

GROUND FREEZING FOR REPAIRING A DAMAGED TUNNEL

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*Reprinted from Proceedings of
13th Southeast Asian Geotechnical Conference
Taipei, Taiwan
November 16~20, 1998, pp.16~20*

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Ground Freezing For Repairing A Damaged Tunnel

SYNOPSIS : Ground freezing technique was adopted in the rehabilitation of a tunnel which was damaged when the tunnel eye was enlarged for the installation of the flexible joint. Water spurting 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.

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 the design. 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.

Described in this paper are the sequence of events and the remedial works taken with emphasis on the procedures of ground freezing. Also described herein are the instrumentation program and the observations made on the ground response to freezing.

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

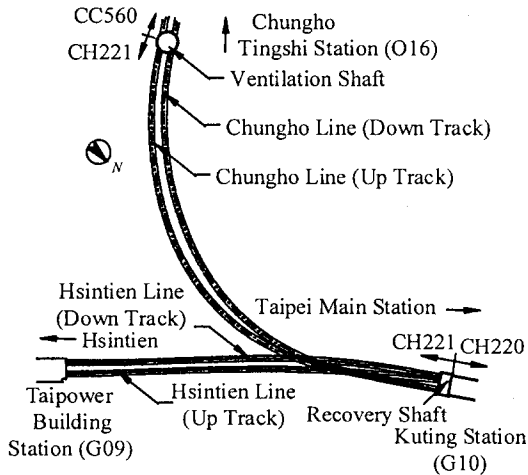


Fig. 1 Location plan

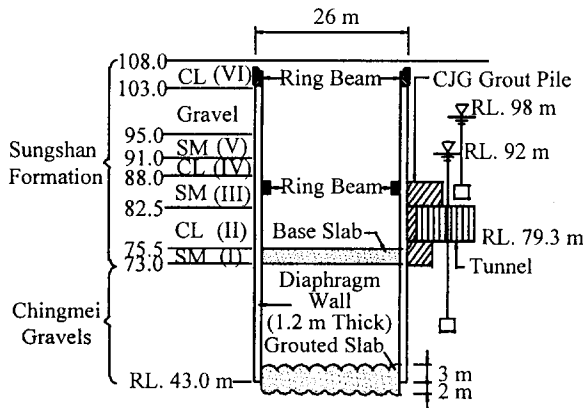


Fig. 2 Ground conditions and configuration of the shaft

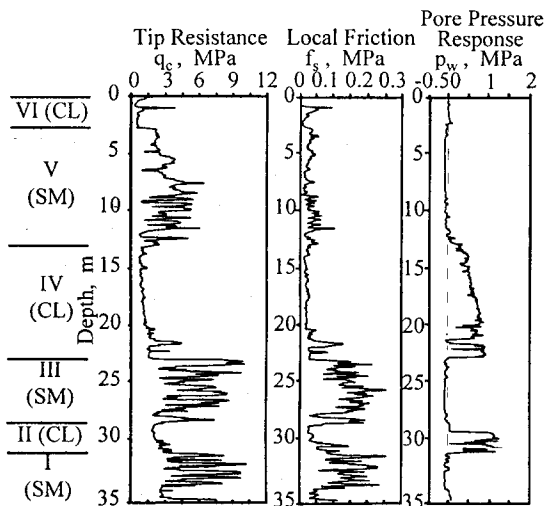


Fig. 3 Typical CPT profile in central Taipei City

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).

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.

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

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 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.

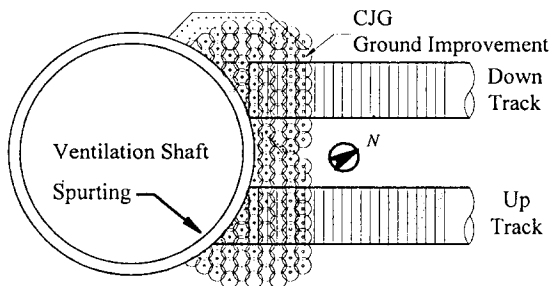


Fig. 4 Ground improvement at portals

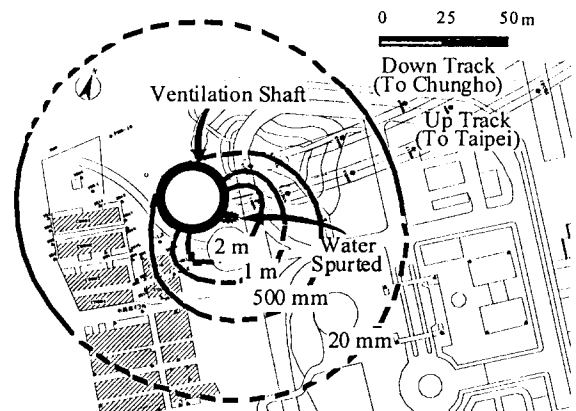


Fig. 5 Ground settlements

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.

