REVIEW AND ADJUSTMENTS OF THE CONSTRUCTION PLAN FOR THE HSUEHSHAN TUNNEL

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ABSTRACT

The Hsuehshan Tunnel is about 12.9 km in length, and is the longest Tunnel of the Taipei-Ilan Expressway that connects the Western end of Taipei to the Eastern end of Ilan County. It is located in the Hsuehshan Mountain Range where geological conditions are varied and complex. The original construction plans for the Tunnel were modified to reflect the conditions of the site during the implementation.

The construction entailed excavating two parallel Main Tunnels each 12 m in diameter and one Pilot Tunnel situated between and slightly below the two main Tunnels. The Pilot Tunnel was to provide service and maintenance for the Main Tunnels during their operation in the future. In the original construction plans, the excavation of the Pilot Tunnel was to begin in July 1991. The drill and blast (D&B) method was to be used for excavating the first 1,000 m and 150 m respectively from the East and the West Portals of the Pilot Tunnel, while the remainder of the Pilot Tunnel was to be excavated by the Tunnel boring machine (TBM). The excavation of the Main Tunnels was to begin in July 1993. The D&B method was to be used for excavating the first 700 m and 150 m of the Main Tunnels from the East and West Portals, while the TBM excavated the remainder of the Main Tunnels. However, the actual length of the Tunnels excavated by each method varied with the geological and construction conditions encountered.

The anticipated distribution of rock formations and groundwater, the positions and scales of the major faults and weak geological zones, etc, obtained during the planning and design stages were not much different from the actual ones observed during the construction. But the low angle shear zones and the precise positions and quantities of groundwater could not be identified completely with existing geological techniques. Consequently, the previously planned excavation lengths and methods were adjusted in reaction to the geological conditions of the site. In this paper the construction plan and the adjustments made to it in the course of constructing these Tunnels are reported and reviewed. The presentation of these adjustments may serve as a reference for future Tunneling works of a similar nature.

Keywords: Drill and Blast Method, D&b Method, Tunnel Boring Machine, TBM, Geological Conditions, Distribution of Rock Formations

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INTRODUCTION

The Hsuehshan Tunnel of the Taipei-Ilan Expressway has a total length of 12.9 km. This Tunnel cuts through the Hsuehshan Range in Northern Taiwan. The Tunnel is located on a plate collision belt of the earth and therefore there are dense concentrations of faults and shear zones. The rock mass is fractured and contains an abundant amount of highly pressurized groundwater. The geological conditions are complicated and varied. Since the commencement of construction work in July 1991, great difficulties were encountered regardless of whether excavation was done through conventional drill and blast method or by means of a TBM. It was impossible to have a thorough understanding of all the varied geological conditions during the planning and design stages. Therefore, during the construction period, the actual construction implementation plan had to be constantly adjusted in reaction to the actual geological conditions revealed through in situ geologic exploration and actual construction situations. Because of this, the actual construction implementation plan often differs from the original contracted construction plan. In September 2004, after 13 years of hard, trying work, the first breakthrough of the Hsuehshan Tunnel was achieved. This paper presents a look at the experiences gained in the construction of the Hsuehshan Tunnel, and casts its sights forward to venture a simple report on future construction design and adjustments. It is sincerely hoped that this previous experience will serve as reference for engineering future Tunnels.

ORIGINAL DESIGN CONSTRUCTION PLAN FOR THE HSUEHSHAN TUNNEL

General Description of the Construction Project

The Hsuehshan Tunnel of the Taipei-Ilan Expressway is situated between Pinglin, Taipei and Toucheng, Ilan. The construction contract was awarded in two separate lots, Lot 4 and Lot 5. Lot 5 was the Pilot Tunnel construction project. The Pilot Tunnel is a Tunnel 4.8 m in diameter with a length of 12.9 km. The main purpose of the Pilot Tunnel was to provide geological investigation ahead in advance of the main Tunnels and also to serve as a work Tunnel for conducting ground pre-treatments. Upon completion of the Expressway, the Pilot Tunnel will serve as a passage for maintenance and emergency rescue access. The Pilot Tunnel construction project was awarded to the Retired Soldiers Engineering Services Administration (RESA) in December 1990 following price negotiation. Construction work commenced in July, 1991. The projected work period was 1,350 calendar days, and it was scheduled for completion on 25th March, 1995. The total contract cost was 2 billion NT dollars.

The construction project for the main Tunnels of the Taipei-Ilan Expressway constituted Lot 4 of the contract. This construction project was comprised of excavating two main Tunnels, each with diameters of 11.7 m and lengths of 12.9 km. These Tunnels were to be two one-way, two lane tubes of a highway Tunnel. The distance between the centers of the Tunnels was 60 m. There were to be 28 connecting pedestrian passages, 8 traffic connecting lanes, and 3 separate ventilation shafts equipped with machine rooms and relay stations. At the Toucheng End there were to be viaducts that connected the Toucheng Section of the Expressway with the Toucheng-Suao Section of the Expressway. The construction project for the main Tunnels was awarded to the Retired Soldiers Engineering Services Administration (RESA) in May 1993 following price negotiation. Construction work commenced in July 1993. The projected work period was 2,250 calendar days, and it was scheduled for completion on 19th September 1999. The total contract cost was 18.5 billion NT dollars.

