

A CASE STUDY OF PIPING FAILURE ASSOCIATED WITH SHIELD TUNNELLING

by

L.S. Lin, D.H. Ju and R.N. Hwang

Reprinted from

*Proceedings of 15th International No-Dig '97, Taipei, Taiwan
November 26~28, 1997, pp.6B-1-1~6B-1-13*

A CASE STUDY OF PIPING FAILURE ASSOCIATED WITH SHIELD TUNNELLING

Ling-San Lin

Director General, Department of Rapid Transit Systems, TMG,
Taipei, Taiwan, ROC

Daniel H. Ju

Director of CDPO, Department of Rapid Transit Systems, TMG,
Taipei, Taiwan, ROC

R. N. Hwang

Manager, Moh and Associates, Inc.,
Taipei, Taiwan, ROC

SYNOPSIS: Making openings on diaphragm walls or base slabs is always a risky operation when the ground is permeable and water table is high. In 1995, piping failure occurred during the opening of one of the tunnel portals at an arriving shaft of the Panchiao Line in the Initial Network of the Taipei Rapid Transit Systems. It created a sinkhole of as deep as 6m and caused serious damages to adjacent structures and unacceptable distortions of tunnel segments. As a result, the construction was delayed by two years and the financial loss was tremendous.

This incident was mainly due to the fact that the ground improvement by grouting did not achieve the desired purpose of providing a watertight housing for the shield machine when the portal was opened. The ground improvement was carefully conducted and its quality was confirmed by a series of tests, and yet, piping still occurred.

The shaft was promptly flooded by recharging to stop the ingress of water. The sinkhole was quickly backfilled and the ground was stabilized by compensation grouting. With all the efforts, the damages were able to be limited to a minimum. The tunnels were sealed and the damaged segments were replaced in compressed air.

This paper presents the sequence of the events, the remedial measures taken and the rehabilitation works.

INTRODUCTION

An underground section of the Panchiao Line, refer to Fig. 1, in the Initial Network of the Taipei Metropolitan Rapid Transit Systems runs alongside the Tahan Creek and underpasses the Hsintien Creek. Groundwater table along the entire route was high and ground conditions were complex. The twin tunnels were excavated by using two earthpressure balance shield machines and were lined with precast concrete segments. The tunnels are the deepest, 33.6m below ground surface, at the location of Vent Shaft A which served as an arrival-and-launching shaft for shield driving. Two portals, refer to Fig. 2, were made on the western wall of the shaft for the shield machines to enter the shaft. In 1995, piping failure occurred when the diaphragm wall was knocked out at the portal to prepare for the arrival of the shield machine in the Up-Track tunnel. This incident resulted in a sinkhole with a surface area of 5,000 m² and a maximum depth of 6m. This paper presents a documentary of the events, remedial measures and the rehabilitation works.

SUBSOIL CONDITIONS

The site was located neighboring the southwest border of the Taipei City where the Tahan Creek joins the Hsintien Creek to become the Tamshui River. The subsoil at the site comprises alluvial deposit, i.e., the so-called Taipei Silts or the Sungshan Formation, to depths varying from 45m to 55m. Underlying the Sungshan Formation is a gravelly layer, i.e., the Chingmei Formation, which is extremely permeable and was once the sole source of water supply for the City of Taipei. A typical soil profile in this area, together with the configuration of the shaft, is shown in Fig. 2. The two tunnels are buried in a silty sand layer, i.e., Layer III in the Sungshan Formation, and the piezometric head at the inverts of the tunnels was about 200 kPa.

GROUND IMPROVEMENT

To prepare for the arrival of the shield machines, Column Jet Grouting (CJG) was conducted to harden the soil at the portals to form two protective tubular shelters for the shield machines to stay temporarily to wait for the opening of the portals. A total of 40 grout columns, 1.8m in diameter, were installed at each of the two portals by injecting mixture of cement-water at high pressure using the triple-tube technique. They were spaced at 1.35 to 1.55m apart, center to center, as shown in Fig. 3.

The treated ground was initially 6.27m in length and was lengthened by 3m using chemical

grouting (CW1) to fully cover the entire shield machines which were 7.68m in length. Tests indicated a permeability of 5×10^{-6} cm/sec of the treated ground. Before the diaphragm wall was knocked out to make the opening, horizontal holes were made through the diaphragm wall into the treated ground to check if leakage would occur. A total of 67 holes were made on the two portals and they penetrated into the treated ground for, upto, 3.1m. Minor leakage did occur and was stopped by injecting OH and LW solutions. To further ensure the safety of construction, 18 additional CJG columns were installed, refer to Fig. 3, right at the back of the diaphragm wall. After the shield machine entered the shelter, CW1 and Set Foam were injected from the inside of the shield in an attempt to fill the fissures, if any, in the treated ground.

