Construction of Underground Space by a New Shield Tunnelling Method: Spiral Tunnelling and Ramification of Multi-circular Face Shield

T. Sonoda, H. Hagiwara, H. Osaki, T. Noguchi and M. Nakamura

Abstract—*Shield tunnels traditionally have been built with single-circle cross-sections. However, considerations related to construction costs and periods, as well as safety, have led to increased use of multi-circular faces in recent years. In the multi-circular face shield tunnelling methods proposed to date, the two circles may be placed either side by side or one above the other. The characteristics of the shield tunnelling methods differ, depending on whether the circles are arranged horizontally or vertically. The H&V (Horizontal variation and Vertical variation) Shield Tunnelling Method uses a special rolling control function in spiral tunnelling with multi-circular face shields. This method allows construction of tunnels that have multi-circular face shields. It also permits construction of tunnels that have multi-circular cross-sections, with the arrangement of the circles varying continuously from vertical to diagonal to horizontal, or vice-versa, as well as ramification from a multi-circular tunnel into separate single-circle tunnels. This paper discusses the H&V Shield Tunnelling Method, the manner in which the method is used, and the construction test used to verify this construction technique.*

Résumé—*Les tunnels creusés au bouclier construits jusqu'alors ont des coupes transversales uni-circulaires. Cependant, ces dernières années, des considérations liées au coût et au temps de construction, ainsi qu'à la sécurité, ont conduit à l'utilisation croissante de boucliers à face multi-circulaire. Dans le creusement au bouclier à face multi-circulaire proposé à ce jour, les deux cercles peuvent être placés soit côte à côte, soit l'un au dessus de l'autre. Les caractéristiques du creusement au bouclier différent selon que les cercles sont arrangés horizontalement ou verticalement. Le creusement au bouclier H&V (variation Horizontale et variation Verticale) utilise une fonction de contrôle spéciale pour le creusement en spirale avec des boucliers à face multi-circulaires. Cela permet aussi de construire des tunnels, qui ont des coupes transversales multi-circulaires, avec un ajustement des cercles variant continûment de la verticale à la diagonale jusqu'à l'horizontal, ou vice-versa, ainsi qu'une ramification partant d'un tunnel multi-circulaire jusqu'aux tunnels uni-circulaires séparés. Ce rapport traite du Creusement au Bouclier H&V, de la manière dont cette méthode est utilisée, et du test de construction utilisé pour vérifier la technique de construction.*

1. Introduction

In recent years, the increasing demand for effective use of the underground in Japan's urban areas has been accompanied by much research related to methods for using deep underground space and construction methods for underground caverns with large cross-sections and tunnels with varying cross-sections. As research has progressed, many new developments have occurred in the techniques for shield tunnelling, which plays a central role in the development of underground space.

Shield tunnels used to be constructed mainly with circular cross-sections for the following reasons:

- Single circles are structurally stronger against the external pressures that are applied to tunnels.
- The ground is excavated by rotating the cutters in closed-type shield tunnelling.
- It is easier to produce shield tunnelling machines and to produce and assemble the segments for circular cross-sections.

However, crowding of the underground and the construction of tunnels as substitutes for aboveground roads that have become too narrow, coupled with (1) the need for rational cross-sectional shapes for tunnels in accordance with their uses and (2) efforts to reduce the cost of tunnel construction, have led to the development of shield tunnels with cross-sections other than single circles.

One such type of new tunnel—the multi-circular face shield tunnel—has the following advantages in comparison with double single-track tunnels with two separate tunnels running parallel to each other and double-track tunnels with two tracks running through a large single-circle tunnel, both of which traditionally have been used for railway tunnels:

- The widths of the site required and tunnel heights can be reduced by having the two circles on top of one another or side by side, facilitating route planning.
- In comparison with the double-track tunnels, the reduction of the unnecessary cross-sectional area results in reduced construction costs.
- In comparison with the double single-track tunnels, the communication facility between the two tracks increases safety.

The H&V (Horizontal variation and Vertical variation) Shield Tunnelling Method presented herein is a new shield tunnelling method that further increases the advantages derived from the use of multi-circular face shields.

