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Investigation of groundwater status for deep underground construction

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ABSTRACT: In deep underground construction, if a confined aquifer exists under a clay layer, excavation of the clay layer may occur serious ground heaving due to the unbalanced groundwater pressure. The accurate measurement of the groundwater is very important for the ground safety analysis and the excavation design. The buoyancy of groundwater is often taken into account in designing underground works. More accurate estimation of the buoyant force can lead to a more reasonable design to improve the economical feasibility. The result of field pumping test contributes to solve geological problems. When the geological conditions are very complicated, such as in the vicinity of a fault, it is difficult to determine a geological section from the drilling logs only. Considering the aquifer as a key layer, we can get a clearer geological image by tracing the aquifer. From the viewpoint mentioned above, the authors examined three results of groundwater surveys and discuss the complex groundwater conditions and other related problems.

1 INTRODUCTION

Water level, volume, temperature and quality are fundamental elements for groundwater. The type and volume of groundwater are governed by composition of precipitation and surface water which recharge the groundwater, in which it interacts with surrounding strata and rocks. Groundwater level and temperature are affected not only by climate, underground conditions and subsurface geology of the region, but also by artificial elements in the environment.

In deep underground construction, serious ground heaving may result to boiling (quicksand, piping), if a confined aquifer exists below the bottom of the excavation. Groundwater also plays an important role in erosion on the back-side of an earth retaining structure caused by insufficient water cutoff measures, and drawdown and ground subsidence in the surrounding region due to drainage (pumping). Another important issue is groundwater pollution and changes in flow conditions caused by underground construction. It is important to understand the composition and continuity of aquifer and impermeable layer (aquiclude), groundwater pressure (groundwater level) and permeability.

It is necessary to conduct groundwater survey to obtain credible data, and to reflect them on the design and construction method of underground structures. There are many factors that need to be studied to obtain appropriate and accurate data on groundwater conditions, such as survey items, measuring methods and accuracy, and analysis methods. Some of them may be practical issues that could be solved by careful deliberation on measuring methods and results on a day to day basis.

From these view points, three examples of groundwater surveys that exemplify the importance of understanding the groundwater conditions are introduced and discussed.

2 CONFINED GROUNDWATER PRESSURE WITH RESPECT TO GROUND HEAVING AT THE BOTTOM OF EXCAVATION

If a sand layer exists below a clay layer at the bottom of excavation for an earth retaining structure, ground heaving may result due to confined groundwater pressure in the sand layer. Accurate measurement of the confined groundwater pressure is essential for ground safety analysis at the bottom of the excavation for the earth retaining structure. Groundwater pressure is often determined through an observation of recovery process of the groundwater level in boreholes used for permeability test.

In this study, an investigation was conducted concerning boiling phenomenon that results in the delay of the recovery of groundwater level. Boiling in the borehole occurred when the groundwater level was lowered in the permeability test.

2.1 *Measurement of confined groundwater pressure*

Figure 1 shows a geological section and confined groundwater levels in the boreholes. The strata consist of the surface soil(B), alluvium layers (As, Ac), Pleistocene clay layer (Dc: 35 to 50 m below the ground level(G.L.-35 to 50 m)), and Pleistocene sand layer (Ds: G.L.-50 to 70 m).

Table 1 shows test conditions such as excavation methods and initial groundwater levels (on pumping up the groundwater before testing) for each point of measurement. Prior to the measurement, the groundwater level for the point No. 2 was lowered to approximately G.L.-20 m. Water was injected into the borehole to raise the groundwater level indicated in the Table, and then the in-situ permeability test (pumping up the groundwater and stopping it to measure the recovery of the groundwater level) was performed. Figure 2 shows recovery curves for each point of groundwater level measurement, and the recovery processes are described below.