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.

As above-mentioned, refrigeration was carried out twice: a) for forming the patching pad at the back of the diaphragm wall to seal off the portal, and b) for forming the cylindrical shelter to circumscribe the damaged segments. To achieve these purposes, refrigeration pipes were buried in the ground and refrigeration plates (rectangular pipes, rather) were mounted on diaphragm walls and tunnel segments for removing the heat in soils. Observation holes were made for measuring the temperatures in the frozen ground. The quantities of all these installations are given in Table 2. The design principles involved and the procedures adopted at the site are discussed in the following sections.

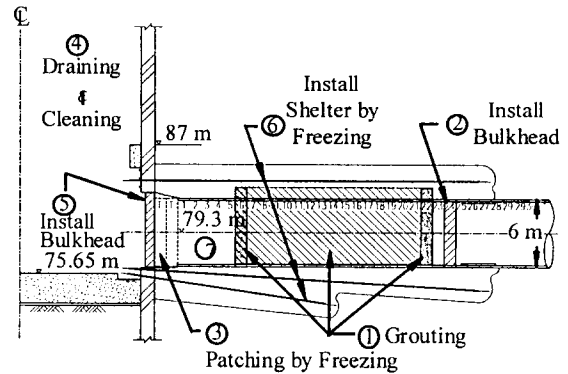


Fig. 6 Sequence of remedial works

6 Stage 1 Refrigeration and the Patching Pad

From a structural point of view, refer to Fig. 7(a) and 7(b), the patching pad at the portal behaved as a thick plate subjected to earthpressures on one side (tunnel side) and atmospheric pressure on the other side (shaft side). The portal was elliptical in shape and had a long axis of $c = 4.5\text{m}$ and a short axis of $d = 3.5\text{m}$ as depicted in Fig. 7(c). The required thickness of this patching pad was computed from the theory for elliptical plates with clamped edges as follows (Aoki and New Asia JV, 1994; Fan and Chao, 1997):

$$t = d \sqrt{\frac{\beta p}{\sigma_u}} \quad \text{Eq.1}$$

where

t : thickness of the pad

Table 2 Quantities of Installation in Stages 1 and 2 Refrigeration

	Location	Description	Size	Quantity	Total Length (m)	Un-insulated Length (m)
Stage1 (Patching Pad)	Behind Diaphragm Wall	Vertical Refrigeration Pipes	50.8mm radius	54	1858	680
		Vertical Observation Holes		12		
	On Diaphragm Wall	Refrigeration Plates	100mm x 50mm	150	304	304
Stage2 (Cylindrical Shelter)	Patching Pad Remains	Vertical Refrigeration Pipes	50.8mm radius	13	448	165
		Vertical Observation Holes		5		
		Refrigeration Plates	100mm x 50mm	34	62	62
	Half Tube	Horizontal Refrigeration Pipes	57.2mm radius	19	580	580
		Horizontal Observation Holes		6		
	Curtain Wall	Vertical Refrigeration Pipes	57.2mm radius	42	1348	336
		Vertical Observation Holes		6		
		Horizontal Observation Holes		1		
	Foundation Mat	Inclined Refrigeration Pipes	57.2mm radius	19	497	497
		Horizontal Observation Holes		3		
Rear End	Refrigeration Plates	100mm x 50mm	62	184	184	

