DISCUSSION AND SOLUTION OF THE TBM TRAPPED IN THE WESTBOUND HSUEHSHAN TUNNEL

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ABSTRACT

The Westbound (WB) Hsuehshan Main Tunnel was excavated with a double shielded, hard rock TBM with a diameter of 11.7 m. In September 1997, the TBM excavation encountered construction difficulties while approaching Shanshin Fault. These difficulties were due to the adverse ground conditions within the fault zones. The excavation was suspended for nearly two months to conduct ground pre-treatment and commence detailed examination of the TBM. In December 1997, the TBM resumed its advance after passing a routine safety check requirement. However, after boring for only 26.5 meters, the reinforced precast concrete segments adjacent to the rear shield of the TBM suddenly collapsed. It was noted that a huge amount of groundwater inflow with spoils was gushing into the tunnel and the WB TBM was inundated. As a consequence, the entire TBM was deeply buried by large amounts of debris induced by the inundation. After detailed assessment by a panel of tunnel experts, it was decided that the TBM should be abandoned. The excavation method switched to the drill and blast (D&B) method, which caused significantly delays on the construction schedule for the completion of the tunnel project. This paper aims to reiterate the mechanisms of TBM hazards. Their engineering solutions in terms of geological investigation, consolidation grouting, drainage hole drilling, and construction of top-heading are given. Hopefully, the experience obtained from this excavation will be a good reference for future tunneling works in similar rock formations.

Keywords: TBM cave-in, consolidation grouting, top-drift, top-heading, concrete segment, groundwater

INTRODUCTION

The TBM used in the construction of Hsuehshan Tunnel was one of the worlds' largest hard rock TBMs and was the first TBM used in a project in Taiwan. With a diameter of 11.7 m, the Westbound TBM (WB TBM) bored northwestwards for a length of 456 m in twenty months after it was lunched on 1996/05/02 from the Sta.39k+358. This was about 1,343m away from the east portal located Toucheng town of Ilan County..

In the meantime, the Pilot Tunnel had been excavated a length of 1,602 m, and the Pilot Tunnel TBM was stopped at Sta. 39k+079, 250 m ahead of the WB TBM. The excavation of the Eastbound main tunnel had reached a length of 1,377 m, and the Eastbound TBM (EB TBM) was approximately 202 m behind the Pilot Tunnel TBM. Both the Pilot Tunnel TBM and EB TBM had been trapped in the Shanghsin Fault in the Szeleng Formation and remedial measures such as ground treatments and the construction of the canopy protections were carried out to ensure safety when the TBMs resumed their excavations. On September 6, 1997, the WB TBM reached the location of the Shanghsin Fault and the advance of the TBM was temporarily suspended in order to conduct ground improvement treatments prior to its recommencing. The locations of the three TBM are shown in Fig. 1.

On December 10, 1997 the WB TBM had advanced Sta. 38k+902 as illustrated in Fig. 2. It was noted that serious deformation had occurred on the installed segmental supports adjacent to rear shield of the TBM, and the advance of TBM was suspended.

At 6:30 pm on December 14, 1997, there was a large water inflow (68 l/s) at the TBM gripper and at the

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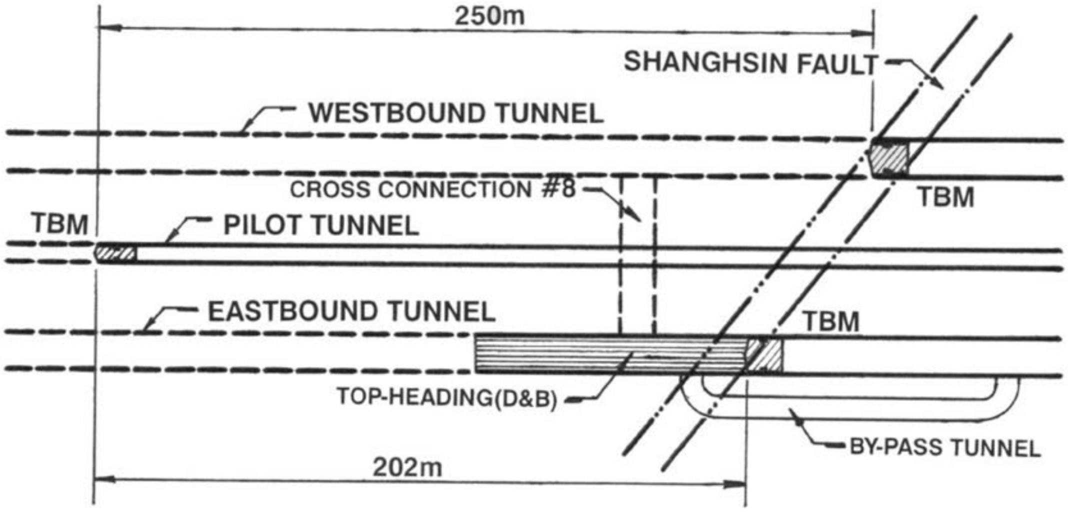