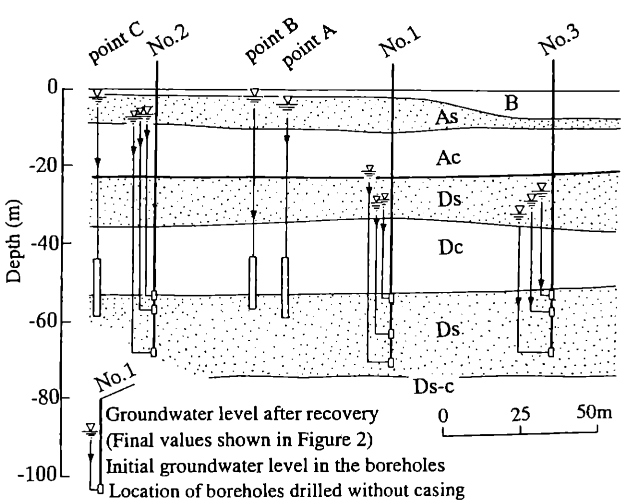

Figure 1. Geological section and location of measuring points for confined groundwater, initial and recovered groundwater level.

At the point No. 1, the groundwater level did not change in the first 30 minutes. Then it started recovering gradually, which continued even after 24 hours. At the point No. 2, the recovery progressed gradually through the whole testing period. At the point No. 3, the recovery curve is steep compared to other points up to 24 hours. Even though all the measurements were taken in the same confined aquifer, the maximum difference in recovered groundwater level was as large as 20 m.

At the point A, the groundwater level in the borehole recovered instantly to G.L.-3.5 m from the initial value of G.L.-13 m. At the point B, recovery in the groundwater level was only 1 m in 24 hours, and 3,000 hours were needed for the full recovery. At the point C, 30 hours were needed for the full recovery. The results of the points A, B, and C significantly differed from each other.

Table 1. Test conditions for the measurement of confined groundwater level.

Measuring points		Testing depth (G.L.-m)	Initial water level before testing (G.L.- m)	Drilling conditions
No. 1	Top	52.5～53.0	37.0	Boring used drilling mud
	Middle	64.0～64.5	34.0	
	Bottom	71.0～71.5	26.0	
No. 2	Top	54.0～54.5	13.0	Boring used drilling mud
	Middle	56.0～56.5	14.0	
	Bottom	68.0～68.5	15.0	
No. 3	Top	53.0～53.5	51.0	Boring used drilling mud
	Middle	57.0～57.5	55.0	
	Bottom	68.0～68.5	55.0	
A		43.0～58.0	13.0	Boring used clear water
B		43.0～53.0	32.0	
C		43.0～58.0	20.0	

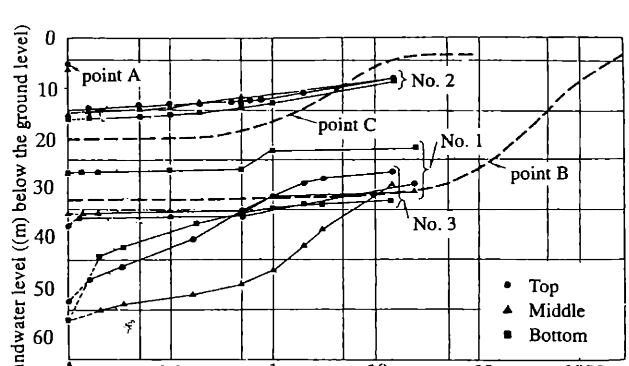

Figure 2. Recovery of groundwater level in the boreholes.

At the point No. 2, the initial groundwater level in the borehole was approximately G.L.-13 m, which is almost the same with that at the point A. Because the groundwater level had been lowered to G.L.-20 m prior to the testing, it could be suspected that boiling had occurred in the borehole. Therefore, the delay in the groundwater level recovery was also induced similarly to the point C. If the initial groundwater level had not been lowered, the groundwater level might instantly recover in the borehole.

2.2 *Boiling phenomenon in the boreholes*

It is possible that actual groundwater levels in the boreholes are affected by (i) disturbance on the inner surface of boreholes due to boiling phenomenon induced by lowering of the groundwater level; and (ii) bentonite adhered on the inner surface of boreholes because of the lack of washing by clear water, as have been pointed out with respect to field tests on permeability (Committee on In-situ Permeability Test of JGS, 1985). Of the two, boiling phenomenon mentioned in the item (i) was studied in detail for this study, because the recovery of groundwater levels in boreholes are affected greatly by initial groundwater level, as discussed in the previous section.

