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UNDERGROUND WATER PROBLEMS IN DEEP EXCAVATION

CONSTRUCTION CONTROL AGAINST BOILING FAILURE IN DEEP EXCAVATION IN SANDY GROUND BY FIELD MONITORING

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SUMMARY

This paper presents a case history of a deep open cut excavation of Nakagawa section for Fukuoka Subway construction which adopted observational method against boiling failure and completed with success by modifying construction based upon field monitoring. One of the difficult conditions for the excavation was sandy layer with high water pressure which was anticipated boiling failure. The boiling was generally considered as one of the difficult phenomena to work with the observational method because of its unpredictable catastrophic nature.

Laboratory experiments showed the existence of the prefailure movements of the ground and the possibility of the application of the observational method against the boiling failure. Construction step was planned to be modified, if necessary, based upon field monitoring and was completed with success.

INTRODUCTION

When Profs.Terzaghi and Peck[1] published the second edition of their famous text book of "The Soil Mechanics and Engineering Practice", they added new chapter of "Observational Method". The Observational Method refers not only to the method of measurments in geotechnical engineering but also the method of construction of geotechnical engineering based upon the observation of the performance and the measurment of the structural and ground behaviour.

As is well known, any geotechnical project encouters some gap between the real construction performance and the desk work designing. It is believed the best way in the geotechnical construction is to observe the performance, to compare it with presumed behaviour and to apply the construction procedure with necessary modification to obtain the safety, speedy and still to keep economical cost performance.

Recently the deep excavation works and the large scale underpinnig works as well as the tunnelling works in the urbanized area h [illegible] widely adopted Observational Procedure with the computerized system which have been so developed as to be called "Realtime Construction Control (RCC) Method".

The deep excavation which was planned to across the River Nakagawa for the construction of Fukuoka Subway Line was the first case history in Japan in two aspects.

One is to have modified the construction design to take off the final strut based upon the field measurments resulting in the smaller safety facter of the retaining wall at the final excavation stage. If the construction had been found unsafe, the govermental construction had been modified to raise the safety factor to keep the safety, on the contrary however, if it had been found "very safe" and even if the modification could produce large merit, there had been little case to lower the safety in the govermental project because the lack of positive confirmation of the safety in most cases. It was the first, as far as the author knows, to have modified the construction step to take off the strut at the final level of excavation based upon the field measurements. The modification had resulted to shorten the construction period about one month as well as construction cost of the owner.

The other is to have adopted the observational method against the boiling failure. The boiling failure had been considered as one of the unpredictable catastrophic phenomena in geotechnical engineering and had been considered as difficult to apply observational method. The only way to avoid the failure was to take enough factor of safety against boiling.

The laboratory experiments showed the existance of the precursor and the application of the observational method was considered feasible.
Measuring the pore pressures at the bottom end of the sheet piles in the excavation field was suggested as the practical way to lead safety construction against boiling failure.

The following sections present this second aspect of the Nakagawa Construction Section; the development and field application of the Realtime Construction Control against boiling failure in sandy ground with high water pressure.

DEEP EXCAVATION AT NAKAGAWA SITE OF FUKUOKA SUBWAY CONSTRUCTION

The construction section of Nakagawa was to across the main river of Nakagawa in Fukuoka city as shown in Fig.1 of the plan view and in Fig.2 of the vertical soil profile. The open cut method was selected as the most safe and

