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Study on 4-centered shield behavior in soft ground

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ABSTRACT: The developed shield behavior measurement system with high accuracy was applied to Roppongi Subway station construction site in Tokyo to make clear the 4-centered shield behavior during construction precisely. Based on the obtained yawing and rolling angles, the 4-centered shield behavior was examined, taking account of the shield operation, such as the operation of the jack pattern, the copy cutter, and the articulate mechanism. As a result, the followings were made clear: 1) the behavior of the 4-centered shield on horizontal plane is similar to that of a circular shield; 2) the articulate mechanisms together with the copy-cutter can control the shield rotation, since those functions can adjust the relative ground displacement, which defines the ground reaction force.
KEY WORDS: shield tunneling method, yawing angle, rolling angle, measurement system.

1 INTRODUCTION

The demands of underground space use in the urban area for the infrastructures and utilities, such as railways, roads, electric transmission lines, sewerage, and water supply, have become increased. While the circular face shield were used as a standard shield in these constructions, recently the non-circular face shield, such as a multi-face circular shield and a rectangular face shield etc., become popular to save the construction cost by reducing the unnecessary excavation area. On the other hands, the construction of the underground structures very near the existing structures increased due to the narrow underground space. In this case, the shield control with high accuracy is required.

Based on the above mentioned necessities, the authors developed the shield behavior measurement system with high accuracy (Sugimoto et al. 1998) and applied it to the construction of Roppongi station in Metropolitan Subway Route No.12 to make clear the shield behavior during construction precisely. Roppongi station is composed of the vertical twin tunnel constructed by the 4-centered shield with vertical articulate mechanism as shown in Photo 1.

This paper introduces Roppongi station site and reports the measured behavior of 4-centered shield, especially the yawing and rolling behavior.

2 SITE DESCRIPTION OF ROPPONGI STATION

In Roppongi station, the two-storage (upper and lower) platforms were constructed as a twin tunnel by the 4-centered shield tunneling method, and the both ends of the station were constructed by cut and cover method, to escape the interrupt of the traffic on ground surface. Figures 1-3 show the plane view, the longitudinal section, and the cross section of Roppongi station with geological profile respectively.

The alignment of Roppongi station tunnel are as follows: 118m length for each 2 tunnels (upper and lower); 502m minimum horizontal radius (right curve); 0.2 % falling gradient.

The geological profile at the construction site is shown in Figure 3. From the ground surface, the ground is composed of top-soil layer (Ts), Kanto loam (Lm, Lc),

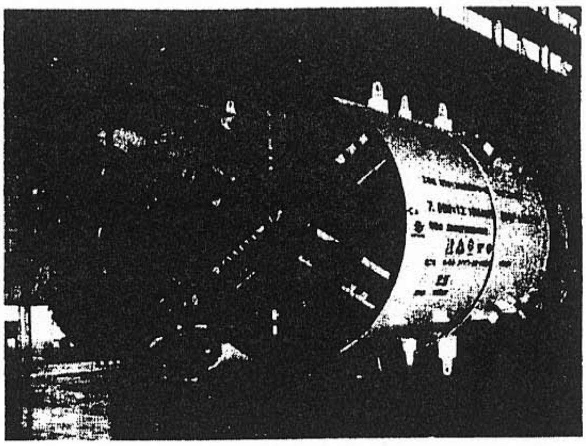

Photo 1 4-centered shield

Tokyo sandy soil (To-s), Tokyo clayey soil (To-c), Tokyo gravel (To-g), Kazusa mudstone (Kam), and Kazusa sandy soil (Kas). The upper shield tunnel is embedded in both Tokyo gravel and Tokyo sand layer, while the lower shield tunnel is in Kazusa mudstone and Kazusa sandy soil ones, where the standard penetration N value is over 50. The ground water level is at about −16m, and the pore water pressure at the center of the lower tunnel is 0.25 MPa. The coefficient of permeability is about 1.31 x 10^{-3}m/ sec, and the coefficient of uniformity is 1.9 or less.

3 4-CENTERED SHIELD

4-centered slurry type shield was adopted for Roppongi station shield tunneling. It has 4 rotary cutters, i.e., two cutters are arranged horizontally in left and right side (Diameter 6.56m) and other two are arranged at central part in upper and lower side (Diameter 1.72m), which are equipped on the same vertical plane. The entire shield body is 7.06m height and 13.18m width. Moreover, the one-chamber method was adopted to make the cutter wing control stable and ensure the easy fluidity.