Three consecutive tests were performed with lowered groundwater levels using a borehole in an aquifer sand layer. Figure 3 shows recovery curves of groundwater levels in the borehole in the lowered groundwater level tests.

The recovered groundwater level in ten minutes for each test indicated gradual decrease, as shown by 96 cm of recovery in the first test, 41 cm in the second, and 36 cm in the third. For the third test in which the groundwater level had been lowered initially to G.L.-14 m, the recovery was only up to G.L.-9.7 m in 24 hours. This level is significantly low compared to the equilibrium groundwater level (at G.L.-3.5 m). After completion of each test, rods were inserted to investigate the conditions inside the borehole.

Raising of soil particles in the borehole was observed in all cases, which indicates the occurrence of boiling. The rise observed were 2 m for the first test, 5 m in the second (increment of 3 m), and 7 m in the third (increment of 2 m). It could be conjectured that similar boiling phenomenon had occurred during the measurement of confined groundwater pressure described in the previous section. Since the boiling causes usually loosing of the gravel, the permeability would be increased. However the boiling disturbed the soil structure to narrow pores between them, on the inner surface of boreholes. The permeability of soils, therefore, was decreased, and consequently the groundwater level recovery was delayed.

The test results indicated that boiling may occur during any in-situ permeability tests and measurement of confined groundwater pressure, which would greatly affect the recovering rate of groundwater levels. Accuracy of groundwater level measurement would be impaired, due to incomplete recovery of water level and other reasons. Thus, it would be necessary to perform, prior to these tests, long-term measurement to confirm the time needed for the groundwater level to reach the equilibrium level, and the range of lowering of the groundwater level which would not induce boiling.

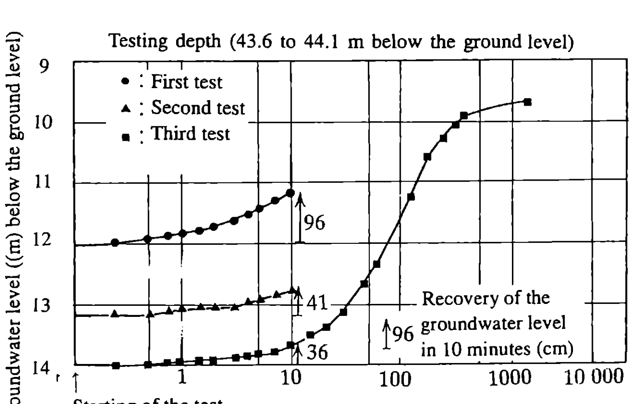

Figure 3. Recovery of groundwater level in the borehole.

3 LONG-TERM RECOVERY OF GROUND-WATER PRESSURE AT THE BOTTOM OF EXCAVATION AFTER LOWERING OF GROUND-WATER LEVEL

For designing a deep underground structure, it is essential to carry out long-term design considering buoyant force, and then to finalize the design on the safer side of all the allowable stress values obtained. For bearing piles and supporting structures, more rational and economic design would be obtained including the buoyant force acting onto the bottom slabs of underground structure. Buoyant force is normally generated by confined groundwater pressure underneath the bottom slab. It is important to estimate the buoyant force for the design of structures when the groundwater level had been lowered during excavation. In this study, a long-term measurement of recovering groundwater pressure at the bottom of a deep underground structure was made, after temporarily lowering the groundwater level during the excavation.

3.1 *Conditions of the site and outline of underground structure*

Figure 4 shows conditions of the ground, together with the outline of underground structure. Geological formation consists of alluvial clay (Ac: G.L.-10.5 to 23 m), Pleistocene sand (Ds_1: G.L.-23 to 30 m), Pleistocene silty sand (Ds_2: G.L.-30 to 34.5 m), Pleistocene clay (Dc: G.L.-34.5 to 54.5 m), and Pleistocene sand (Ds_3) underneath. The earth retaining structure has an inner diameter of 23.6 m and excavation depth of 27.35 m, the thickness of the retaining wall being 0.6 m, which is a diaphragm wall 35.6 m long installed into the Dc layer.