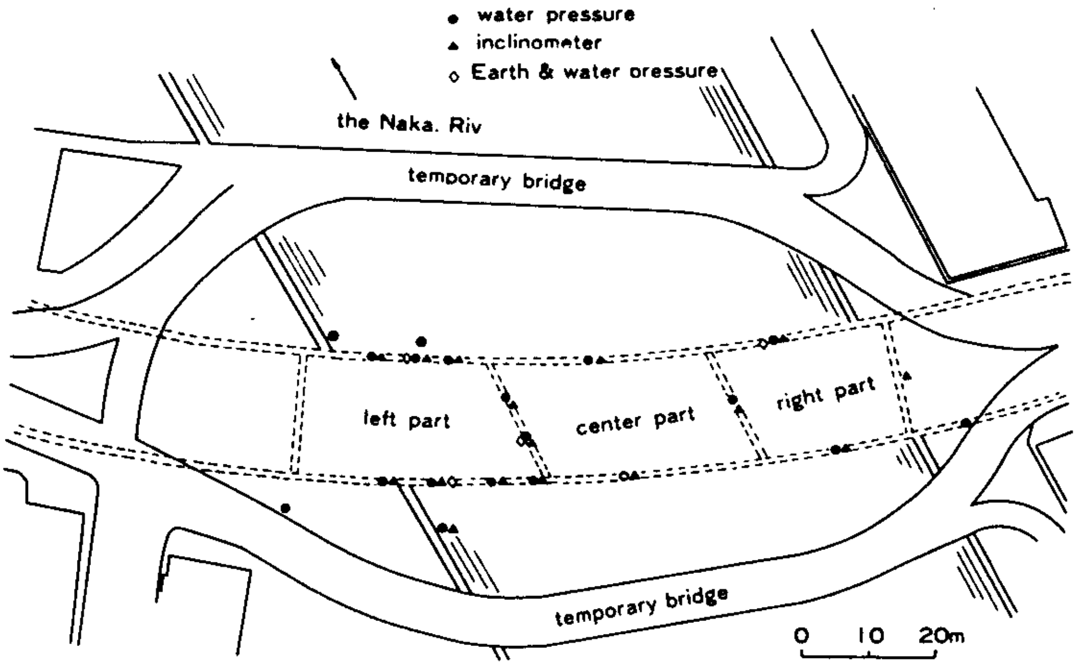


Fig.1 Plan view of excavation site Nakagawa construction section, Fukuoka

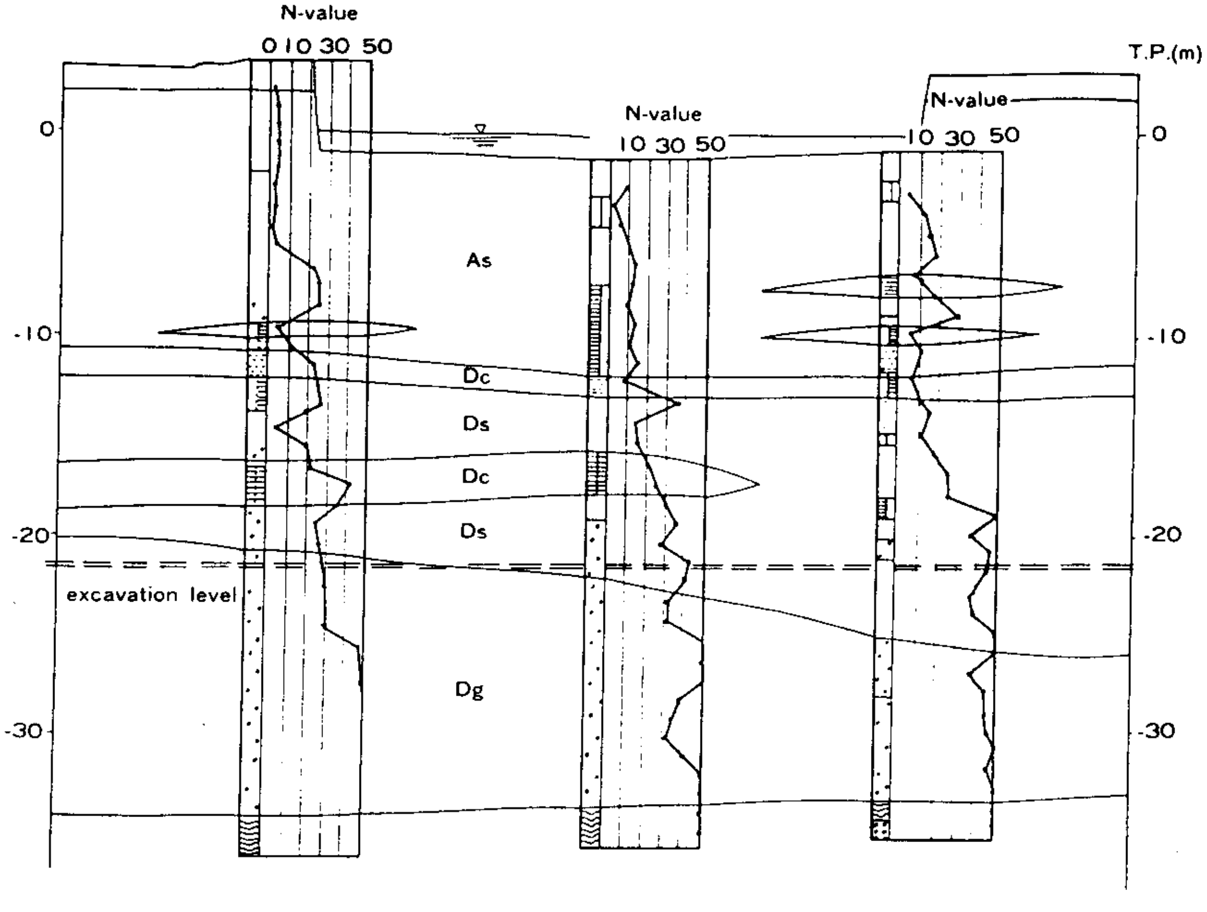


Fig.2 Geotechnical profile at Nakagawa site

economicalone based upon the comparison among the possible methods of construction.

The river Nakagawa is famous for its steep stream and the width was 74m at the construction site. The water level of the river is affected by the sea level and changes between TP±1.0 m. The water level by the past flood recorded to have risen as high as to have submerged the park near by the river whose level is TP+4.2m.

To minimize any possible flood disaster, the construction section was considered to be separated into several parts which were planned to construct one part for one year under dry season.

Geotechnical condition is shown in Fig.2. Below the river bed ground surface, the holocene alluvial sand(As) exists with thickness of about 10m followed by alternative formation of diluvial age of clay layer(Dc), sand layer(Ds) and gravel layer(Dg) with thickness of about 20-25m. Bed rock of shale exists at the level of 30-35m below the river bed surface.

Ground water was found to form different ground water flows according to the a few sand layers separated by impermeable clay layers. Two typical flows were easily identified by the difference of the natural water head. These are free surface water in the alluvial sand layer and confined water flow in the diluvial sand and gravel layer separated by the diluvial clay layer with water head of TP-0.5 and TP-2.5m each.

