APPLICATIONS OF LONG-DISTANCE BORING TECHNIQUES IN HSUEHSHAN TUNNEL

Lee-Ping SHI[1], Jung-Sung TSENG[2], Tse-Hao YEH[3]

ABSTRACT

There were many unpredictable problems such as highly fractured shear zones and huge inflows of pressurized water discharges which were interactively impacting the excavation works in the Hsuehshan Tunnel. In order to deal with these problems, the long-distance boring techniques were used to investigate the geological conditions. The process, length and duration of wire line boring and reverse circulation boring methods are described. The difficulties encountered during drilling included borehole collapsed with large quantities of flowing rate, high rate of bits damaged, shield pipes broken down and stuck of sampling. It is worth to note that long-distance probing information is very good for the TBM excavation, especially in the difficult geological condition. The engineering properties of Szeleng Sandstone can also be evaluated from these investigations. Using the revised drill machine on the TBM head, the criteria of boring rate to rapidly distinguish rock formation are developed. It is recommended that the long-distance boring investigation must be cross-referred with the data acquired from tunnel seismic prediction and resistivity image profile methods to get the most comprehensive understanding of the geological conditions.

Keywords: the Hsuehshan Tunnel, Long-distance boring, Geological investigation

INTRODUCTION

The Hsuehshan Tunnel is the longest tunnel in Taiwan and it is the most important transporting route for the development of eastern region, so how to finish the construction work as quickly as possible is a key issue in the planning stage. According to the European experience, the driven rate by TBM can be raised up to several times as compared to D&B method. As this is the first time using TBM for tunneling in Taiwan, there was a little bit optimistic anticipation on completing the Project. However, the extremely unfavorable ground condition broke down the whole hopeful scheme.

The Seikan Tunnel is a valuable national asset, which required about quarter of a century foconstruction. Furthermore, in the near future, it has another mission to be used as a tunnel for the Hokkaido Shinkansen Bullet

The pilot tunnel started to use TBM for excavation at December 1992. The driven length was about 1080 m when the tenth stoppage happened in February 1996. The phenomena from the first to seventh TBM stoppages can be generally described as the collapse of excavation face and a great volume of debris coming out from bucket of cutter head. It didn't seem too much difficult to get out of the jammed condition. After the seventh stoppage, there was a combination effect of high inflows pressurized groundwater. Under the interaction of fractured shear zone and highly pressurized water influxes, the loosening zone was more enlarged due to its fine grain material continuously carried out by discharge water. Finally the TBM was buried and the support systems were ruined by the increasing pressure. It seemed that the tenth stoppage was most serious stuck in the pilot excavation.

The main difficulty of the construction came from the geological condition, particularly in the Szeleng Sandstone layer. Because the distributions of geological structure and groundwater are very complicated, it is not easy to predict exactly the insitu condition before excavation, especially for irregularly high or low angle shear zone which hide a large quantities of pressurized groundwater. Those interactively combined effects

1. Manager of Division I , Planning and Information Department , RSEA Engineering Co.
2. Chief of Planning Section , Pei-Yi Project Office , RSEA Engineering Co
3. Deputy Director , Pei-Yi Project Office , RSEA Engineering Co

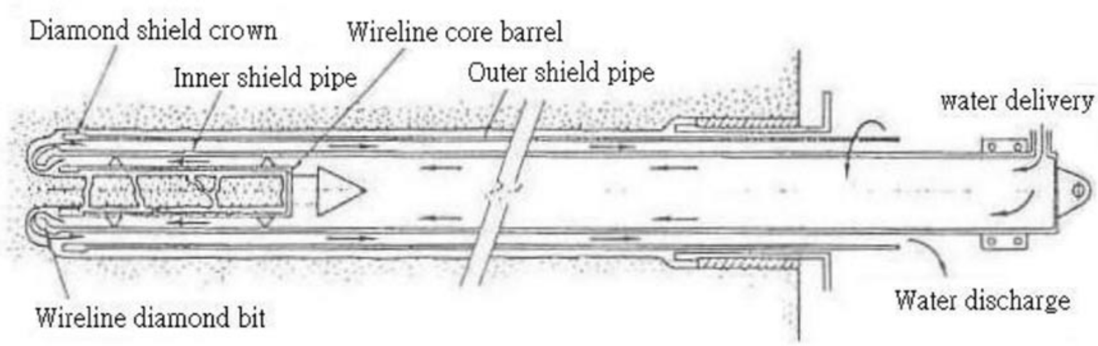

Figure-1 Schematic view of wire line boring method

created a lot of problems during excavation (Hsieh and Shi, 1998).