Free groundwater level is near the surface and confined groundwater levels in the Ds_2 layer underneath the clay layer and the Ds_3 layer are all equal to G.L.-3.5 m.

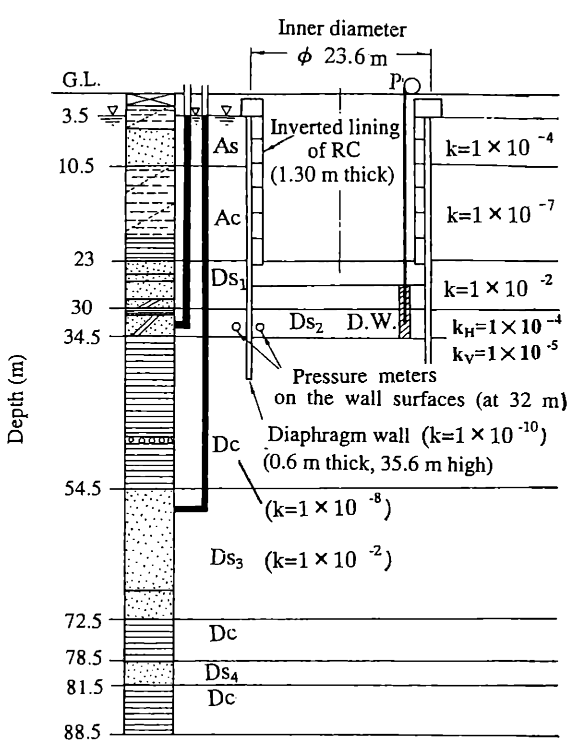

Figure 4. Geological conditions and outline of underground structure.

Upon excavation, a deep well was drilled down to G.L.-35 m within the enclosure of the earth retaining structure, in order to lower the groundwater pressure to G.L.-32 m. The purpose was to lower the confined groundwater pressure within the Ds_1 layer at a depth below G.L.-23 m and the Ds_2 layer, as well as to improve excavation efficiency. The groundwater pressure was measured by pore water pressure meters on wall surfaces, placed on the inner and outer surfaces of the diaphragm wall, at G.L.-32 m .

3.2 *Results of measurement and discussion*

Figure 5 shows construction process of the earth retaining structure and measurement results of groundwater pressure compared with analysis results. The groundwater pressure on the outer surface of the excavated portion did not change much from approximately 280 kPa either before or after excavation. On the other hand, groundwater pressure at the inner surface of the excavated portion dropped to that at the point A because of the pumping up be in the deep well, and measured 76 kPa at the end of excavation. The deep well was shut down after completion of the works for the bottom slab, and the pressure changed to 98 kPa at the point C (2 months after the shut down of the deep well), to 138 kPa at the point D (18 months), and then to 141 kPa at the point E (62 months). Since the groundwater pressure at the point E outside of the diaphragm wall measured 280 kPa, the groundwater pressure inside of the wall recovered approximately 50%.

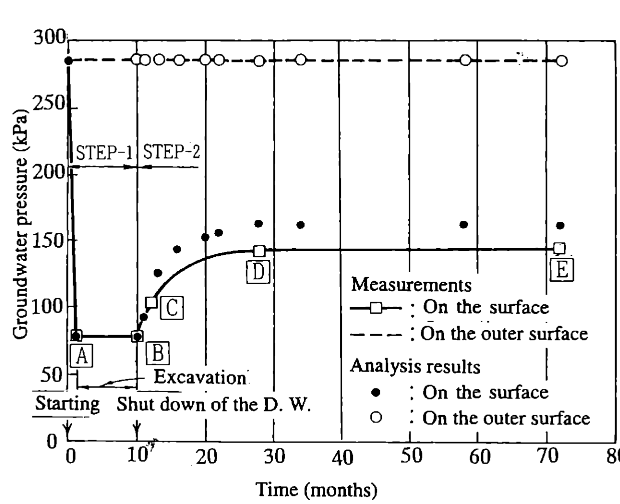

Figure 5. Construction process and measured groundwater pressure compared with analytical results.

