Flooding of A Working Shaft during Construction of Taipei MRT

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SYNOPSIS：A tunnel was seriously damaged when the portal was enlarged for the installation of the flexible joint. Water spurted at the invert and the flow soon became uncontrollable. The shaft had to be flooded to balance the groundwater pressure. A total of 23 segments of the tunnel lining were damaged and had to be replaced. Freezing was first carried out to seal off the opening so the water in the shaft could be drained and the shaft could be cleaned. Freezing was again carried out to form a tubular shelter to surround the damaged section of tunnel for the segments to be replaced subsequently.

Described in this paper are the sequence of events and the remedial works taken. Also described herein are the legal aspects of the case.

1. Introduction

Experience has indicated that groundwater was responsible for most of the failures which occurred during underground constructions. Groundwater is potentially dangerous whenever excavation is deep and there exists a water-bearing stratum near the bottom of excavation. Normally groundwater problems are properly taken care of in designs. However, problems still occurred frequently during constructions. This is particularly true when openings are made on existing structures, for examples, for constructing crosspassages between two tunnels or making connections between tunnels and stations of rapid transit systems. In such cases, once leakage occurs, it will be difficult to seal off these openings and to stop the groundwater from spurting because of the site constraints and obstructions from the existing structures.

In the construction of the Initial Network of Taipei Rapid Transit Systems (TRTS), an incident occurred as a result of the spurting of groundwater when the connection was made to a working shaft and resulted in damages to a section of tunnel. The shaft had to be flooded to balance the groundwater pressures inside and outside the shaft. Subsequently, freezing technique was used to patch up the portal to enable the shaft to be drained and cleaned. Freezing was again carried out to form a tubular shelter to enclose a section of tunnel to enable the damaged segments to be replaced.

2. Ground Conditions

As depicted in Fig. 1, the Ventilation Shaft in Construction Contract CH221 is located between Guting Station (Station G10) of the Green Line (i.e., the Hsintien Line) and Tingshi Station (Station O16) of the Orange Line (i.e., the Chungho Line) of the Taipei Rapid Transit Systems. It served as a working shaft for launching all the four tunnel drives, two towards the north and two towards the south.

Figure 2 shows the soil profile at this site. As can be noted that at the surface there exists a thick layer of Sungshan Formation which is underlain by the so-called Chingmei Gravels at a depth of 35m below the ground surface. A typical CPT (cone penetration test) profile for the central city area of Taipei is given in Fig. 3. There are six sublayers in the Sungshan Formation of which Sublayers VI, IV and II consist of soft silty clays (CL) while Sublayers V, III and I consist of loose to medium sands (SM). The stratigraphy at this site is quite similar to what is shown in Fig. 3 except that there exists a gravelly layer in Sublayer V. Representative properties of the subsoils in the Sungshan Formation are given in Table 1. The Chingmei Gravels underneath the Sungshan Formation contains gravels of various sizes and is extremely permeable. This gravelly layer was the main source of water supply of the City of Taipei till the 60's. Because of its ample storage capacity of groundwater and the extremely high permeability, this Chingmei Formation was responsible for several major failures during the underground construction of TRTS (Lin, Ju and

Hwang, 1997; Moh, Ju and Hwang, 1997, Ju, Duann and Tsai, 1998, Chen, Pei and Hwang, 1998).

