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Movements of adjacent ground during deep excavations – A survey on Japanese literature

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1. Introduction

In this paper, we share some examples of studies conducted on the problems relating to movements of the adjacent ground during excavation and installation of retaining systems.

2. Types of movements

When monitoring the movements of adjacent ground during excavations employing braced walls or cantilever walls, response of the ground appears to be dependent on each work stage, such as ① installation of walls, ② soil improvement or auxiliary measures such as dewatering, ③ installation of foundation piles that are placed precedently, ④ groundwater lowering during excavation, ⑤ back filling, ⑥ removal of struts or walls, etc. Various changes in the soil are seen, such as immediate elastic deformation, consolidation deformation, secondary consolidation deformation, and plastic flow.

Peck (1969) described that the settlement depends upon ① soil properties, ② size of excavation, ③ method of excavation and braced walls and ④ workmanship contractors.

In order to develop design standards, most studies on excavations with retaining structures have concentrated on the structure itself, for example, on the earth pressures and water pressures acting on walls, the loads of struts, and movements of the walls. However, due to the increasing number of construction being made near existing structures and buried facilities, and at newly placed landfill areas, and because new types of analyses such as the finite element method (FEM), are becoming more popular among geotechnical engineers, studies on other subjects, such as settlement of the ground surface behind retaining walls, lateral displacements, and heaving at the bottoms of excavations are increased.

In this paper, we share some examples of studies conducted on the problems relating to movements of the adjacent ground during excavation and installation of retaining systems.

3. Categories of studies on movements in adjacent ground

Studies on the subject can be broken down into the following categories:

① Ground surface settlement during excavation.
② Lateral movements of ground during excavation.
③ Heaving at the bottom of excavation during excavation
④ Ground surface settlement due to removal of walls or struts.

Studies of category ① are the most popular. Most of ② are analyzed by the FEM. Studies of category ③ are usually conducted or deep excavations. A few study projects of category ④, which examined ground settlement due to withdrawing steel sheet piles, have been conducted so far, however, this is one of the important subjects among the problems related to movements of adjacent ground.

4. Studies on ground surface settlements

The purpose of these studies is mainly to develop methods of predicting settlement. The studies can be divided into the following three categories.

① Prediction empirically based on available measured data.
② Prediction assuming sliding surface.
③ Prediction by the FEM.

Representative examples are shown in Table 1.

5. Studies on lateral movements in ground

In these studies the FEM is used in most cases. Themes included are the plastic zone expanded by the excavation, effective stress analysis together with consolidation, etc.

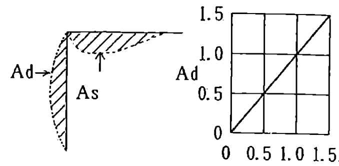
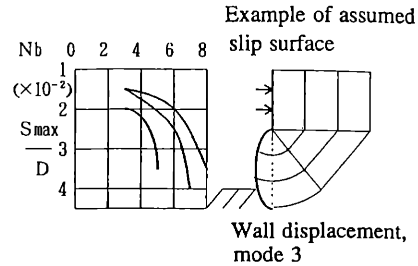
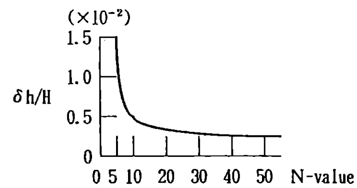
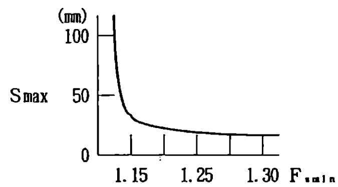
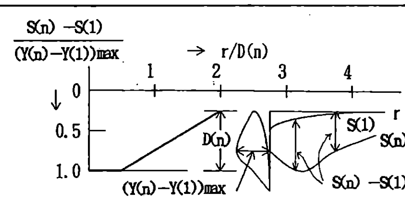
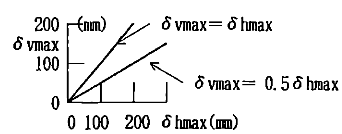
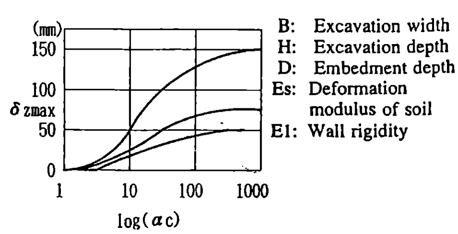
Analyses of displacement in ground during excavation using the FEM have been carried out by different methods for modeling and setting conditions. These are the soil properties, setting of boundary conditions or input conditions, choice of element type, finite element equations, modeling of structural members, handling of the contact area of wall and ground, handling of ground water or pore water, etc. Thus, it is important to confirm the possibilities of reproducing these conditions by verifying the design parameters and by comparing analyzed data to actual performance.