THE EVENTS

At 01:30 of July 16, 1995, an inflow of water, with an estimated rate of 200 m³/hr, was observed at the invert when the diaphragm wall was knocked out to prepare the portal for receiving the shield machine in the Up-Track tunnel. Sand bags were placed in front of the portal in an attempt to stop the flow in vein. Set Foam was injected and grouting was applied from the inside of the shield in an attempt to seal off the hole, but this did not lead to any improvement of the situation. Within hours, the flow increased to a rate of 500 m³/hr and a large quantity of soil was washed into the shaft. The water appeared to have come from the Chingmei Formation which is practically an underground reservoir. The bolts on segments started to burst and the segments started to deform. Much water entered the tunnel from cracks on segments and rushed to the shaft. The situation was judged to be dangerous, the efforts of stopping the water were abandoned and all the workers were ordered to retreat to the surface at 04:00. The ground behind the diaphragm wall finally collapsed resulting in a sinkhole, with a maximum depth of 6m, right above the shield machine. Ground settlements extended to a distance of 70m from the shaft as shown in the contour in Fig. 4.

Actions were immediately taken to limit damages to minimal and to prevent the situation from deterioration, including

- Raising the water level in the shaft by recharging water directly into the shaft and also pumping water into the Up-Track tunnel from the other end. The ground water finally rose to RL 89.5m in the shaft and segments in both tunnels were flooded to a distance of 800m or so from the shaft.
- Backfilling the sinkhole. The quantity of fill reached a total of 4,850 m³ at the end of operation. The underground cavities were filled by compensation grouting. A total of

2,710 m³ of LW grout was injected. The locations of grout holes are shown in Fig. 5.

- Installing a row of sheet piles to prevent the influence zone from expanding. The layout of sheet piles is shown in Fig. 5

All these measures were taken promptly and they effectively arrested ground settlements within a couple of days. All the works, except compensation grouting, were completed on July 20. Compensation grouting, however, continued till July 30 when its effectiveness was confirmed.

The safety of Hwachiang Bridge, of which the nearest pier (refer to Fig. 4 for location) is only about 15m away from the center of the sinkhole, was a major concern to everyone. Fortunately, instrument readings indicated that the bridge was unaffected. The piers were founded in the Chingmei Formation which is difficult to be eroded. The shops to the west of the shaft, however, settled by a maximum of 320mm. They were judged to be unsafe for business and had to be closed. Cracks occurred on the slabs of fish ponds, which were used for fishing as a recreation, inside these shops and water in these ponds was completely gone. The shop owners were compensated for the shops, ponds, the fish killed, and the loss of revenue. These shops were finally demolished and rebuilt.

INVESTIGATIONS

To determine the extent of disturbance to the subsoils and to confirm the improvement made by compensation grouting, eight boreholes, 22m to 45m in depth, were sunk and SPT tests were performed. Results indicated that the ground was effectively densified.

The settlements of the tunnels were estimated by checking the elevations of the tunnel crowns by drilling to reach the crown. The maximum settlement of the tunnel was found to be 1.46m for the Up-Track tunnel and a total of 39 rings (Ring Nos. 780 to 818) were found to have settled. Fig. 6 illustrates the distortion of the Up-Track tunnel. For information, the last segment in the Up-Track tunnel was Ring No. 818 which was still inside the shield.

At the time the incident occurred, the Down-Track tunnel was already completed to the shaft and, in fact, the shield machine had already been launched and 25 rings had been erected in the second drive to the east of the shaft. The last segment before the shaft was Ring No. 837. The maximum settlement of the tunnel was found to be 0.34m and a total of 34 rings (Ring Nos. 800 to 833) were found to have settled.

Grouting was carried out to stabilize the disturbed soils under the two tunnels and to fill up

cavities. A total of 15.3 m³ of CB grout was injected by drilling next to the concrete segments from ground surface.

Divers were sent to the bottom of the shaft to check the conditions of the shaft. The structure of the shaft was found to be unaffected. The sands at the bottom of the shaft was estimated to be 1,500 m³ in volume. The shaft was cleaned in August for the subsequent operation to be carried out.

REHABILITATION OF THE UP-TRACK TUNNEL

Divers were sent into the tunnels in mid-September to examine the conditions of the tunnels. The sand inside the Up-Track tunnel was estimated to be about 3,300 m³. The damaged segments had to be removed and replaced. After evaluating all the alternatives, it was decided that the rehabilitation be carried out in compressed air.

The portal was sealed, refer to Fig. 7, by a concrete retaining wall so the water in the shaft can be drained. Steel cages were laid by divers to work as formwork and concrete was poured to a final height of 9m. At the time the incident occurred, work had already been carried out at the portal on the eastern wall to prepare for launching and the diaphragm wall had been knocked out to the last 100mm in thickness. It was afraid that a similar incident might occur therein, therefore, this portal was also sealed by a concrete wall, but only to a height of 7.5m. These retaining walls were completed at the end of October and the water in the shaft was drained in November.

