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Measurement of the earth pressure acting on a shield machine and its application to automatic advancing control of the shield

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The earth pressure acting on a shield machine was measured during construction to investigate the relationship between the earth pressure and the movement of the shield machine. From the results of the measurements, a coefficient of the subgrade reaction was defined as an index of the ground properties that are closely related to the shield movement. The idea of an automatic advancing control method for shield machine is discussed by studying the relationship between the movement of a shield machine and the distribution of the earth pressure acting on the shield machine.

1. INTRODUCTION

A shield machine is a piece of construction machinery that digs a tunnel by excavating soil under the ground like a mole. Figure 1 (a) shows an outline of the tunneling method with a shield machine. A shield machine usually has a rotating cutter face in the front, onto which a large number of cutter bits are attached. The cutter face is driven into the tunnel heading to excavate the soil. The shield machine also has a large number of hydraulic thrust jacks in the rear. It advances by pressing the jacks against the lining segments that have been assembled during the previous step of construction.

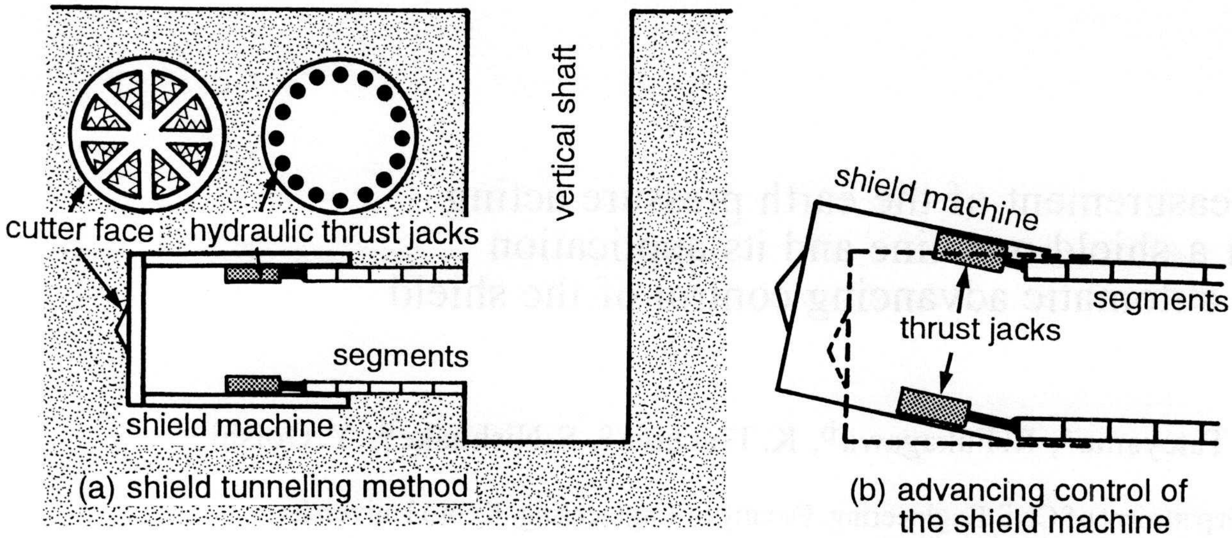


Figure 1. Tunneling method with a shield machine

The advancing direction of the shield machine can be determined by controlling the extension of each thrust jack to dig the tunnel along the specified route, as shown in Figure 1 (b). Control of the jacks is usually done by removing the deflection of the current location and direction of the shield machine from the designed ones. Due to the complicated and changeable ground conditions, however, we sometimes come across cases in which the skillful technique of operators is required to control the jacks precisely. The purpose of this research is to develop a new method of controlling the thrust jacks more precisely and more smoothly by monitoring the ground conditions and by determining the optimum control conditions for the ground conditions. The soil estimation and optimum control system which are developed will contribute to the automatic control of shield advancement.

2. EARTH PRESSURE ACTING ON AN ADVANCING SHIELD MACHINE

When a shield machine advances along a straight route under the ground, it is thought to be acted upon by earth pressure at rest from the surrounding ground, as shown in Figure 2 (a). However, when a shield machine advances along a curved route, some parts of the shield machine are thought to be pressing heavily on the ground and other parts are detached from the ground.