2. H & V Shield Tunnelling Method

2.1. Characteristics

In the multi-circular face shield tunnelling methods that have been put to practical use so far, the two circles are placed either side by side or one above the other. The characteristics of the tunnelling methods differ in the following ways, depending on whether the circles are arranged horizontally or vertically:

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Tunnelling and Underground Space Technology, Vol. 7, No. 4, pp. 355–361, 1992. Printed in Great Britain. 0886-7798/92 $5.00 + .00 Pergamon Press Ltd

- Tunnels with horizontally arranged circles are easier to construct when they intersect with underground structures, and are safer against disasters when used as railway or road tunnels.
- Tunnels with vertically arranged circles are easier to construct when the tunnels have sharp corners, and are safer with regard to their surroundings.

Having the freedom to select horizontal or vertical arrangement according to the planning and construction conditions will allow planners to exploit the advantages of each method, and will increase the advantages to be derived from the use of multi-circular face shields.

In the H&V Shield Tunnelling Method, a multi-circular face shield with a special articulation mechanism is used to construct two tunnels very close to each other in a spiral; the two tunnels are arranged horizontally, diagonally, and vertically. The structure of the shield tunnelling machine also allows ramification from a multi-circular tunnel into single-circle tunnels. Figure 1 is a conceptual drawing of the H&V Shield Tunnelling Method.

The H&V Shield Tunnelling Method has the following advantages in addition to the conventional multi-circular face methods:

- The height of the tunnel can be reduced by arranging the circles horizontally when there are restrictions on the tunnel height at intersections with underground structures.
- The width of the tunnel can be reduced by arranging the circles vertically in sections where the width of the available site is small.
- Where ramification of the tunnel is required for utility tunnels and underground railway stations, underground ramification can be carried out, allowing continuous excavation without the vertical shafts required in conventional methods.

Unlike the case for single-circle face shields, rolling of the shield tunnelling machine needs to be controlled with multi-circular face shields, because rolling of the multi-circular face shield could lead to alteration of the internal cross-section, intrusion into the clearance, and hindrance to assembly of the segments. The use of an effective rolling control mechanism in the H&V Shield Tunnelling Method makes stable excavation possible with a minimum amount of rolling, even during periods of excavation in the non-spiralling section.

2.2. *Shield Tunneling Machine*

The H&V shield tunnelling machine consists of two articulated shield tunnelling machines joined together, ensuring that their cutter face plates will be on the same plane. The front bodies of the two shield machines have sliding structures to enable them to be articulated separately, while the rear bodies are joined with an unhinged structure. For ramification of the shield tunnel, the rear bodies, which are joined together with bolts, are separated in the ground by taking off the bolts.

The H&V shield tunnelling machine has three mechanisms for spiral excavation: a cross-articulation mechanism; a copy cutter; and a spiral jack. These mechanisms also incorporate the control functions for preventing the tunnelling machine from toppling and rolling.

1. **Cross-articulation mechanism.** The excavation direction of the two front bodies of the shield tunnelling machine is made to diverge by articulating the front bodies in different directions. The rotational force created in this way is used for spiral excavation. The amount of spiralling (rotating angle per unit length) can be controlled through adjustment of the angle between the front bodies (see Fig. 2).

2. **Copy cutter.** This mechanism reduces the ground reaction that hinders spiral excavation and facilitates the articulation operation of the cross-articulation mechanism.

3. **Spiral jack.** The deviation of the shield jack in the direction along the circumference from the direction of the advance of the shield tunnelling machine separates the thrust and the component force acting in the direction of the rotation.

2.3. *Segments*

Two types of segments are used in the H&V Shield Tunnelling Method, according to the uses and structural characteristics of the tunnels. Joined-type segments are used when joining the two tunnels; separate-type segments are used when constructing two separate single-circle tunnels very close to one another. For both segment types, circles are used as the basic shape of the tunnels (see Fig. 3), because of the structural advantages and because the cross-sections remain the same during rotation when circles are used.

1. **Jointed-type segments.** The jointed-type segments for the straight sections are created by joining the conventional single-circle segments parallel to one other. The single-circle segments are joined at an angle in creating joined-type segments for the spiral sections. This means that the only parts requiring special shapes are the pieces for the connections. All the rings of the spiral segments have the same shape if the amount of spiralling remains constant. The advantage of these segments is that the connections facilitate the construction of emergency passages between the tunnels.