Since the source of all problems came from the geological condition, it is the most important task to get a comprehensive understanding of the geological properties ahead of the excavated face. In this paper, the applications of long-distance horizontal boring methods include wire line boring and reverse circulation boring are discussed. The problems encountered, techniques improved and experience gained from these methods are described in detail. The applications of other methods such as revising the drill machine on TBM head, tunnel seismic prediction and resistivity image profile are also taken into consideration.

Unlike the vertical borehole which only gets the small area of ground data for tunnel excavation, the long-distance horizontal drilling can usually get more geological information from the excavation face. The torque capacity of the machine is large, more than 400 kg-m in general. It is not easy to let the whole heavy equipment set well down to the working site, therefore the boring length are planned to reach as long as possible. The shield pipes are used from the larger size and then gradually down to the smaller size to get the longest distance of the borehole.

LONG-DISTANCE BORING

The first wire line boring

There was a water discharge over 100 l/sec and water pressure as high as 20 kg/cm2 after the tenth stoppage in the pilot tunnel. The long-distance boring techniques were introduced to investigate the location of the shear zone and water bearing layer. The first long-distance probe was driven by wire line method as shown in Figure-1 at pilot tunnel station 39k+150. The side enlargement of the tunnel for the space of apparatus must be done before driving. The cores can be taken out by the wire line without removing or dismantling the rods, outer barrel assembly and bits. It is the most efficient method for the long-distance boring.

The target of the driven length was set at 300 m. Since the company for driving had just finished about 700 m boring in the Shihlin Hydropower Project, it was quite sure to get good result. However, there were many water influxes and borehole collapsed during drilling, it needed to be pre-grouted and re-bored over again and again. The diameter of borehole must be changed to the smaller size under this difficult condition. At last, the drilling work was stopped at 107.25 m due to the rod broken down to the bottom of borehole. It took about 52 days in this drilling work.

There were 22 cases of water flowing out during boring, the maximum pressure was 20 kg/ cm2 and the rate of flow was 21 l/sec. In order to deal with the borehole collapse problem, several stabilizing agents were tried to use but no significant effect was found. Total volume about 130 m3 of the cement mortar was injected to the rock drainage hole under this condition due to all of the joints around hole filled with cement grouting material. There were totally 42 bits used in this case.

Reverse circulation boring

In order to overcome the difficulties of unstable borehole used for the drainage, the reverse circulation boring system as shown in Fig. 2 was introduced to the job site (RSEA Engineering Co., 1997). It has been achieved about 2000 m length horizontal borehole in construction of the Seikan undersea tunnel. The water supplying between outer and inner shield pipe is the special design of this system. In the highly fractured rock mass with pressurized groundwater, the rock samples are washed