The Original Construction Plan

At the planning stage of the Hsuehshan Tunnel, the drill and blast (D & B) method of Tunnel construction was a mature method. Hence it was feasible to excavate the Hsuehshan Tunnel using the drill and blast method. However, for the proposed 10 km length of the Tunnel that would be located within the area of the Taipei Water Source Conservancy, the use of the drill and blast excavation method might pose a serious threat of pollution to Taipei's main water source, and setting up a new water treatment plant would involve excessive expenditure. The Hsuehshan Tunnel was to be 12.9 km in length, and the third longest Tunnel in the world. If the drill and blast construction method were to be adopted, and excavation were to proceed from the Toucheng End going in only one direction, the estimated construction period would be as long as 20 years. Furthermore, the maximum caprock over the Tunnel was in excess of 700 m. If extra work faces were to be set up to increase the progress of work and reduce the working period, the access Tunnels for such work faces would be over 2 km long. Thus, all things having been considered, the conclusion was that constructing the Hsuehshan Tunnel using the drill and blast method would be riddled with difficulties. On the other hand, Tunnel boring machines (TBMs for short) had been in use in most long Tunnel construction projects in the world, and were achieving excellent results especially in small cross section Tunnels. After considering the fact that TBM Tunnel excavation was achieving excellent results while imposing very minimal impact on the environment, and also considering the possibility of advancing Tunnel construction techniques in Taiwan, top executive officers from the client, consulting firms, and the contractor toured a subsurface flood control pipeline project that was employing a TBM to excavate Tunnels with diameters of 9.1 to 10.8 m in Chicago, in the United States. At the time of the visit, that TBM excavation was attaining an average advance rate of 335 m per month. Upon returning from this tour, the contractor expressed confidence in excavation using TBMs, and made an estimate of advancing at a monthly rate of 350 ~ 400 m in ground with good geological conditions and advancing 250 ~ 300 m in ground with faults or difficult geological conditions. From that date on, TBM excavation became an important study topic for all investigative stages of the Hsuehshan Tunnel Project.

Asian Expressway Consultants (AEC) performed a detailed study comparing excavating the Hsuehshan Tunnel by means of the conventional drill and blast method with using TBMs. In the report, it was concluded that excavating the Hsuehshan Tunnel using TBMs was superior to excavating through the drill and blast method. Therefore, the AEC recommended using the TBM. The following arguments also favoured utilizing TBMs for excavating the Hsuehshan Tunnel:

1. 10 km of the total 12.9 km length of the Hsuehshan Tunnel is located within the Taipei Water Source Conservancy Area. Relevant authorities expressed strong concerns over minimizing pollution in the Water Source Conservancy Area.
2. The conventional drill and blast excavation method would require additional work faces somewhere along the Tunnel alignment, and this would mean excavating access Tunnels for these work faces. The length of such access work Tunnels would be 20 km and have longitudinal gradients of 8%. There would be many difficulties in regards to the mucking, draining, and ventilation of these access Tunnels. In addition, there would be six work faces within the water conservancy area.
3. The Hsuehshan Tunnel was to be 12.9 km in length. If the conventional drill and blast excavation method were to be employed, and resulted in an expected advance rate of 50 m per month, excavation in one direction would mean that the Tunnel would require 20 years to complete. This was deemed highly uneconomical.
4. There was a 10 km stretch of ground with good geological conditions that would be highly suited to TBM excavation. In this stretch, TBM excavation would be several times faster than the conventional drill and blast method, and demand less construction workers. The remaining 3 km of ground with less than desirable geological conditions would be pre-treated to facilitate TBM excavation.
5. Excavation by TBM going in an East to East Portal would facilitate mucking and draining and have the least impact on the environment. Waste material from the excavation could be utilized for fill in the construction of the Toucheng Interchange.
6. Long Tunnel TBM excavation has become a trend in Tunnel engineering in the world. TBM performance has been greatly improved in recent years, and has gained wide recognition. The use of TBMs in the excavation of the Hsuehshan Tunnel would double as a training program for TBM operators in future long Tunnel excavation projects in Taiwan.
7. Employing TBMs in the excavation of the Hsuehshan Tunnel was jointly decided on by foreign experts who were experienced with TBMs or TBM operations. These experts deemed excavating the Hsuehshan Tunnel using TBMs to be viable following detailed appraisals that took into consideration economic and time factors, safety and labour demand issues, and construction feasibility.

In accordance with the contract stipulation, the Pilot Tunnel would be constructed using the drill and blast method. This was mainly due to the fact that geological conditions at the East Portal of the Tunnel were less than ideal for excavation by TBM. Hence, if this Portal section of the Pilot Tunnel was to be excavated using the drill and blast method, the time schedule would allow for the time to acquire the TBM. It could be manufactured, transported to the site, assembled and eventually launched for operation. Excavation by drill and blast would also prepare the launching site for the TBM at the East Portal. The West Portal of the Pilot Tunnel would then be used as a site for the dismantling of the TBM following its exiting of the Tunnel. Under this scenario, the first 1000 m of the East Portal Section, and the first 150 m stretch at the West Portal would be excavated through drill and blast method, while the rest of the Tunnel would be excavated by the TBM. To enhance the advance rate of the excavation, it was stipulated that the TBM should be capable of segment erection during excavation, and thus, a double shielded TBM was chosen. The contractor's proposal stipulated that the advance rate for the drill and blast method would be 50 m/month. The contractor's proposal also stipulated that the advance rate for TBM excavation at the East Portal of the Pilot Tunnel would be 220 ~ 670 m/month, depending on the geological conditions (Figure 1). Since this was the first time any TBM had been used in Taiwan, it was stipulated in the contract that the first 3 km should be constructed through technical cooperation with a foreign firm that had prior TBM Tunnel excavation experience. For this contract, the contractor opted to enter into technical cooperation with Robbins Co., U.S.A., the manufacturer of the TBM. Robbins' operators would actually be performing the excavation operation for the first 3 km of the Tunnel while also acting as technical supervisors to RESA operators to achieve the goal of technology transfer.

The Lot 4 construction planning philosophy was similar to that of the Pilot Tunnel philosophy. The first 800 m of the East Portal and the first 150 m of the West Portal would be excavated by the drill and blast method. The balance of the Tunnel would be excavated by double shielded TBM heading from the east towards the west. The contractor submitted an estimated drill and blast advance rate of 60 m/month. For the TBM the contractor submitted an estimated average advance rate of 358 m/month. Since the contractor lacked experience working with TBMs, it was stipulated in the contract that the contractor should seek technical cooperation with a foreign firm with TBM operation experience. Following evaluation, the contractor entered into a technical cooperation contract with the French firm Spie Batignolles (S.B.). Spie Batignolles would be responsible for the excavation of the Eastbound Tube of the Main Tunnel, and assume a supervisory duty in training RESA operators in excavating the Westbound Tube of the Main Tunnel. The design and manufacture of the two TBM's for the main Tunnel had been adjusted in accordance with reference to that of the Pilot Tunnel. These TBM's were designed and manufactured by Wirth of Germany.