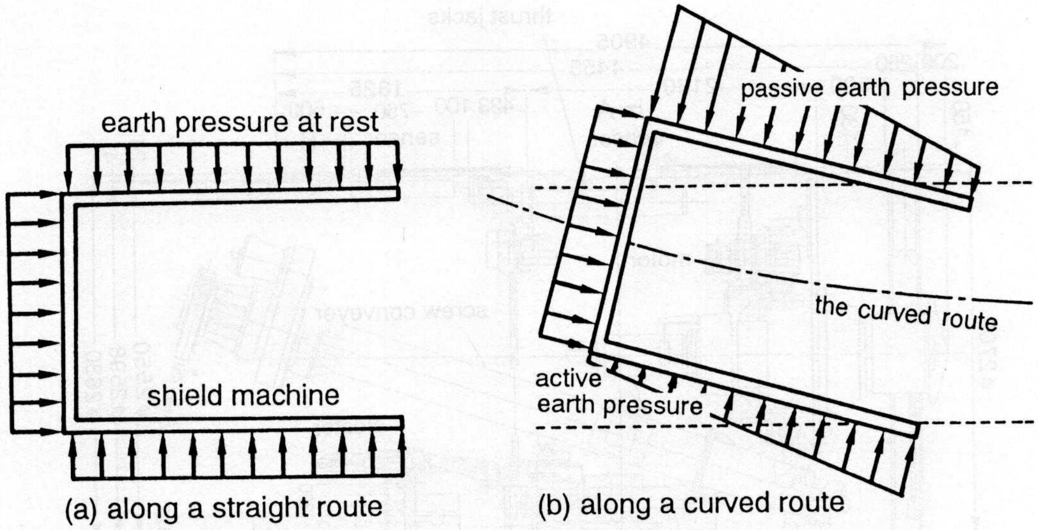


Figure 2. Earth pressure acting on a shield machine

This is because the direction in which the shield machine is advancing changes from step to step. Therefore, the amount of earth pressure acting on the shield machine is increased or decreased according to the relative displacement of the shield machine to the surrounding ground, as shown in Figure 2(b).

The unbalanced earth pressure acting on the shield machine greatly affects the movement of the shield machine, and thus, the estimation of the earth pressure distribution acting on the shield machine will play an important role in determining the advancing control of the shield machine.

3. MEASUREMENT OF THE EARTH PRESSURE ON THE SHIELD MACHINE

As the first step of our research, we measured the earth pressure, which acts on the advancing shield machine, to study the relationship among the earth pressure acting on the shield machine, the ground properties, the control pattern of the thrust jacks and the advancing movement of the shield machine. Figure 3 shows the shield machine used in taking the measurements. The machine was a high-density slurry and an articulated shield. It was divided into front and rear sections, which were connected by articulating hydraulic jacks. The shield machine could be bent by adjusting the extension of the articulating jacks at the center to face it into a sharp curve. In this paper, the effects of the articulated bending was not excluded from the discussion to make the problem simple and the data measured in the section, in which the articulated bending was not carried out during construction, were treated in the discussion.