Fig. 1 The Layout of the TBMs adjacent to Shanghsin Fault (September 1997)

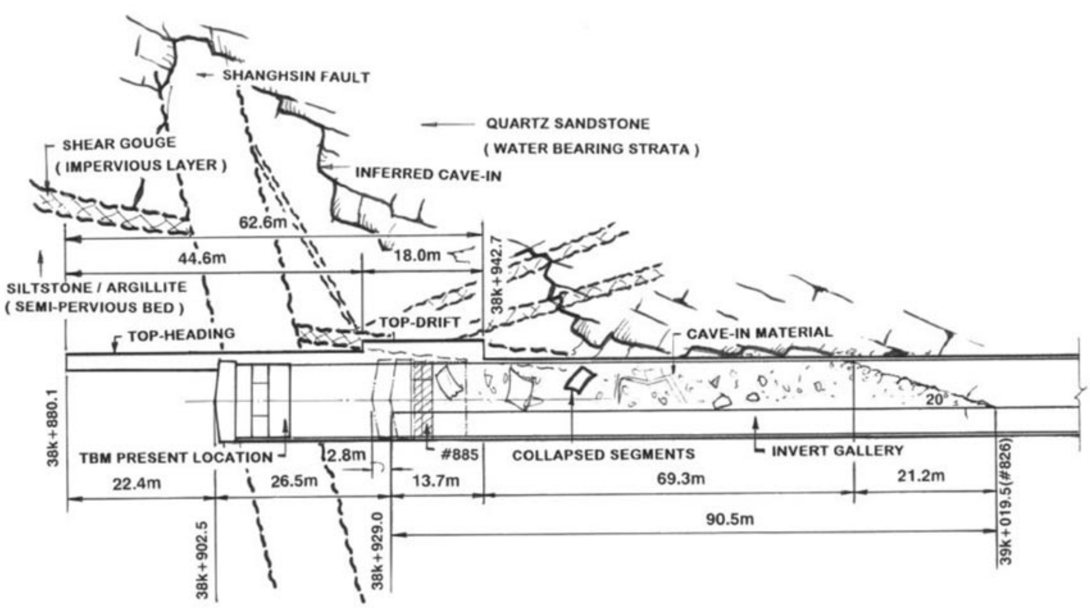


Fig. 2 Conceptual Geological Profile of the Stalled WB TBM

rear part of the TBM when the TBM advanced to Sta. 38k+902.5. The TBM excavation was halted immediately. The installation of H200x200 heavy steel rib reinforcement had been considered for locations which had major water seepage and had cracks in the installed precast segments. However, at 3 am on the next day, the existing cracks were getting wider and wider, and appeared in the crown segments and hillside segments between segment Nos. 885 and 886 (see Fig.2). Tunnel squeezing towards the hillside was found to be associated with the unstable segments. By 8 am on the same day, water inflows had increased to 185 l/s, and the installation of the steel rib reinforcements seemed impossible. In the meantime, the tunnel squeezing had deteriorated towards the hillside.

At 2:45pm on December 15th, precast segments near the seaside gave way and fell off, followed by a large amount

Photo 1. TBM Deeply Buried by Large Amounts of Debris after Inundation.

of groundwater inflow of 300 l/s that suddenly gushed into the tunnel. This sudden inflow was accompanied by sheared clay and rock fragments. The segments kept falling in a chain-reaction and the rate of water inflow increased to 500 l/s at 10 pm. As a consequence, the entire TBM was buried deep beneath large amounts of debris caused by the inundation. It was found that the watery debris which buried the TBM extended for a length of 90m towards the Toucheng end. Photo 1 shows the condition of the debris in the backup system behind the TBM. The actual length of the section with fallen segmental linings was unknown but the estimated volume of the cave-in materials might have reached 7,000 m .

At 10:00 am on December 16th, the water inflow increased to a rate of 750 l/s, and the tunnel cave in became stabilized. By 2:30 pm on December 17th, two days after the first collapse, water inflow decreased to 660 l/s and then gradually decreased to 50 l/s.

GEOLOGICAL CONDITIONS

After crossing the Chingyin Fault, the WB TBM encountered rock mass mainly belonged to the Szeleng Formation. Between Sta. 38k+950 and Sta. 38k+880, the rock types were mainly coarse-grained quartzite or quartz sandstone, intercalated with alternations of fine sandstone, siltstone and argillite. The rock mass was intensely fractured due to the influence of the Shanghsin Fault. The attitude of bedding plane in this section was N39 W/27 N, and hence intersected the axis of the Westbound Main Tunnel at a small angle. Three sets of high angle joints were noted in which the mean attitudes of these discontinuities were N11 W / 74 E, N42 W / 80 E and N29 E / 70 W respectively. The rock mass adjacent to the Shanghsin Fault was located at the southern flank of a regional anticline structure. Hence, flexural slip folding occurred commonly in the rock strata. Such flexural slip folding tended to form plastic sheared clay seams along the bedding planes and formed impervious layers which could block the water conductivity within the rock mass.