A cutoff curtain wall was installed by solidifying the sand in the tunnel at the location of Ring No. 775. Grouting was carried out from the surface by drilling through concrete segments. The sand between this curtain wall and the portal, which had already been sealed, was then grouted using cement-betonite mixture to form a solid plug. CJG grouting was carried out, refer to Fig. 8 for section, from ground surface between Ring No. 772 and Ring No. 818 to stabilized soils within 4.0m from the tunnel. The treatment for the soils beneath the tunnel had to be postponed to a later date because of the presence of the shield machine and the auxiliary facilities in the tunnel blocking the drilling.

A bulkhead was installed at the location of Ring No. 37 and the tunnel was pressurized in February, 1996, to a maximum pressure of 2.1 bar. The damaged segments was removed and replaced ring by ring. After all the segments were replaced, air pressure was released. The electrical and mechanical equipments in the shield were removed and the shell was abandoned and left in place to become part of tunnel lining. For making the final connection to the shaft,

freezing method was adopted to solidify the soils around the portal so water would not get into the shaft through gaps and cracks. A total of 66 vertical pipes were installed from the ground surface and 11 horizontal pipes from the shaft for the coolant to circulate.

Freezing started in January, 1996 and the soil temperatures were closely monitored. After the effectiveness of freezing was confirmed, the temporary concrete retaining wall was demolished and the remaining diaphragm wall at the portal was knocked out in July, 1997, to expose the shield from its front. On August 2, 1997, when the shield was fully exposed, a piece of drift wood and a PVC pipe were found right at where leakage was first observed. Whether they were responsible for the incident remains to be investigated.

REHABILITATION OF THE DOWN-TRACK TUNNEL

As mentioned previously, at the time the incident occurred, the shield machine in the Down-Track tunnel had already passed the shaft and was 25m into the second drive. The second drive was unaffected by the incident and the shield machine was still usable. The equipment in the machine was cleaned and repaired after the shaft was drained. The driving resumed in January, 1996 and the entire tunnel was completed in July, 1996.

In the first drive, sand stretched to a distance of 50m behind the shaft and was estimated to be 100 m³ in volume. A curtain wall was installed at the location of Ring No. 801 and another curtain wall was installed at the location of Ring No. 833. The installation started with drilling through concrete segments from ground surface and inserting steel tubes into the holes. Horizontal beams were then welded onto these tubes by divers to make a lattice. Finally, steel sheets were welded onto this lattice to become a diaphragm. The space between these two curtain walls was completely filled using cement-bentonite grout.

A bulkhead was installed at the location of Ring No. 37. The tunnel was dewatered and compressed air was applied in August, 1996 to repel ground water. The damaged segments were removed and new segments were erected. The work was completed in June, 1997.

CONCLUSIONS

The incident started with a minor leakage and resulted in a delay of 2 years and a financial loss exceeding NT\$ hundreds of million. It illustrates how dangerous groundwater can be in underground constructions. After the incident, the project owner, designer, and consultant all worked closely with the contractor, days and nights, unselfishly to have the problems solved. The international contractor was able to obtain full support from his headquarters and to work out the many solutions which are both unique and innovative. With all these efforts, the

problems were able to be solved within the minimum time possible.

ACKNOWLEDGMENTS

The authors wish to express their sincere gratitudes to the Contractor, Kajima Corporation/Ta-yu-wei Construction Co., Ltd. Joint Venture, for providing the detailed information and for the excellent job done. They are also grateful to their colleagues in the Department of Rapid Transit Systems for their endeavor. To the valuable contributions made by the Detailed Designer, Sinotech Engineering Consultants, Ltd. and the Geotechnical Engineering Specialist Consultant, Moh and Associates, Inc., the authors are deeply indebted.