2. **Separate-type single-circle segments.** Spiral tunnels can be constructed by combining standard straight and tapered segments, as in the construction of curves by conventional methods. The advantages of simultaneous construction of two tunnels very close to each other is that there is no need to provide reinforcement to the tunnel constructed first, and there is no need for the ground improvement that is required when tunnels are constructed close to one another by conventional methods.

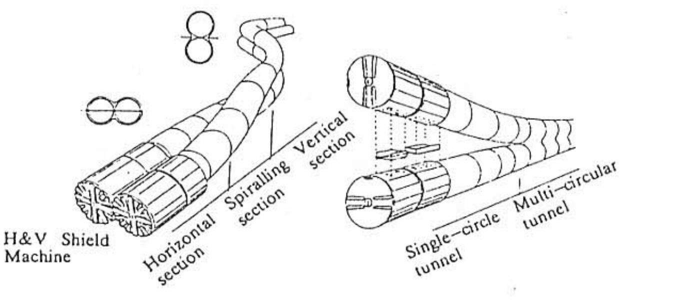

Figure 1. Concept of the H&V Shield Tunnelling Method.

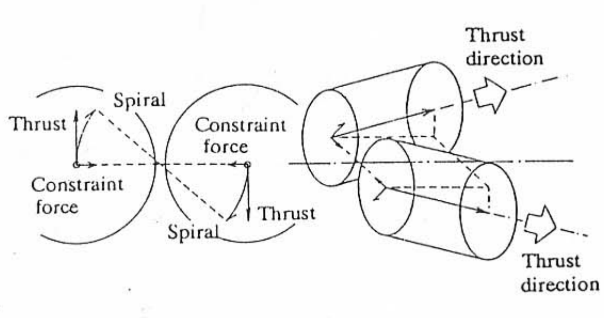

Figure 2. Spiral excavation mechanism.

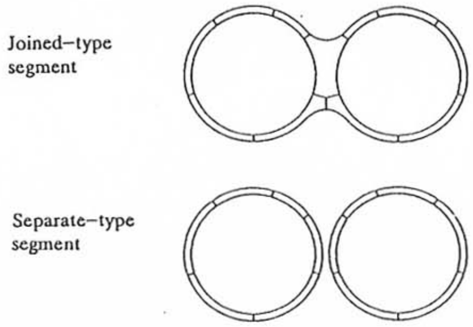

Figure 3. Two types of segments.

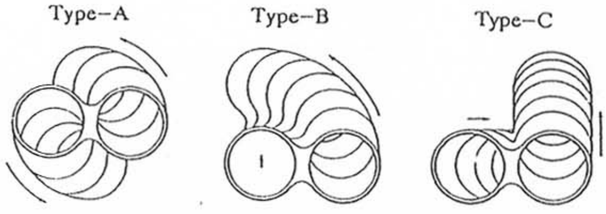

Figure 4. Examples of spiral tunnels.

2.4. Alignment and Cross-Section Types

The alignment of the spiralling sections can be varied by changing the centres of rotation, as shown in Figure 4. In Type A alignment, the axis of rotation is the centre of the two tunnels; in Type B, the centre of one tunnel is used as the rotation axis; and in Type C, the rotation axis itself is made to move. Type A allows rotation over the shortest distance, while type B is effective when the alignment of one tunnel has already been decided. Type C, with no plane or longitudinal composite curves in either tunnel, facilitates conformity with alignment standards. It is also possible to construct two tunnels with different diameters for combining tunnels with different uses.

3. Examples of H&V Shield Tunnelling Method Applications

3.1. Underground Railway Station in Restricted Construction Site (Fig. 5)

The two tracks of the underground railway line preferably should be placed side by side at a station from the point of view of safety and functions. When the station is to be built in an area with restrictions on the construction site because of the small width of the road above, the tracks may need to be placed on top of each other. In such cases, the two tunnels running side by side in the normal section or at the stations on either side are made to run one above the other by creating a 90-degree spiral before and after the station, to construct a station sited on a narrow strip of land.