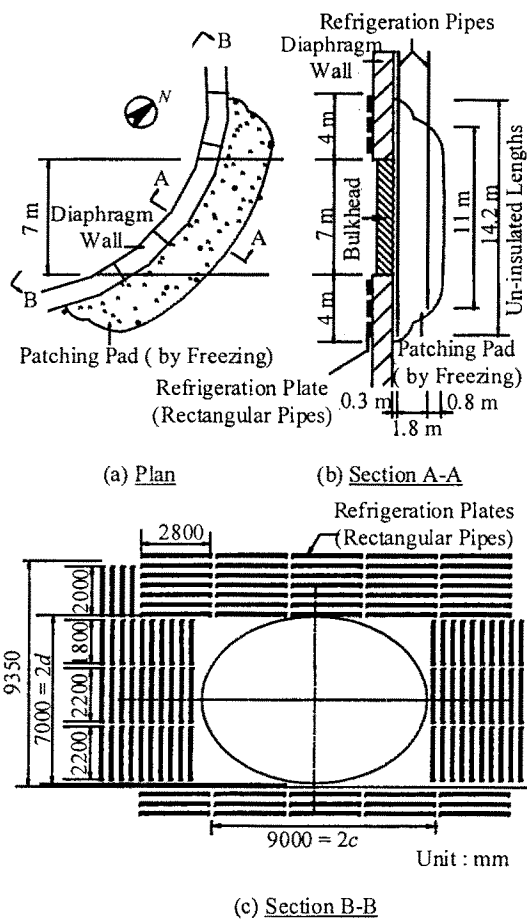


Fig. 7 The patching pad and the bulkhead

d : short axis of the opening

β : shape factor

p : earthpressures

σ_u : allowable compressive strength of the frozen soil against bending

The shape factor, β , is a function of the aspect ratio, i.e., d/c , of the opening. For an aspect ratio of $d/c = 3.5\text{m}/4.5\text{m} = 0.78$, $\beta = 1.1$. The earthpressures, p , were assumed to be uniformly distributed on the pad with their amplitudes equal to the at-rest earthpressure at the tunnel invert. For an earthpressure coefficient of $K_0 = 0.5$, a depth of 31.7m to the invert, and a groundwater table at a depth of 3m below surface, $p = 482$ kPa. The recommended unconfined compressive strength of the frozen soil at a design temperature of -10°C is $\sigma_u = 1.8$ MPa against both tension and bending. For a factor of safety of 2, the theoretical thickness of the pad was found to be $t = 2.7\text{m}$. Allowing

an error of 0.2m in the verticality of refrigeration pipes, a thickness of the pad of $t = 2.9\text{m}$ was adopted in the design.

As depicted in Fig. 7(b), two rows of refrigeration pipes were installed behind the diaphragm wall from ground surface. All the pipes were 100mm in diameter and were made of two co-axial tubes for the brine to be circulated. The first row of pipes were installed at a distance of 300mm away from the wall. The second row of pipes were installed at a distance of 1.8m further away. There were a total of 27 refrigeration pipes in each row. Because of the deviations from their positions during drilling, these pipes did not align as accurately as planned. The inclinations of the refrigeration pipes were determined by probing and the true positions of the pipes at the depth of the center of the tunnel are shown in Fig. 8.

It is conceivable that, as illustrated in Fig. 9(a), the soil immediately next to the refrigeration pipes would be frozen into individual columns first. These columns would expand in all the radial directions and, as time went by, refer to Fig. 9(b), would connect to each other to become plates. Subsequently, the two plates would grow laterally and the theory for refrigeration plates would apply. The rate at which these frozen columns grew in the radial directions and the rate at which these plates expanded laterally are a rather complex function of too many parameters, such as the ambient temperature, thermal properties of soil, the size of refrigeration pipes, etc. and had to be calculated by using a computer program which handles these parameters numerically.

The thermal properties of soils used in the computations are given in Table 3. Frankly speaking, the values given therein are, rather, typical values for natural soils and do not represent the properties of the sediments been frozen. The sediments in the damaged tunnel could not be sampled nor tested.

