GROUNDWATER SURVEY OF THE HSUEHSHAN TUNNEL AND ITS EXPLORATION DURING CONSTRUCTION

Wen-Yu LIOU[1], Ting-Huai HSIAO[2]

ABSTRACT

The in situ permeability tests performed during the route selection and design stages indicated that the Lugeon numbers of the intact rocks were between 1 and 20; while those of the rocks in the fault fractured zones were more than 20. This indicated the possibility of a high groundwater surge when excavating in the zones of high permeability. The total groundwater inflow for the Hsuehshan Tunnel was estimated to be 180,000 l/min, or 3 m^3/s, during the basic design stage. Besides that, the foreign experts predicted that the maximum long term inflow in the fault-fractured zone could be about 1,000 to 2,000 l/sec.

Because of the high groundwater surge encountered in the Szeleng Sandstone during the tunneling, an additional exploration program was conducted in 1997. A conclusion was arrived at: the fault zone was an excellent confining layer, but the fractured zone around the fault was an aquifer. The thick shale intercalated with sandstone usually constitutes a transverse confining layer. The combination of the low-angle confining layer and high-angle fault plane formed a trellised groundwater storage pattern. The relationship between the shallow and the deep groundwater seemed unclear because of that pattern. Nevertheless, highly permeable rocks, such as the Szeleng Sandstone, and vertical fault fractured zones might possibly interconnect with various isolated aquifers.

Geological boring, ground resistance imagery profiling and geophysical seismic surveys were performed in the construction stage for further locating the Shihtsao Fault and the boundary between the Szeleng Sandstone and the overlying Kankou Formation. The results indicated that the Shihtsao Fault intersected the tunnel at about sta. 32k+100 - 32k+145. The fault was a reverse fault with the fault plane dipping 50-60° near the ground surface. Fault exposures observed in the field showed that the thickness of the fault-fractured zone ranged from 40 to 70 m with a 0.5-1.3 m thick shear of fault gouge. The rock mass disturbed and fractured by the faulting was estimated to be 230 m wide. The gouge clay contained in the Shihtsao Fault fractured zone was an excellent confining layer; so a large quantity of groundwater might have been trapped in the footwall of the fractured zones. The local topography and elevation indicated that the pressure of such a groundwater body might be as high as 34 kg/cm^2. Furthermore, there were 20-30 m wide fractured zones on top of and beneath the contact of the Szeleng Sandstone and the Kankou Formation, forming a groundwater head of about 350 m in height.

The groundwater inflow in the construction stage indicated that the hydro-geological model fit the trellised groundwater pattern. But no high pressure groundwater was found in the Shihtsao Fault. Groundwater was kept in permeable layers between the confining layers. The groundwater inflow in the fine sandstone, the inter-bedding of shale and sandstone, or in the Tsuku Sandstone was influenced by rock types at the contact of the Szeleng Sandstone and the Kankou Formation. The small quantity of groundwater inflow in the Shihtsao Fault and at the contact point of the Szeleng Sandstone and the Kankou Formation resulted from the success of the pre-drainage in advance of the drilling.

Keywords: groundwater survey, groundwater exploration, during construction.

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1. Geologist, Sinotech Engineering Consultants, Ltd. E-mail : wyliou@mail.sinotech.com,tw
2. Geologist, Sinotech Engineering Consultants, Ltd. E-mail : thhgeo@mail.sinotech.com,tw

RESULT OF DESIGN STAGE

Annual rainfall for the area along the alignment of the Hsuehshan Tunnel reaches 3,000mm; the groundwater table in the area is therefore rather high. Field investigation results pointed out the fact that with the exception of the Shihpai-Hsinfeng Falls and the highway areas, all of the streams in the valleys in the area along the alignment of the tunnel are running with water throughout the entire year. In the Shihpai area, the Hsinfeng Falls area and the Taipei-Ilan Expressway areas, streambeds turn dry during the dry season, indicating that the rock masses underlying the streambeds in these areas are high in water permeability.