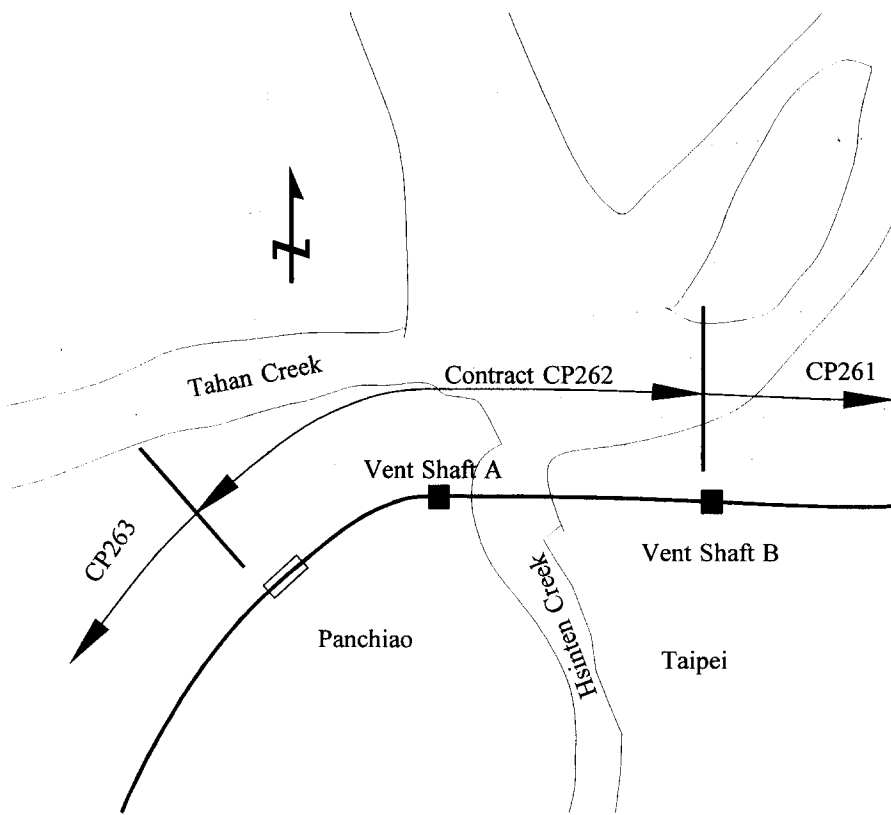


Fig.1 Location of the Site

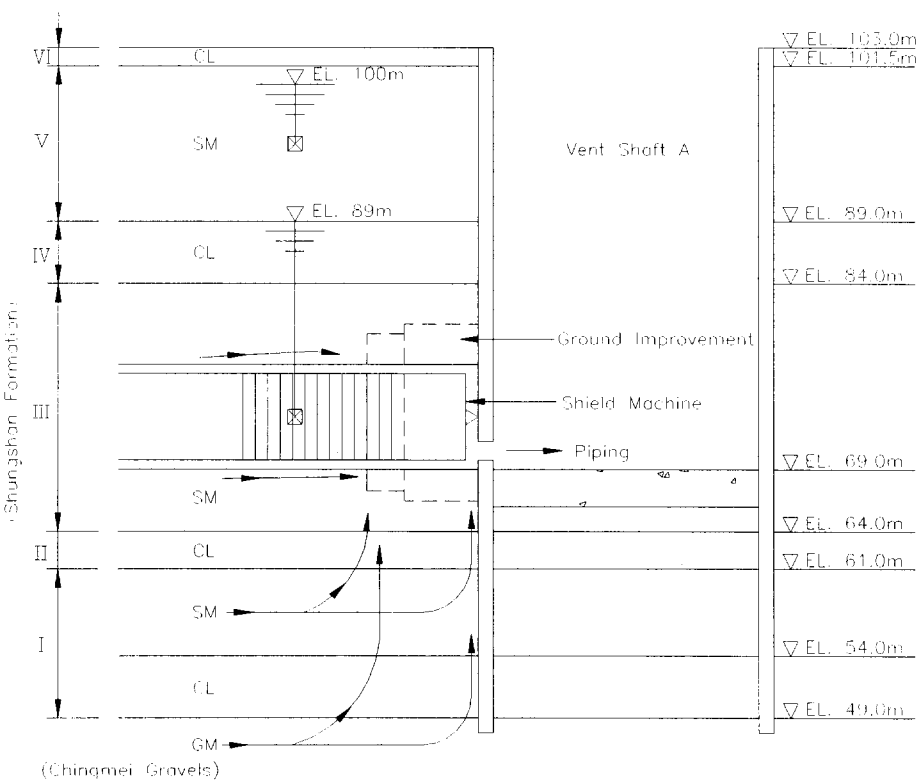


Fig.2 Soil Profile and Configuration of the Shaft

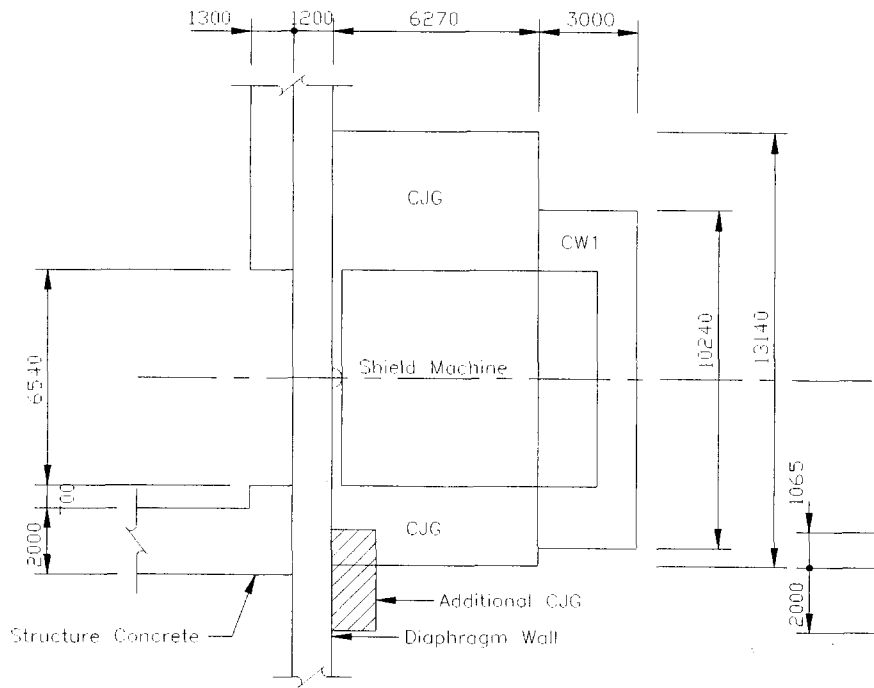
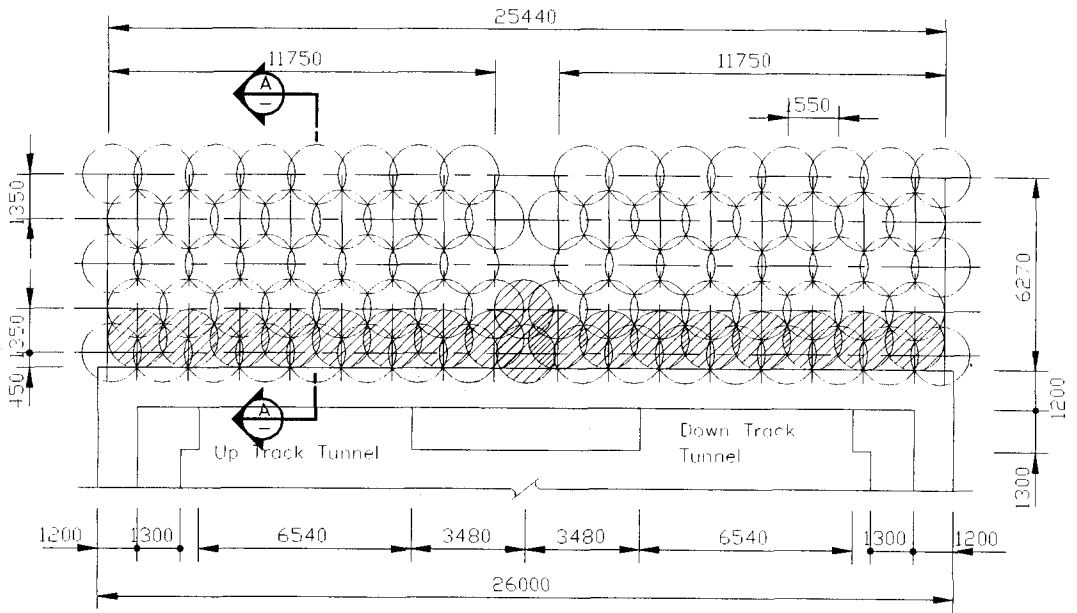