Before the construction began, the Shanghsin Fault had been recognized as one of the many important geological structures along the tunnel alignment within the Szeleng Formation. Its probable location within the Westbound Main Tunnel had been estimated through the Pilot Tunnel excavation. At the mishap area, the Shanghsin Fault was estimated to cross the Westbound tube at Sta.38k+915 to 38k+905 (central line, El. 61.5m). Rock masses beyond the fault zone were mostly riddled with shear fracture zones, thus forming a fault brecciated zone some tens of meters in width. The Shanghsin Fault extends at an attitude of N77 W/78 S towards both sides, and is a normal gravity fault in nature. The hanging layer at the Toucheng end of the tunnel, south of Sta.38k+915, slipped downward, while the foot wall north of Sta. 38k+905, at the Pinglin end, relatively moved upward, attaining a vertical throw of 8m. Fig. 3 shows a three dimensional block diagram in which the spatial relationship between the TBM and the major geological features are presented. The bedding attitudes of the sheared clay seams within the quartzose sandstone masses of the Szeleng Formation are rather gentle. It seams that the rock discontinuities did not appear to maintain regular frequency of occurrence, based on the investigation conducted in April 1997. That investigation revealed that the occurrences of shear clay seams in the foot wall of the fault, as well as

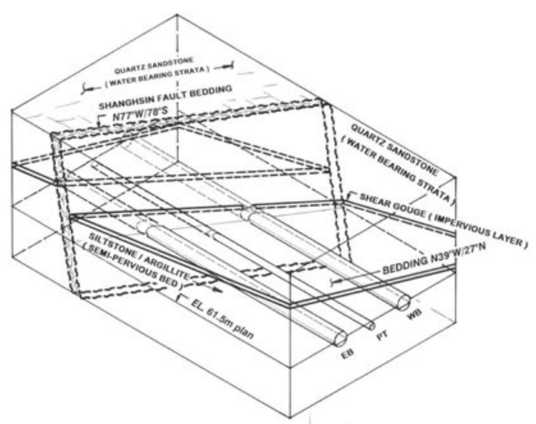


Fig. 3 Conceptual Structural Geological Model adjacent to Shanghsin Fault

in the rock mass above the crown of the tunnel, were accompanied by water ingresses.

In September of 1997, the WB TBM cut through a rock comprised of siltstone and argillite with an intercalation of a sheared clay seam 30cm in thickness in the hanging layer. This penetration caused breaking of the coarse-grained quartz sandstone reservoir bed with a large quantity of groundwater surging into the segmental area of the TBM, however, the segments were not damaged.

GROUND TREATMENTS BEFORE THE MISHAP

The boring records of the TBMs from the Pilot Tunnel and the Eastbound Main Tunnel through the Shanghsin fault zone indicated poor rock conditions with high-pressure groundwater. The Eastbound TBM was shutdown for ground treatments and canopy protection construction. Consequently, geologic probing and ground treatments were also applied to ensure the Westbound TBM could pass through. The process is shown as follows:

* On April 5, 1997, a drilling hole with a depth of 34.8 meters from the Pilot Tunnel toward the Westbound Tunnel encountered a high water inflow of 13.8l/s with 3kg/cm pressure and a clay seam of 30cm thick.
* From April 14,1997 to September 3, 1997, consolidation grouting was carried out from Pilot Tunnel toward the Westbound Tunnel. There were 6,545 bags of cement injected into 40 grouting holes, with an average depth of 36 meters.
* On July 5, 1997, additional grouting work was carried out from the Pilot Tunnel to consolidate predicted weak zones of the Westbound Tunnel. Up to July 28, 1997, a total of 2,564 bags of cement were injected into 8 grouting holes. The depth of these holes varied from 24m to 32m.
* On September 9, 1997, a TSP (Tunnel seismic perspective) survey was conducted after a huge water inflow (124l/s) at Sta.39k+929, which indicated three distinct weak zones were located in front of the TBM head. The rock mass strength of the Westbound Tunnel was very poor.
* In the Pilot Tunnel, coring was used to exploring the geologic features in front of top heading. The coring went toward the portal and parallel to tunnel alignment. On September 18, 1997, the drilling encountered water inflow 12 l/s with a pressure of 3.5kg/cm2 at a depth of 32 meters. The ground water vanished after several days.
* The top heading excavation from segment “A" of ring No.4 behind the Westbound TBM commenced on September 21, 1997 for ground treatments and potential water inflow drainage. With probing 3 m ahead of each ring during the top heading excavation, up to December 8, 1997, it showed no sign of potential water inflow.
* From October 5, 1997 to October 8, 1997, to proceed with the further drainage of the potential water inflow, 3 NX drainage holes with high attitude angles from Pilot Tunnel were re-drilled. The drainage rate average was from 12 to 14 l/s during the first day, and then the drainage rate dropped significantly to 1 to 2 l/s in the following days.
* To ensure that the top heading excavation would pass through the geological weak zones, a 20 meters core was completed, followed by the decision to excavate the top heading up to Sta. 38k+880.