ACTUAL GEOLOGIC CONDITIONS OF THE HSUEHSHAN TUNNEL AS REVEALED BY EXCAVATION

The Hsuehshan Tunnel is located in the slightly metamorphosed sedimentary rocks of the Hsuehshan Range which is a geologic sub province of the Central Mountain Range. Rock formations there were affected by folding and faulting. The maximum overburden there was over 700 m. Approximately one quarter of the Tunnel alignment was to be in Szeleng Sandstone. These rock formations are located in the East half of the Hsuehshan Tunnel, approximately east of Sta. 36 K. These rock formations are mainly comprised of light grey to white quartz sandstone with occasional intercalations of dark grey, fine to medium-grained quartzite and carbonaceous shale. The intercalations are from several centimetres thick to several tens of centimetres thick. The quartzose sandstone is hard but brittle, and when affected by orogenic compressive and faulting processes, is intensely fractured and faulted, and the rock mass is highly fragmented. Groundwater there is either stored in fragmented rock masses or when stopped by fault zones, stored behind the fault zones, forming excellent subsurface aquifers. The remaining three quarters of the Tunnel alignment were underlain with rocks of the Kankou Formation, the Tsuku Formation, the Tatungshan Formation, the Makang Formation and the Fangchiao Formation. The lithologies of these formations are mainly sandstone, shale, and alternations of sandstone and shale (Figure 1).

The alignment of the Hsuehshan Tunnel cuts through six regional faults. Arranged in an east to west order, these faults are the Chinying Fault, the Shanghsin Fault, the Paling Fault, the Northern Branch of the Shihpai Fault, the Southern Branch of the Shihpai Fault and the Shihtsao Fault. Tunnel excavation also revealed that the Tunnel also intersects numerous unnamed small faults besides these six regional faults. The alignment of the Hsuehshan Tunnel also cuts through a number of fold structures including the two major fold structures which are the Yingtsulai Syncline and the Taotiaotsu Syncline. There are also nine other fold structures. Most of these fold structures occur in rocks of the Tatungshan and Fangchiao Formations, with only one exception: the fault block between the Paling Fault and the Shanghsin Fault seems to be a gentle anticlinal structure formed of fine-grained quartzose sandstone of the Szeleng Sandstone. This anticlinal structure plunges towards the Southeast. This is the only fold structure located within the rocks

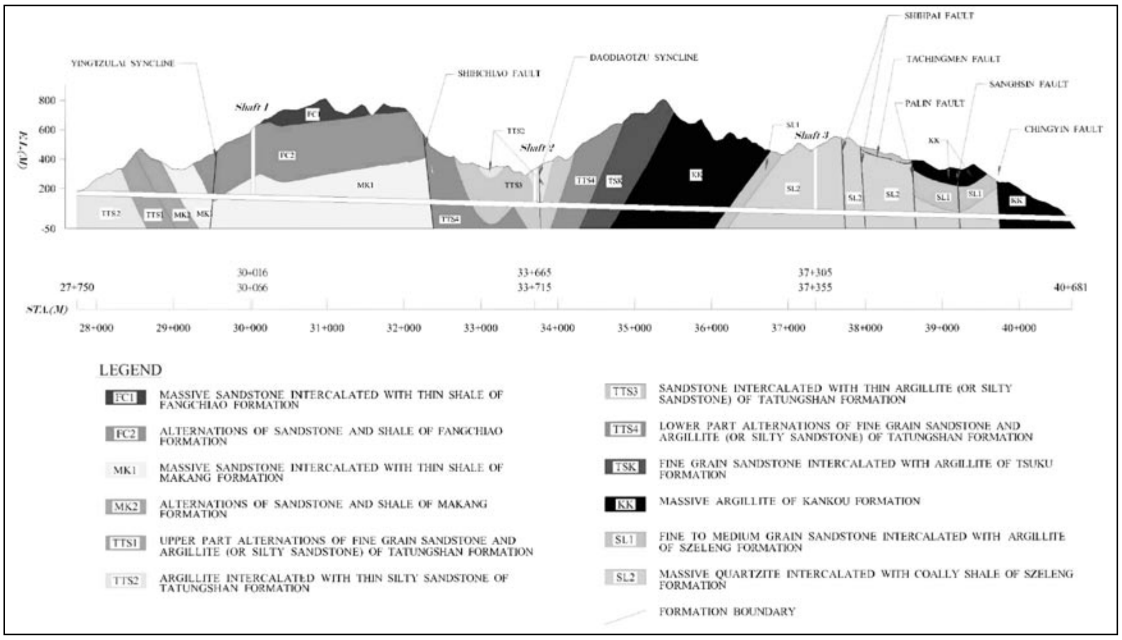

Figure 1. Geologic Profile Section along the Hsuehshan Tunnel

of the Szeleng Sandstone along the Hsuehshan Tunnel alignment.

During excavation, the Hsuehshan Tunnel, inclusive of the Pilot Tunnel and the main Tunnels, encountered 98 shear fracture zones with widths of over 50 cm. These included the 13 sites where the Pilot Tunnel TBM was trapped, the 36 incidences of groundwater influx, and the 42 cave-ins and collapses during the drill and blast excavation. In general, the lithologies and rock mass qualities on the Western half of the Hsuehshan Tunnel are better than those on the Eastern half.

MODIFIED CONSTRUCTION PLAN FOR EXCAVATION OF THE HSUEHSHAN TUNNEL

Since commencement of construction work for the Hsuehshan Tunnel in 1991, three construction stages are recognized:

Stage 1. July 1991 to December 1998. Execution of Tunnel construction work followed the construction plan as laid down in the contract. This called for completion of the Pilot Tunnel on 25th March, 1995. The entire Tunnel was slated to open for traffic by the end of 1999.