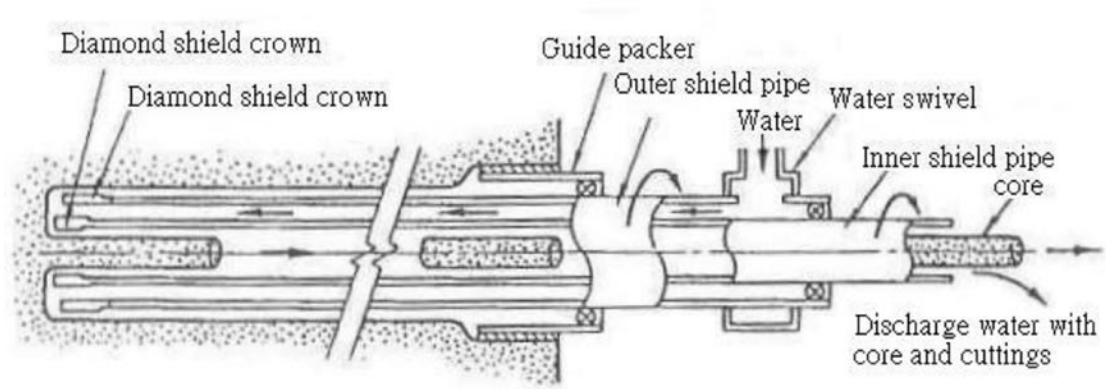

Figure-2 Schematic view of reverse circulation boring method

out by the flow from the end of borehole. The geologist must stay at job site to make the judgment about the ground condition immediately. If the quantity of flow is too large for the operation of boring, then this borehole can be remained for draining.

There are two boreholes drilled by reverse circulation boring system. These two boreholes are categorized as the second and the third horizontal long-distance drilling respectively. The second one drilled at pilot tunnel station 39k+119. After 30 days, the drilling length approached to 107 m, it encountered 18 kg/cm2 water pressure and 117 l/sec flowing rate. This borehole was left as drainage pipe to release the highly pressurized water. 46 bits and 36 old shield pipes were used for this boring. The third drilling location started from station 39k+019. In order to improve the high damage rate of bits and shield pipes, the strengthen bits and the new pipes were used. When the length of drilling to 126 m, duration about 60 days, it encountered 12 kg/ cm2 water pressure and 80 l/sec flowing rate. This borehole was also remained as drainage pipe. There were 41 bits and 23 shield pipes used in this investigation.

The typical fractured rock samples from the second borehole are shown in Photo-1 and Photo-2. It is noted that there is a highly fractured zone followed by the fault gouge at depth 59 to 61 m in Photo-2. It was found that the thickness of the fractured zones and fault gouges were about 3 to 5 m. From insitu geological condition, it can be regarded as a continuous fault whose influential scope for tunnelling may be up to 20 m. When the borehole was drilled into this fault in the beginning, from station 39k+060 to 39k+057, there was very little groundwater. Until it was bored through station 39k+046, the flowing rate and water pressure were increasing gradually. It was realized that there was some groundwater behind the fault. After drilling to 39k+023, the flowing rate suddenly increased up to 100 l/sec. It was worth to note that there must be one groundwater passage or a large volume of water storage. Therefore, the tunneling works here were planned and constructed very carefully.

Boring by grouting

Since it seemed to be unavoidable problems for the borehole collapsed with high pressurized groundwater influx during drilling, the sophisticated grouting method for wire line boring was proposed to increase the length of investigation (Groundmat Construction Co., 2000 and 2003). The grouting materials include cement, calcium chloride ($CaCl_2$), plasticizer and bentoline. The calcium chloride is used to fasten the strength developing process, the plasticizer can increase the workability, and the bentoline is used to strengthen the water proof effect. In order to make the bentoline sufficiently mixed with water and get inflated liquid very quickly and to solve the problem of the very limited space for storage, the colloidal high-shear cement grout mixers were utilized.

There were three boreholes drilled by this method. The fourth one located from the pilot station 38k+437 to 38k+175. It was expected to explore the condition of the Shihpai Fault. When drilled to the length of 262 m, it is found that the deviation was 9 m above the designed route. The work stopped due to the samples far away from the face of excavation. It expended 73 days for boring work and 27 bits were used. The fifth borehole started from the end of previous one. After 130 days boring, it reached the length of 480 m. The sixth borehole located from station 32k+250 to 31k+770, 480

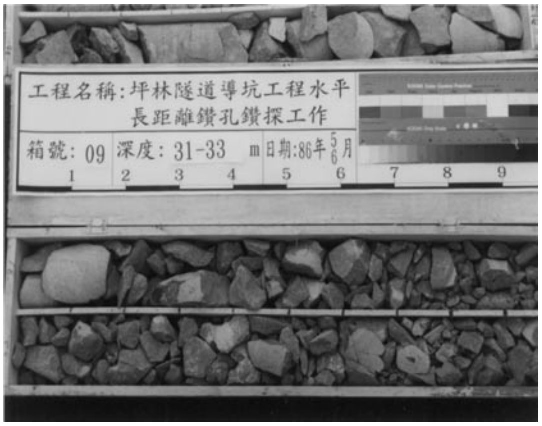

Photo-1 Fractured rock samples from the second borehole at depth 31-33 m.