The results of rock mass permeability tests performed during the Route Selection Stage and the Design Stage (Fig 1) showed that the permeability indices of the intact rock masses fell between 1 and 20 Lugeons. The permeability indices for fault zone materials are generally in excess of 20 Lugeons, hence, in local areas there might be the problem of high permeability, and this might cause large influxes of water to gush into the tunnel during tunnel excavation.

The Consultant for the Basic Design estimated the total volume of water ingress for the entire length of the 12.9 km tunnel to be 180,000 l/min, or 3 m3/sec. Worthy of mention is that the initial water ingress at the periphery of the tunnel excavation face might exceed the long-term water ingress of the tunnel. When tunnel excavation enters into an aquifer, the groundwater at the excavation face may conspicuously increase within a matter of a few months. But then this water may gradually dwindle and decrease towards a steady state.

SUPPLEMENTARY EXPLORATION DURING CONSTRUCTION

Engineering geological data from the Hsuehshan Pilot Tunnel pointed out the possibility that tunnel excavation might possibly be confronted with peak water ingresses, and not just confronted by long-term water ingress. The Board of Advisory Consultants predicted in September 1990 that the maximum water ingress from the fractured zones and the fault zones would be around 1000 to 2000 l/s, thus a Contractor undertaking the task of tunnel excavation should take this into consideration when opting for an excavation method and selecting equipment for tunnel excavation.

During the tunnel construction, excavation of the West Portal of the tunnel progressed smoothly. However, in excavation of the Eastern section of the tunnel, construction work was brought to a halt many times due to collapses resulting from large influxes of groundwater. Furthermore, there were frequent protests from local residents who suspected that sudden groundwater decreases in surface gullies were directly caused by these water ingresses into the tunnel. Because of this, the Taiwan Area National Expressway Engineering Bureau (TANEEB) contracted Sinotech Engineering Consultants, Ltd. to conduct a study entitled "Study, Investigation and Evaluation of Groundwater Influx Issues for the Hsuehshan Tunnel". Further, in January 1999, TANEEB invited a number of foreign experts in this field and held an Advisory Consultants Board Meeting on the Construction of the Hsuehshan Tunnel. Among the issues discussed, most of these foreign experts agreed that the conditions of the rock masses would become better with the advance of tunnel construction progress as reported in past investigative evaluation reports. The experts, nevertheless, recommended a rechecking of the subsurface geological conditions of the rock masses underlying the yet to the excavated section of the tunnel alignment. With due consideration of the fact that supplementary geological investigation during construction is an important step in all engineering projects that helps in unravelling disputes arising out of geological issues, the parties concerned reached an agreement that the consulting board’s recommendation should be accepted, and supplementary geological investigations during the construction stage were performed in the following sections to investigate the position of the Shihtsao Fault and the groundwater distribution(See Fig. 2):

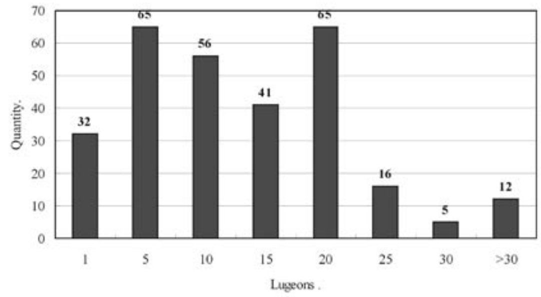

Fig 1 The Results of the Permeability Tests Performed during the Route Selection Stage and the Design Stage

1. The section between Eastbound line Sta31k+500 to Sta33k+000(Area A), corresponding to the section along Pilot Tunnel Sta31k+917 to Sta33k+419. The