Stage 2. January 1999 to November 2001. In this stage, due to serious work delays and grave damage to the TBM in the Westbound tube of the main Tunnel an alternative construction plan was proposed. In this revised plan, additional excavation faces were added in order to catch up with the delayed work schedules. The adjusted date of completion for the Pilot Tunnel was February 2003, with the entire Tunnel open for traffic in June 2003.

Stage 3. After December 2001: The Eastern half of the Hsuehshan Tunnel was still being excavated in the section with adverse geological conditions, and construction results were negligible. A revised construction plan, based on past construction experience and consulting board conclusions, was drafted. In this revised plan the drill and blast excavation was extended. An additional work face was added in the Pilot Tunnel by way of Ventilation Shaft No. 2. Completion date for the Pilot Tunnel was adjusted to April 2004, and the entire Tunnel would be open for traffic in December 2005.

The time schedules for the above construction stages are presented in Figure 2.

Changes to construction plans made during the various stages, and justification for these changes are presented as follows:

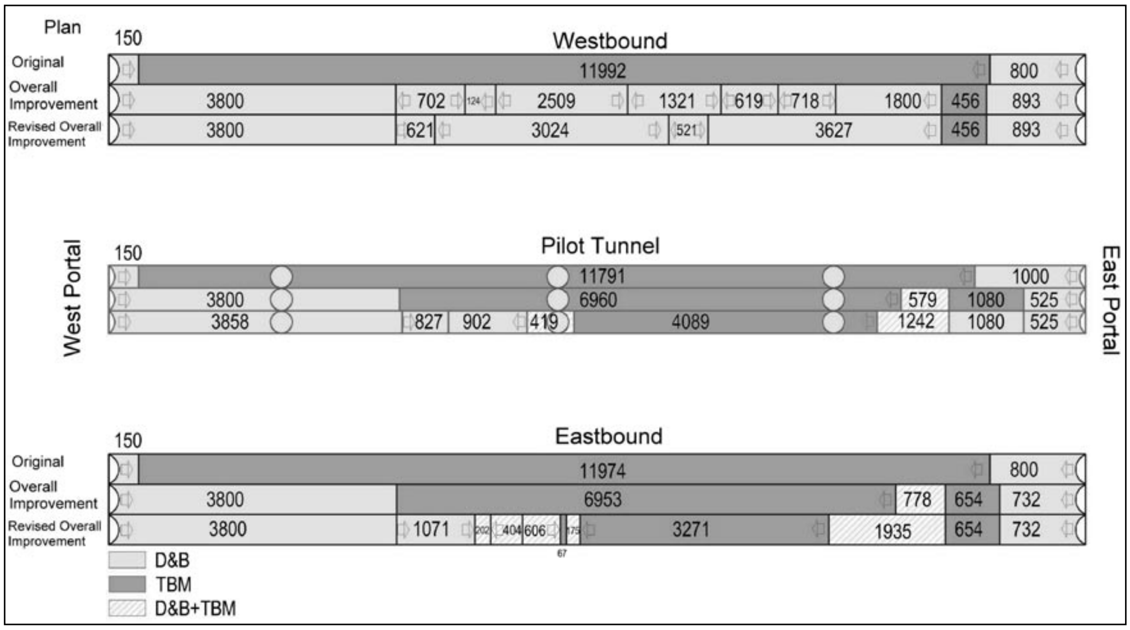

Figure 2. The Construction Plans for the Various Stages of the Hsuehshan Tunnel

Stage 1 (Results of Execution of Original Contract Plan)

(1) Pilot Tunnel

Construction work on the Pilot Tunnel began on 15th July, 1991. Design and manufacturing of the TBM began in December 1991. The TBM was manufactured in Robbins' factory in the United States of America, and test assembled at the factory in August 1992. It was then shipped to Taiwan and assembled within one month of arrival. Excavation of the Pilot Tunnel by the TBM began in December 1992. On February 5th, 1996, approximately three years later, the total length excavated was 1,080 m. The advance rate, inclusive of the rescuing of the trapped TBM, was about 30 m/month on average. The average advance would have been 79 m/month, if the time spent rescuing the trapped TBM were excluded. The best one month advance was 205 m, and the best one day advance was 16 m. During this period, the TBM was trapped or mired down 10 times. The maximum instantaneous water influx of the first seven trappings was 40 l/sec. The last three incidences of the TBM being trapped occurred in ground underlain by Szeleng Sandstone. Here the rock was intensely fractured. The spacing of the fractures or shear zones ranged from 100 to 200 m. They were all accompanied by large quantities of instantaneous groundwater influxes up to a maximum of 185 l/ sec. Rescue operations for the first trappings took about one to three months, whereas the last two incidences required more than 10 months. Following these ten incidences of the TBM being trapped, an advisory consultants' board meeting was called in an attempt to formulate an emergency measure that would overcome the severe situations ahead. This consultants' board was comprised of foreign and domestic experts and scholars in the fields of Tunnel excavation or TBM excavation operations. The advisory board concluded that it would be advisable to excavate the next 1,500 m stretch of ground within the Pilot Tunnel from where the TBM was mired down at the 10th trapping, which was at Sta. 39K+079, by means of the drill and blast excavation method, a method the contractor was most familiar with. Consequently, a detour Tunnel was excavated to gain access to the front of the TBM, and excavation of the Tunnel reverted back to the drill and blast method. The first half of the detour Tunnel was the site of the trapped TBM. The geological conditions there were quite undesirable. Furthermore, the rock mass at the site was severely disturbed as the result of numerous cave-ins and collapses during excavation of the Pilot Tunnel and excavation of the detour Tunnel. There was also a threat from the large quantity of groundwater influx. Thus, excavation of the Tunnel was divided into three sections: the top-heading, the benches and the invert, and they were excavated in sequence. When Sta.