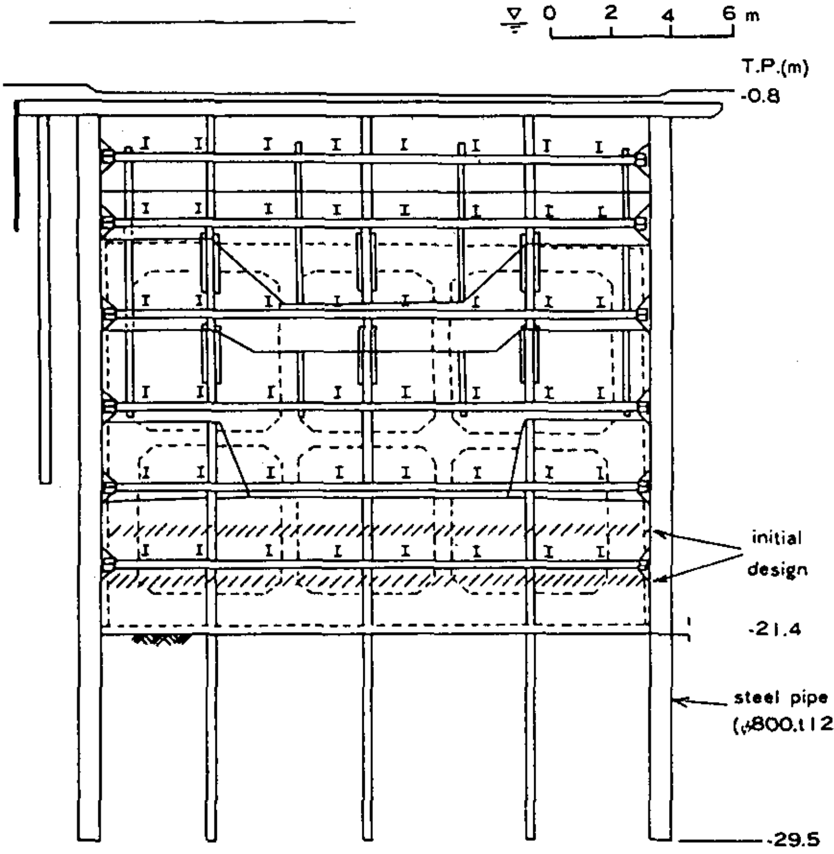


Fig.3
Vertical section of the temporary retaining structure with barcing
initial design;
number of bracing was seven designed to set at the shaded level.
final design;
six bracings based upon Observational Method.

Based upon the field pumping test, the permeability coefficient was estimated as $k = 3.5 \times 10^{-4} cm/sec$ assuming the effective thickness of the transmitting layer of 16m. The affecting radius estimated was 50m.

The construction methods were further considered to take care of the environmental effects such as the stopping underground flow and the settlement of the nearby structures anticipated by the subway construction.

Under the above designing conditions, the temporary retaining wall was designed as continuous pipe piles(diameter ;$\phi = 800mm$, thickness; $d = 12mm$, length; $l = 30-33m$) with supporting struts as shown in Fig.3. The number of the strut in the initial design was seven and decreased to six based upon the observational method. In Fig.3, the final retaining structure with six struts is shown. The shaded part in Fig.3 shows the position of lower two struts in the initial design. The level of the bottom of the sheet piles was designed to keep some clearance from the impervious shale rock to allow the under ground water flow. The construction was decided to be divided into three parts(left, right and central river) to construct the temporary retaing wall in each part during dry season, the top of the excavation area was covered by a steel roof to allow river water to flow without decreasing the stream section area of the river. Deep well pumping to decrease the water pressure in the sand layer below the excavation area and grouting to strenghen the ground as well as to decrease the permeability near the bottom of the piles to impede the incoming flow are also planned as auxiliary construction methods.

LABORATORY EXPERIMENTS ON BOILING FAILURE

The boiling failure of ground is defined as a sudden formation of the underground pipe through which flow of water takes place carrying the surrounding soils out of the ground resulting in ground failure. Safety against boiling has been proposed by Terzaghi[2] with the critical value of hydraulic gradient in the case of unform sand layer with free water surface.

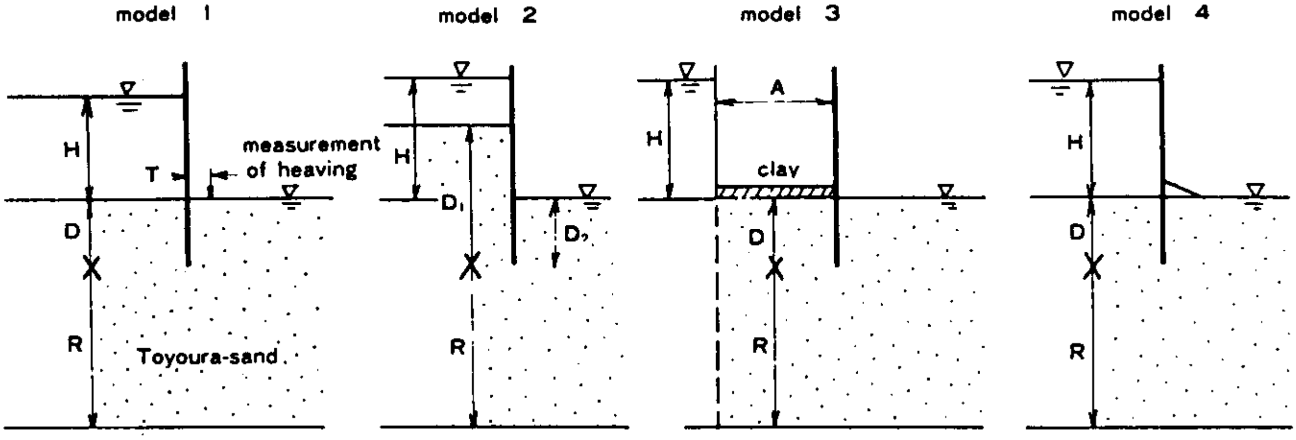
The boiling faifure at the Nakagawa site was anticipated by the incoming flow from a confined sand layer under the bottom of the sheet piles.