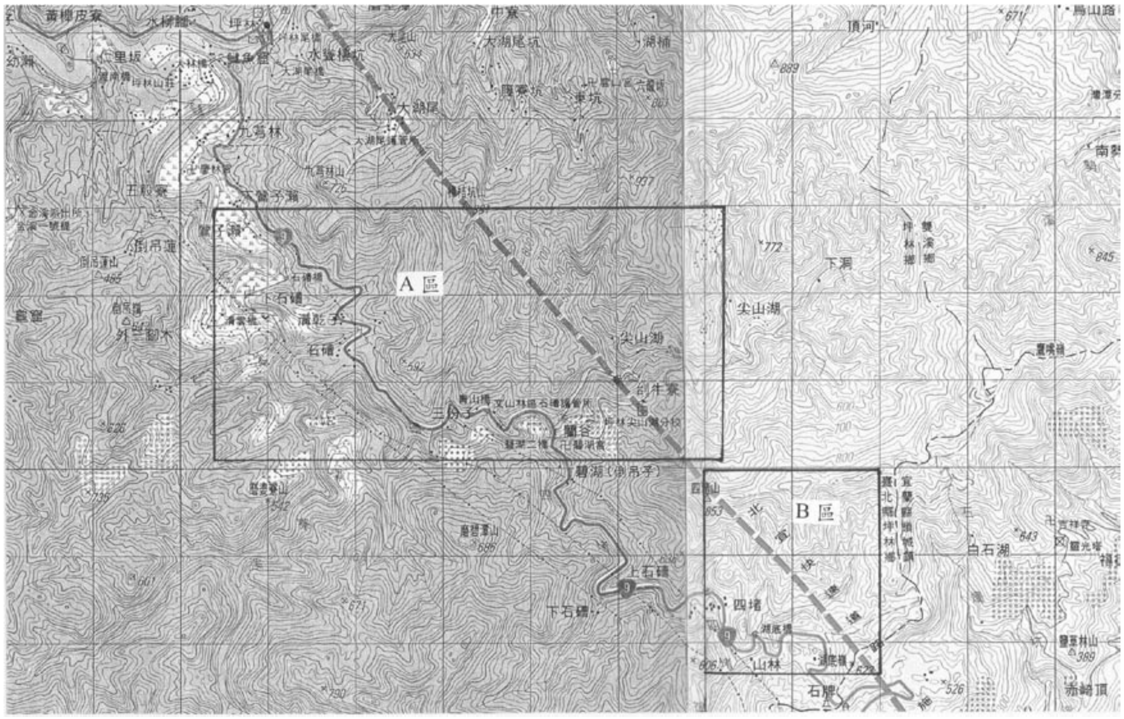

Fig. 2 Location of Supplementary Investigations during Construction Stage

main purpose of the investigation was to define the ground surface extent and position of the Shihtsao Fault, and to define the rock mass characteristics of the ground along the Shihtsao Fault and in the fold area to the Southeast.

2. The section between Eastbound line Sta36k+000 to Sta37k+000(Area B), corresponding to the section along the Pilot Tunnel Sta36k+421 to Sta37k+419. The main purpose of this investigation was to verify whether there was any large scale shearing along the bedding planes at the contact point between the quartzite of the Szeleng Sandstone and the argillite of the Kankou Formation, as well as to gain knowledge on changes in bedding plane inclinations of the subsurface rock formations.

3. In view of the fact that controlling groundwater is of vital importance to tunnel construction, and that the area between the Shihtsao Fault and the No. 2 Ventilation Shaft is a topographic low, water from the ground surface tended to collect there and percolate downward, it thus was desirable to understand the spatial distribution of the groundwater in the area of concern. Recommendation was hence made to conduct a ground electric resistivity imagery profiling survey to a length of 1500 m.

Results of Rock Mass Permeability Tests

This test is performed in a selected hole in the rock mass to be tested. The length of the test is generally 4m. Among the test holes, CB-1 failed due to water influx. Two sets of tests were performed for test hole CB-2. Test results are presented in Table 1. The permeability index for the rocks of the Szeleng Sandstone was 54.3 Lugeons and the permeability index for the rocks of the Kankou Formation was around 23.0 Lugeons.