3.2. Underground Railway Station Facilitating Change of Trains (Fig. 6)

One of the tasks in ensuring the safety of the passengers and improving the economic effect of the underground railway is to make it easier for passengers to change trains at the stations. By rotating the tunnel for one of the tracks 180 degrees between two stations, as shown in Figure 6, passengers can change trains on the same platform without going up and down stairs. Such an arrangement alleviates crowding at the station and reduces the time required for changing trains, making it more convenient to use the underground railways.

3.3. Separate Drains (Fig. 7)

Simultaneous construction of drains for sewage and stormwater is made possible by the H&V Shield Tunnelling Method, resulting in reductions in the construction work and the areas of land required for operation bases, e.g., for the starting shafts. The capacity for spiralling and ramification permits construction of drains with different inclines, as well as branching of the drains in separate directions.

4. Verification Test

4.1. Aims

Information relating to design was collected with the following aims for the purpose of establishing the H&V Shield Tunnelling Method:

- Verification and assessment of the characteristics of spiral excavation and confirmation of the performance of the spiralling mechanism.
- Verification of ramification from a composite tunnel to single-cross-section tunnels by separation of the shield tunnelling machine.
- Segment stress measurement.
- Studies on the effects of the spiral excavation on the surrounding ground.

4.2. Test Period and Site

The tests were conducted during a period from October 1989 to March 1990. The site was an outdoor test yard at the Technical Research Institute of Hazama Corporation.

4.3. Test Route

The excavation length of 70.5 m was divided into the following four sections to verify the excavation conditions and to compare the conditions with different cross-section types (see Fig. 8):

1. Horizontal, 12 m, straight.

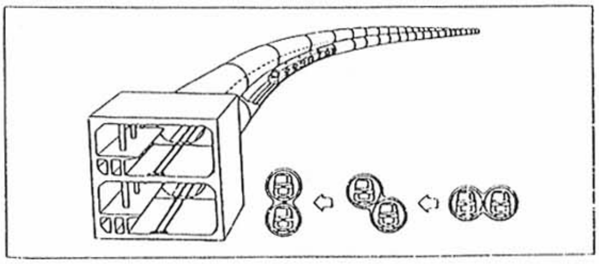

Figure 5. Underground railway station in a restricted construction site.

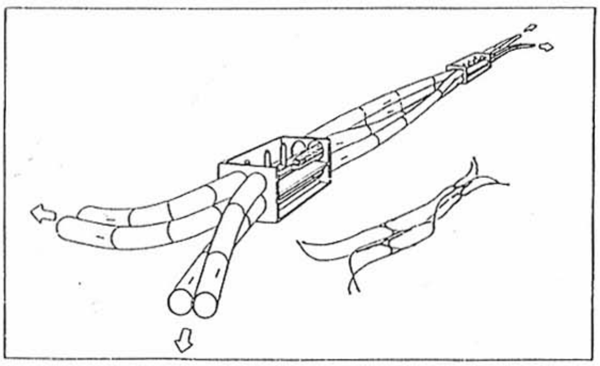

Figure 6. Underground railway station facilitating change of trains.

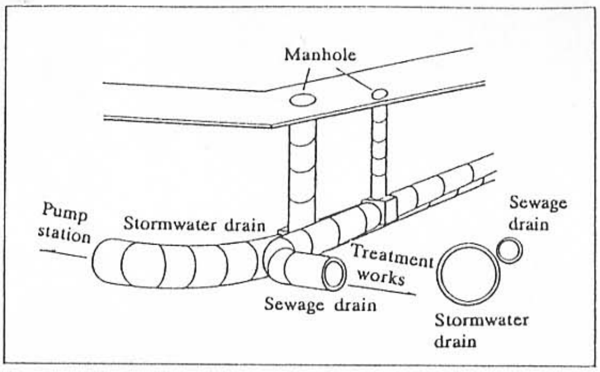

Figure 7. Separate drains.

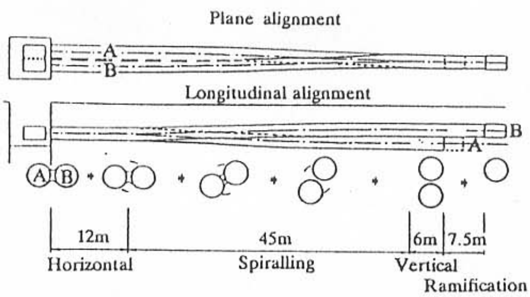

Figure 8. Test route.