39K+052 was reached, the geological conditions were better. Full cross section excavation was then resumed. During the excavation operation, a number of sections with poor geological conditions were encountered and they were all overcome with team effort. The experiences gained working in these sections enabled the drafting of a standard mode for ground treatment of rock mass similar to those that occurred in this section. In essence, the main principles of this standard mode lie in the grouting and draining of the ground with the adverse geological conditions to make it suitable for excavation. From March 9th, 1997 to December 13th, 1998 a total length of 223 m was excavated in the detour Tunnel.

(2) Main Tunnel

A. Eastbound Tube

Excavation commenced at the East Portal of the Eastbound Tube in August 1993, and the drill and blast method was used. By April 1995, in 20 months, a total of 732 m was excavated. The average advance rate was 36 m/month. The French firm Spie Batinolles entered the Tunnel in May 1996 to construct the sliding cradle for launching the TBM. In September 1996 as the TBM was readied for launching, Spie Batinolles claimed that excavation work in the Main Tunnel by the TBM might be ahead of the advances in the Pilot Tunnel, hence they were risking geologic hazards not contained in the contract, and requested increase in payment. If their request were refused, Spie Batinolles would cease to work. Following much negotiation, RESA ousted Spie Batinolles from the work site because of contract violations. Excavation by the TBM was taken over by RESA. By July 1997, a total of 653 m was excavated in the Eastbound Tube. The best one day advance rate was 17.8 m, and the average monthly advance rate was 65 m/month. In view of the difficulty encountered in the Pilot Tunnel when excavating the site of the Shanghsin Fault, the Eastbound TBM stopped when it approached the Shanghsin Fault. A top heading adit was constructed, and the incompetent rock mass was removed. The top heading adit was then supported while the lower half of the cross section was excavated by TBM. From July 1996 to July 1998 a total of 469 m was excavated in the Eastbound Tube by TBM.

B. Westbound Tube

Excavation commenced at the East Portal of the Eastbound Tube in August 1993, and the drill and blast method was used. By April 1995, in 20 months, a total of 893m was excavated. The average advance was 42 m/month. The best monthly advance reached 85m. The Westbound TBM was launched in January 1996, and full face excavation began in May 1996. The TBM was trapped ten times during this period of operation due to undesirable geological conditions. The first seven times the TBM was trapped was due to small scale cave-ins but no groundwater influxes. The average duration for treating the ground was 16 days. The last three times the TBM was trapped occurred within the same section. This happened when the TBM reached Sta. 38K+929 and a tremendous quantity of groundwater rushed into the Tunnel through gaps between the supporting segments. In December 1997, the TBM reached Sta. 38K+902.5 and it encountered an influx of another large quantity of groundwater. The Tunnel was buried by rock debris that was brought into the Tunnel by the vast quantity of water. The length of the section of the Tunnel that was buried was 90m, and the total volume of cave-in material was 7,000 m3, the maximum instantaneous water influx reached 750 l/sec. The TBM was crushed in the mishap. Technicians from the manufacturer of the TBM inspected the damaged TBM and estimated that it would take three years to repair the TBM at a cost of more than the cost buying a new unit. The contractor made a detailed evaluation, and made a recommendation proposing that the TBM be dismantled. The contractor also recommended conducting drill and blast excavation for the entire remaining length of the Tunnel. In this 20 month period, the total length excavated by TBM in the Westbound Tube of the Main Tunnel was 455.5 m. The average advance rate had been only 23 m/month, and nevertheless, the best advance rate in one day was 14.7 m. From the first day excavation commenced in July 1996 until June 1997 the total excavated length was 458 m.

Stage 2 (Overall Improvement Plan)

1. Revised Plan

Geological conditions at the East Portal of the Hsuehshan Tunnel were quite poor. The excavation of the Tunnel, either by the drill and blast method or by the use of a TBM had been plagued with difficulty, and the excavation operation was drastically behind schedule. In order to immediately resolve the situation effectively, the client invited experts and scholars, both foreign and domestic, to an advisory consulting board meeting. The main theme of this advisory consulting board meeting was to review the construction plan and to make revisions in order that a viable construction plan could be realized. The advisory board meeting, the fifth one of its kind, was held in March, 1998. The conclusions and recommendations reached at the advisory board meeting presented the following suggestions: The drill and blast excavation method should be employed to excavate the Tunnel through the Shihpai Fault (Sta. 37K+750); an additional TBM should be launched at the West Portal of the Pilot Tunnel and commence excavating in an eastbound direction; to make room for drill and blast excavation at the East Portal, the mired TBM should be dismantled and removed from the Tunnel for repair; perform boring of horizontal long boreholes, both in the Pilot Tunnel and in the main Tunnel, as means of advance geological investigation; such advance probing should be aided with TSP profiling to further unravel the geologic conditions ahead of the excavation face; The use of wet shotcrete and steel fibre reinforced shotcrete in conjunction with heavy steel sets should be considered for Tunnel support. Another advisory consulting board meeting was called again in January 1999. And in accordance with conclusions and recommendations made at the board meeting, the contractor, based on past construction experience and with reference to the actual geological conditions revealed by Tunnel excavation, formulated an "Overall Improvement Plan" for submission. The "Overall Improvement Plan" was reviewed by an ad hoc committee under the Public Infrastructure Construction Engineering Commission. The commission ruled that the construction would be increased by means of contract alteration. The date of completion for the Tunnel was set to be June 2003 when the Tunnel would be open for traffic. This ruling was approved by the Executive Yuan. The contents of the "Overall Improvement Plan" are briefly presented as follows:

(1) The East Portal of the Eastbound tube shall continue excavation through a topheading adit to remove poor quality rock mass. The estimated length to be excavated is 628m. Full face excavation by TBM will be resumed depending on the geological conditions of the ground.

(2) The TBM at the East Portal of the Westbound tube will be dismantled. The entire alignment of the Westbound tube would be excavated by the drill and blast method. When conditions allow, additional work faces, via access through the Eastbound tube and traffic cross-connections, will be added.

(3) A detour Tunnel will be excavated in the section at the site of the 10th time the TBM was trapped in the Pilot Tunnel to reach the front of the TBM to perform TBM rescue work. Excavation will be continued by the drill and blast method from this point onward. The TBM will resume excavation when fully repaired.