As for the pitching of shield, it was considered that the

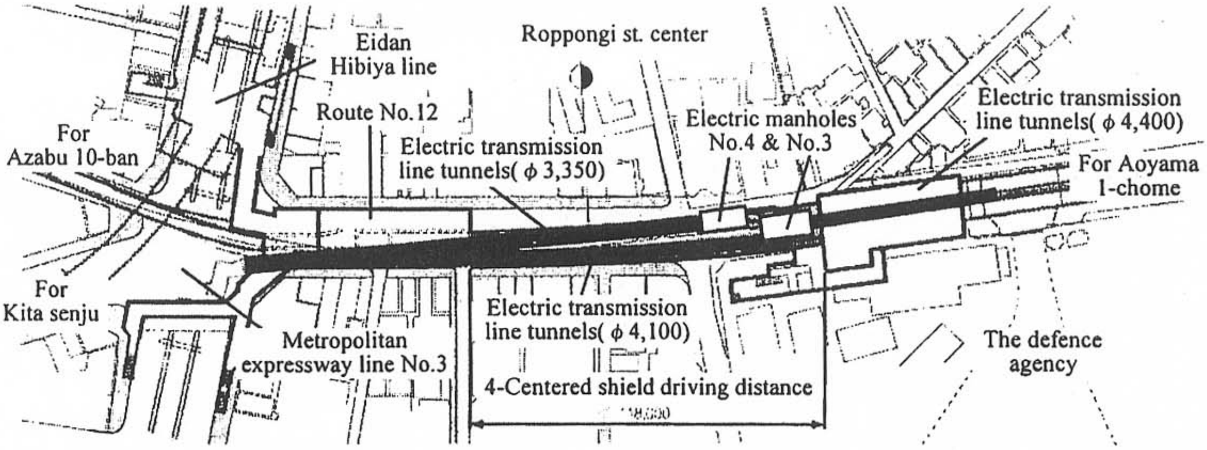

Figure 1 Plane view of Roppongi station

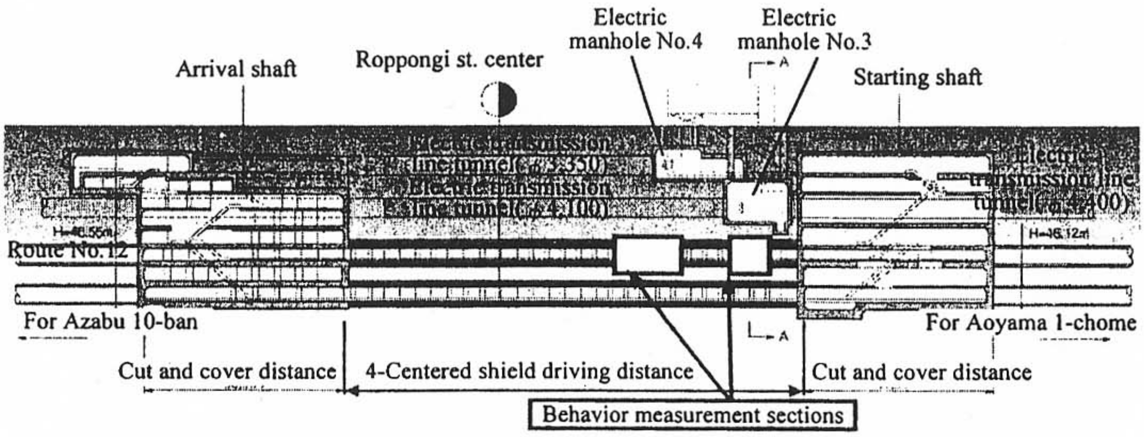

Figure 2 Longitudinal section at Roppongi station

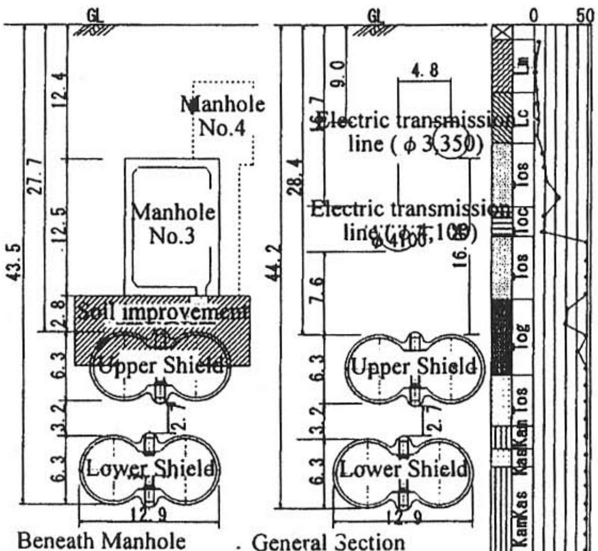

Figure 3 Cross-section and geological profile at Roppongi station

pitching of 4-centered shield could be controlled by similar way to a rectangular face shield. On the other hands, it is necessary to take care of the rolling of the shield since the shield body is quite wide in transverse direction. Therefore, two up-down articulate mechanisms, which is called as H & V mechanism, at the both sides of the front shield body, was adopted (maximum articulate angle is ±1 deg.), to control the rolling of shield easily during excavation. The use of such articulate mechanism together with the copy-cutter, to control the rotation of the shield easily, is one of the characteristics of this 4-centered slurry shield.

Figure 4 shows the outline of the 4-centered shield and Table 1 shows the shield specifications.

4 SHIELD BEHAVIOR MEASUREMENT SYSTEM

The continuous measurement system on the shield behavior throughout the whole construction stage, i.e., the excavation stage and the segment installation stage, was developed. (Sugimoto et al. 1998, Kouraba et al. 2000) This measurement system is composed of 2 sets of total stations with automatic tracking function and 2 sets of prisms equipped on shield. Each total station carries out the real time survey of the position of each prism, as illustrated in Figure 5 and Photos 2-3, and the yawing angle is calculated from the co-ordinates of 2 prisms, instead of the