Photo-2 Fractured rock samples from the second borehole at depth 59-61 m.

m in length. It was drilled to investigate the condition of the Shihsao Fault. The duration of work was 92 days and 17 bits were used. Summary of these 6 borehole conditions are shown in Table-1.

DIFFICULTIES IN LONG-DITANCE BORING

The problems observed during these horizontal long-distance borings, such as borehole collapsed with large quantities of flowing rate, high rate of bits damaged, shield pipes broken down and stuck of sampling, are described as the followings .

Borehole collapsed with large quantities of flowing rate

It can be found that the major problems were coming from the borehole collapse with large quantities of flowing rate in long-distance boring. The maximum flowing quantities was 117 l/sec and the maximum water pressure was 20 kg/cm2. The appropriate grouting method must be adapted in order to increase the length of drilling. It is worth noted that the boring length increase from 100 m to 480 m when the suitable grouting materials were used as shown in Table-1.

High rate of bit damaged

It was observed that the damaged rate of bit was high in Szeleng Sandstone. Generally a new bit needed to be exchanged after 5 to 10 m drilling. The bits were instantly suffered very high impact reactions due to the characteristics of highly fractured and extreme hard rock. The bits were easily torn down and worn away under this condition. It also spended much time to renew the bits and re-drill the hole.

Shield pipes broken down

The shield pipes were often broken down during the long-distance drilling. Two failure mechanisms for the breakage of shield pipes can be considered. One was pipes cut by the sharp edges of hard rock; the other was too much bent of pipes during drilling. When the borehole collapsed, the shield pipes could be cut or damaged by the sharp edges of the fallen hard rock under its rotating. The damaged scotch became the source of the breakage under the action of thrust and torque applied. It is noted that the bent of shield pipes might also cause the failures. For example, the allowable deviation of reverse drilling system is 2o for 300 m boring. If the bent declination over the designed angle, it need to apply more torque from the power supply. The pipes usually break down at the connections or damaged sections under this circumstance. It is found that there are so many shear zones or faults which can really influence the drilling direction and cause problems during

Table-1 Summary of the long-distance boring results

Borehole No.	Boring length, m	Duration, day	Boring rate, m/day	Bits used
1st	107	52	2.1	42
2nd	103	30	3.4	46
3rd	126	60	2.2	41
4th	262	73	3.6	27
5th	480	130	3.7	63
6th	480	92	5.2	17

Table-2 Boring rate without taking cores for different rock formation by down-the-hole drill machine

Rock formation	Boring rate, m/min
Quartzite	10~30
Argillite	30~50
Fault or shear zone	>50

drilling..

Stuck of sampling

The irregular and sharp shape of rock samples which are carried out by supplying water may be stuck in the inner shield pipe. These samples cannot be taken out without withdrawing each inside pipe. It is a time-consuming work. If boring through fractured rock mass, it is necessary to use cement grouting for stabilizing the ground.

Similar problems encountered in TBM excavation

The borehole drill can be thought as a down-scale TBM excavation. The problems encountered in drilling will be expected to happen in TBM excavation. General speaking, the difficulties in TBM excavation could be more serious than in drilling. It is noted that the difficulties encountered in TBM excavation include collapse of rock mass, large quantities discharge with high water pressure, obstruction of TBM, high rate of wear and damage of disc cutter, indent and breakage of shield, etc. It was almost what happened in the long-distance boring. Therefore the information from long-distance boring is a good index for TBM excavation. It is worth using long-distance probing for the TBM excavation, especially in the difficult geological condition.