Fig.3 Ground Treatment

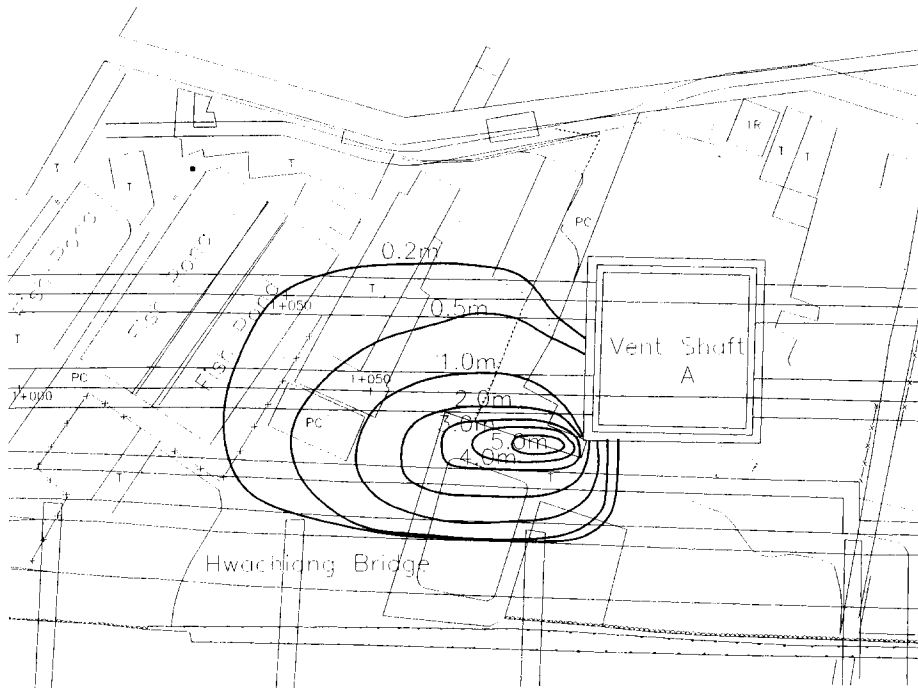


Fig.4 Settlement Contour

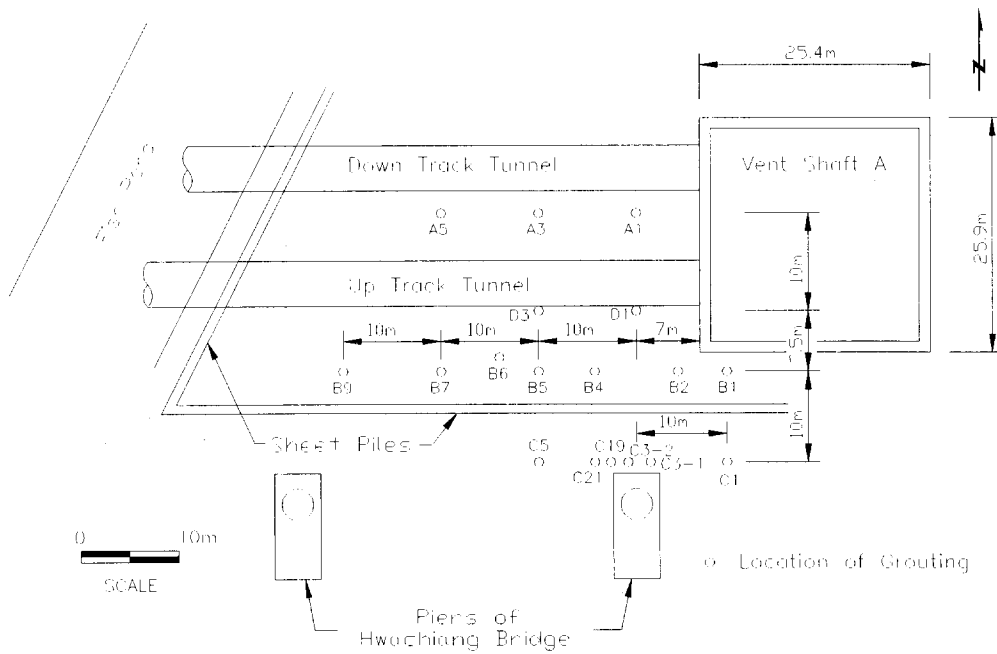