If the groundwater pressure continues to recover in this manner, it would take approximately 130 years to return to the original state.

The groundwater pressure was analyzed using the saturated and unsaturated seepage flow analysis (an axially symmetrical seepage flow analysis; Nishigaki, 1991).

In the analysis, the processes from before the excavation to the shut down of the deep well was denoted as STEP-1, and the recovering period after shut down of the deep well following the completion of the bottom slab as STEP-2. Figure 6 shows the geological conditions and groundwater pressure in excavated site. By setting the vertical component of permeability coefficient for the Ds_2 layer at k_V=1 x 10^{-5} cm/s with respect to the horizontal component k_H=1 x 10^{-4} cm/s, it was possible to present the time-based change of the analysis results as having similar trend as the measurement results.

It could be concluded that for a deep underground retaining wall reaching an impermeable layer, it takes extremely long time for recovery of groundwater pressure which had been lowered initially for excavation underneath the bottom slab. Design of deep underground structures should take this factor into consideration.

4 GEOLOGICAL MAPPING BASED ON HYDRAULIC CONTINUITY OF GROUNDWATER

In a transient zone between a plain and mountains, we often encountered faults and geological conditions are usually complex. Hence, it is difficult to judge the continuity of strata only from drilling logs in these regions.

In this study, confined aquifer was used as a key layer to clarify hydraulic continuity of a confined sand aquifer through field pumping test, based on which the geological section has been successfully drawn.

4.1 *Results of the pumping test*

Figure 7 shows geological section for a region where the pumping test was conducted. The location of screens of pumping wells and piezometer in observation wells, and initial groundwater pressure were indicated in this figure. Figure 8 shows the fluctuations of groundwater levels measured at observation wells during pumping in the pumping well P-1.

Table 2 shows the continuity of groundwater observed by the pumping test in P-1 and P-2. The mark ○ indicates that observation points have shown drawdown of groundwater level in accordance with pumping, and the mark × indicates any changes in the groundwater level. It can be seen that observation points 1, 4, 7 and 9, and observation points 3, 6 and 8 form separate groups, respectively. On the other hand, observation points 2 and 4, which are located in adjacent boreholes at similar depth, show no sign of interconnection of groundwater flow between them.

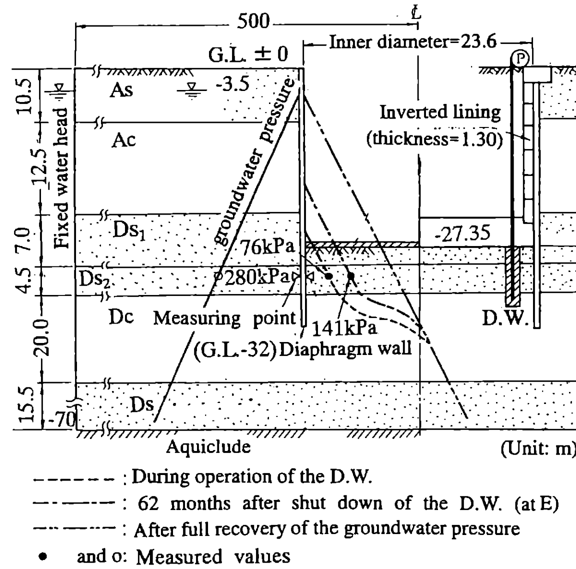

Figure 6. Geological conditions and groundwater pressure in excavated site.