Ground treatment measures included excavating a length of 18m of top drift by drill and blast. This top drift was located at the end shield, directly above the TBM and expanded sideways to form a top-heading when it reached the cutter-head of the TBM. The top heading extended as far as Sta. 38k+880. The total length of the top drift and top heading sections was 62.6m. The arch-shaped top-heading was located at the top part of the excavation face, as a function of consolidating rock masses and protection works at the crown to ensure that the TBM would pass through the fractured rock masses in the Shanghsin Fault. The TBM excavation resumed after the top-heading was completed. The trapped telescopic shield was freed through excavation. By December 14, 1997, the TBM had excavated to Sta. 38+902.5 and then the mishap occurred.

REMEDIAL MEASURES AFTER THE MISHAP

Immediately after the mishap, the Engineers and the representatives from TANEEB and RSEA met and the following emergent measures were carried out:

At the Westbound Tunnel

* Where segments were damaged without fall-off, the H100x100 steel rib reinforcement was installed, and

rock bolts with shotcrete were also applied when necessary.

* Segments were consistently inspected. The volume variations of water influx were measured to help formulate the method of reinforcement.

At the Corresponding Section of the Eastbound Tunnel

* H150x150 steel rib reinforcement were erected where there were high water pressure ingresses and the crown segment had sunk. On the hillside of the Pilot Tunnel, drainage holes were drilled towards the Eastbound Tunnel at corresponding points.
* Segments were continuously inspected and volume variations of water were measured to formulate the reinforcement.

At the Corresponding Section of the Pilot Tunnel

* Cracks appeared on the seaside of the tunnel at the joints of segments. The H100x100 steel rib reinforcements were erected and shotcrete was applied.
* There was occurrence of pressurized water seepage on the hillside and an adequate number of drain holes was drilled.
* There was water seepage on the seaside, continuous inspections were performed on the seepage, and the measurement of volume variations of water influx was performed for formulation of reinforcement.

DISCUSSION ON THE CAUSES OF FAILURE

The mishap first occurred 26.5m behind the TBM, at segment Nos. 886 and 885. The cave-in propagated from this location towards the portal of the tunnel and ended at segment No. 826. Thus this mishap started as a local accident then expanded to a cave in 90 m long. Segment Nos. 886 and 885 were the key zones causing the mishap. The causes of this mishap and the failure mechanism can be summarized as follows:

* The mishap was triggered by the failure to conclude backfilling after the erecting of segments. This was the first occurrence that differed from the past trappings of the TBM cutter-head which were caused by the poor stand up nature of the unsupported rock mass. This mishap occurred as a result of converagence of the squeezing zone. Local segment failure developed in to a cave in.
* The failure was located within the fault disturbed zone of the Shanghsin Fault. As the rock mass was fractured, there was no distinctive orientation. For this reason, this failure is very similar to failure in soft rock under squeezing stress, where support systems fail to reinforce the rock ring to form a rock arch. Thus, it is without a doubt a stress-induced failure.
* After the TBM had passed through, there was no water seepage from the segments. The water ingress failure was caused by loosened rocks and damaged impervious beds which triggered the mishap.

The segment stability, rock load capacity and hydraulic loads were improved through the accumulation of tunnel excavation and consolidation grouting completion. The excavation of a top-drift changed the boundary conditions that affected its bearing capacity. A study of the failure mechanism for the segments started from the load and the boundary conditions. These can be summarized as below:

* Although water ingress appeared in September 1997 at Sta. 38k+940 of the Westbound Tunnel, it did not cause any mishaps. It can be ascertained that tunnel excavation had progressed into another area subject to groundwater threats. Prior observations on the distribution of groundwater contained in isolated fissures, disclosed that such undetectable water formations could considerably increase hydraulic pressure, thus increasing the stress on the segments.
* Since the location of the initial failure was within the disturbed zone of the Shanghsin Fault, the geological conditions there are less desirable. The self-supporting capacity of the rock mass is weaken due to its highly fractured state. Furthermore, the excavation of the top-drift tended to expand the disturbed zone of the rocks surrounding the tunnel, while forming a gap in the rock ring to make it impossible for rock arch formation. For the process of stress re-distribution, the occurrence of such a gap caused high stress concentration and as a result loosened the rock mass. For this reason, the excavation of work pit caused the loss of the rock arch, which was an unfavorable factor in the stability of the large cross section tunnel excavation.
* In general, with the progression of the excavation face, three-dimensional stress re-distribution can