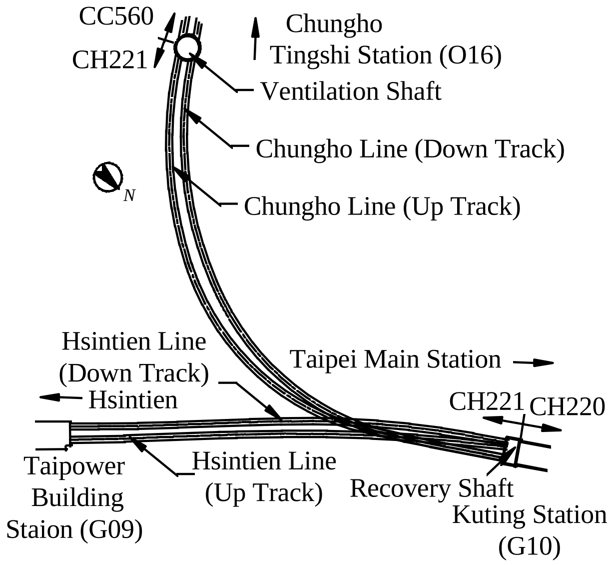

Fig. 1 Location plan

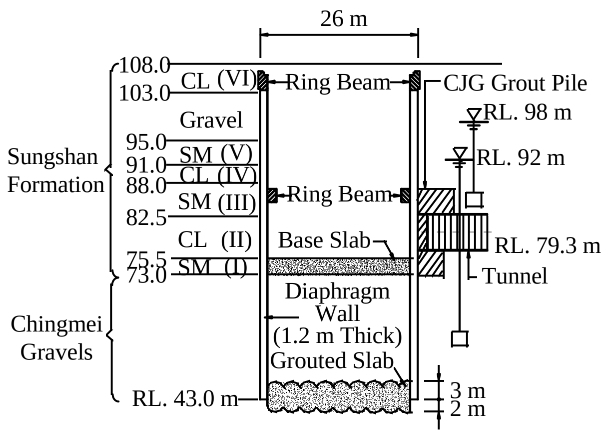

Fig. 2 Ground conditions and configuration of the shaft

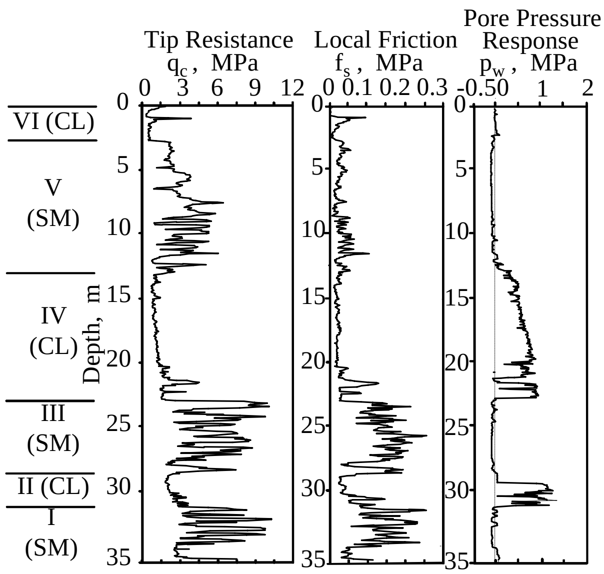

Fig. 3 Typical CPT profile in central Taipei City

Table 1 Representative Soil Properties

Sublayer	Total Unit Weight, kN/m^3	Water Content, %	Liquid Limit, %	Plasticity Index, %	Particle Size Distribution %			
					Gravel	Sand	Silt	Clay
VI	18.3	36.1	44.0	18.8	0	5	47	48
V	20.7	21.1	-	-	3	68	19	10
IV	19.3	29.2	28.0	6.3	0	24	60	16
III	19.9	24.7	-	-	0	73	18	9
II	19.5	28.3	28.0	8.5	0	25	64	11
I	21.1	18.8	-	-	0	80	14	6

Sublayers V and III are indeed separated by two aquitards, i.e., Sublayers II and IV, and become independent aquifers with different piezometric levels. However, the piezometric levels in all the sublayers in the Sungshan Formation did move in phase with the piezometric level in the Chingmei Gravels, indicating moderate leakage in these two aquitards (Moh and Hwang, 1997). At this site, the piezometric levels in Sublayers V, III, and I were at RL 101m, 98m and 92m, respectively. The piezometric level in the Chingmei Gravels was practically the same as that in Sublayer I, i.e., at RL 92m.

3. Construction

This circular ventilation shaft is 26m in its outer diameter and was retained by 16 diaphragm wall panels of 1.2m in thickness during excavation. These diaphragm wall panels were interlocked with horizontal reinforcing bars across the joints. Excavation was carried out to a depth of 35m below ground surface. Because the bottom of excavation was immediately underlain by the Chingmei Gravels, which is practically a water reservoir, piping and blow-in were the two major concerns in selecting the method of construction. After evaluating all the options for groundwater control, it was decided to extend the diaphragm walls to a depth of 65m and to grout the soils at the toe of the diaphragm walls to form an impervious plug for cutting off seepage flows and for obtaining a factor of safety of 1.25 against blow-in.