(4) At the West Portals of the main Tunnel and the Pilot Tunnel, excavation through drill and blast will be continued and extended to 3.8 km.

(5) Additional work faces going at both directions will be opened in the Westbound tube to perform 2.5 km of excavation.

(6) Additional work faces, via access through the Pilot Tunnel, ventilation shafts and ventilation relay stations, will be opened in the Westbound tube when conditions allow.

(7) Additional work faces, via access through the Eastbound tube of the main Tunnel and traffic cross connections, would be opened in the Westbound tube.

2. Execution Results

(1) Pilot Tunnel

When the TBM in the Pilot Tunnel was trapped for the 10th time in February 1996, a detour Tunnel was excavated in order to perform rescue work on the TBM. During excavation of the detour Tunnel, cave-ins occurred quite a number of times, thus a number of completed bypass adits were also buried by rock debris from the cave-ins. Finally the detour Tunnel reached the front of the TBM, and the TBM was freed. Judging from the trapping of the TBM and the geological conditions revealed in excavation of the detour Tunnel, the geological conditions ahead of the present site would need ground treatment to allow excavation using the TBM. The TBM which had been standing still for close to two years was parked at the completed Pilot Tunnel for the ventilation relay machine room of Ventilation Shaft #3 to facilitate repair and modification work. Also, a high efficiency drill rig HB-40A would be mounted on the TBM in the hopes that when the TBM became mobile and began excavating again, the geological conditions ahead could be properly understood. Meanwhile, the section in front of the TBM was reached via bypass adits, and excavation by drill and blast method was continued. During the excavation using the drill and blast method, several sites of adverse geological conditions were encountered. The contractor employed boring ahead to probe and grout for grounds at site method, and followed the operation model for geological investigation and treatment through grouting developed during excavation of the detour Tunnel, and was quite successful in safely crossing these sites of poor geological conditions. The results were quite impressive. By September 2000, drill and blast excavation had completed 1,242 m; the best one month advance rate was 96.5 m. During the time the drill and blast excavation was in progress, the TBM was repaired and had moved to the excavation face where the drill and blast excavation had stopped. In December 2000, full face excavation using the TBM was resumed, and by November 2001 it had excavated a total of 542 m. During this excavation period, the TBM had become mired in April and August of 2001, and rescue treatments had lasted 2.5 and 4 months, respectively. The best one month excavation advance by the TBM was 168 m; the average advance rate was 109 m (not including stoppage time and time spent on rescue treatment).

The geological conditions at the West Portal excavation face were acceptable, and the construction operation went smoothly. From December 1996 to November 2001, the total excavated length was 3,168 m. In November 1999, excavation encountered adverse geological conditions at the axial part of the Yingtsulai Syncline that caused support deformations. The ground was treated through grouting and excavated successfully. During this time the best one month advance rate was 120 m, and the average advance rate was 53 m.

During this stage, by the end of November 2001, the drill and blast excavation at the East Portal had completed 1,764 m. The TBM excavation had completed 1,622 m. The drill and blast excavation at the West Portal had completed 3,430 m. This meant that a grand total of 6,816 m had been excavated, which comprised 53% of the entire length of the Hsuehshan Tunnel.

(2) Main Tunnel

A. Westbound Tube

The Westbound Tube East Portal TBM encountered serious mishap in December 1997. The damaged TBM was inspected by the original manufacturer, and the manufacturer estimated that it would take 38 months with a cost of NT1.4 billion to repair the TBM. A detour Tunnel was then excavated to the front of the TBM. The plan was to revert to the drill and blast excavation method, to treat the collapsed section that had been excavated by the TBM, and to dismantle the damaged TBM. In May 1998 the collapsed section had been restored and the TBM had been dismantled and moved outside of the Westbound tube. The excavation of the Westbound tube was then continued using the drill and blast method. By November 2001 the total excavated length was 1,904 m. During this period, three cave-ins had occurred, the most serious of which occurred in April 2001 at Sta. 37K+099 when a large quantity of groundwater gushed into the Tunnel causing the severe cave-in. It took 7 months to clear and one life was lost. During this period the best one month advance rate was 100 m, and the average advance rate was 42 m.

At the West Portal, excavation by the drill and blast commenced in August 1998, and was continuing. By November 2001 the total length excavated was 2,394 m. During this period work was halted for three months due to protests from local residents. The other significant delay was the ten months the contractor spent on seeking a joint venture partner. During excavation, poor ground conditions were encountered at the axial part of the Yingtsulai Syncline. This ground with adverse geological conditions was treated by grouting and draining and excavation went on without mishap. The best one month advance rate was 90 m, and the average monthly advance rate was 61 m.

Ventilation Shaft #2 is approximately 250 m deep. The fresh air and the exhaust air shafts were excavated down to the bottom in November 1999 and January 2000, respectively. In August 2000, excavation on the upper half of the machine room was completed. In order to add an additional work face to the Westbound tube, machinery, equipment, and facilities were set up at Ventilation Shaft #2. This included a high speed winch, mucking facilities, waste water treatment plant, hazard prevention apparatus, and draining and ventilation facilities. In March 2001, all the equipment was assembled;

heavy equipment was brought in to start the drill and blast excavation work. By November 2001 excavation in the direction of Toucheng was 396 m; and in the direction of Pinglin it was 397 m, the total excavated length was 793 m. During this excavation period, a groundwater influx accompanied by a cave-in occurred at the Taotiaotsu Synclinal fold. The groundwater influx reached 80 l/sec, and the total volume of cave-in material was 100 cubic meters. The best one month advance rate was 110 m; the average monthly advance rate was 85 m.

Up to November 2001, in this stage, the drill and blast excavation at the East Portal of the Westbound tube had completed a length of 2,697 m. The length excavated by the TBM was 456 m. Thus, the total excavated length was 6,788 m, which was 53% of the entire length of the Hsuehshan Tunnel.