2. Ninety-degree spiral over a 45 m length (2 degrees/m).
3. Vertical, 6 m, straight.
4. Ramification, 7.5 m (Track B only).

The spiralling was performed at a constant rate in the counter-clockwise direction, with the centre of the two tunnels as the rotation axis. This gave the plane alignment of the tunnels the shape of a cosine curve, and the longitudinal alignment that of a sine curve.

4.4. Ground and Geological Conditions

The ground at the test site consists of the Kanto loam layer at the top and the Shimousa layer underneath, with more or less horizontal stratification (see Fig. 9). The groundwater level is thought to be approximately G.L.-3 m.

For both Tracks A and B, the soil at the starting point (horizontal arrangement) consists of clay fine sand and silt, with an admixture of sand with N-values of 1 to 3. The soil type changes along the spiral; clay fine sand with N-values of 1 to 3 is found around the end of Track B, while clay fine sand with N-values of 2 to 13 are found at the end of Track A (vertical arrangement).

4.5. Shield Tunnelling Machine Specification

The test machine was a 3,500-mm-long slurry-type shield tunnelling machine having two bodies, each with a diameter of 2,120 mm. The machine had the following characteristics:

- The bodies of the shield tunnelling machine could be separated to allow ramification.
- A detachable diaphragm was installed between the tails of the two bodies for assembly of either joined-type or separate-type segments.
- A gap of 50 mm was maintained between the two circular cutter faces positioned on the same plane.

4.6. Segments

Two types of segments (joined-type and separate-type) were used in the test. Both types were steel segments with an external diameter of 2,000 mm and a width of 750 mm, leaving a distance of 2,170 mm between the centres of the two tunnels (see Fig. 10). The inclination of the spiral joined-type segments (inclination of segment ring joint faces) was given as 2.17 degrees from the planned route, using the following equation:

$$\text{Inclination } \alpha = \tan^{-1}\left(\frac{D \times \theta}{L}\right)$$

where

D: spiral radius = 1.085 m
θ: spiral angle = 90 degrees (π/2 rad)
L: spiral section length = 45 m

As shown in Figure 11, straight joined-type segments were used at the start, spiral joined-type segments in the middle, and separate-type single-circle segments towards the end. Abnormal-shaped spiral segments were used at the start of the spiral to create a gentle curve, while joint segments were used at the 45-degree point, at the junction between the sections with joined-type and separate-type segments.

5. Test Results

The shield evacuation progressed smoothly and the spiral and ramification tunnel construction was completed as planned.

5.1. Excavation Control

5.1.1. Spiral Excavation Plan

The articulation angle and copy stroke of the shield tunnelling machine required to produce the planned alignment were determined prior to implementation of the test.

The articulation angle, obtained geometrically from the planned alignment, was the same as the inclination of the segment at 2.17 degrees. The articulation angle was increased slightly in the test to 3 degrees to compensate for the reduction in the copy cut and to obtain a greater spiral effect. The copy stroke was set at 30 mm.

5.1.2. Spiral Excavation Control and Results

The plane and longitudinal paths of the from bodies of the shield tunnelling machine for Tracks A and B are shown in Figure 12. Because of the articulation angle, the paths of the front bodies are found inside the planned align-

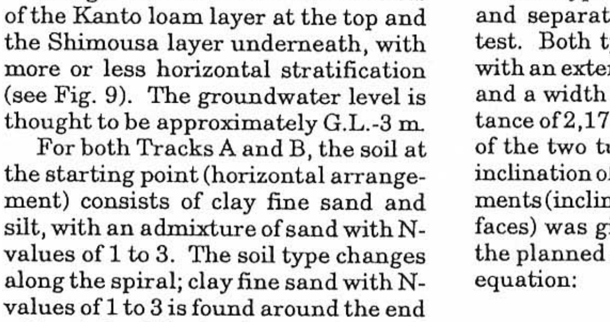

Figure 9. Boring profiles of the test route.