To clarify the mechanism of the boiling failure under the confined flow and to find any measurable values to predict the failure and to establish construction control method against the boiling, a series of laboratrory tests was carried out.

The four models of different configurations were tested with a sheet pile embedded 8cm below the sand layer which was formed using the standard Toyoura sand($G_s = 2.63$, $D_{50} = 0.12mm$, $U_c = 1.75$) within an experimental box of dimensions of 60cm, 80cm and 20cm (height, width and length).

These models were shown in Fig.4. The model 1 is the fundamental case of horizontal sand layer with a sheet pile under free surface water condition. The model 2 is the excavation case under free water condition. The model 3 is the confined flow of water with excavation. The model 4 is to assess and confirm the effect of the berm at the sheet pile against boiling.

Observation and measurument of the flow lines, water head at the selected points and heaving of the suraface of the down stream ground at sheet pile were made during the tests of the boiling which was caused by lowering the water level at the excavation side. One of the typical example of the laboratory results is shown in Photo 1 and Fig.5.



(D=D₂=8cm,D₁=18cm,R=30cm,A=40cm,T=3cm)

Fig.4 Four models of boiling experiment

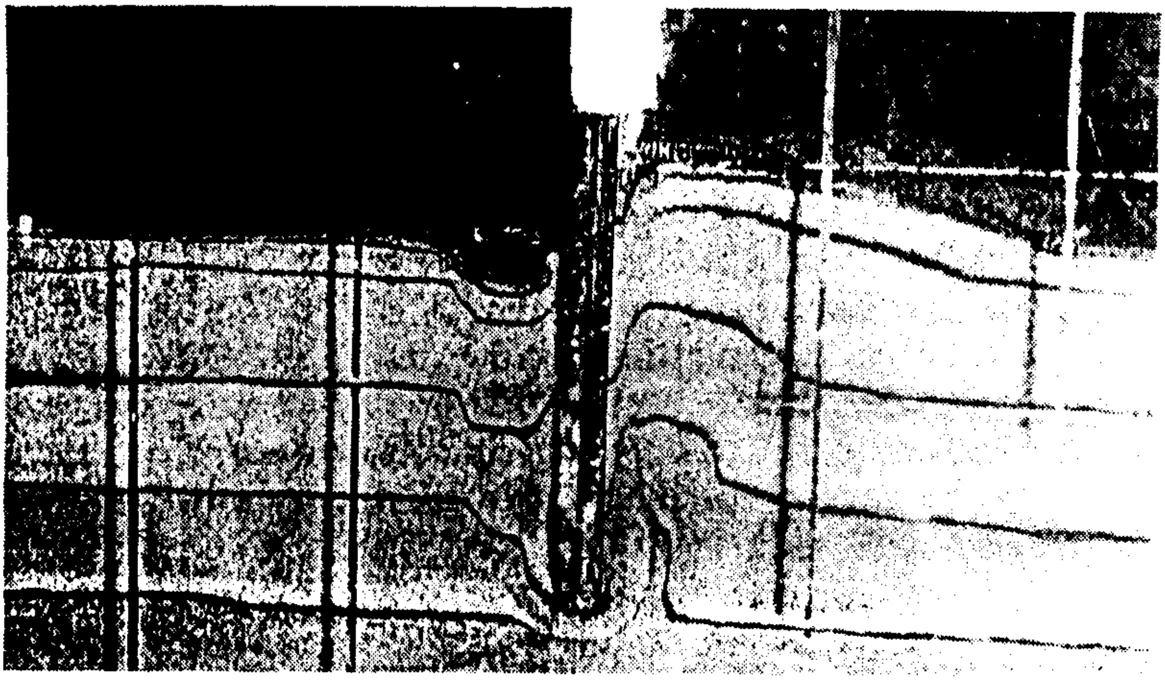


Photo 1 Ground movement before catastrophic boiling failure (test model 1)

Photo 1 shows the precursory ground movements around the sheet pile as well heaving of the ground surface in down stream side. Fig.5 shows the increase of the heavings ,the change of the seepage pressure(P_u) normalized by water head($\gamma_w H$) and the decrease of two Factors of Ssafety(F;Terzaghi/F1;Kochina) against the increase of the water head(H). The complete boiling occurred at water head was rized to about $27cm$ which was nearly equal to Kochina's critical head calculated as about $26cm$. The precursory movement was identified at $H=17cm$ which was found to give about $FS=1$ by Terzaghi.

Several conclusions obtained by the laboratory tests are as follows,

(1) The process of boiling failure may be separated into two stages; the first stage of the preliminary movement of soils around the sheet pile is observed before the second stage of the catastrophic failure.