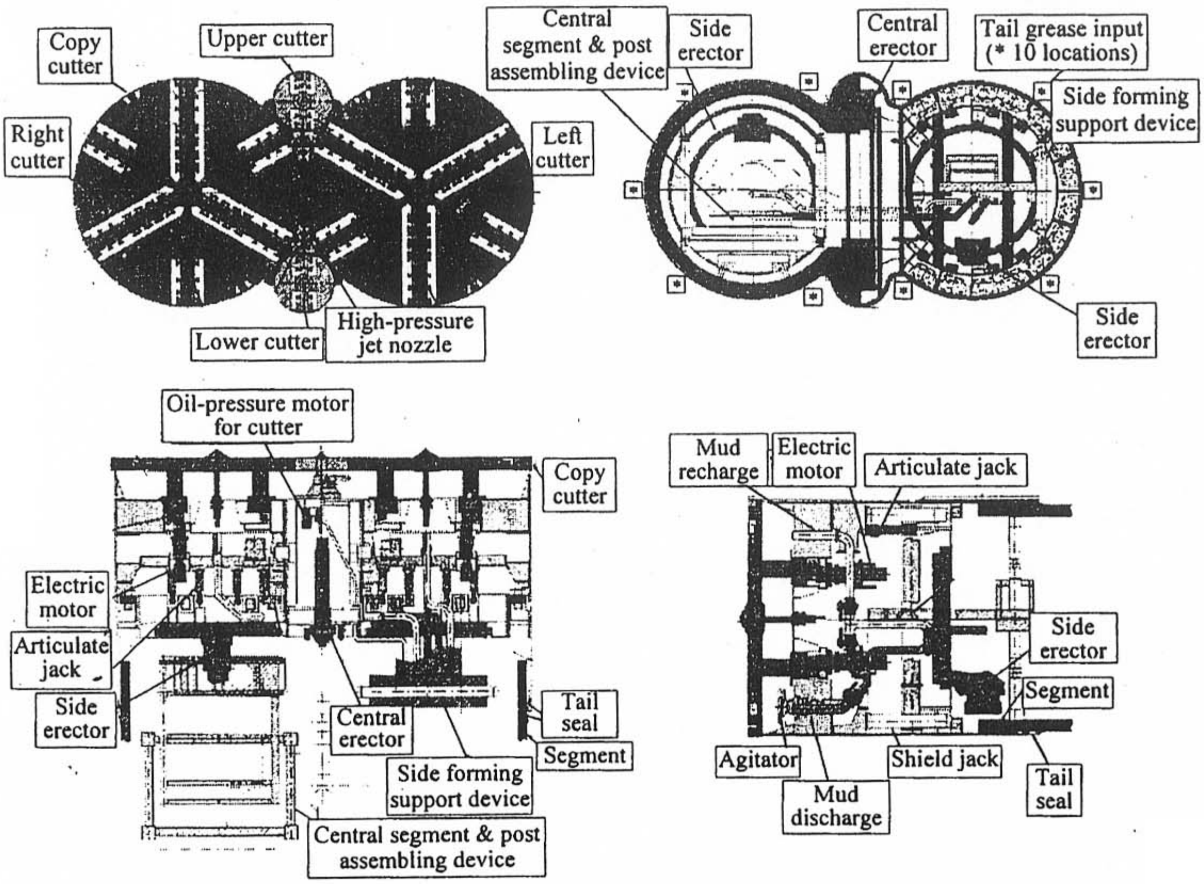

Figure 4 Outline of 4-centered machine

Table 1 4-centered shield specification

Shield Body specifications		
Max. width x max. height x length		13180 x 7060 x 8100mm
Cutter outer diameter		Left & right: 6560mm, Up & Low: 1720mm
Shield jack		2500 kN x 1500 ST x 35 Mpa x 28 pieces
		1500 kN x 1500 ST x 35 Mpa x 6 pieces
Equipped total thrust force		79000 kN
Thrust force in single vert. Surface		1.04 Mpa
Cutter disk specifications		
Left & Right	Cutting method	Reversal rotation in all excavating section
	Torque	Operating 3210 kN.m
	Rotation frequency	0.8 r.p.m
	Electric machine	30 kW x 4 P x 9 pieces x 2
Up & Low	Cutting method	Reversal rotation in all excavating section
	Torque	Operating 83 kN.m; Max. 104kN.m
	Rotation frequency	0 - 3 r.p.m
	Oil pressure motor	SX 504 x 2 pieces x 2
Rolling Control Device Specifications		
H & V Shields (Cross Articulate) Device		
Articulate jack		1250 kN x 150 ST x 30 Mpa x 16 pieces
Articulate angle		Up-down ± 1 degree

gyro compass. Furthermore, the pitching and rolling angles are measured by the inclinometers. It is noted that the distance between 2 prisms must be longer in transverse direction, so as to secure the accuracy of the calculated yawing angle.

And, it was applied to the double-track railway tunnel with about 10m diameter to confirm the performance of this measurement system. As a result, it was confirmed that this measurement system provides the shield behavior with higher accuracy, compared with the conventional measurement system, especially for yawing angle. (Konishi et al. 1999)

The shield behavior was measured continuously in the upper tunnel from ring 31st to 46th, as shown in Figure 2. The measurement was carried out with 30 seconds interval during excavation and 5 minutes interval during the shield stop.