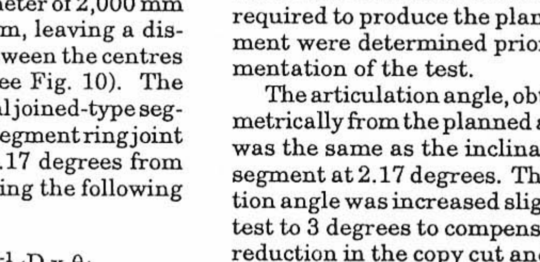

Figure 10. Spiral joined-type segment.

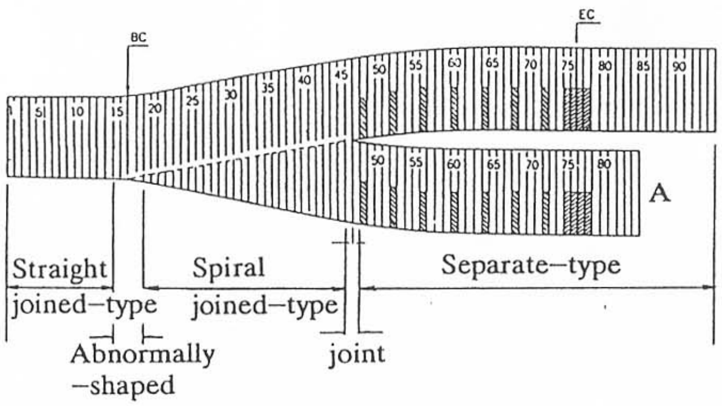

Figure 11. Arrangement of segments.

ment in the plane alignment and outside it in the longitudinal alignment. The front body path generally preceded the planned alignment.

The amount of meandering was greater in the latter half of the spiral excavation in the plane alignment and in the first half in the longitudinal alignment. This is because the deviation in the spiral angle is more likely to affect the longitudinal alignment in the first half of the excavation, and the plane alignment in the second half.

The spiral excavation was controlled by adjusting the articulation angle. The articulation angle in each excavation ring and the amount of spiralling per ring are shown in Figure 13. The articulation angles are given as sums of the angles for Tracks A and B. It can be observed from the figure how the shape of the spiral follows the articulation operation.

Figure 14 shows the correlation between the articulation angle and the amount of spiralling. The correspondence between the two has been adjusted to allow for the time difference between the articulation operation and the movement of the spiral. It is clear from the figure that the amount of spiralling is proportional to the articulation amount of spiralling by adjusting the articulation angle.

5.1.3. Overall Orientation Control

As with conventional shield tunnelling machines, the yawing and pitching of the shield tunnelling machine as a whole could be controlled by selective operation of jacks.

5.1.4. Ramification

Ten rings were constructed on Track B only, to confirm that the shield tunnelling machine could be used to construct branch tunnels underground. The ramification work is outlined below.

The two front bodies of the shield tunnelling machine are joined with a pin, while the rear bodies are joined with a skin plate and bolt. A waterstop plate was installed in the pinhole after the pin was removed from the front bodies. The rear bodies were separated by removing the bolt and cutting off a part of the skin plate. Excavation of Track B resumed after the separation work was completed. The part of the tunnel completed after the separation was constructed in the same way as conventional single-circle shields.

5.1.5. Excavation Control

Because the H&V Shield Tunnelling Machine had two separate chambers and slurry transportation equipment, the slurry pressure on the cutting face was controlled separately. In the test route, the earth cover for Track A increased and that for Track B decreased as the two tracks spiralled, and the control value for the slurry pressure on the cutting face was altered with the progress of the spiral. There was no correlation between the cutting face slurry pressures on the two tracks, as the cutting faces remained independent of one another (see Fig. 15).

The values of the excavation characteristics are given in Table 1. There were no special features resulting from the spiral excavation, because the values were much the same as for conventional slurry shield excavation.