B. Eastbound Tube

Excavation at the East Portal of the Eastbound tube was done by means of topheading excavation starting at Sta. 38K+858. The intent of this was to pre-treat the stretch of ground with the adverse geological conditions. Excavation using a TBM would resume as the ground conditions improved. By November 2001 the total length excavated through the topheading method was 1,866 m, the best one month advance rate was 68 m, and the average monthly advance rate was 38 m.

The drill and blast excavation of the West Portal of the Eastbound tube commenced in September 1998. By November 2001, the total excavated length was 2,466 m. During this period work was halted for three months due to protests from local residents. The other significant delay was the ten months the contractor spent seeking a joint venture partner. The best one month advance rate was 86.5 m, and the average monthly advance rate was 65 m.

By November 2001, the drill and blast excavation at the East Portal of the Eastbound tube had completed 732 m. The length excavated by the TBM was 2,509 m. The West Portal drill and blast excavation was 2,935 m. Thus, the total excavated length was 6,176 m, which was 48% of the entire length of the Hsuehshan Tunnel.

Stage 3 (Revised Overall Improvement Plan)

1. Revised Plan

In the Overall Improvement Plan for stage 2, the Hsuehshan Tunnel was scheduled to open for traffic in June 2003. However, up to December 2001, excavation advances for the Pilot Tunnel and the Eastbound and the Westbound tubes of the main Tunnel were lagging way behind schedule. They were only 53%, 48%, and 53% completed, respectively. It was ascertained following evaluation that the Tunnel would not be open for traffic in June 2003. An advisory consulting board meeting on the Hsuehshan Tunnel of the Taipei-Ilan Expressway, comprised of experts and scholars, both domestic and foreign, was called again in December 2001. The recommendations and conclusions of the board meeting were that as many additional work faces as was feasible should be set up to speed up the overall progress of the construction. In early 2002, the Public Construction Commission of the Executive Yuan called a special meeting on the Hsuehshan Tunnel engineering plan. The meeting concluded that the client, contractor and the supervisor should jointly draft a plan for further execution of the project. A team composed of representatives from the client, the contractor and the supervisor then followed the conclusions obtained in the special meeting. Based on past construction experiences, this team then drafted a revised set of countermeasures referring to 16 projected sites with poor geological conditions for submission. A new completion date was projected for 2005. The submitted draft was approved by the Executive Yuan, and contained the following points of importance:

(1) The TBM excavation rate was adjusted: the excavation rate in the Pilot Tunnel would be 300~450 m/month; in the main Tunnel, 150~200 m/month.

(2) By way of Vertical Shaft #2, in the Pilot Tunnel, a work face would be opened in the direction of Pingling. In the case of the East Portal, the TBM work was less than satisfactory, and a work face should be added in the direction of Toucheng.

(3) The excavation section at the West Portal of the pilot Tunnel using drill and blast was to be extended 0.8 km more than the original length of 3.8 km.

(4) The drill and blast excavation operations at the West Portals of the Eastbound and Westbound tubes were to be extended 0.9 km and 0.5 km respectively on the original 3.8 km length.

(5) Perform supplementary excavation to 1.1 km in the Eastbound tube through access via the Westbound tube. Through the top heading method, remove the 150 m

length of poor ground to facilitate TBM excavation.

(6) Continue excavation through the topheading method at the East Portal of the Eastbound tube. Resume TBM excavation when rock mass quality improved.

(7) Open an additional work face for drill and blast excavation in the Westbound tube via the Westbound tube and the relay station of the #2 Ventilation Shaft. Perform supplementary excavation for 528 m.

2. Result of Execution

(1) Pilot Tunnel

TBM excavation resumed on November 17th 2001 following repair after it had been trapped for the 12th time at the East Portal of the Pilot Tunnel. In June of this period, there was a stoppage of 47 days in order to install steel plates and abrasion resistant steel plates onto the neck of the TBM. This was because some of the steel plates at the neck of the TBM had been worn out from excavating for such a long period of time in the hard Szeleng Sandstone. In this stage, the TBM had excavated 1,221 m in ground underlain with Szeleng Sandstone. In this 8 month period, 323 cutter discs were replaced. The record was 109 cutter discs replaced in one month. Upon leaving the Szeleng Sandstone and entering into a sedimentary rock area, the lithology of the rock formations was no longer as hard as the Szeleng Sandstone, and the advance rate rapidly increased. The best one month advance rate reached 400.8 m, and the best one day advance rate was 24.7 m. Thus attaining what could be achieved by a TBM, and clearing all doubts about TBM excavation. However, in June 2003, the TBM was trapped again as it encountered a zone of incompetent rock mass. On top of this, there was a stoppage concerning work safety, and the total time spent amounted to three months. On October 12th, 2003, the TBM reached the breakthrough point, and fulfilled its mission. The total excavated length was 3,618 m. In December 2003 the TBM was dismantled at the dismantling yard, and was completely dismantled by April 2005.

From December 2001 to May 2003 the total excavated length at the West Portal of the Pilot Tunnel was 904 m. The projected advance rate was 50 m, and the actual average monthly advance rate was 66 m, with the best advance rate being 93 m/month, a result that was slightly better than expectations. The breakthrough was projected to be at the end of 2003 but the actual breakthrough came 7 months earlier.

An extra work face was opened in May 2002 and excavation immediately commenced. The goal was that the Taipei-Ilan Expressway would open for traffic at the end of 2005. The projected breakthrough was at the end of 2003. The actual excavated length was 904 m, and was completed in May 2003. The best one month advance rate was 121 m; the average monthly advance rate was 82 m. Both were better than projected and records.

(2) Main Tunnel

A. Westbound Tube

The East Portal of the Westbound tube suffered a large quantity of groundwater influx accompanied by many serious cave-ins at Sta. 37K+099. In May 2002, excavation was resumed after a successful ground treatment operation. After this incidence, the drill and blast excavation operation went smoothly. In March 2004, excavation was completed, on time and within the projected schedule. During this stage, the total excavated length at the East Portal of the Westbound tube was 1,825 m. The best one month advance rate was 126.4 m, with a monthly average advance rate of about 75 m.

