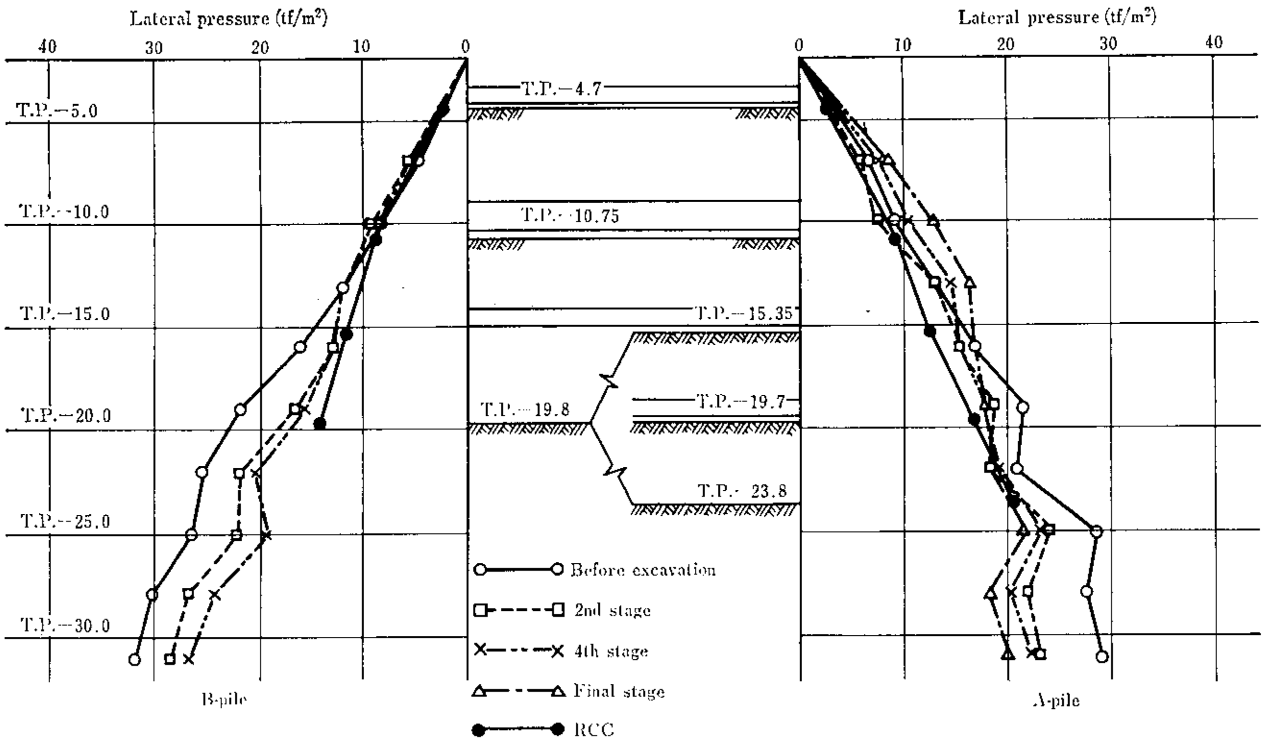


Fig. 12 Distribution of lateral pressure measured at each stage and analysed by RCC

at the back of the retaining walls and the lateral pressure obtained from the search for parameters by RCC system. Their distributions are closely similar to each other; namely, though lateral pressure coefficient, K_a, which was 0.7 to 0.8 at the initial stage of excavation gradually decreased with the advance of excavation and became 0.5 to 0.6 at the final stage of excavation. This was an important factor in controlling deformation and stress of the retaining walls. Furthermore, the passive earth pressure of alluvial silt deposit at the level of T.P. −25 to −35 m was more resistant than the preset value which had been studied at the end of the secondary excavation. As a conclusion, it can be said that these factors as a whole contributed to the safety and security, making the overall excavation work well balanced in spite of the reduction of one stage.

3.4 Conclusion

Although it was an unprecedented large-scale deep excavation in poor, cohesive soil, the excavation work was achieved without any problem.

In general, displacement and stress of the retaining walls at excavation are caused by interaction between neighboring earth and structures, and it is very difficult to predict them accurately. Further, a variety of uncertain elements are added to make the execution far more difficult.

Therefore, execution of the retaining walls was carried out under an execution control system in which RCC system was fully utilized along with instrumentation control using various gages and instruments so as to obtain accurate analysis of the present and the future of the retaining walls. The knowledge thus obtained was reflected in the execution work from time to time. As a result, the original five-stage struts were replaced with four-stage struts, with a saving of one stage. The following can be cited as reasons for the safe and successful execution:

(1) Measuring instruments were installed at important points so as to grasp interrelationship between respective measured values for a synthetic evaluation.
(2) The struts were made of reinforced concrete with large rigidity, thus preventing abnormal earth pressure and minimizing the deformation of soil.
(3) By studying excavation procedures, it was made possible to prevent deviated earth pressure by differences in soil conditions, etc. and abnormal deformation of retaining walls.
(4) Correspondence between measurements and execution was improved by, for example, starting excavation from around the piles having necessary measuring setup.
(5) The parameters of soil selected by actual state analysis corresponded well to the measured values of earth pressure cell, which allowed to grasp accurately the interacting behaviors of soil and the retaining walls and to make precision prediction.
(6) Measurement of lateral pressure and stress of the retaining walls led to confirming the precision of analysis.