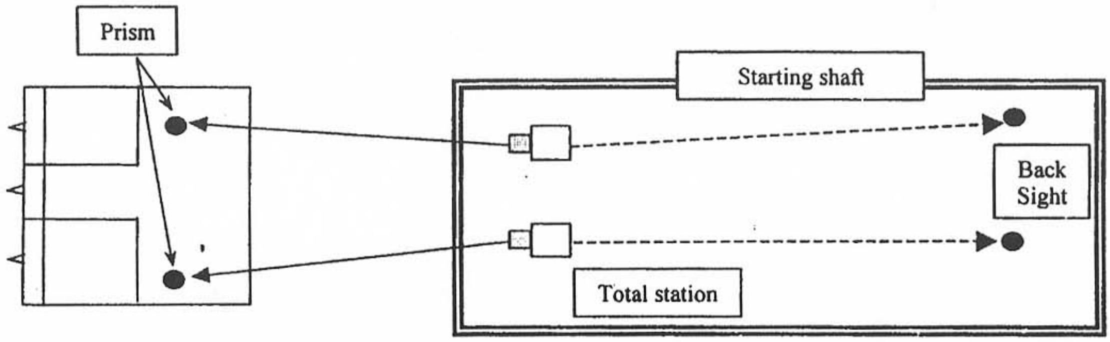

Figure 5 Outline of developed shield behavior measurement system

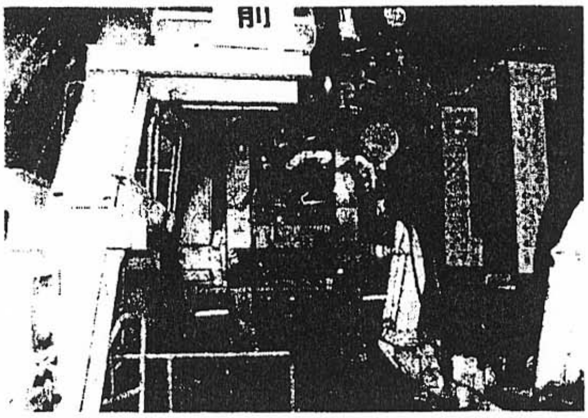

Photo 2 Left prism set in the post

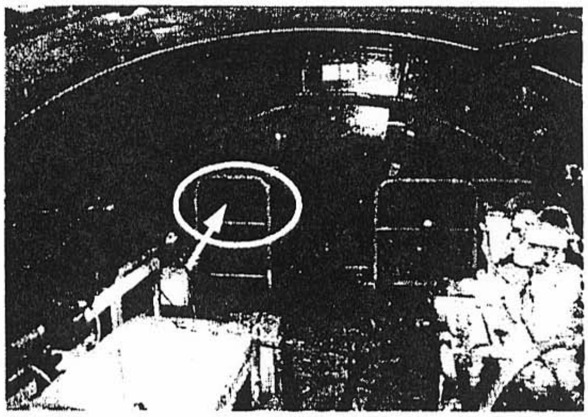

Photo 3 Right prism set in the ring girder

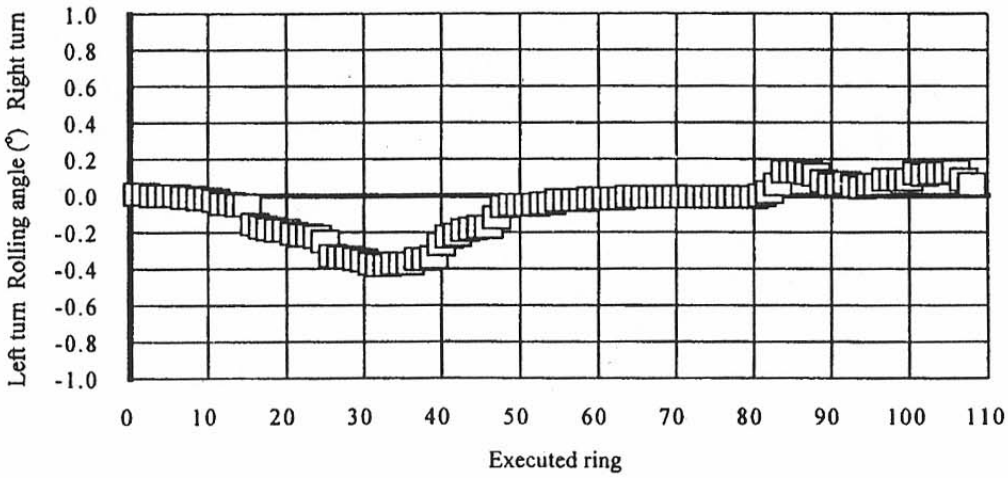

Figure 6 Measured rolling angle in upper shield

5 SHIELD BEHAVIOR

5.1 Rolling of shield during excavation

In case of 4-centered shield tunneling, it is important to control the rolling of the shield precisely, in order to install the pillars at the center of the section in accurate vertical direction and to secure the tail clearance. Figure 6 shows the rolling angle during excavation in the upper tunnel by the inclinometer. The rolling of the shield started after 10th ring. Up to the rolling angle was over 0.2 deg, the jack pattern and the cutter rotation direction were changed to correct the rolling of the shield, but no effect was observed. When the rolling angle reached over 0.3 deg (ring 30th to 42nd), the above mentioned articulate mechanisms were applied, i.e., the left shield bodies look 0.05 deg upward and the right shield bodies look 0.23 deg downward. Moreover, 50mm overbreak at the upper part of the left shield body was applied during ring 27th-30th by using the copy cutter. As a result, the rolling of the shield began to move back to the planed one, and finally at ring 50th the rolling angle became almost 0 deg. These facts indicate that the excavated area and the ground condition have a predominant role for the rolling of the shield, and the shield jack pattern, i.e., the horizontal and vertical jack moment, has less effect on the rolling of the shield.