5.2. Earth Pressure Around Segments

Earth pressure cells were installed on the outside of the segments to measure the changes in the loads according to segment types. The results indicate that the loads acting on various parts of the segments are not affected by whether the two tunnels are arranged

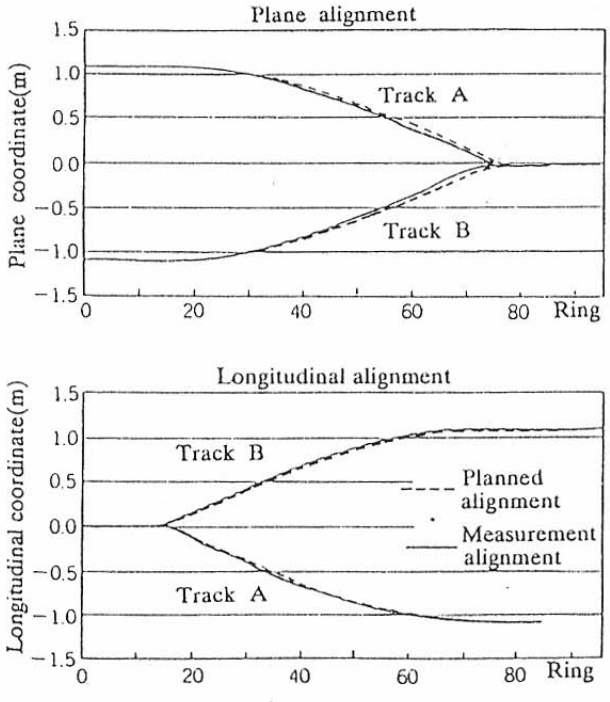

Figure 12. Path of the front bodies of shield machine.

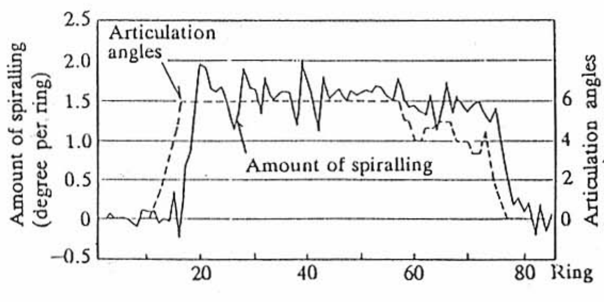

Figure 13. Articulation angle and amount of the spiralling per ring.

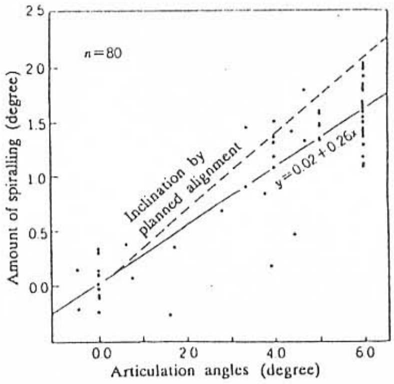

Figure 14. Correlation between the articulation angle and the amount of spiralling.

Table 1. Results of the excavation characteristics.

Characteristics		Track A	Track B
Slurry pressure on the cutting face	Average	0.52 kg/sq. cm	0.28 kg/sq. cm
Cutter torque	Average Maximum	$\alpha = 0.44$ $\alpha = 0.67$	$\alpha = 0.34$ $\alpha = 0.46$
Thrust per unit area	Average Maximum	17.2 t/sq. m 25.7 t/sq. m	
Excavation speed	Average	14.2 mm/min.	

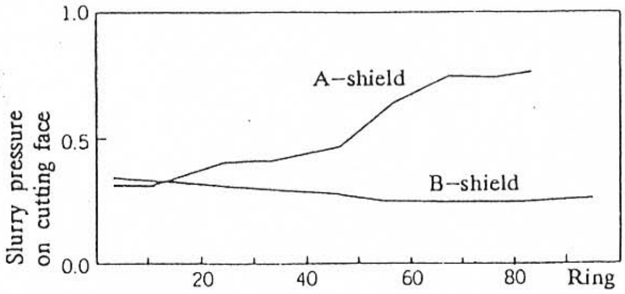

Figure 15. Slurry pressure on the two cutting faces.