6. Studies on Heaving at the Bottom of Excavations

Examples of these studies are an investigation report of the amount of heaving measured at an excavated diluvial deposit, a method of predicting the amount of heaving when soft clay deposit is excavated, etc. Possible causes of the heaving effect are ① elastic rebound due to release of overburden pressure, ② swelling due to recovery of hydro-static pore water pressure, ③ heaving due to lowered undrained shear strength caused by elastic rebound and swelling. Most studies are concentrated on subject ①.

Also, some studies using the composite solution of soil and water by adopting the FEM to analyze the effects on how seepage water influences heaving at the bottom of excavations due to boiling or heaving phenomena.

Table 1 Methods for Predicting Settlement of Adjacent Ground during Braced Excavations

Proposers	Outline of Prediction Method	Ground	Conceptual Diagram of the Method
Naito, et al. (1958) (Empirical)	Solve for volume Ad (amount of deformed soil) and As (amount of settlement of ground surface), due to deformation of walls, which are the same. In recent years, amount of deformation of walls is computed by the "elasto-plastic method," and amount of settlement is predicted from the relationship shown in the conceptual diagram.	Plastic cohesive soil	
Maruoka, Ikuta, Aoki, Sato, et al. (1978) (1991) (Theoretical)	Determination of the relationship between the maximum amount of settlement Smax (calculated as the following condition: a sliding surface is assumed according to the stress characteristic curve defined by Bransby (1975), and the wall displaces along with the sliding surface and appears on the ground surface.), and the heaving stability number Nb, proposed by Peck. After that, sliding surfaces are assumed by various methods, and the sliding surfaces are patterned for computing settlement of surface ground. The settlements are compared with measured data. D is the depth of excavation.	Soft cohesive soil	
Japanese National Railways (1979) (Empirical)	Relationship between N-value measured near the bottom of excavation and the maximum horizontal displacement of wall, δh divided by the final excavation depth H are examined, and if N-value becomes smaller than 5, the maximum horizontal displacement of wall becomes larger. This relationship is very similar to the relationship between Smax and Fsmin that was defined by Matsuo and Kawamura (as shown below) and the relationship defined by Mana and Clought. (1981)	Cohesive to sandy soils	
Matsuo and Kawamura (1981) (Empirical)	Showing that when the minimum safety factor Fsmin in a circular sliding surface becomes less than 1.15, the maximum amount of settlement, Smax, suddenly increases (based on construction in soft cohesive soil). The relational expression for Smax and Fsmin is: $S_{max} = 1/(0.654\ F_{smin} - 0.719)$ (where $F_{smin} \geq 1.10$)	Soft or medium cohesive soil	
Maruoka and Ikuta (1986) (Empirical)	Data collected from soft cohesive alluvial soil or sandy alluvial soil with N-value less than 10 are summarized for relationship between displacement of wall and adjacent ground.	Soft cohesive and alluvial sandy soil with SPT N less than 10	
Sugimoto and Sasaki (1987) (Empirical)	The maximum amount of settlement of surface ground, δvmax, will be 0.5 to 1.0 times the maximum horizontal displacement of wall, δhmax, and is confirmed based on measured data, and proved by the FEM analyzing method. These results are similar to results obtained by Mana and Clough (1981).	Cohesive to sandy soils	
Sugimoto (1986) (Empirical)	Factors affecting the maximum amount of ground surface settlement, dzmax are extracted by using the many measured data quantification theory, and these factors are combined to find the excavation coefficient αc. Then the relationship between αc and the maximum amount of ground settlement is determined. This relationship is verified by the FE analyzing method. Excavation coefficient $\alpha c = BH/\beta_D D$ Embedment coefficient $\beta_D = (Es/E1)^{1/4}$	Cohesive to sandy soils	

Note: The contents in parenthesis under the proposers column are the category of the prediction method, either theoretical or empirical.

7. Studies on amount of ground surface settlement upon removal of walls

A few studies have been conducted on this subject. When soldier piles or steel sheet piles are withdrawn, soil adhering to the piles is removed with the piles and voids in the ground will be created. These void cause the adjacent ground to settle. The studies were made on prediction methods for the amount of settlement.

8. Primary factors contributing for movements

Primary factors contributing for movements of ground adjacent to braced excavations were statistically analyzed with measured data and the results were extracted as follows: ① type of the ground, ② depth and width of excavation, ③ stability of bottom of excavation, ④ rigidity of walls. These factors are basically the same as the primary factors affecting stability of retaining structures. Thus, to consider these factors to be able to take corrective action for movements of the ground is also a means to secure the stability of the whole retaining structures.

As mentioned in paragraph 2, it is possible to observe the movement of ground adjacent to excavations together with retaining structures at each work stage. Work stages before and after excavation, too, give us various study subjects, such as stability of slurry walls and deformation of adjacent ground during construction of diaphragm walls, movements due to soil improvement, movements due to removal of struts and walls, movements due to backfill, etc. Studies on these subjects have been gradually increasing recent years.

Today, when large scale braced excavation work is taking place, monitoring of retaining systems, as well as monitoring the movements of adjacent ground, is becoming more emphasized.

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