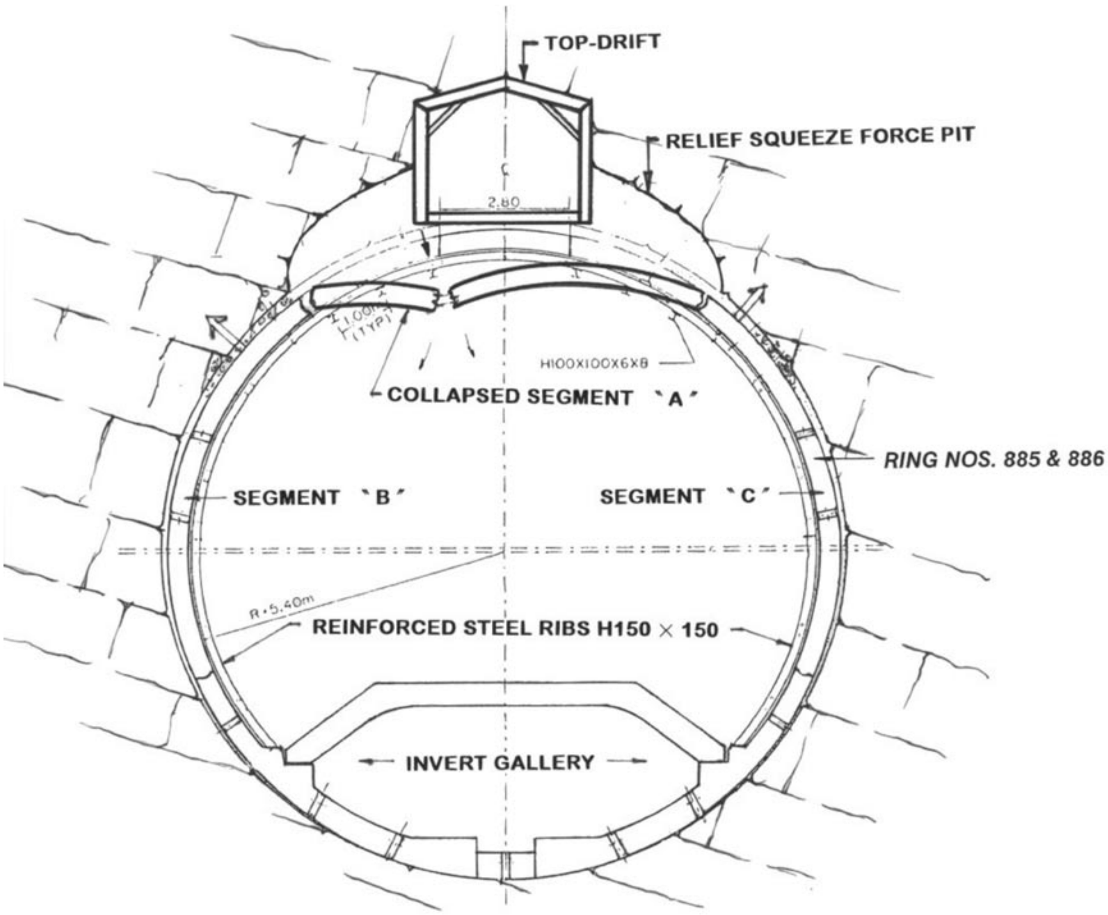


Fig. 4 Excavation by Top-drift

occur in the rock mass around the tunnel due to pressure relief. The stress stops once the excavation face gets far away, usually greater than three times the tunnel diameter. Also plane strain equilibrium is attained again. Prior to the present mishap, segment Nos.886 and 885 were close to the excavation face and at the re-adjustment stage of stress in the surrounding rock mass. Furthermore, before the mishap, the TBM had advanced 26m in four days. Such rapid excavation might have disturbed rock mass of these two segments. Thus, the present mishap occurred at the moment that the rock masses was undergoing stress adjustment, rather than in the rock mass equilibrium stage when the TBM was far away. These two conditions were significant in terms of the rock mechanism. In other words, the mishap occurred at the elasto-plastic stage, rather than being related to the creep of the rock mass.

* The excavation of the top drift and top heading to free the telescopic shield lost support behind the crown segment as schematically shown in Fig. 4 and Fig. 5. The segment was, therefore, subjected to a stress condition different from the originally designed hoop compression load. Consequently, the structure of segment Nos. 886 and 885 changed from arch to beam. Since the bending stress exceeded the bending strength, cracks occurred causing the caving of the overburden rocks. In addition, several dozen segments failed due to the squeezing action from segment Nos. 886 and 885 that were supposed to provide lateral support to these segments. When a sufficient amount of cave in rock forms a volume plug, it will stop this domino effect.

The above factors have a sequential relationship. In summary, the main cause of this mishap was that the excavation of the top working drift placed the rock arch and segments of the tunnel under adverse stress conditions.