(2) The critical head given by Terzaghi(1943)[2] corresponds to the first stage, while that given by Kochina(1962)[3] meets with the second stage. The main reason of the difference between these methods is that Terzaghi simplified problem to ignore the side friction force along the failure surface, while Kochina included the frictional force. Under the same condition, Terzaghi's formula gives smaller safety factor than Kochina's and is found to correspond to the initiation state of the first stage for not only for the condition of single sand layer with free water surface but also for those of interbedded sand layer with confined water flow as well as for the berm effect.

Safety factor given by Terzaghi is simple and still accurate enough to predict initial phase of the first stage of the boiling failure and is given by the ratio of the buoyant weight of the assumed boiling prism to the uplift seepage force by the pressure distribution along the bottom surface of the prism.

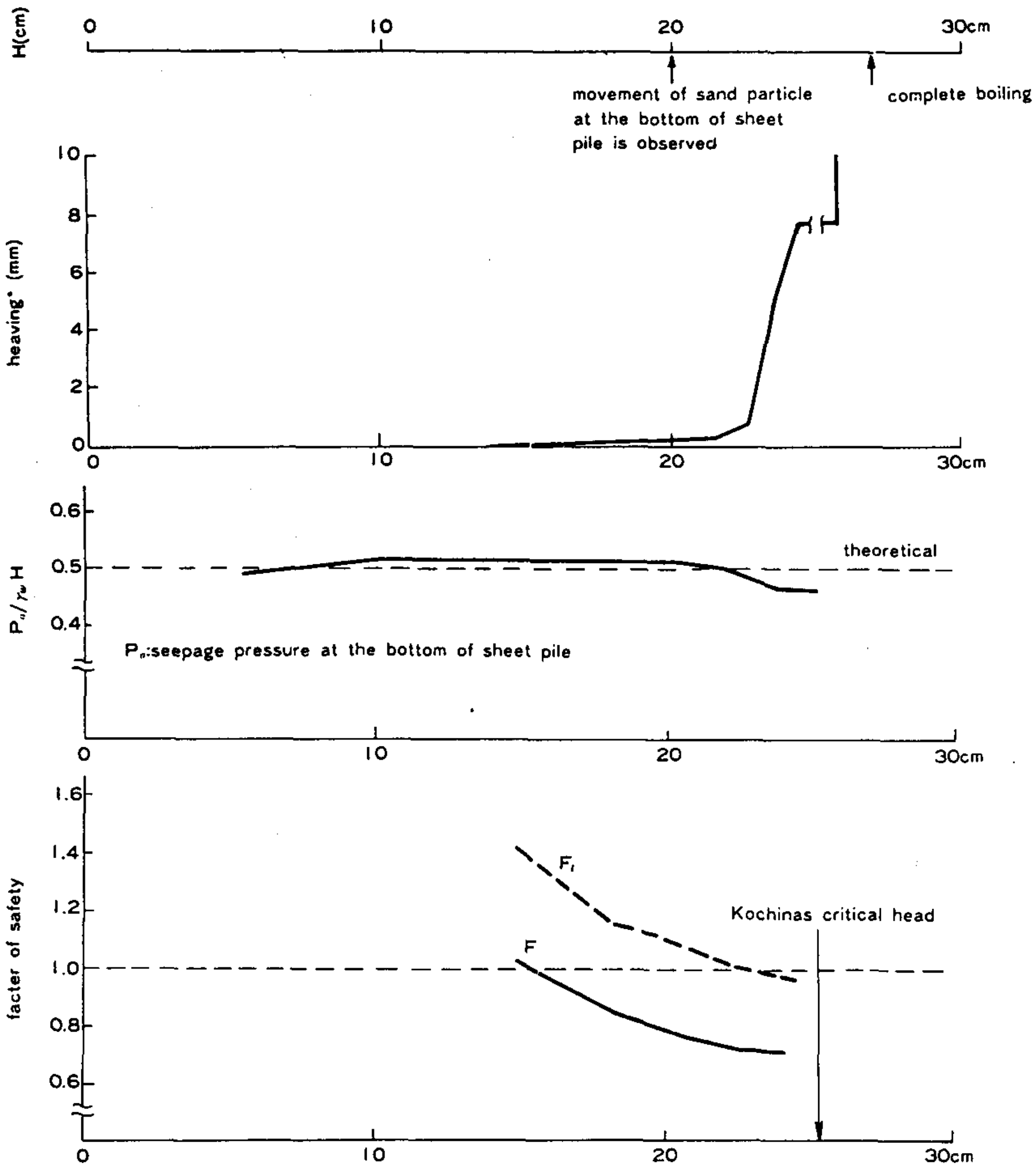
CONSTRUCTION CONTROL BASE UPON IN-SITU MEASUREMENT

Laboratory experiments have shown the initiation of the first stage of the boiling failure corresponds to the condition of the Terzaghi's method of boiling analysis. It was decided to identify the safety level based upon the pore water pressure distribution at the level of the bottom of sheet piles compared to the hydraulic state of Terzaghi's critical condition. It should be noted that the state of FS=1.0 given by Terzaghi is still safe until the side friction effects fully mobilized. However, the frictional force depends upon the relative density of the sand layer. Very loose sand layer should be careful because the additional resistace force available from friction resistance may be small against boiling failure.

Direct measurements of the water pressure distribution beneath the excavation site was difficult. Instead, it was proposed that the water pressures at the bottom tips of the sheet pipes were to be measured as a reference value based upon which the uplift water forces could be estimated.