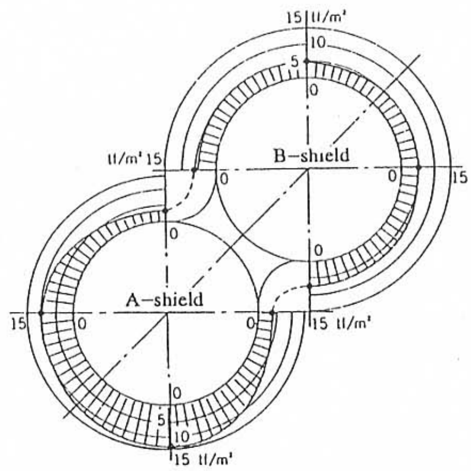

Figure 16. Earth pressure around segment (42 degrees).

horizontally, diagonally, or vertically; the load distribution simply corresponds to the earth cover. The earth pressure distribution on Ring 44 (42 degrees) is given in Figure 16.

5.3. Ground Deformation

Ground surface settlement and ground inclination were measured to assess the effects of the spiral excavation on the surrounding ground. The measurement results are summarized below:

- Seventy to eighty percent of the final ground surface settlement occurred with the passage of the tail of the shield tunnelling machine, as is the case with conventional shield excavation.
- The final ground surface settlement for horizontal, diagonal and vertical arrangements ranged from 6 to 9 mm; there were no major differences between the different types of tunnel arrangements.
- The extent of the settlement was slightly smaller with the vertical arrangement than with the horizontal arrangement.

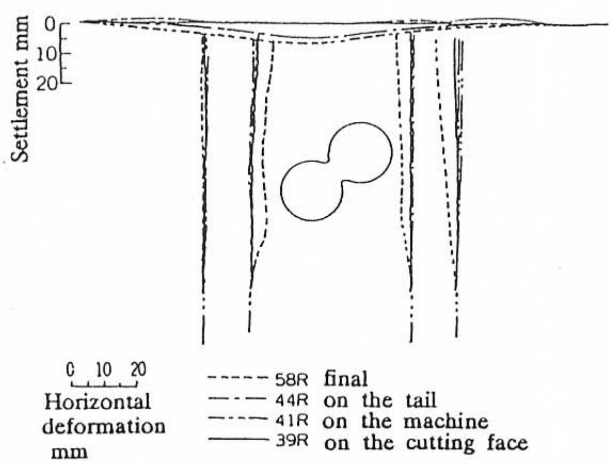

Figure 17. Example of the ground deformation measurement results.

- Examples of the ground deformation measurement results are given in Figure 17. The centre of settlement tends to move toward the deeper shield in the case of diagonal arrangement.
- Figure 18 shows the results of ground deformation measurement for the diagonal arrangement and the results of FEM analysis implemented prior to the test. The two agree closely, indicating that predictions can be made with a fair degree of accuracy using the same prediction analysis procedure as for conventional shield excavation.

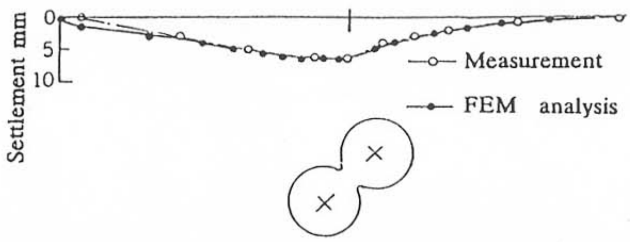

Figure 18. Comparison between ground deformation measurement and result FEM analysis.

6. Conclusion

The verification test results confirmed the possibility of constructing two tunnels positioned extremely close to each other, spiral tunnels and ramification tunnels, as well as the performance of the spiralling mechanisms and, in particular, the effectiveness of the cross-articulation mechanism. It was also found that the excavation characteristics and ground deformation with the H&V Shield Tunnelling Method are more or less the same as those that results when conventional single-circular shields are used.

The development of procedures for effective use of underground space using this method and detailed investigations on the lining structure are underway at present.

The authors believe that the H&V Shield Tunnelling Method will make significant contributions to the effective use of underground space in the future. □

Acknowledgment

Finally, the authors would like to express their gratitude to all those from whom they received guidance and cooperation in developing the H&V Shield Tunnelling Method.

References

Sonoda, T. et al. 1990. Development of and verification tests on H&V Shield Tunnelling Method. In *Proceedings of the 45th Annual Conference, Japan Society of Civil Engineers, September 1990*. Tokyo: JSCE.

Sonoda, T. et al. 1990. Verification tests on H&V Shield Tunnelling Method, Tunnels and Underground, *Doboku Kohgakusha* (November 1990).