The Installation and Measurement of Piezometers and Groundwater Observation Wells

During the drilling of hole CB-1, a large quantity water ingress was encountered at depth 115m below the ground surface. A simple measurement performed at the collar of the hole showed that water flow increased with an increase in borehole depth, from 13.3 l/sec to 30.0 l/sec, and the hydraulic pressure at the collar of the hole increased from 2.1 kg/cm^2 to 4.2 kg/cm^2. Following the installation of an auto-recording piezometer at a depth of 122m below the ground surface, the initial hydraulic

Table 1 Results of Lugeon Tests Performed during the Construction Stage

Borehole No.	Test depth (m)	Lugeon
CB-1	95.4~100.00	23.0
CB-1	258.50~263.10	54.3

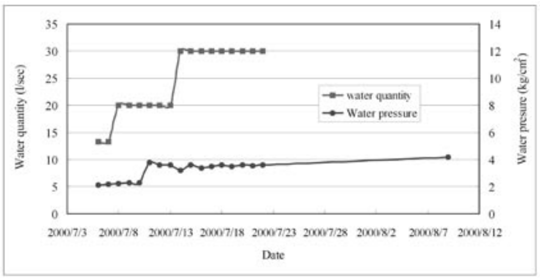

Fig. 3 Hydraulic Pressure at Collar of Hole and Water Flow Historic Curves of CB-1 during Boring

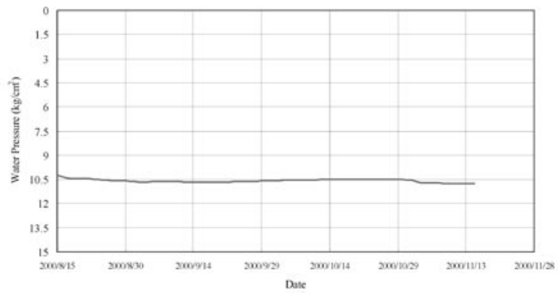

Fig. 4 Chart of Historic Curves for Piezometer Observation Results from CB-1

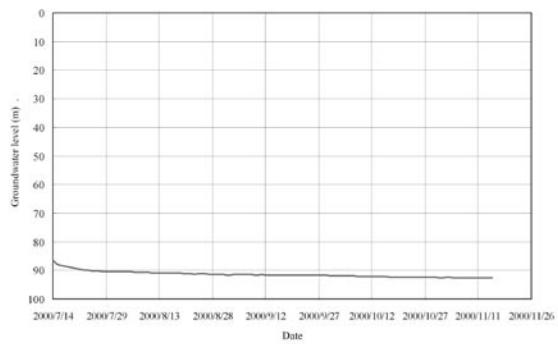

Fig. 5 Chart of Historic Curves for Piezometer Observation Results from CB-2

pressure was 10.25 kg/cm^2 on 08/15/2000, and was 10.65 kg/cm^2 on 09/23/2000. Refer to Figure 4 for details. Another self-recording piezometer was installed in CB-2 at a depth of 420m below the ground surface. The initial groundwater table was at 87m below the ground surface. On 09/23/2005 the groundwater table stood at 92m below ground surface.

Ground Electric Resistivity Imagery Profiling Survey Results

The ground electric resistivity imagery profiling survey extended from Sta31k+200 to Sta32k+700 on the eastbound main tunnel alignment. The survey was extended to include the two ends of the survey line in order to have sufficient results. In the actual final survey, the coverage embraced Sta31k+095~32k+805 on the Eastbound main tunnel alignment. The total length was 1710m. To ensure an adequate survey depth, the spread between survey stations was set at 15m. Seventy five electrodes were used in the survey, thus the total spread length was 1125m. Following data manipulation and screening, the electric resistivity imagery profiles were then subjected to two dimensional reverse back regression interpretation, and a 2-D reverse back regression imagery profile of survey line RIP-1 was obtained, as shown in Figure 7. The following presents a description of the main distribution of the groundwater as indicated through the ground electric resistivity imagery profile obtained from survey line RIP-1. The intactness of the rock mass as evaluated from interpretation of the collected ground electric resistivity imagery profiles is also presented.