The diaphragm walls were supported by two ring beams as shown in Fig. 2 without any other types of internal bracing. Lateral deflections of the wall during excavation were within 10mm, which were very small in comparison with the deflections observed for box-shape braced excavations with similar depths of excavation. This indicates that circular shafts out-perform rectangular ones as far as wall deflection is concerned.

Although this section of the route is part of the Chungho Line, the two tunnel drives to the north of the shaft were within the scope of Construction Contract CH221 of the Hsintien Line. They were excavated by using two slurry type shield machines and lined with reinforced concrete segments of 6100mm in outer diameter and 250mm in thickness. The other two tunnel drives to the south of the shaft were the responsibility of the contractor of Construction Contract CC560 of the Chungho Line. These two tunnel drives had not been started at the time when the incident occurred.

As depicted in Figs. 2 and 4, ground treatment was carried out outside the shaft to form a cylindrical shelter at the portal of each of the twin tunnels before launching the shield machine. These two shelters were provided for the shield machines to stay temporarily and to cut off the path of water flowing into the shaft through the fissures surrounding the shield. Each shelter was made of 62 grout piles formed by high pressure grouting using the column jet grouting technique (CJG). All these grout piles were, theoretically, 1.8m in diameter and were installed in a triangular pattern as shown in Fig. 4. The overlaps between neighboring piles were theoretically 240mm maximum.

4. The Incident

The shaft was successfully constructed and the two tunnels towards the north of the shaft successfully completed. Leakage occurred at the invert on 1 April, 1994 (Day 0), when the portal of the Up-track tunnel was enlarged for installing the flexible joint between the tunnel and the shaft. Although, as depicted in Figs. 2 and 4, ground treatment had been carried out to solidify the surrounding soils, water was able to find its way into the shaft. Because the Chingmei Gravels is an extremely permeable water-bearing stratum, once seepage paths developed, the surrounding soils quickly liquefied under the great hydraulic gradients. The flow soon became out of control. The large flow brought much soil into the shafts and the surrounding ground kept on subsiding. All the attempts failed to stop the water from spurting and the shaft had to be flooded to prevent the situation from deteriorating. The flow rate was estimated to be, as much as, 7 cubic meter per minute at the time when the rescue operation was abandoned (Fan and Chao, 1997).

The water level inside the shaft rose to RL 92m and became steady in an elapsed time of 48 hours. With the top of the base slab at RL 75.5m, the total quantity of the water running into the shaft was therefore about 7,000 tonnes. The sediments in the shaft reached a thickness of 7m and the top of the sediments was at the same level as the tunnel crown. The water line stretched to a distance of, as far as, 579m from the shaft in the Up-track tunnel while the entire length of 580m of the Down-track tunnel, which has a smaller gradient than the Up-track tunnel, was submerged. Even the recovery shaft next to G10 Station at the other end was flooded with a depth of water of 8m. A sinkhole was created above the tunnel and the maximum ground settlement exceeded 3m. The 20mm settlement contour, refer to Fig. 5, extended to a distance of 80m from the tunnel portal where the leakage occurred. A couple of apartment buildings to the southwest of the shaft were damaged beyond repair and had to be demolished and rebuilt.

The damages to the tunnel segments were investigated by probing the tunnel crowns from the ground surface. It was found that 23 segments in the Up-track tunnel were damaged with a maximum settlement of 1.5m occurring at the 12th ring behind the wall. The Down-track tunnel, however, was unaffected.

