

## Construction of subway extension of Kyoto city

— Huge Rectangular Shield Tunnel —

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### Subway of Kyoto City

Kyoto, the former and historical capital of Japan for over 1,000 years, began in 1981 to operate the Karasuma Line which runs 13.7km from south to north as the first subway line. This line was followed in 1997 by the Tozai Line which runs 12.7km from west to east-south as shown in Figure 1. The subway system of Kyoto City was further required to serve for the traffic network combining together with other rail lines. As a part of such an important project, 2.4km of extension from the east-south end of the Tozai Line was proposed by Kyoto City and this plan was approved by the Japanese Government to be implemented.

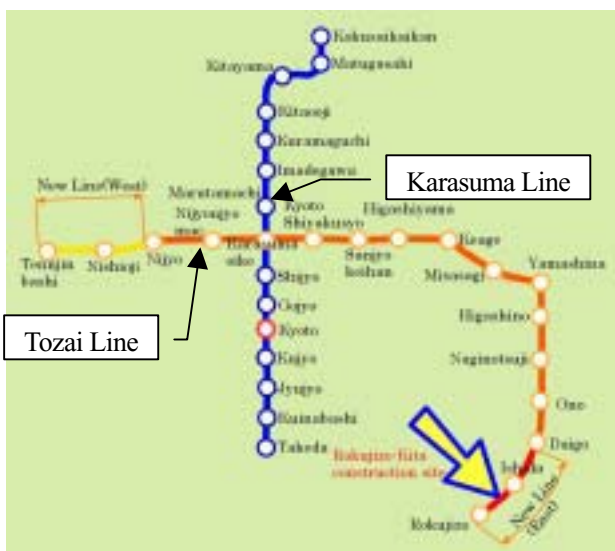


Fig.1: Subway map of Kyoto City

Two new stations along the extended line, Rokujizo and Ishida Stations, were to be built by the cut-and-cover method while the rail tracks between the stations were to be built by the shield tunnel method. The construction of the extended line, which is one of typical urban engineering works, was initiated in 1999.

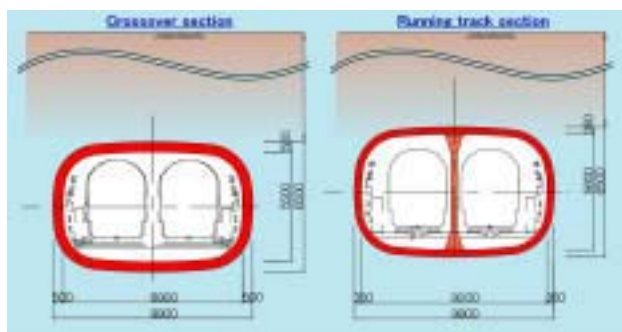
Particularly the construction works near Rokujizo Terminal faced to a lot of difficult issues from the technical point of view. A key to solve these issues was how to construct efficiently the crossover part where the trains transfer from the south-bound line to the north-bound line. This report summarizes the design and construction processes of the crossover section near Rokujizo Terminal.

### Huge Rectangular Shield Tunnel

The Technical Committee of the Kyoto Municipal Traffic Bureau continued to discuss carefully about the construction method for 57m long crossover section just next to Rokujizo Station and finally decided that it should be built by a rectangular shield tunnel without the center pillars and that 703m long running (non-crossover) part up to Ishida Station by a rectangular shield tunnel with the center pillars as illustrated in Figure 2. The reasons why the shield tunnel was adopted even for 57m long crossover section are

- 1) the road above the subway has a quite heavy traffic as a bypass of Route 1,
- 2) it has advantages in cost and construction period if the environmental impact was considered.

The circular shape is, of course, the most popular for the shield tunnel and its design method is well established through many experiences. A rectangular shape of shield tunnel was, however, employed to make both of the track level and the ground coverage appropriate. Indeed the total height of the rectangular tunnel was reduced into almost 2/3 of that in the case of the circular one. The outer horizontal length of the tunnel section is 9,900mm while the outer height is 6,500mm.