The shape of the distribution of the water pressure along the bottom of the assumed prism (the dimension of the prism:height$=D$,width$=D/2$, where D is the length from the excavated level to the bottom of the sheet piles) as shown in Fig.6

It was found by computer simulation and further confirmed by laboratory test that the excess water pressure measured at the bottom of the sheet piles could be considered as a representative point and related to the upwards seepage force as



$$F = \frac{\gamma' D}{P_0}$$

$$F_x = \frac{\text{effective weight}}{\text{seepage force}} \quad \text{(width of D/2)}$$

★ heaving is measured at the point shown in Fig.4,model I

Fig.5 Laboratory Experiment Result (test model 1) Changes of heaving, pore pressure and FS with increase of water pressure height

$0.73 \times U_m$)(U_m; exesspore water pressure measured at the bottom of the sheet pile). Factor of safety against boiling is defined as

$$F.S. = D \times \frac{\gamma}{0.73 \times U_m} \qquad (1)$$

where γ ; buoyant unit weight

The above safety factor given by eq(1) is considered as a guide number to show the degree of the safety against boiling and may be used to control the construction procedure.

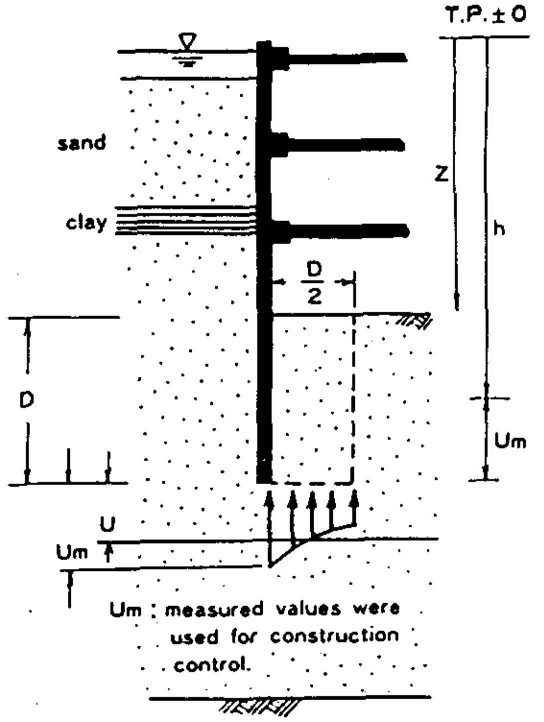


Fig.6 Excess pore water distribution related to boiling failure for the confined flow in sand layer in Nakagawa site

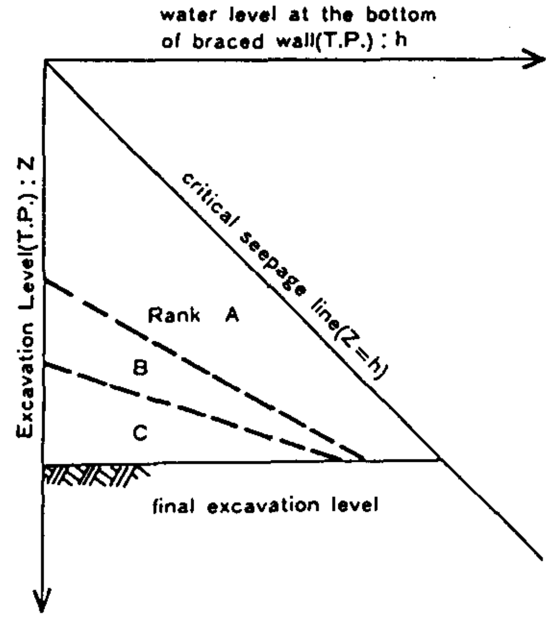


Fig.7 Water Head Path diagram for boiling failure control

Water pressures at the bottom of the piles were measured at representative points as shown in Fig.1. Automatic measuring personal computer system was installed and linked with an alarming system if the porewater pressure exceeded the threshold value which was determined accoding to the excavation level.

A diagram named "Water Head Path" was used, as shown in Fig.7, which shows changes of water head level measured at the bottom of the sheet pile vs. the level of the excavated ground. In this diagram, the relation of the excavation level and the water head at the bottom of the sheet piles becomes a strait line if the safety factor keeps the a constant value. The plotted in-situ values are evaluated to compare with preplotted equi-FS lines.

Another characteristic line is Critical Seepage Line(CS-Line) which corresponds to a state where the water head at the bottom of the sheet piles equals to the excavation level.

If the plotted point is above or on the CS-Line, the water head at the bottom of the sheet piles is less than or equal to the excavated ground surface and no seepage of the water from the underground is expected.

Rank	State	Factor of safety	Measured potential	Indication
A	Safety	$F_t > 1.5$	$h < h_A$ (=negative)	Scarcely, seepage
B	Caution	$1.5 \geq F_t > 1.1$	$h_A < h < h_C$	Movement of soil particles around the bottom of braced wall, piping.
C	Danger	$F_t \leq 1.1$	$h \geq h_C$	Heaving of the excavation bottom near braced wall, piping, boiling.

Rank	State	Measurement	Construction control
A	Safety	Water pressure at the bottom of braced wall.	Continuing of measurement.
B	Caution	Water pressure, movement of steel piles and adjacent ground below the excavation grade.	Dewatering.
C	Danger	Water pressure, movement, heaving of the excavation bottom.	Counter weight with soil or water, grout injection, another deep well.