Fig.5 Remedial Works

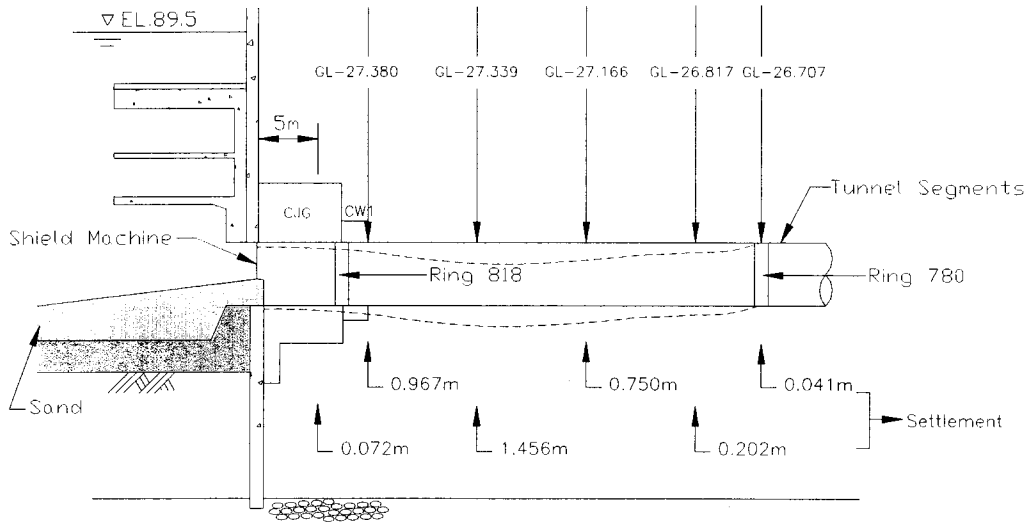


Fig.6 Settlements of the Up -Track Tunnel

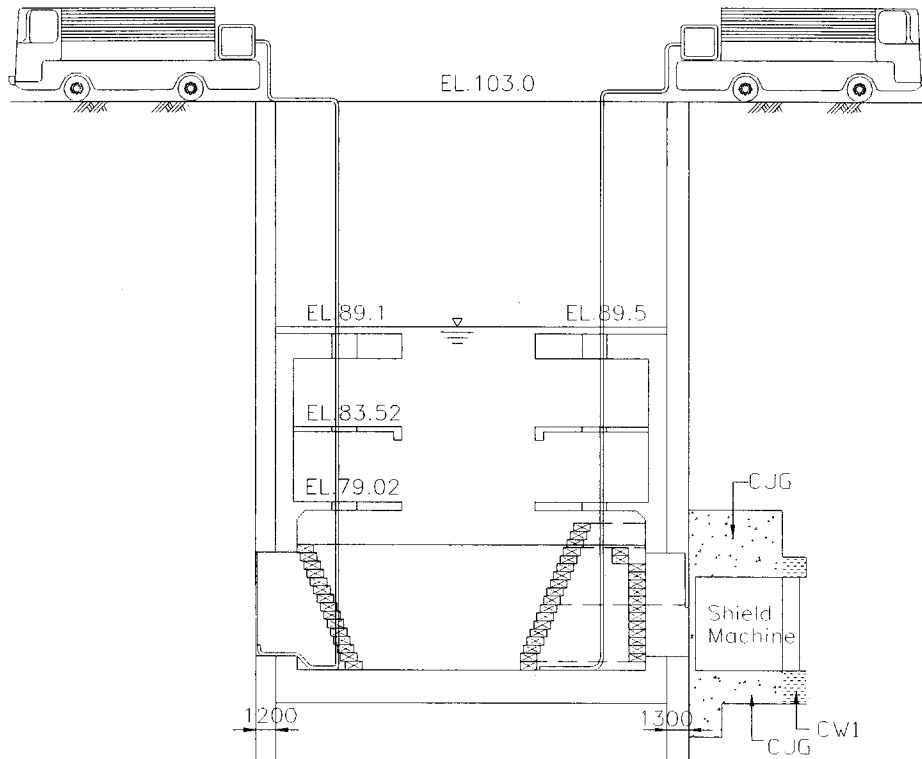