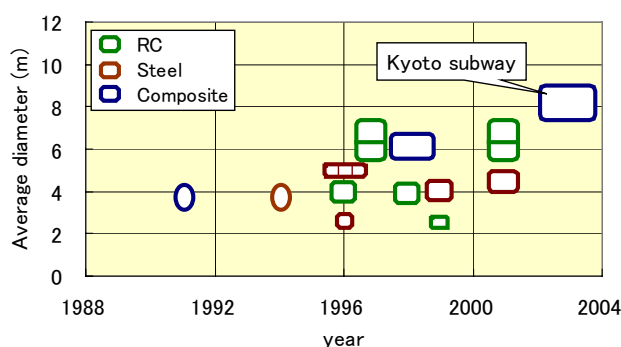


**Fig.2: Two different cross sections**

This huge rectangular crossover section without the center pillars was surely a worldwide new trial in the history of the shield tunnel. One of the most difficult problems in the design of the tunnel segments at this section was how to confirm the mechanical function of the rectangular shield tunnel which has no center pillar.

**Rectangular Shield Tunnels in Japan**

The non-circular shield tunnel excavated by the closed type machine is rather new. Figure 3 shows the chronological development of the non-circular shield tunnel in Japan. In the early stage, the 12m<sup>2</sup> cross section of vertically-long elliptical shape was constructed. In the following 10 years, the triply-enlarged cross section of non-circular shield tunnel with 1.6 of flatness ratio (long radius/short radius) became in practical use. The shield segments were mainly made of steel or were the composite structure of steel shell and cast concrete. But no reinforce concrete (RC) segment has been adopted for



**Fig.3: Development of non-circular shield tunnel in Japan**

the case of the rectangular shield tunnel which has no center pillars. The segment thickness of the steel or composite structure can be, in general, smaller than that of RC segment. There are actually some cases where the ratio of the thickness of segment to the longest diameter is around 5%.

Through a lot of investigation, the composite type of segments with 500mm of thickness was considered to be the most appropriate for the crossover section. On the other hand, the segments of the running section which has the center pillars are made of the ductile cast iron (DC). The top and bottom segments connected by the center pillars are of the corrugate type DC which is highly rigid while other segments are of DC with 4 beam-stiffeners. The thickness of the DC segments was designed to be 350mm. No secondary lining was made for both of crossover and running sections.

The expected rigidity and bearing capacity for the composite and the DC segments were confirmed through the segment-piece test and the assembled-segments test for both types of sections. Photo 1 shows the assembled-segments test of the composite type. As the test results,

- 1) the so-called “spring-beam model” is applicable to the rectangular section when the structural analysis is done.
- 2) the sufficient bearing capacity is assured for both types.



**Photo 1: Assembled-segments test on composite segment rings**



*Photo 2: Connecting part of two different sections*

Some amount of vertical deformation discontinuity cannot be avoided at the connecting part of the crossover portion and the non-crossover (running) portion since both types of segments have the different structural properties. To smoothen such discontinuity, 5 rings of transit interval was placed by using the composite segments with the adjusting center pillars. Photo 2 shows the connecting part of two different sections.