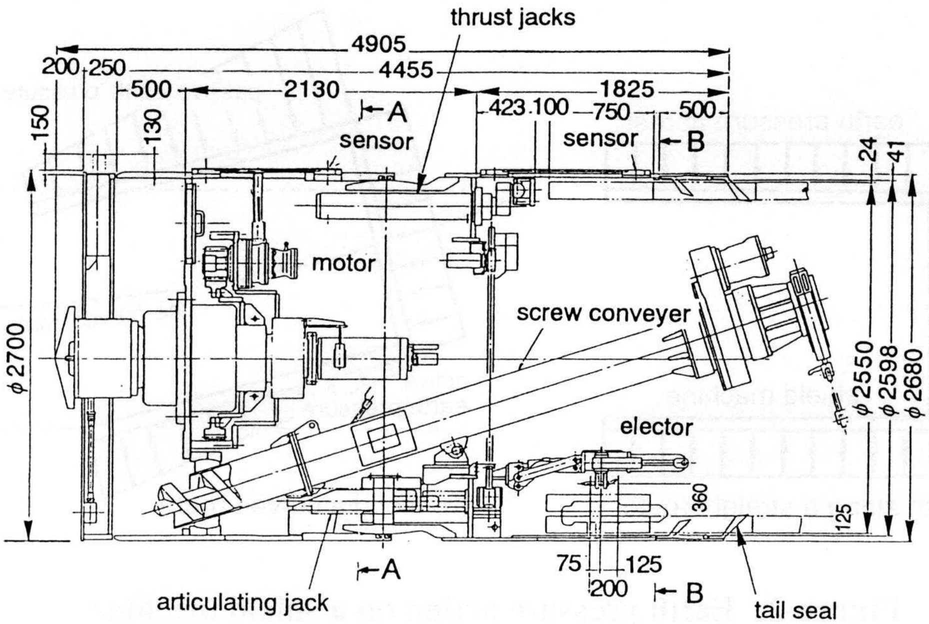


Figure 3. The shield machine used in the measurements of the earth pressure

The external diameter and the length of the shield machine were 2680 mm and 4905 mm, respectively . The earth pressure acting on the shield machine was measured at a distance of 300 meters by earth pressure sensors attached to sixteen points on the outside of the shield machine.

Figure 4 shows the arrangement of the earth pressure sensors. The advancing distance and the direction of the shield machine were measured with a surveying system and a gyroscope equipped to the shield machine, respectively.

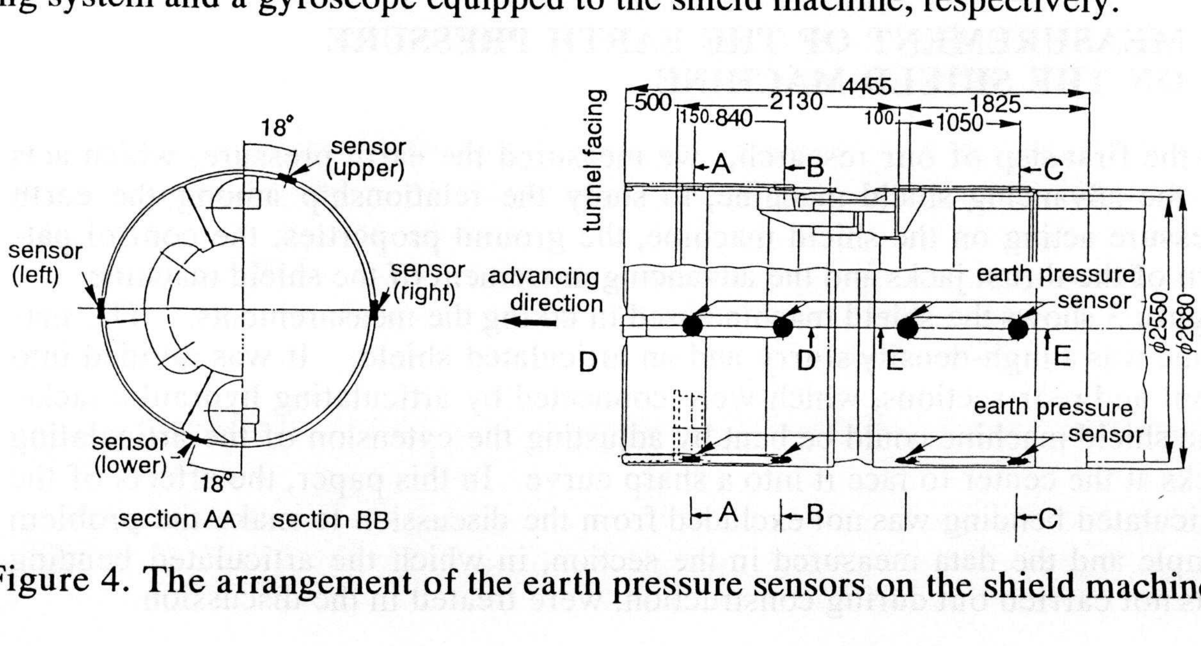


Figure 4. The arrangement of the earth pressure sensors on the shield machine

The earth pressure, the advancing distance and the direction of the shield machine were recorded as time-series data at the distance of 300 meters. The ground at the field where the measurements were carried out was a stratum composed of alluvial and diluvial clays.