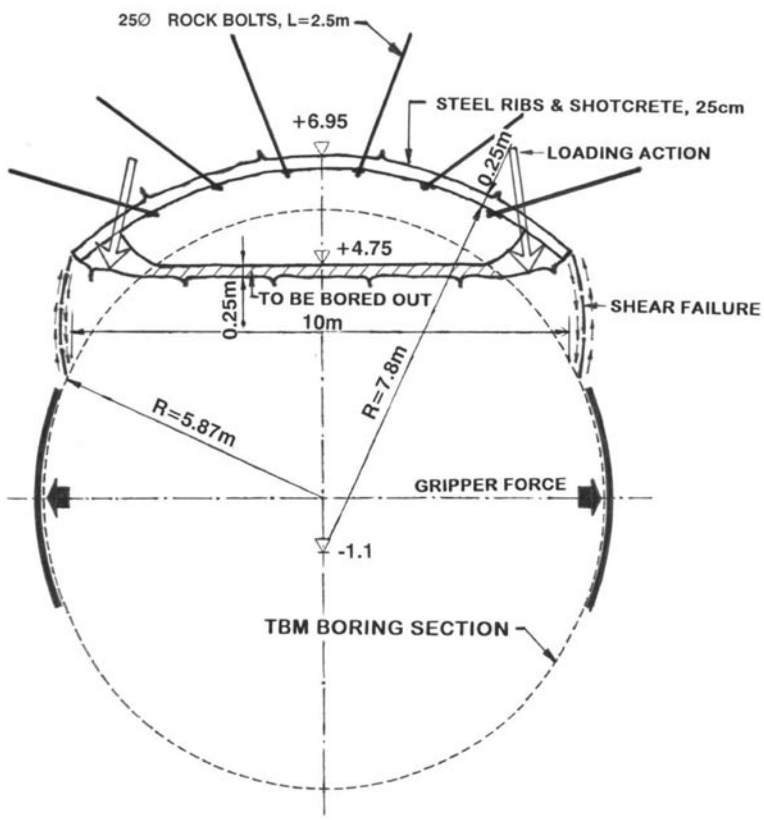


Fig. 5 Excavation by Top-heading

In addition, the rapid advance of the TBM and the delayed backfill of voids behind the segments caused the loosening of more rocks around the tunnel. The excess loose rock led to a great amount of groundwater ingressing into the tunnel. The segments failed because of the combination of the unfavorable rock load and the hydraulic load and triggered a domino effect to expand the cave-in rapidly.

Construction Sequence

In July 1997, TBM excavation had progressed to Sta. 38k+933. However, segment reaction and backfill were not completed until December 12th. There was a 7 to 8.5 cm gap between the excavated rock face and the segments. The prolonged idle time without supporting rocks around the tunnel caused the loosening of the rock mass. When passing the Shanghsin Fault, the torque used for the TBM cutter-head might have been too great. For example, the torque of 12,112 kNM used in August 30th disturbed the adverse rock mass adjacent to the Shanghsin Fault.

No backfill for the 2.6m(H) x 2.8m(W) top drift to form confining pressure resulted in various loading on the segments. The actual circular strength did not function well and was prone to failure under stress (See Fig.4).When the invert of the top heading was excavated by the TBM, the rock pressure sustained by the top heading was transmitted to the lateral support footings. However, the support footings were again truncated by the TBM. Without any means of support, the tunnel rendered stress concentration leading to shear failure that caused the crown to cave in and groundwater to gush in (See Fig.5).

Investigation of the Shanghsin Fault and the Aquiclude Beds

Based on the experience gained by the excavation of Shanghsin Fault the data collected from excavation of the Pilot Tunnel in 1995 as well as the Eastbound tunnel in 1997, it was indicated that the Westbound Tunnel will encounter the Shanghsin Fault at Sta. 38k+915 to Sta.38k+905. All parties involved, including the clients, construction supervisors, and the construction workers proceeded with caution. There was a detailed in-situ investigating of the argillite and the Shanghsin Fault and drain holes A1, A2 and A3 were drilled from work pits in the Pilot Tunnel. The depths of the drain holes were 37m, 40m, and 31m, respectively and the water surge depths were 29m, 26m, and 31m, respectively. Drainage pipes were constructed to drain the groundwater but draining was not complete. In summary, records from the Pilot Tunnel provided sufficient geologic information as well as logical geologic structural interpretations for the main tunnel excavation.

Geological variations were frequent in the two tubes of the Hsuehshan Tunnel. As the Shanghsin Fault was near, the water aquicludes were especially so. When a major fault is approached, a detailed investigation through probe hole drilling should reveal the actual geological situation. Moreover, although the Pilot Tunnel served well to provide rock mass geological information, the cross section of the main tube was 9 times larger than the Pilot Tunnel. Thus, even though the Pilot Tunnel had pass through the same ground without any difficulty, the main tube with its larger cross sections might not necessarily pass through the same rock mass conditions without any difficulty.