1. Figure 6 indicates that the ground electric resistivity structure of the subsurface rock formations are in a high inclination, implying that the groundwater distribution is connected up and down into one zone throughout the fault fractured zone.
2. In general, for rocks of low porosity or with poorly developed fractures, the ground electric resistivity is high. As indicated in Figure 6, the ground electric resistivity for the rock formations underlying the survey line is mostly not high, except for some local sites. Thus it was estimated that the ground underlying the survey line contained a large quantity of groundwater.
3. Also as indicated in Figure 6, there are two major aquifers beneath the survey line. These aquifers

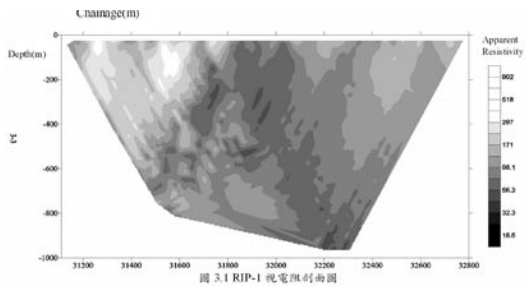

Fig. 6 Chart for Apparent Resistivity Profile of RIP-1

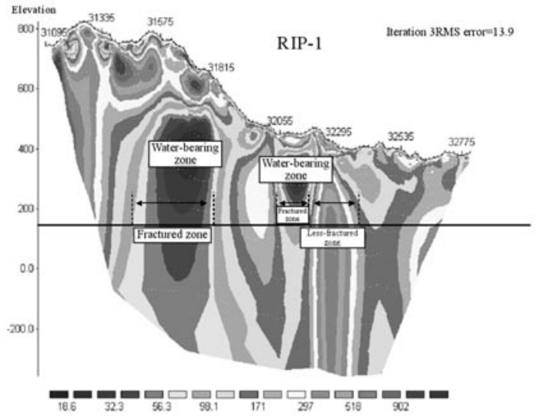

Fig. 7 Chart for Result of RIP-1

are located in the vicinities of Sta31k+665 and Sta32k+100 on the eastbound main tunnel. Of these, the aquifer at Sta31k+665 is the larger.

The aquifer at Sta31k+665 on the eastbound main tunnel is well connected at the point where the tunnel alignment passes through this location. This means that the groundwater from this aquifer may flow into the tunnel, and cause a water influx. Furthermore, the elevation of this aquifer is about 500m above sea-level as compared to 350m for the tunnel, thus tunnel excavation will encounter this high pressure groundwater aquifer when construction advances to this location.

According to the ground electric resistivity imagery profile, the aquifer at Sta32k+100 on the Eastbound main tunnel is less well connected, and of a smaller size. It was anticipated that this aquifer would not cause a large water ingress into the tunnel. Nevertheless, this location is where less fractured rock mass with higher ground electric resistivity changes to more intensely fractured rock mass with lower ground electric resistivity. During tunnel construction, care should be exercised to anticipate this abrupt change in rock mass intactness.

Results of Analysis and in Situ Investigation Based on the above

In the project area the Shihtsao Fault trends in a general east-west direction, and intersects the Eastbound main tunnel alignment at Sta32k+100~32k+145 (corresponding to Sta32k+517~32k+562 on the Pilot Tunnel Alignment). Here, the fault is a moderately inclined reverse fault; its inclination at the ground surface is about 50 to 60 degrees. In the field, the observed width of the fault disturbed shear fracture zone is from 40 to 70 meters. Within this fault fractured zone the rock mass is fractured with intercalations of shear gouge varying in width from 0.5 to 1.3m. Where the fractured zone intersects the tunnel, the width is around 45 meters, while the disturbed rock mass, including the fault fractured zone, is estimated to reach a width of 230 meters. As an effect of the faulting, there are folds of variable tightness occurring on the northern and southern sides of the fault. At the fold axial zone of a group of concentrated folds on the south there should be small scale secondary faults of shear fractures. Fault fracture zones of the Shihtsao Fault are an excellent aquitard, thus there are groundwater reserves in the fracture zones in the rock mass on the northern side footwall. Estimation and in situ measurements indicated that the hydraulic pressure at the tunnel height elevation might be as high as $34kg/cm^2$, furthermore, the tunnel section Sta32k+000~33k+000 (corresponding to Sta32k+417~Sta33k+419 on the Pilot Tunnel Alignment) passes underneath a river valley, tunnel excavation at this site will face the problem of a large quantity of groundwater ingress.