APPICATIONS OF OTHER METHODS

Although the long-distance boring is helpful investigation for TBM excavation, it spends too much of time and money. In order to solve these kinds of problems, the alternative methods such as revising the drill machine on TBM head, tunnel seismic prediction and resistivity image profile were also taken into consideration.

Revising the drill machine on TBM head

There was one drill machine built on the TBM head, but its original design did not seem suitable in Szeleng Sandstone. Its torque capacity was too small to get more than 20 m boring. After reconsideration, the down-the-hole hammer type of drill machine was chosen to substitute the old one. Its torque capacity increased to 800 kg-m with 65 mm outer diameter bit. It can get 50 m borehole without taking the cores in 12 hours. The rock formation can be determined by the boring rate using this machine. It is really easier and much more time saving work than that of long-distance boring. According to data obtained from job site, the corresponding boring rate with different rock formation is shown in Table-2. It can be seen that the harder of the rock formation responses the slower of boring rate. Using these experienced criteria, the insitu geological condition can be quickly judged.

TSP and RIP methods as preliminary investigations

Except the long-distance boring, the TSP and RIP methods were also used for this Project. The shear zones or faults can be roughly detected about 100 m to 150 m ahead of the excavation faces by the TSP method. It can quickly get the general views about the discontinuous geological condition. Because it is quite easy to perform the TSP survey on excavation face, it became a routine work during the pilot tunnelling. Meanwhile, following some good results got from hot spring survey and discharge source investigation in tunnel excavation, the RIP method was also promoted in this Project. The aquifer can be distinguished by the RIP method from the ground surface in a short period of time. This method was performed at the pilot sta. 36k+800-38k+200, east bound sta. 29k+200-31k+200 and sta. 32k+700-34k+200, total 6 km in length.

Since the distribution of geological structure and ground water can be determined by TSP or RIP method on large scale, the long-distance boring plan can be efficiently proposed according to the results surveyed by TSP and RIP methods. The information got from long-distance boring can also be used to check the geological conditions acquired from TSP and RIP methods.

CONCLUSIONS

In order to deal with unstable and huge inflows of pressurized discharge problems during the Hsuehshan Tunnel excavation, the long-distance boring techniques were used to investigate the geological conditions. There were six long-distance borehole drilled by wire line boring and reverse circulation boring method. The boring length increased from 100 m to 480 m after some appropriate grouting method was adapted. The difficulties encountered during drilling include borehole collapsed with large quantities of flowing rate, high rate of bits damaged, shield pipes broken down and stuck of sampling. The properties of Szeleng Sandstone can be concluded as high strength, joints well developed to highly fractured with faults and shear zones, and unexpected huge inflow of high pressurized water discharge. Since the borehole drill can be considered as a down-scale TBM excavation, it is worth to note that long-distance probing investigations are very good for the TBM excavation, especially in the difficult geological condition. Using the revised drill machine on TBM head, the experienced criteria from boring rate to rapidly judge rock formation are developed. It is recommended that the long-distance boring investigation must be cross-referred with the data acquired from tunnel seismic prediction and resistivity image profile methods to get the most comprehensive understanding of the geological conditions.

.

REFERENCES

* Hsieh, Y.S. and Shi, L.P. (1998), “The Engineering Characteristics of Szeleng Sandstone in the Pinglin Tunnel of Taipei-Ilan Expressway Project”, Proceedings of Regional Symposium on Sedimentary Rock Engineering, pp. 51-56.

* RSEA Engineering Co., (1997), Test Drilling for Horizontal Long-distance Probe and Evaluation of Available Methods for Grouting and Water Sealing in the Pinglin Pilot Tunnel of Taipei-Ilan Expressway Project (in Chinese).

* Groundmat Construction Co., Reports of Long-distance Borehole LHD-4 (July 2000), LHD-5 (Oct. 2000) and LHD-6 (2003) in the Hsuehshan Pilot Tunnel of Taipei-Ilan Expressway Project (in Chinese).