Figure 5 shows an example of the earth pressure measurements plotted against the advancing distance. The earth pressure in this figure is expressed by a set of data measured at section 165.6~167.2 on both sides of the rear section of the shield machine. Figure 6 shows the direction of the shield machine measured at the same section of the field as Figure 5. Although the shield machine in this section advanced along an approximately straight route, a slight correction to the advancing direction was made by controlling the thrust jacks to remove the shield location error which was induced during the advancement. It can be seen from these figures that changes in both the earth pressure and the advancing direction were brought about by the correction of the shield location errors. Changes in the earth pressure are thought to have been induced by the relative displacement of the shield machine to the ground, for example, additional earth pressure will be mobilized when some part of the shield machine moves into the ground and soil is compressed at this position, as shown in Figure 2(b). We assume here that when some part of the shield machine moves into the ground, and thus, it presses against the ground, changes in the earth pressure are proportional to changes in the relative displacement of that part of the shield machine to the ground, and that when a part of the shield machine moves off the ground, and thus, it is detached from the ground, the active earth pressure acts on that part of the shield machine [1]. Figure 7 shows the above mentioned relationship between the earth pressure and the relative displacement.

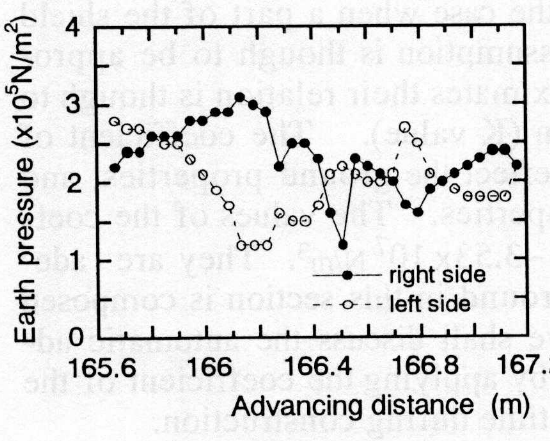


Figure 5. An example of the earth pressure measurement

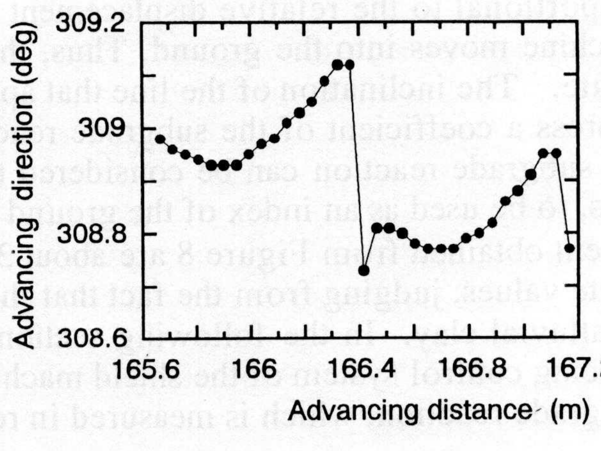
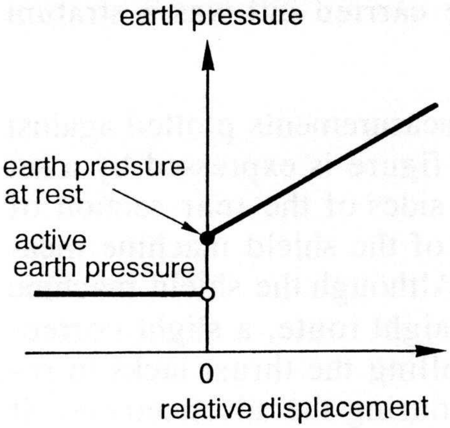