Table 1 Evaluation of Rank of safety against boiling failure vs. factor of safety, related in-situ indication, measurements to be made and counter measures for construction control

On the other hand, the plotted point becomes under the CS-Line, the water head at the bottom of the sheet piles is higher than the ground surface and seepage from the excavated ground surface should be expected.

The diagram of Water Head Path can be used for easy and quick assesment of safety against boiling failure.

The evaluation of the safety factor and the related in-situ indication, the items of the measurements to be made as well as the general counter measures for construction controls are shown in Table 1.

RESULTS OF FIELD MEASUREMENT AND REALTIME CONSTRUCTION CONTROL

The construction started with the excavation work at the first part of the left river side in 1977. Steel piles with diameter of 800mm with thickness of 12mm were driven by a specially developed pile driver equipped with vibro-hammer and water jet as well as auger cutter, where the driving piles by diesel hammer was not allowed by the excessive noise which was restricted by environmental consideration.

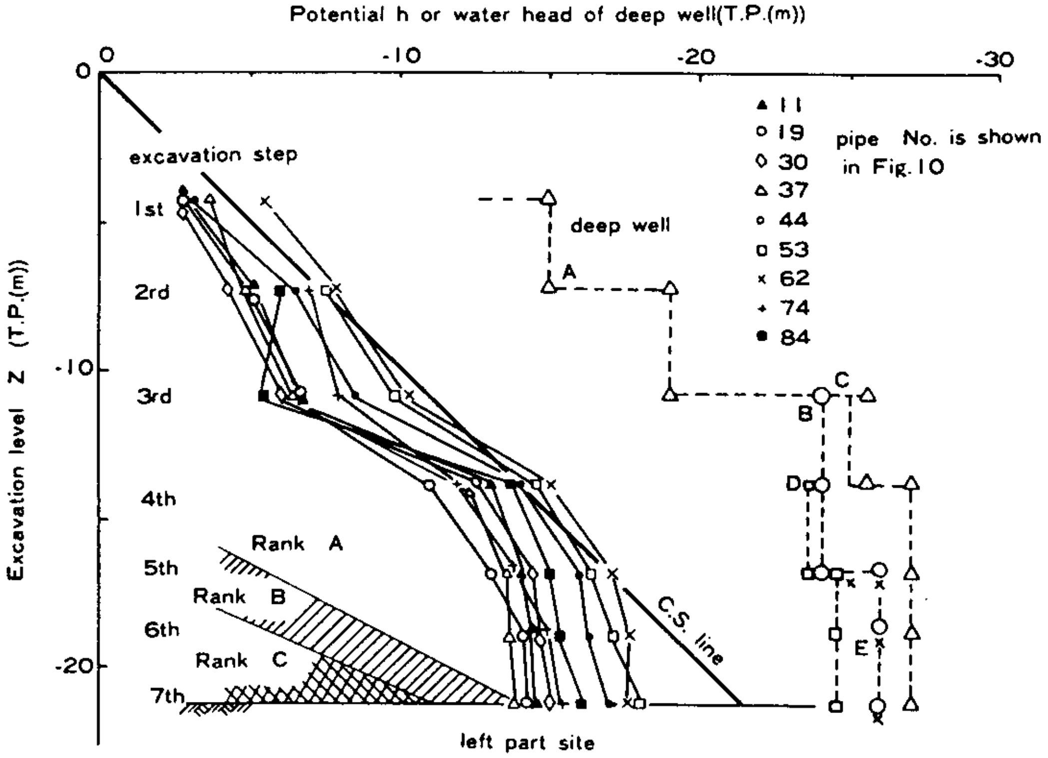


Fig.8 Measured Water Head Path at Nakagawa site

The piles at whose bottoms the water pressures were to be monitored or along which the inclinations were to be measured were preselected and the auxiliary pipes of small diameter to be used for measurements were installed with the main pipes.

Since the ground surrounding pipes was anticipated to be disturbed and loosened by auger and jet cutter treatment, the ground along the pipes was grouted to improve the soil strength as well as to increase impermeability.

Five deep wells with diameter of 1,200mm were installed with a double pipe wall structure to dewater the deeper water flow only. Each deep well was tested to obtain its dewatering characteristics which was to be used to control pore water pressure distribution at the excavation level.

During the process of the excavation, the measured water head at the bottom of the sheet pile was plotted in Fig.8 showing the water head path. It is seen that before the fourth step excavation, these path were traced along the CS-Line within the A-rank of "Safety Zone". During the fifth and sixth steps of the excavation, water head path were found to get lower than the CS-Line.

Based upon these data, several points were anticipated to shift down to the B-rank of "Caution Zone" at the final step of the excavation.