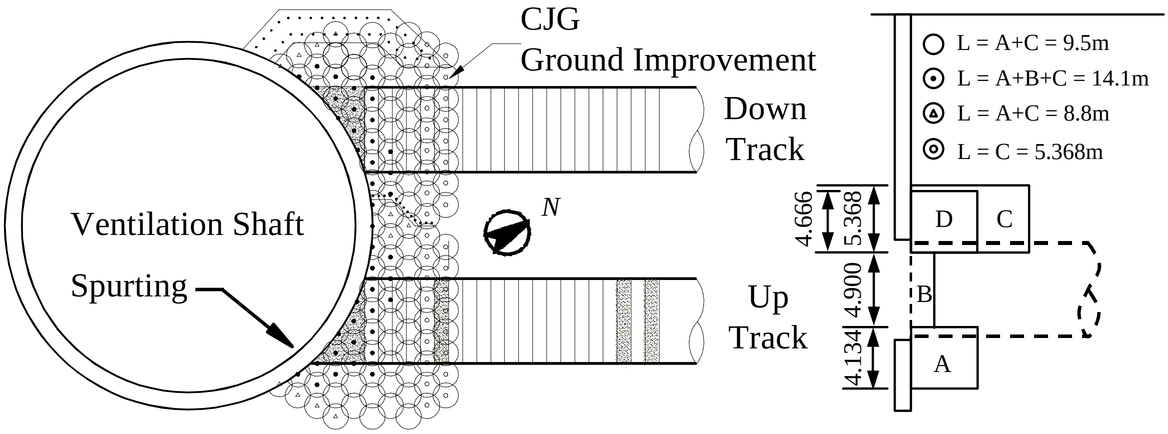

Fig. 4 Ground improvement at portals

5. The Remedy

It took 3,000 cubic meter of material to backfill the sinkhole. The ground was stabilized by using compensation grouting to fill up cavities. To enable the damaged segments in the Up-track tunnel to be replaced, refer to Fig. 6, the sediments between the 6th ring and the 22nd ring behind the diaphragm wall were grouted to form a plug. The tunnel was drained and cleaned from the other end and a steel bulkhead was installed at the location of the 24th ring. A patching pad was formed by using the freezing technique to seal off the portal from the back of the diaphragm wall. After the water in the shaft was drained and the shaft was cleaned, a steel bulkhead was installed to seal off the portal from the front. The sequence of all these actions is illustrated in Fig. 6 (Aoki/New Asia JV, 1994).

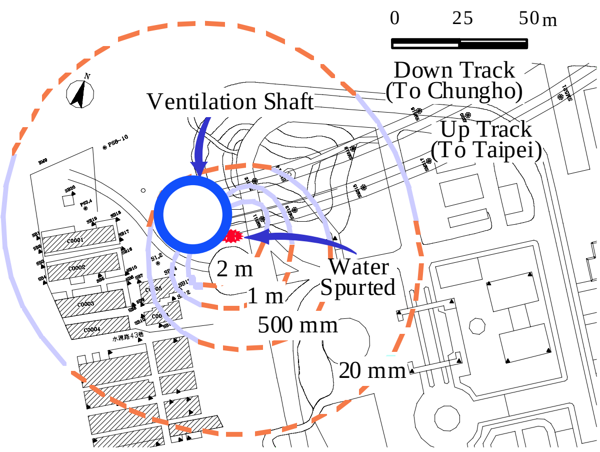

Fig. 5 Ground settlements

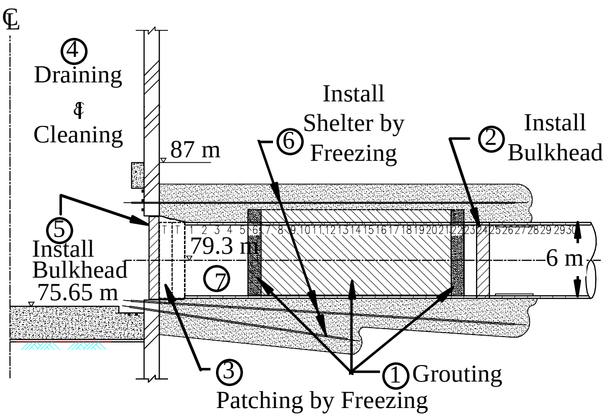

Fig. 6 Sequence of remedial works

A cylindrical shelter was then formed by using the freezing technique to circumscribe the damaged segments entirely. With this shelter in place, the two bulkheads and the grout plug were removed and the tunnel was cleaned. The damaged segments were dismantled and replaced. The damaged section of the tunnel was fully watertight and the bulkheads at the both ends of the grouted plug were able to be removed without worry. It took nearly two months to demolish the grouted plug and clean up the tunnel (Day 477 to Day 532). The damaged segments were dismantled and replaced by new ones with exactly the same design. The new segments were assembled in the shaft and pulled into the tunnel ring by ring. They were bolted together after their positions were properly adjusted. Once all the rings were in place, the voids outside these rings were grouted. The restoration was completed and refrigeration plants were shut down on October 24, 1995 (Day 571 following the incident).