Figure 6. An example of the direction of the shield machine



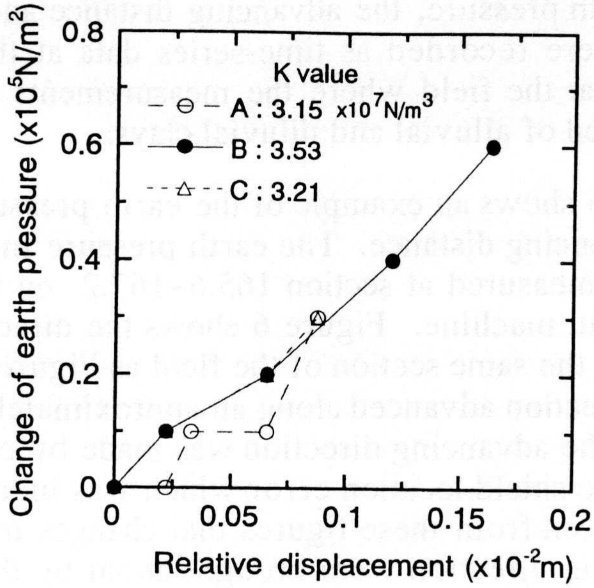


Figure 7. Assumuption on the earth pressure

Figure 8. The results of the measurements of the earth pressure

The relationship between changes in the earth pressure and changes in the relative displacement of the part of the shield machine to the ground was investigated from the measured data to confirm the above mentioned assumption. Figure 8 shows the results of these investigations where changes in the earth pressure are plotted against the relative displacement of the shield machine to the ground. The values of the relative displacement in this figure were calculated from the data of the advancing direction of the shield machine. This figure shows that the changes in the earth pressure can be recognized as being proportional to the relative displacement in the case when a part of the shield machine moves into the ground. Thus, the assumption is though to be appropriate. The inclination of the line that approximates their relation is though to express a coefficient of the subgrade reaction (K value). The coefficient of the subgrade reaction can be considered to reflect the ground properties, and thus, to be used as an index of the ground properties. The values of the coefficient obtained from Figure 8 are about $3.15 \sim 3.53 \times 10^7$ N/m^3. They are adequate values, judging from the fact that the ground in this section is composed of alluvial clay. In the following section, we shall discuss the automatic advancing control system of the shield machine by applying the coefficient of the subgrade reaction, which is measured in real-time during construction.

4. IDEA OF AN AUTOMATIC ADVANCING CONTROL SYSTEM FOR SHIELD MACHINES

The automatic advancing control system of the shield machine can be created with the coefficient of the subgrade reaction as follows.

(1) The route of the tunnel is usually given as part of the tunnel planning data.

(2) The position and the direction of the shield machine at any point along the route, which the shield machine should follow in order to advance along the route, are determined from the data taken along the route of the tunnel.

(3) The relative displacement of the shield machine to the ground can be calculated from the position and the direction of the shield machine at any point along the route.

(4) The value of the coefficient of the subgrade reaction should be determined for the ground by measuring the changes in the earth pressure acting on the shield machine and the relative displacement of the shield machine to the ground in real-time during construction.

(5) The distribution of the earth pressure acting on the shield machine is evaluated from the value of the measured coefficient of the subgrade reaction and the calculated relative displacement of the shield machine to the ground, following the assumption that when some part of the shield machine moves into the ground, changes in the earth pressure are proportional to changes in the relative displacement of that part of the shield machine to the ground, and that when a part of the shield machine moves off the ground, the active earth pressure acts on that part of the shield machine.

(6) The thrust force and its acting point for advancing control can be determined through the equilibrium of force and momentum, which are composed of the advancing force and the distribution of the earth pressure, etc.

(7) The method for controlling the thrust jacks is determined to mobilize the thrust force and its acting point obtained in the previous step (6).

In real construction, the ground properties usually vary according to their location in the ground, and thus, errors in the positioning of the shield machine will be encountered. Therefore, the value of the coefficient of a subgrade reaction should be renewed by measuring it frequently during construction. And some support of an ordinary advancing control method, made by removing the deflection of the current location from the designed one, will be necessary during real construction. Although the advancing control method that we discussed in this paper has a lot of problems yet to be solved, the advancing control of a shield machine will become easy to execute with this method and we expect that an automatic advancing control system for shield machines with this method will be realized in the near future.

5. CONCLUSION

The earth pressure acting on a shield machine was measured during construction to investigate the relationship between the earth pressure and the movement of the shield machine. From the results of the measurements, it was clarified that the earth pressure changes in accordance with the relation with the relative displacement of the shield machine to the ground, and that the coefficient of the subgrade reaction can be defined from the measured data to express the relationship between the earth pressure and the relative displacement.

The idea of an automatic advancing control method for shield machines is introduced by discussing the relationship between the movement of a shield machine and the earth pressure acting on it. The coefficient of the subgrade reaction should be used effectively to evaluate the distribution of the earth pressure acting on the shield machine and to determine the method of advancing control of the shield machine. Continuous research will be conducted to realize the idea of the automatic control system for shield machines.

The evaluation of ground conditions and the determination of the optimum control method for construction machinery suitable to the ground conditions are difficult but important problems in developing construction robotics. The research we have reported in this paper deals with one such topic.

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