Figure 7 shows the rolling angle by the developed measurement system and the inclinometer during the excavation stage and the segment installation stage from rings 40th to 42nd. There is a difference between them. This is supposed to come from the setting error of the total station and the inclinometer. However, both rolling angles have the same tendency with elapsed time. Moreover, the measurement system can catch the slight changes of the rolling angle and can provide the smooth change of it. Therefore, this measurement system is considered to provide the more reliable data.

5.2 Yawing of shield during excavation

Figure 8 shows the yawing angle of the shield obtained by the shield behavior measurement system and the planned direction angle of the tunnel from ring 30th to ring 46th. In this section, the planned horizontal alignment is a right circular curve with 502m radius and the excavated ground is relatively hard. Therefore about 100mm outbreak was applied at the right side of the shield, i.e., the inner curve side. Consequently, the yawing angle of the shield agreed rather well with the planned one.

Figure 9 shows the yawing angle of the shield during the excavation stage and the segment installation stage from rings 40th to 42nd, where the rolling and the yawing of the shield change drastically, as shown in Figure 6 and 8. The total thrust force was almost constant with about 3.0×10^4 kN at front and rear body. The yawing angle of the shield increased around 0.1 deg for each ring during excavation due to the curve alignment and it mostly occurred at the start of the excavation. On the other hands, when the excavation stopped for installing the segment, the shield did not return back to the previous direction. These reasons can be explained by the copy-cutter effect, i.e., the shield can take a balance without the rotation since the overbreak reduces the ground reaction. These behaviors were also observed at the circular shield in hard ground. Therefore, it is suggested that the behavior of the 4-centered shield on horizontal plane is similar to that of a circular one.

6 CONCLUSIONS

The yawing and rolling angles of the 4-centered shield were measured continuously by using the developed shield measurement system to make clear the shield behavior with high accuracy during construction. As a result, the followings were made clear.

1) The shield jack pattern, i.e., the horizontal and vertical jack moment, has less effect on the shield behavior. On the other hands, the articulate mechanisms installed in both left and right shield bodies together with the copy-cutter can steer the shield rotation, since those function can adjust the relative ground displacement, which defines the ground reaction force.

2) The behavior of 4-centered shield on horizontal plane has the similar tendency to that of a conventional circular shield. Therefore, the 4-centered shield can be regarded as a circular shield.

As a future research, there is a plan to verify the kinetic

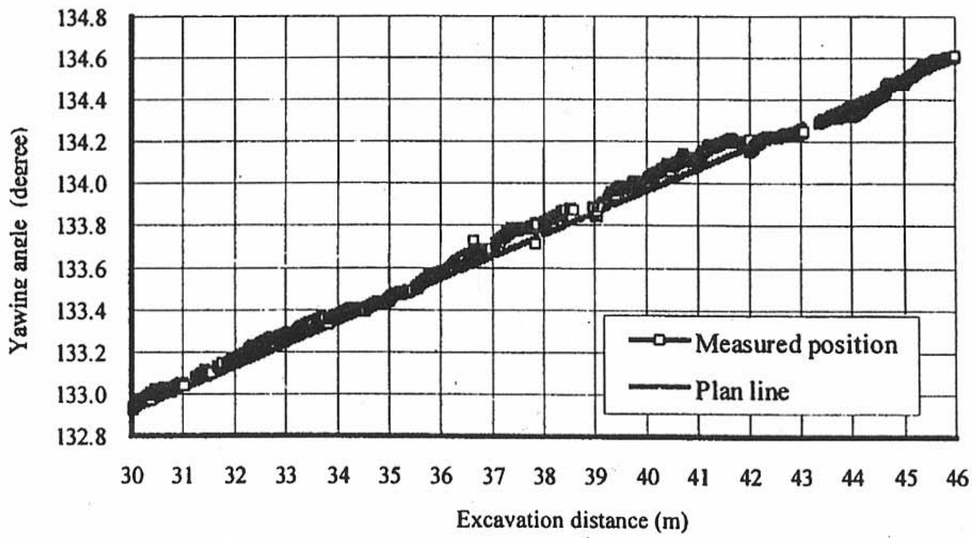

Figure 7 Measured yawing angle in upper shield and planned horizontal direction angle