In the West Portal section, after crossing over the Yingtsulai Syncline work progress gradually fell into pace with the expected progress. Excavation was completed in September 2003. During this stage, the total excavated length was 1,566 m. The best one month advance was 112 m, with a monthly average advance rate of about 73 m; these rates were much better than those in the past. The projected completion date was mid-February 2004; the actual completion date was 5 months ahead of the projected date.

Excavation operations at the Toucheng facing work face and the Pinglin facing work face in Vertical Shaft #2 were completed in March 2004, in line with the projected date. During this stage, the total excavated length was 2,231 m. The best one month advance was 97.8 m, with a monthly average advance rate of about 83 m.

Excavation commenced on the additional work face through the Pilot Tunnel via the relay station of Ventilation Shaft #2 in the Pinglin direction in April 2003. In December 2003 an additional work face in the Toucheng direction was added. Excavation works progressed slowly due to limitations of space, mobility and equipment. In March 2004 the breakthrough was accomplished. The total excavated length of these work faces was 520 m, with a best one month advance rate of 62 m.

B. Eastbound Tube

At the East Portal of the Eastbound tube, excavation through the top heading method was continued to Sta. 36K+923. It was then appraised that the ground conditions were improving, and in April 2002 the TBM was launched at the work face. Full face excavation by TBM was resumed in September 2002. However, at Sta. 36K+440 the TBM was trapped once again when adverse geological conditions were encountered. Rescue work lasted 5 months. From that point on, TBM excavation went smoothly with an improved advance rate. In August 2004, full face excavation by TBM was completed. And in February 2005, TBM excavation of the lower section was also completed. During this stage, the total TBM excavated length was 3,513 m. The best one month advance was 360 m, the monthly average advance rate was 140 m, and the best one day advance rate was 17.9 m.

The geological conditions in the area of the later excavation at the West Portal of the Eastbound tube were good; thus the excavation advance was normal and slightly better than the projected advance. A later excavation on this area was completed in February 2004. However, due to trapping of the East Portal TBM, there was a considerable delay. To realize the target of the entire Tunnel being open for traffic in September 2004, an additional 209 m was excavated in May 2004. During this stage, the total excavated length was 1,916 m. The best one month advance was 106.5 m, with a monthly average advance rate of about 71 m.

In accordance with the Revised Overall Improvement Plan, and via the #2 Ventilation Shaft and the Westbound tube, the contractor opened 6 more work faces at vehicular cross connections 4, 12 and 14. These were completed in June, August, and September 2004 respectively. The total excavated length from these work faces was 1,186 m. The best one month advance rate was 79 m.

The entire excavation operation of the Hsuehshan Tunnel was completed in mid-September 2004, when the Tunnel was broken through. Works to follow include lining the Tunnel, the equipping of ventilation machine rooms, the equipping of machine rooms of the relay stations, pedestrian cross connections, vehicular cross connections, road surfacing, signs, markings, electrical and mechanical equipment, and traffic control signs. During this time coordination and control will be the major issues. Following completion of the Tunnel excavation the lining and machine room works will require an immediate increase in the work force. To meet the target of opening for traffic at the end of 2005, electrical and mechanical equipment works were started concurrently with other civil engineering works in the various sections in the Tunnel. Thus, the equipment, the work force and the number of work faces in the Tunnel will reach their peak. The client, the construction supervisor and the subcontractors for civil, electrical and mechanical works should conduct frequent meetings on work coordination to review construction difficulties and interface coordination. Only with well organized teamwork can the goal of opening for traffic in 2005 be attained.

REVIEW AND RECOMMENDATIONS

1. Among the many varying factors in a Tunnel construction project the geological factors have the greatest influence. It is usually not possible to completely discern all information on the geological conditions during design and planning stages. The only alternative is to perform adjustments to the construction plan based on the actual situations encountered and the overall considerations of the entire construction plan to achieve the best effect.
2. When considering newly introduced construction methods or construction machinery, the design and formulation of a construction plan should be comparatively conservative. Due consideration should be paid to the geological and the hydrological conditions of the construction site and the contractor's management and construction experience working in a foreign country. This will assure that the construction plan will not drift too far from the designated course.
3. TBM excavation methods differ from the drill and blast excavation methods in that it is not possible to make direct observations on the geological conditions at the excavation site. For this reason, advance probing and other means of supplementary investigation should be performed during TBM excavation to gain an understanding of the geological conditions ahead of the

excavation face in order that counter measures can be taken in case adverse geological conditions are encountered.

4. When excavating using TBMs, a detailed treatment plan for sections with poor geological conditions should be drafted ahead of time. Such treatment plans should clearly state the modes of grouting and the amount of time spent for removal of ground in poor geological conditions, and the methods to be used. This will allow proper and immediate measures to be taken when encountering sites with adverse geological conditions, and help to avoid the bogging down of the TBM.

5. Success or failure of the construction of a long Tunnel depends on construction management. Construction management should be well planned and adjusted ahead of, during, or following construction execution. Emergency counter measures should also be planned well in advance.

6. In TBM excavation, the surrounding construction and safety conditions are better than those of the drill and blast method. However, care should be exercised in selecting the appropriate TBM for a particular type of ground with specific geological conditions. Advance probing is mandatory in TBM excavation; hence the drill rig mounted on the TBM should possess the capability to adequately perform the necessary drilling for investigation. For a larger area underlain with adverse geological conditions, horizontal long distance drilling should be employed; this could be supplemented by TSP, HSP and ground resistivity profiling investigations.

7. Regardless of whether excavation is done by TBM or by means of the drill and blast method, encountering poor geological conditions or sudden influxes of large quantities of groundwater always amounts to hazards of a major scale. Hence, pre-treating ground with adverse geological conditions is mandatory in drill and blast Tunnel excavation. A treatment mode should be established in advance.

8. Construction management and techniques for TBM excavations are far more difficult and important than in drill and blast excavation methods. Thus the selection process of choosing a contractor to undertake TBM excavation construction should be very strict in requiring that there is a guarantee of engineering quality and adequate progress.

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