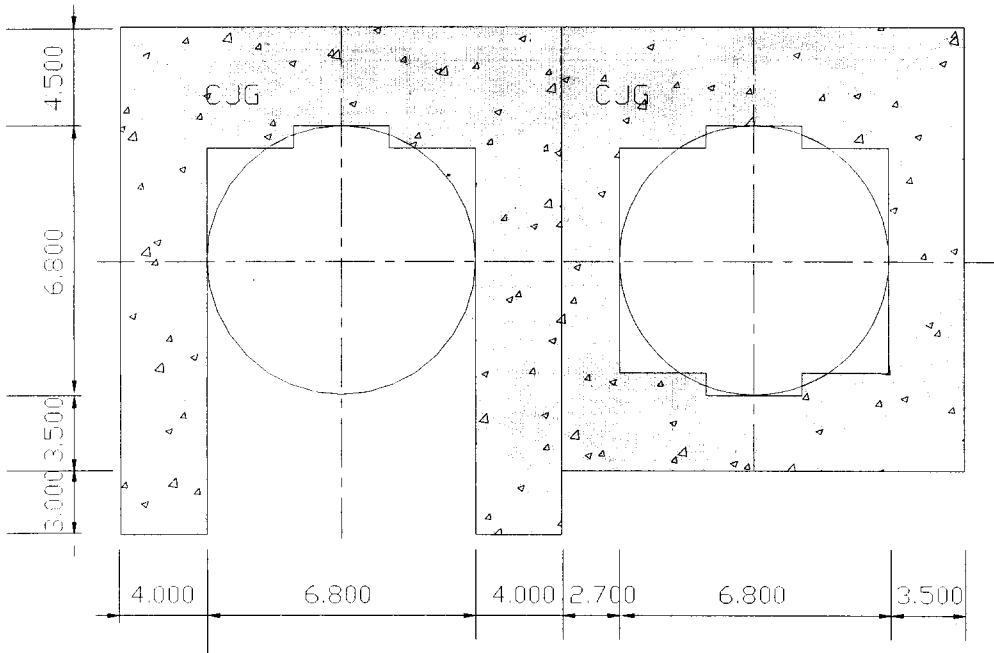
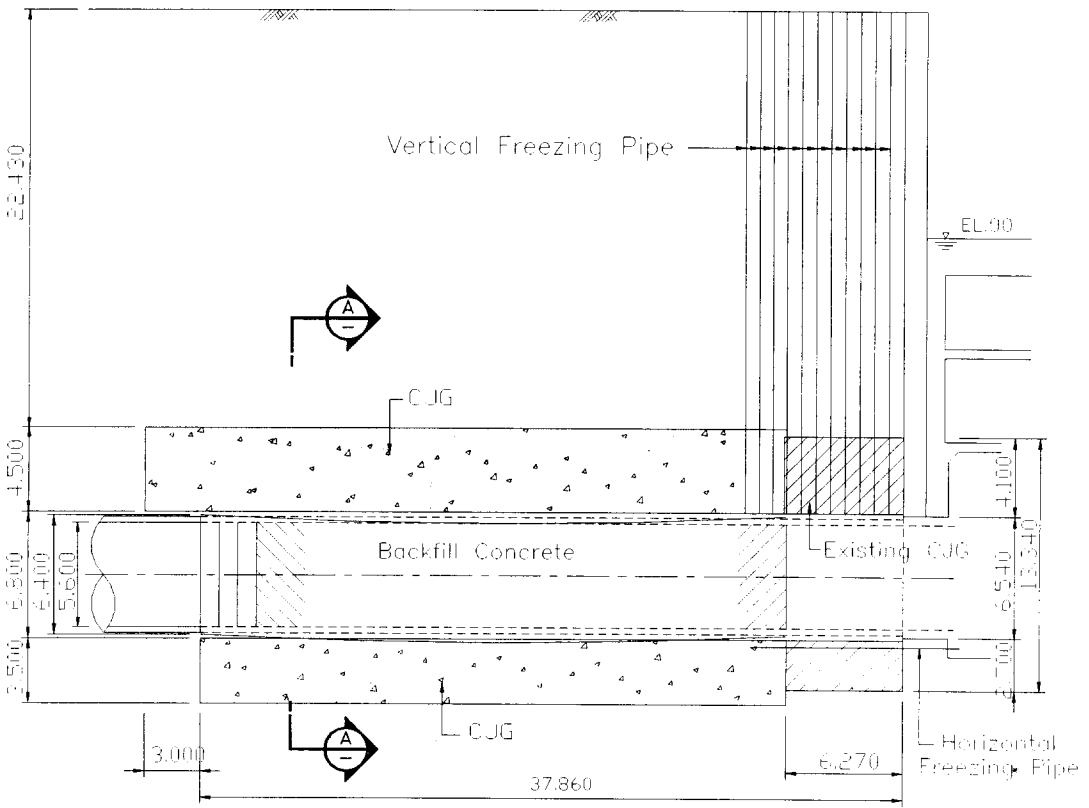
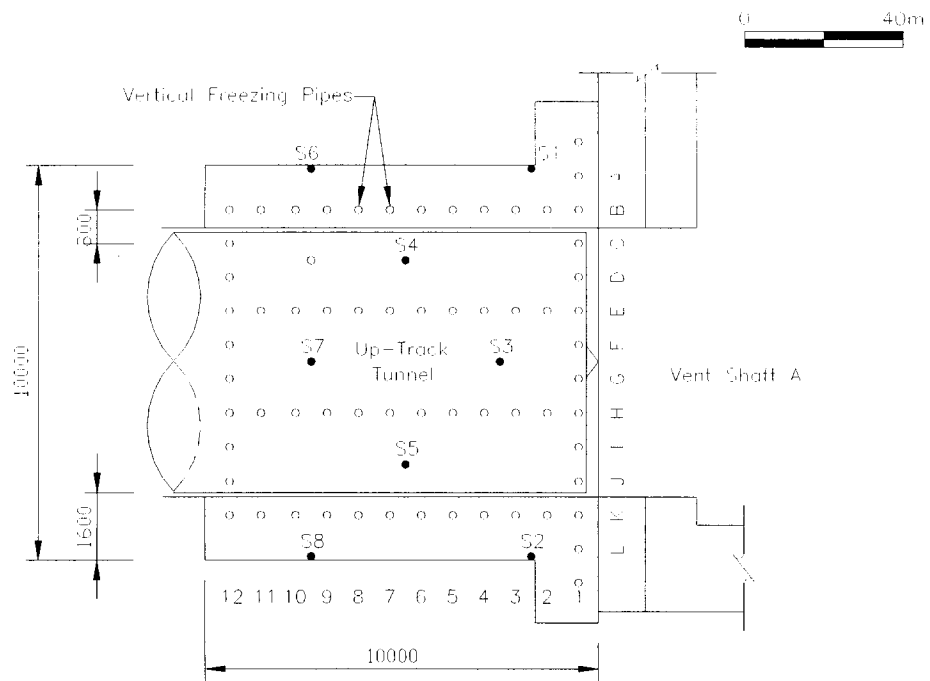