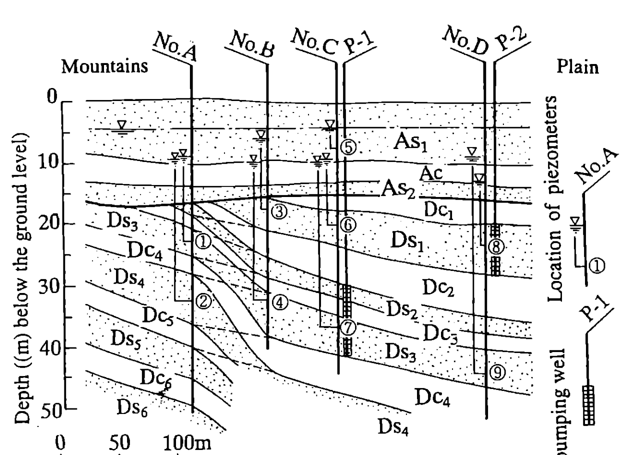

Figure 7. Geological section and groundwater levels in pumping and observation wells.

4.2 *Clarification of the geological conditions*

The dotted lines on Figure 7 indicate a geological section initially drawn based on the results of geological survey using cores obtained drilling logs. At this stage, no geological information such as strata condition was available. Although it was assumed at a start that each stratum stretch out horizontally, the following has been clarified by the pumping test: (i) the Ds_1 layer appears to the right of the borehole B due to a flexure, and this layer is not a part of the strata to the left (the mountain side) of the borehole B, being detached by the disconformity at the base of an alluvial layer; (ii) the Ds_2 layer underneath stretches out horizontally to the right (the plain side), but forms a flexure (such as a fault) in the vicinity of borehole B, and connects with a sand layer at a point directly underneath the alluvial layer near the borehole A; and (iii) the Ds_3 layer similarly connects with another sand layer in the upper part of the borehole A due to a flexure, starting in a vicinity of the borehole B toward the mountain side.

Solid lines in Figure 7 show a precise geological section based on the continuity of confined sand aquifer. The section clarifies complicated geological formation in a transient zone between a plain and mountains, especially near a flexure.

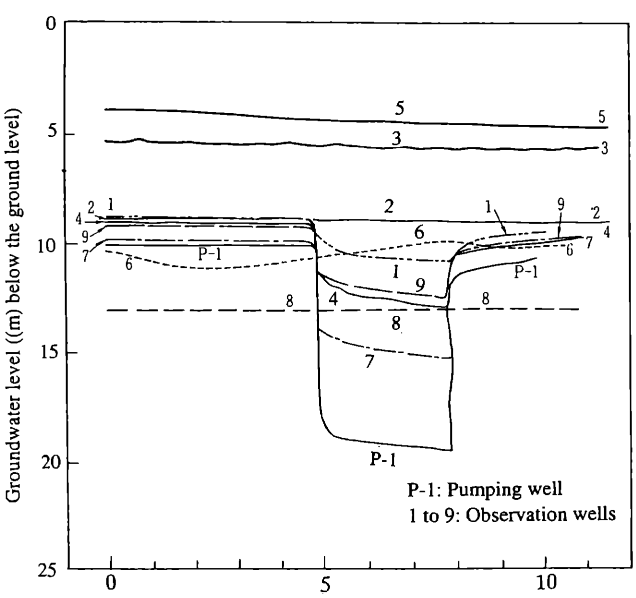

Figure 8. Fluctuations of groundwater level in pumping and observation wells during the pumping test (pumping in P-1).

Table 2. Continuity of the groundwater clarified by the pumping test.

Observation well	A		B		C			D	
Piezometers No.	1	2	3	4	5	6	7	8	9
Pumping well P-1	○	×	×	○	×	×	○	×	○
Pumping well P-2	–*	–*	○	×	×	○	×	○	×

* - indicates measurement data being not available

5 CONCLUSION

In order to minimize effect of underground construction on the surrounding ground, it is necessary to gather information on geological characteristics and the ground as much as possible. Consideration should be given especially to geological formation which is classified according to layer conditions, depth of buried landforms, etc. This is because strata of ages later than alluvial layers are greatly affected by ground subsidence and deformation caused by changes of the groundwater levels. In addition, it is important to grasp not only the layer conditions, but also the points of abrupt changes in strata distribution.

We emphasized the importance of surveys on groundwater at each step of deep underground construction comprising geological survey, design, and construction. Since there are numerous factors that differs for each case of deep underground construction, it is desirable to consider appropriate survey methods for each of them.

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