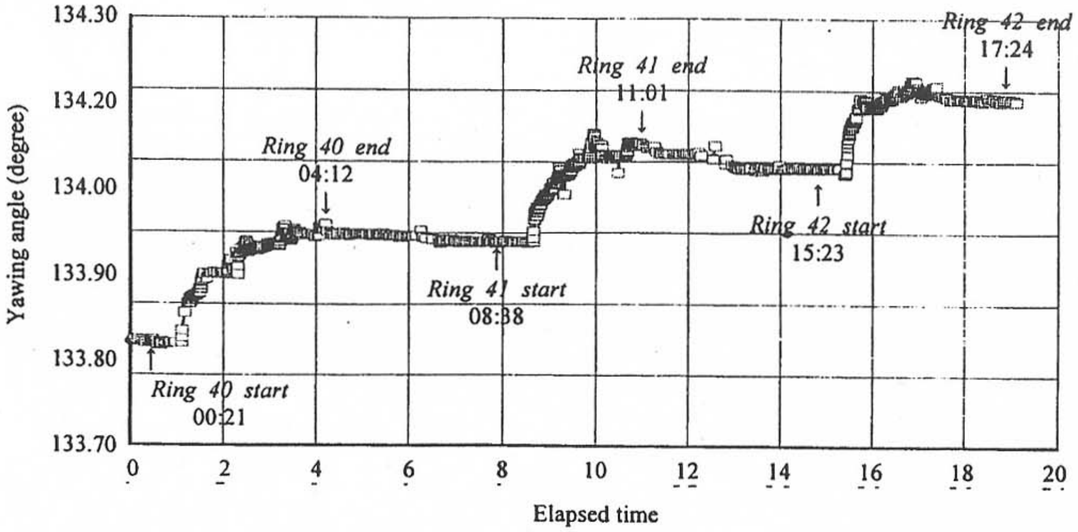

Figure 8 Yawing angle vs. elapsed time (rings 40th o 42nd)

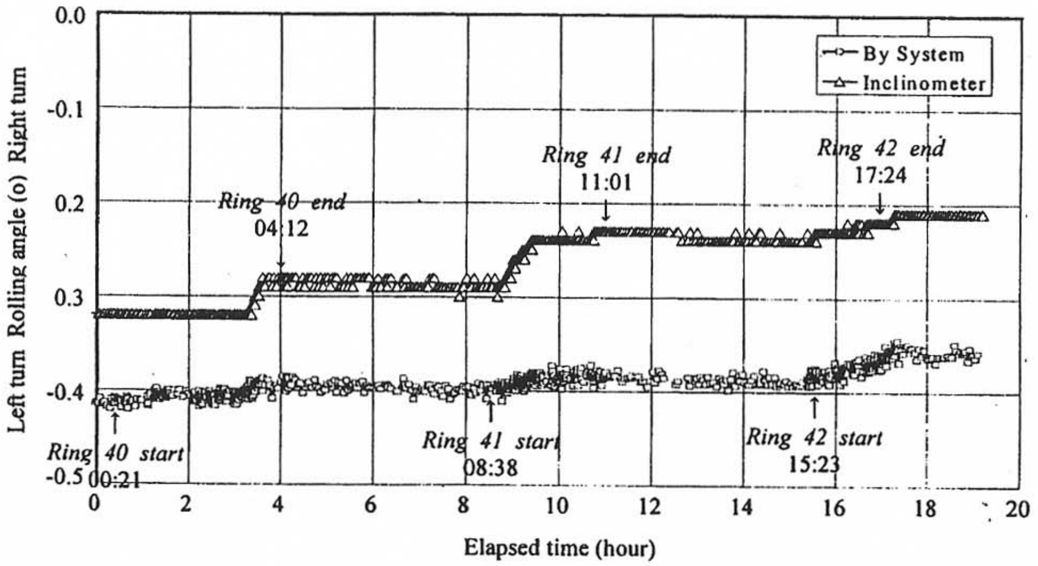

Figure 9 Rolling angle vs. elapsed time (rings 40th to 42nd)

model expressing the shield behavior by using the obtained data.

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