Fig.7 Concrete Retaining Walls for Sealing the Portals (Up-Track Tunnel)

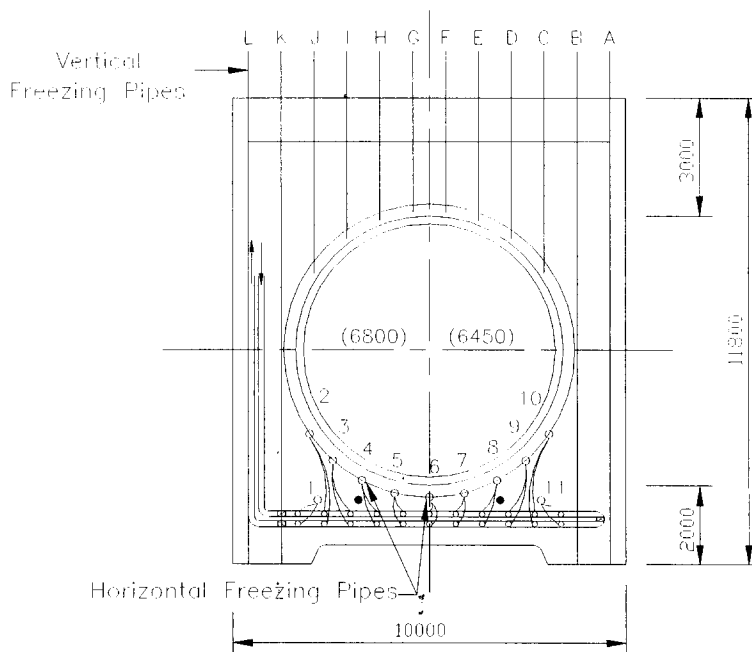


Section A-A

Fig.8 CJG Ground Improvement for Rehabilitation



(a) Plan



(b) Elevation

- Freezing Pipe
- Temperature Measurement Tube

Fig.9 Arrangement of Freezing Pipes