MISHAP AREA RESTORATION

From March 24 to 30, 1998, the big TBM manufacturer WIRTH (West Germany) assigned a technical supporting group to the site for the TBM rescue evaluation. They forecasted 38 months of rescue time at an expense of 1.4 billion NT dollars. Considering the cost and time estimates, the Constructor RSEA decided to dismantle the buried TBM and used drill-and-blast method for the excavation of the remaining section of the Westbound Tunnel. Details are described as follows:

Detour Tunnel Excavation

∗ A detour tunnel by seaside was excavated to access follow-up excavation of the Westbound Tunnel by the drill-and-blast method. The subsequent tunneling used top heading or top heading-and-bench, depending on the geological conditions. Fig.6 shows the plan of the detour tunnel adjacent to the mishap area.

∗ The detour tunnel also provided access for cavity filling and consolidation grouting above the collapsed area in the Westbound Tunnel.

∗ In preparation for railway transportation for the follow-up excavation in the Westbound Tunnel, the entrance of the detour tunnel opened at Sta.39k+042, which connected the main tunnel ahead of the TBM. The entrance of the detour tunnel can be seen in Photo 2(a). The distance between the detour tunnel and the main tunnel was 18 meters to reduce the possible excavation impact on the rock mass around the main tunnel. The length of detour tunnel was 79 meters.

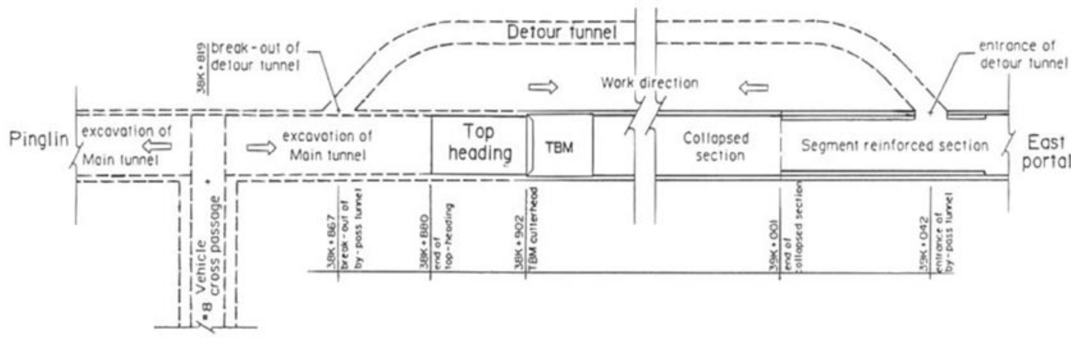
Follow-up Excavation

The No. 8 vehicle cross passage was excavated by top heading (see Fig.6). Commenced on February 3, 1998 and completed on April 19, 1998, it accessed the face of the buried TBM via eastbound tunnel. This was finished ahead of schedule in order to have time to excavate the remaining Westbound Tunnel before the detour tunnel was completed. After completion, access for the excavations then shifted to the Westbound Tunnel to avoid the water-bearing zones being penetrated by the top heading again. The preliminary goal was to pass through the Paling Fault by short-bench excavation methods and rail haulage.

Restoration Measures for the Collapsed Section

The blocked tunnel was recovered by excavating the collapsed material in benches with a modified support system so the collapsed section could be excavated safely. Photo 2(b) shows the condition when the cutter head finally appeared after timely mining work. Meanwhile the bench excavation can fully restore the tunnel support system and minimize the quantities of precast segments demolished. Grouting to consolidate loose rocks and to fill any existing voids above the crown of the tunnel were carried out after the excavation. At the tunnel crown and in the enlargement area, the installation of pipe roofing was executed in advance to ensure a safe excavation operation. The prompt installation of a supporting system was done to temporarily stabilize B and C arch segments. In general, the steps of the excavation and installation of the support system are shown in Fig. 7 and described as below:

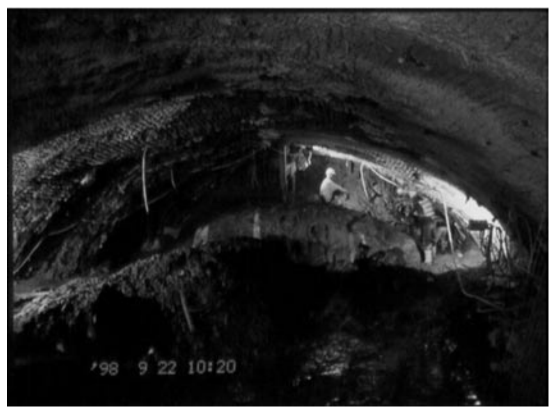
∗ The first round of pipe roofing was installed through