### **Shield Machine**

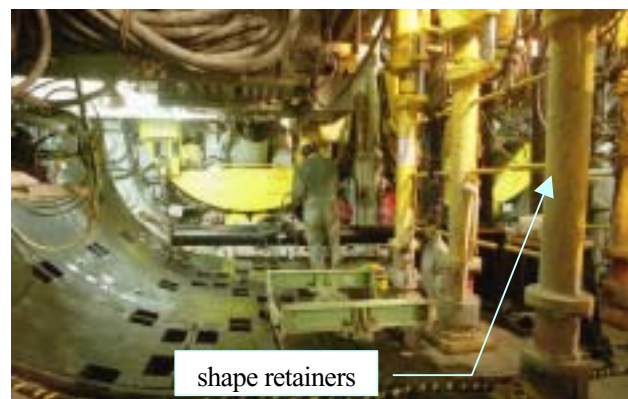
The geological strata from the surface at the construction area are the alluvium, the upper diluvium (terrace deposit) and the lower diluvium (Osaka Group) in order. The shield tunnel was constructed from the south end passing through the upper diluvium to the lower diluvium. The ground coverage is around 12m while the ground water level is located 2-5m below the surface. Most typical shield machine for the rectangular tunnel is of the high density slurry type. Several excavation methods such as “the multi-axes type”, “the swinging type”, “the over-cutter type”, “the eccentric cutter type”, “the eccentric multi-axes type” and “the cylindrical drum type” are practically applied. But experiences of long excavation of the non-circular tunnel for the sandy ground were quite few compared with the circular section since the problems of the reliability of excavation mechanism and the abrasion of bit cutters were still unresolved. Finally the Wagging Cutter Shield method

was adopted for this tunnel which excavates the ground mainly by wagging a pair of cutter heads within a limited angle and has a special over-cutting system to excavate the corners of the rectangular section. Photo 3 shows the front view of the shield machine.



*Photo 3: Wagging Cutter Shield Machine*

The erector which controls 6 axes works to assemble the segments. Three shape retainers shown in Photo 4 are equipped with to reduce the initial deformation of the shield tunnel where no center pillar is installed.



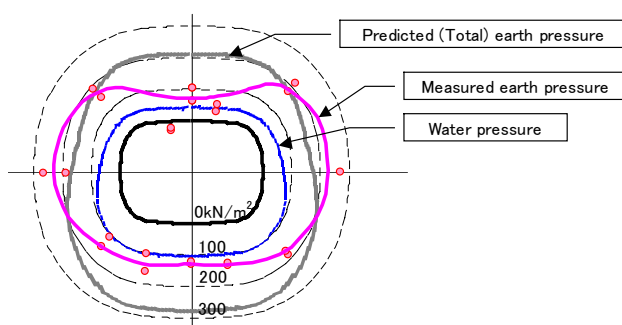
*Photo 4: Shape retainers*

### **Construction Achievement**

The shield machine launched from Rokujizo Station in February, 2002. The initial advancement per

day was 1.72m at the crossover section and 3.15m at the running section. The average advancement per day at the steady state was improved up to around 6m. The following findings were remarked.

- 1) The vertical earth pressure at the crossover section was reduced down to the half of the predicted value after removing the shape retainers as shown in Fig.4.
- 2) On the other hand, the magnitude of the deformation was close to the predicted value. This is considered to be due to the displacement gap between the adjacent segments which was ignored in the analysis.
- 3) The earth pressure and the member forces of the DC segments were almost close to the predicted ones.
- 4) The mechanical conditions of the composite segments and the DC segments were stable with the high safety factors.



**Fig.4: Earth pressure at the crossover section (after removing the shape retainers)**

**New Challenge**

What was the most important point of this construction project is whether the technology established through the circular shield tunnel is applicable to the huge non-circular shield tunnel. The lateral earth pressure of the circular tunnel is believed to increase surely by the vertical deformation at the excavation process which makes the tunnel structure more stable from the mechanical point of view. But such a fundamental mechanism of tunneling has not been verified for the huge rectangular tunnel. In other words, the prediction of

the earth pressure applied to the huge rectangular shield tunnel was quite an interesting and challenging subject. A lot of discussion and experiments by engineers from the beginning of the project for several years led to a new breakthrough for the shield tunneling technology. Based upon the careful procedure as well as the detailed observation on site, the construction was completed very safely and successfully as shown in Photo 5. The deformation and the stress states of the tunnel to date are



kept to stay within the predicted range.

**Photo 5: Completed crossover section (March, 2004)**