On the eastern section of the Hsuehshan Tunnel, the Szeleng Sandstone is in conformable contact with the Kankou Formation. The boundary between these two rock formations is exposed on the ground surface at Sta36k+420 on the eastbound main tunnel (corresponding to Sta36k+839 on the Pilot Tunnel Alignment). At this boundary, the inclination is 22 , and it is thus estimated that this boundary intersects the tunnel at Sta35k+370~35k+390 on the Eastbound main tunnel alignment (corresponding to Sta35k+794~Sta35k+814 on the Pilot Tunnel Alignment). In the Design Stage, the intersection was at Sta35k+890 on the eastbound main tunnel alignment, corresponding to Sta36k+312 on the Pilot Tunnel Alignment. As a consequence, at the tunnel elevation, the length of the Szeleng Sandstone exposure is increased by 500~520m towards the west as compared with the design stage configuration. Also, above and beneath the boundary, there were fractured zones, 20 to 30 meters wide. Piezometric observation results from CB-2 indicated that this section was well underneath the groundwater table with a hydraulic head of 350m, indicating possible water influx problems during the tunnel construction.

Fault planes and shear planes commonly constitute aquicludes due to the presence of water-proofing fault gouge and shear gouge. However the fracture zones occurring immediately behind these zones of weakness are rich water bearing zones. The fact that CB-1 encountered a large quantity of groundwater after it went past the Shihtsao Fault would serve as an example. In addition, in the present section of the Tunnel, the location where the Tunnel cuts through the Shihtsao Fault is subject to high hydraulic pressure as well as high overburden pressure, hence the groundwater ingress would be quite immense. With reference to an excavation rate of 1.2m per advance, and assuming that an aquifer 1.2m in thickness was penetrated, estimation would give an initial maximum water ingress of 140 l/sec, reaching and maintaining at 78 l/sec after 15 days. The present investigation indicated that a high pressure water pocket occurs behind the Shihtsao Fault, thus if tunnel excavation proceeded in a west to east direction, the chance of encountering sudden high pressure groundwater might be reduced. However, since the gradient of the tunnel inclines towards the east, the draining of groundwater in the tunnel through gravitational means would not be feasible. If tunnel excavation follows an east to west direction, then the gravitational draining of water is applicable, but there will still be the problem of sudden high pressure water influxes when cutting through fault zones. Thus it can be said that regardless of whether tunnel excavation is advancing east to west or west to east, as this section is reached, precautionary measures aiming at abating large quantities of groundwater ingress should be taken. Such precautionary measures include the drilling of advance boreholes to identify geological conditions and distribution of groundwater ahead of the excavation face. Thorough understanding of the geologic as well as hydrogeological conditions ahead would render planning of the countermeasures more efficient and practical.

DISCUSSION

The water ingressed that occurred during the construction of the Hsuehshan Tunnel indicated that the water ingression occurred in a manner manifested by water bodies occurring in isolated "cells". There was no large groundwater ingress during the excavation of the tunnel in the vicinity of the Shihtsao Fault. The groundwater there occurred as separate, sealed water bodies between beds. These water bodies do not connect, nor do they flow. At the contact point between the Szeleng Sandstone and the Kankou Formation, the groundwater occurrence was under the control of the geological characteristics of the beds. Groundwater influx occurrences coincided with sites of fine-grained sandstone in the argillite, alternations of sandstone and argillite, or in the sandstone of the Tsuku Sandstone. There was no water ingress from argillaceous beds. Formational contact between the Szeleng Sandstone and the Kankou Formation or at the Shihtsao Fault did not show large quantities of water ingress as had been assumed, this was deemed the result of the predraining of the water through drain holes and horizontal drain holes drilled during the construction stage, thus lowering hydraulic heads in the vicinities of the work faces.

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