EXCAVATION OF MAIN TUNNEL	EXCAVATION OF DETOUR TUNNEL	WORK ACTIVITES IN COLLAPSED SECTIOIN	REINFORCEMENT OF EXISTING SEGMENTS
1.EXCAVATE THE UPPER PORTION OF VEHICALE CROSS PASSAGE	1.EXCAVATION OF DETOUR TUNNEL	1.RECOVERY EXCAVATION	1.REINFORCE SEGMENTS A. B. C
2.EXCAVATION TOWARD PINGLIN	2.CAVITY GROUTING	2.EXCAVATION OF TOP HEADING TOWARD TBM CUTTHEAD	2.SUPPORT ARCH DECKS
3.EXCAVATION TOWARD EAST PORTAL			3.CONSOLIDATION GROUT

Fig. 6 Layout Plan at the Mishap Area

(a) Construction of Bypass Tunnel



(b) Front Remining

Photo 2. Rescuing the WB TBM

Photo 3. Dismantling of the WB TBM

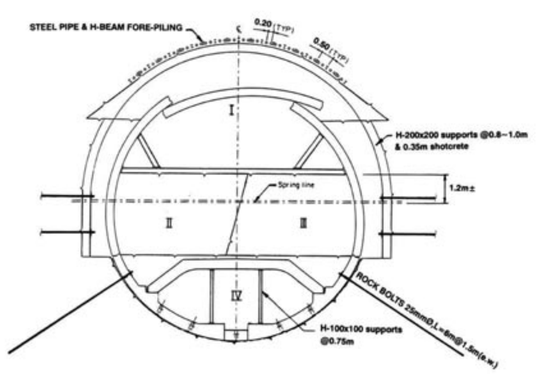


Fig. 7 Excavation Sequence and Support System

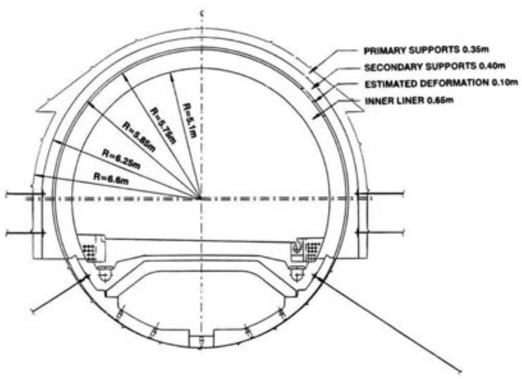


Fig. 8 Final Section after Restoration

segment ring No. 838 at a vertical angle of 25 . The pipe spacing around the tunnel arch was 40cm. Following with the pipe installation, the consolidation grouting used a cement/sodium silicate mixture (LW grout). Collapsed material was removed and segment ring No. 838 was reinforced by a 50cm long advancing stages followed by steel rib installation.

* Step A: After the completion of the above steps, the tunnel was enlarged and advanced 5 to 6m, with steps between 50 and 75cm. To ensure safe operation, steel rib supports were installed during each step with a 35cm thickness of shotcrete over the tunnel arch. At the top heading section, the invert was closed using H200x200 steel beams installed above the top of the precast segments B and C. During bench excavation, the invert was closed using H100x100 steel beams as well.
* Step B: The second round of pipe roofing proceeded after the initial 5 to 6m advance to the face. The pipes in the second round inclined at an angle of 10 with 20 to 40cm spacing around the arch. This was followed with grout injection using LW grout mixtures to consolidate the loose materials above the crown prior to excavation.
* Step C: Repeated procedures described in step A in order to advance the tunnel an additional 5 to 6 m.
* Repeated steps B and C until the top heading advanced approximately 30m after bench excavation commenced and carried out in a coordinated manner until the recovery excavation reached the shield section of the TBM. To minimize the required amounts of segment demolition, the bench excavation was carried out in 1.5m long steps to correspond to the length of the precast liner rings.
* Once the bench excavation advanced about 20 to 30m, consolidation and backfill grouting as well as invert cleanup commenced in the restored tunnel section up to the TBM. The final section of the tunnel after the restoration is shown in Fig. 8.
* The buried TBM was dismantled in a very short period from November 12, 1999 to December 29, 1999. Some useful parts of the TBM were recovered for reuse in the Eastbound TBM. In Photo 3, the dismantling of the WB TBM is illustrated.

CONCLUSIONS AND RECOMMENDATIONS

Due to the mishap that occurred on December 15, 1997 in the Westbound tube of the Hsuehshan Tunnel at Sta. 38k+902.5, the TBM was buried by a cave-in 90 meters in length.

In the incident, overloading on the precast segments adjacent to the mishap area was first noted and then followed by serious cave-in which resulted in the complete burial of TBM. The major causes were estimated to be associated with the poor rock mass conditions near the Shanghsin Fault. The delayed backfill of the cavity behind the segments or the loosened zone caused by the excavating of the top drift, and the active groundwater inflow.

Under the consideration of time and cost, the TBM was dismantled and the drill and blast method adopted for the excavation of the remaining section of the Westbound main tunnel.

The restoration work lasted for 34 months and was accomplished successfully in efficient, safe and economic ways even though the working conditions were severe. The restoration experience obtained in this mishap area might be a valuable reference for future tunnel construction in similar situations.

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