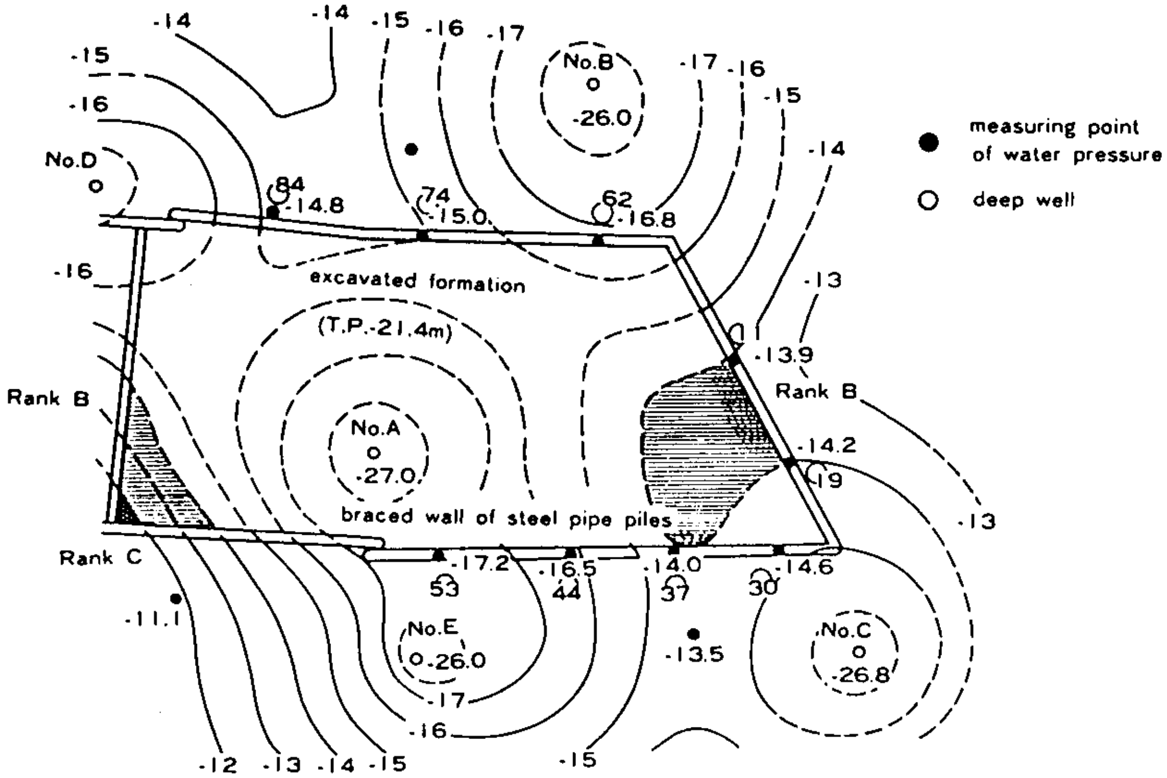


Fig.9 Equi-potential line at final stage of excavation by computer simulation base upon measured water head distribution

Since the measured values were limited to the observed points, the areal distribution of the pore water pressure in and around the excavated ground was necessary to eavaluate the safety against boiling.

The measured water heads at the bottom of the sheet piles as well as deep well points were used to analyse to estimate the distribution of the water head in and around the exavation area by computer simulation.

Fig.9 shows the analytical result of the simulation with the equi-waterhead lines of the areal distribution at the level of the bottom of the sheet piles. The shaded area indicates the safety rank B-rank or C-rank of "Caution Zone" or "Danger Zone".

Based upon the result of safety rank, the excavation procedures were modified as follows,

(1) Control of the excavation sequence; the edge portion, which was expected to give "berm effect" to increase the safety, was planned to be excavated later than other area of excavation to shorten the duration of the exposing the site with the lowest safety before making concrete slab followed by the excavation.

(2) Additional treatment of dewatering by deep well; the existing wells were flushed and the pumping level was lowered.

(3) Additinal and increasing field monitoring; heaves of the excavated surface as well as any horizontal movement of the ground at the bottom of the piles were monitored.

(4) Emergency Plan; additinal set of deep well pumps and electric generator was prepared in case of trouble and power failure.

Small pipings at a few points and seepage near the wall were found during the final excavation stage, however, neither heavings nor horizontal movements of the ground at bottom of the sheet piles were recognized.

The excavation work was safely completed without having catastrophic failure of boiling.

CONCLUSION

Conclusions obtained based upon the experiences of the construction control method against the boiling failure applied for the deep excavation of sandy ground at Fukuoka City were as follows,

(1) Laboratory experiment shows the precursory ground movements before the catastrophic boiling failure. The precursory movements are heaving of the ground surface and horizontal soil movement around the bottom of the sheet piles.

(2) The hydraulic states corresponds to the initiation of the precursory ground movement is practically the same as the design condition proposed by Terzaghi. On the other hand, those of the catastrophic failure is found to correspond to the failure state defined by Kochina. The above results may also be applied to the boiling failure of not only free surface water flow in sand ground of the half space but also confined flow within the horizontal sand layer.

(3) The safety against boiling may be avoided by keeping the water head at the bottom of the sheet piles less than some threshold value which correspond to the initiation of the precursory movement state.

(4) A simple chart called as "Water Head Path" is found useful to plot the measured water head to identify the level of the safety against boiling failure and to follow the change of the safety level with the process of the excavation.

(5) In Nakagawa construction site, the Realtime Construction Control System, which is personal computerized version of the Observational Method, was used to achieve safe, speedy and still economical construction.

Main item of the measurements for the boiling failure was the porewater pressures at the bottom level of the sheet piles and these data were automatically gathered by computer and used to see the level of the construction safety.

Even though some portion of the excavated area showed near the critical condition against boilig during the final stage, the safety was kept by pre-arranged careful modification of the construction procedure.

(6) Based upon the above experience, the observational method can be considered as a reliable method to predict and to avoid the boiling failure in sandy ground with high water pressure, provided that enough field measurements are made and modification procedures are carefully discussed beforehand and arranged if necessary.

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