6. Legal Aspects

In addition to physical damages made to the shaft and its surroundings, this incident caused serious impact on the construction schedule of the adjacent Contract CC560 because the shaft served as the launching shaft for the two tunnels running toward the south. Legal actions were taken by the contractor of Contract CC560 against the project owner, i.e., the Department of Rapid Transit Systems of the City of Taipei, and the contractor of Contract CH221 on two arguments: (1) delay in delivery of the shaft, and (2) changes in ground conditions due to the disturbance to the ground and due to the ground treatments carried out to stabilize the ground. According to the contract, the contractor was entitled to compensations if adverse physical conditions were encountered. Although it was not spelled out anywhere, changes in ground conditions were considered to be valid reasons for claims in several cases.

To investigate the causes of the incident so the responsibility could be clarified, a committee was appointed by the court in February 1997 with two members representing the contractor of Contract CH221, two members representing the contractor of Contract CC560, and the fifth representing the project owner. After reviewing all the documents and the evidences unveiled during the remedy works and interviewing site staff, the committee members reached the consensus that the water originated from the Chingmei Formation. However, opinions diverged regarding how water was able to get in the shaft. Figure 7 depicts the 3 possible water paths been considered:

Path A — the gap between the tunnel lining and CJG treated ground assuming that it was not properly grouted

Path B — the gaps between CJG columns, or between CJG columns and the diaphragm wall, either due to discrepancies in treatment or due to ground movements

Path C — sand lenses in Sublayer II which was not fully treated

Because Sublayer II was deemed to be clayey and sufficiently impermeable by the contractor, some of the CJG columns (refer to Fig. 2 for soil stratigraphy and Fig. 4 for CJG columns) did not extend throughout the full thickness of this sublayer.

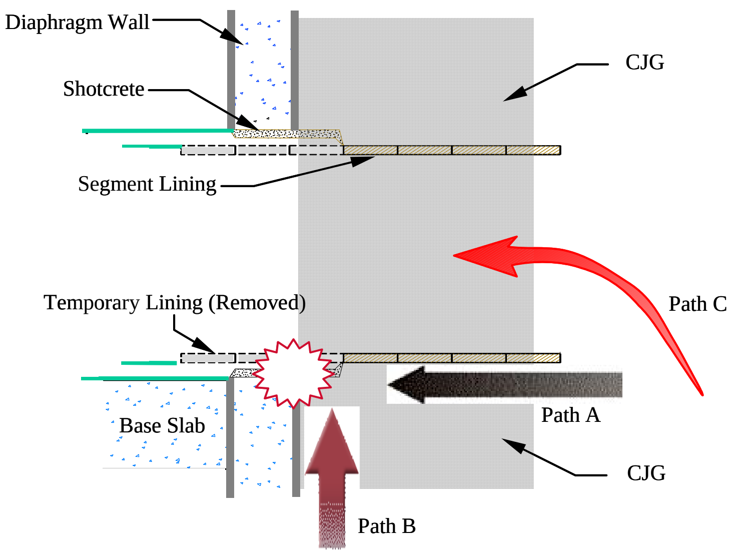

Fig. 7 depicts the 3 possible water paths

As can be noted from Table 2, although the differences in opinions on the three possibilities were very marginal, Path C was slightly favored. Water was therefore assumed to get into the shaft through sand lenses in Sublayer II and the associated scenario was considered to be the basis for determining the responsibilities. It was reasoned that if all CJG the columns indeed extended into Sublayer II for the full thickness, the incident would not have happened. Accordingly, it was decided that the contractor for Contract CH221 was responsible for the partial omission of CJG treatment in Sublayer II. Since the grouting program had been reviewed and accepted, the client was partially responsible. Furthermore, the contractor was responsible for not carrying out additional grouting as planned prior to widening the portal. Originally, the contractor proposed to carry out chemical grouting from the grout holes on all the rings in the CJG treated zone to a distance of 1.5m beyond the these rings to seal up all the voids, if any. However, grouting was carried out to a distance of only 300mm to 400mm and the quantity of grout injected was very little.

Table 2 Opinions of Committee Members on Water Paths

	Member A	Member B	Member C	Member D	Member E
Path A	H	H	L	L	L
Path B	M	M	H	L	L
Path C	L	L	M	H	H

Notes: H – high possibility M – medium possibility L – low possibility

As a result of this judgment, the contractor of Contract CC560 was granted time extension and was compensated for the loss associated with this incident.

7. Acknowledgment

The permission from the Department of Rapid Transit Systems of Taipei Municipal Government for publishing the data presented herein is appreciated.

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