4 Technical Significance

In designing retaining walls, it is very difficult to grasp accurately the strength and distribution of lateral pressure acting on the back of the retaining walls or the horizontal soil reaction coefficient values on the passive soil, thus making a number of assumptions unavoidable. Since such assumption at the stage of designing will remain as uncertain factor in execution, a variety of on-site measurements are made to compare with design values so as to assure a safe progress of excavation.

However, what the engineers want to know are how actual excavation changes lateral pressure and horizontal soil reaction coefficient which both are not clear at the time of designing, and further what influences this change will have on the excavation to be made in the future.

The development of RCC system was motivated by the above needs of the engineers. In this system for construction execution control, lateral pressure and soil reaction induced on the retaining walls are estimated from actual state analyses, and, based on these results obtained, future behaviors of the wall and the surrounding soil are predicted, with all these data of on-site measurements fed back to the phases of execution and designing of the wall in the form of graphical display.

In actual state analysis by RCC system, the deformation of retaining walls measured by inclinometer is emphasized, thus obtaining parameter values (such as lateral pressure coefficient, horizontal soil reaction coefficient, etc.) which cause a deformation almost equivalent to that actually measured. The reason for emphasizing the deformation of retaining walls was that sliding inclinometer could give data at almost continuous multiple points, permitting measurements in a manner more suitable, reliable and economical than with earth pressure cell and strain gage. It should be noted here that the parameter values obtained through the actual state analyses would lead to a useless actual state analysis, if they have a meaning quite different from design theory. However, as has already been explained in Chapter 2, the structure model used in RCC system is an elastoplastic model based on design theory for retaining walls, and the values of parameters selected are corrected so that the values left uncertain when designing will approach the real values. This is as if a large-scale on-site test were executed for each step of excavation with soil coefficients examined at each time. Also in the execution example given in Chapter 3, the lateral pressure distribution and stress distribution of retaining walls, obtained from actual state analyses, well coincide with the measured values, proving that the actual state analysis by RCC system is appropriate.

Another important characteristic of RCC system is its capability for future prediction. Making use of the values of parameters obtained through actual state analysis, it sequentially predicts deformation and stress of the retaining walls as well as soil reaction in each respective subsequent step. By this, engineers can not only confirm the safety of the retaining walls using the results of actual state analyses and those of prediction analyses, but also continue excavation with confidence in its safety in the future. In the event that predicted values are by far different from the design values, design modification such as addition or omission of struts can also be carried out easily, and in the case of such modification, its safety can be examined through comparison between the preceding predicted values and measured values (values of actual state analysis) at the following excavation stage. The important point in prediction is its prediction accuracy. **Figure 13** shows the trend of prediction accuracy for the maximum displacement of retaining walls at the final excavation in each excavation stage (execution example given in Chapter 3). Although predicted values largely vary at the initial stage of excavation, prediction error becomes converged within 10% when excavated depth exceeds 60% of the final depth. Prediction accuracy of RCC system executed in the past presents a similar tendency[3], and therefore this is a satisfactory accuracy

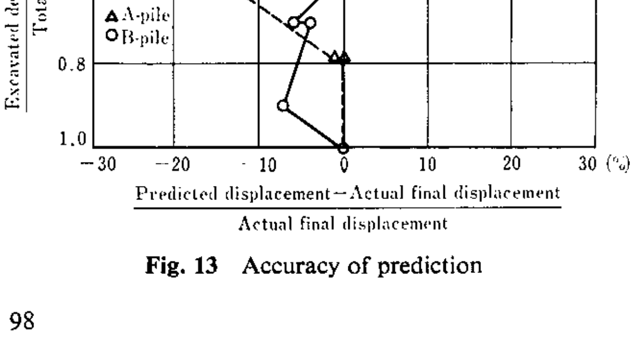


Fig. 13 Accuracy of prediction

from practical viewpoints.

As mentioned above, RCC system is a total system intended to feed the information obtained from execution back to designing or execution planning rapidly and safely, and it is a method for bringing design theory based on many assumptions closer to reality. In the analysis by RCC system, multidimensional simultaneous equations must be solved repeatedly in search for parameters, etc., and if by ordinary method, this will become impracticable even with large-scale computers. For that reason much ingenuity was taxed as described in Chapter 2, and therefore it was only with development of computers and advanced analytical methods that this system was made possible.

5 Summary

The foregoing chapters described RCC system, particularly, main improvements made to the old system, its applications, and its technological significance. The application cited in Chapter 3 is one of the most ideal cases because RCC system proved its efficiency by not only achieving satisfactory results with full demonstration of its function but also saving one strut stage in an unprecedentedly large-scale deep excavation work in soft soil.

The RCC system is now used by many users with increasing reputation. However, problems such as deformation by creep of soil, and preload of struts call for further studies.

Last but not least, the authors extend their hearty thanks to the officers of Sewage Bureau of Tokyo Metropolitan Government for their kind and suitable advice in the excavation work at Sunamachi Sewage Treatment Station as well as to those engineers of Kajima Corporation for their generous help with the smooth analysis work using RCC system.

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