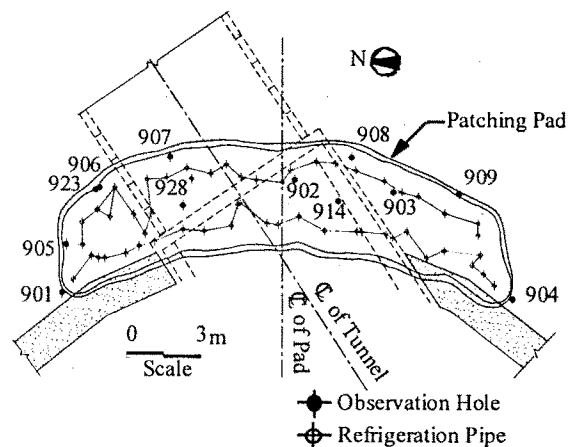


Fig. 8 Layout of refrigeration pipes and observation holes

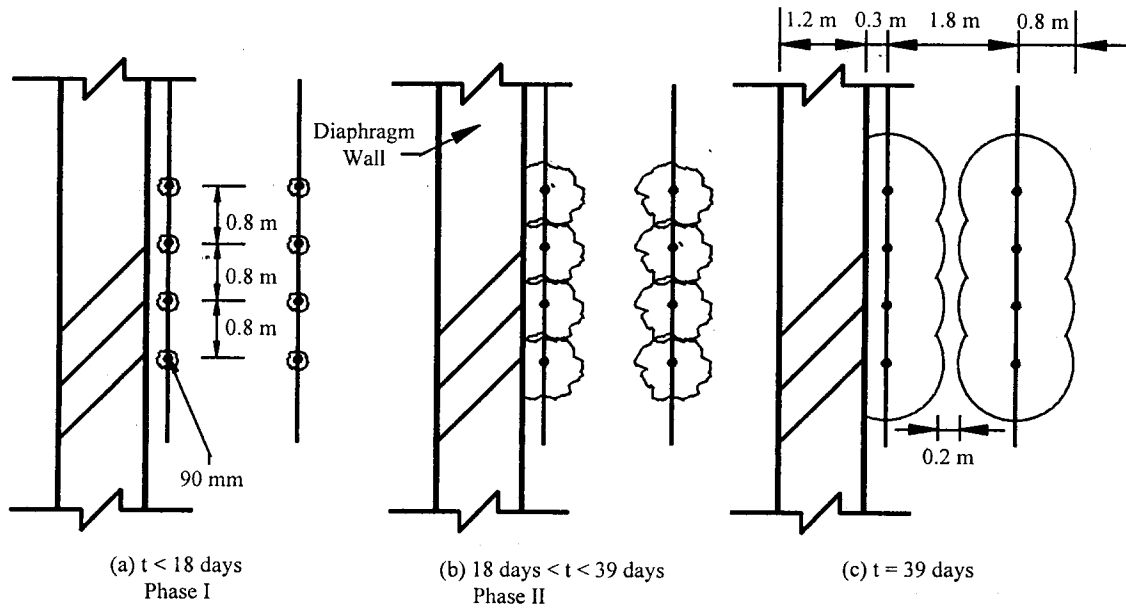


Fig. 9 Progress of freezing (Plan view)

Table 3 Representative Thermal Properties of Soils

	Before Freezing	After Freezing
Porosity(m ³ /m ³)		0.6
Density(kg/m ³)	1720	1649
Specific Heat Capacity (kcal/kg°C)	0.49209	0.30982
Thermal Conductivity (kcal/mh°C)	1.2254	2.3137
Thermal Diffusivity(m ² /h)	1.4478 x 10 ⁻³	4.5288 x 10 ⁻³
Latent Heat of Fusion(kcal/kg)		28.9273

The two rows of refrigeration pipes were 1.8m apart and pipes in each row were installed at 0.8m spacings. As can be noted from the design curve given in Fig. 10, it would take 18 days for the individual columns to grow to a radius of 0.4m (phase I). By then, these columns would have become two refrigeration plates and the theory of refrigeration plates would apply (phase II). The parameters in developing the design curve shown in Fig. 10 are defined as follows:

- θ_{∞} : ambient temperature (24°C)
- θ_b : brine temperature (-25°C)
- θ_f : freezing temperature (0°C)
- a : radius of pipes (50.8mm)
- P_i : spacing between pipes (0.8m)
- ρ : porosity of soil (0.6)

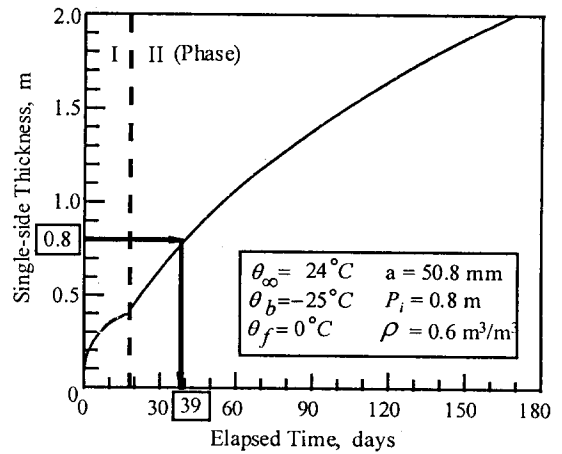


Fig. 10 Estimation of require period for Stage 1 refrigeration

It would theoretically take three more weeks for each of these two plates to grow to a thickness of 1.6m, i.e., 0.8m on each side of the central axis. Because the two plates were 1.8m apart, theoretically, there would be a gap of 200mm between the two plates at this time, refer to Fig. 9(c). However, it would be reasonable to expect these two plates to expand at a faster rate than what the theory predicted in consideration of the interaction effects between the two plates. It was therefore assumed that a solid "iceberg" of 2.9m in thickness would be formed in a period of refrigeration of 39 days. This assumption was proved to be quite correct as to be demonstrated in a later section of this paper.

Brine (Calcium chloride: CaCl_2) was used to remove the heat from the soil mass. Figure 11 shows the energy required for maintaining the temperature of the brine in a 1m section of single, un-insulated, refrigeration pipe at a constant value of -25°C . As can be noted, more energy would be required in the beginning to remove the heat from the ground. As the thickness of frozen soil grew with time, the energy required would drop gradually. The total length of the refrigeration pipes was 1,858m, of which 1,178m was insulated and 680m was in contact with soil. In addition, there were a total length of 304m of rectangular refrigeration pipes to be mounted on the diaphragm wall. To avoid confusions, these rectangular pipes will be referred to as "refrigeration plates" hereinafter to differentiate them from the circular pipes. Based on Fig. 11, a design chart (Fig. 12) was developed and used to estimate the capacity of refrigerating plant required. It takes into consideration of the heat absorbed by all the refrigeration pipes and plate. The relationship shown in

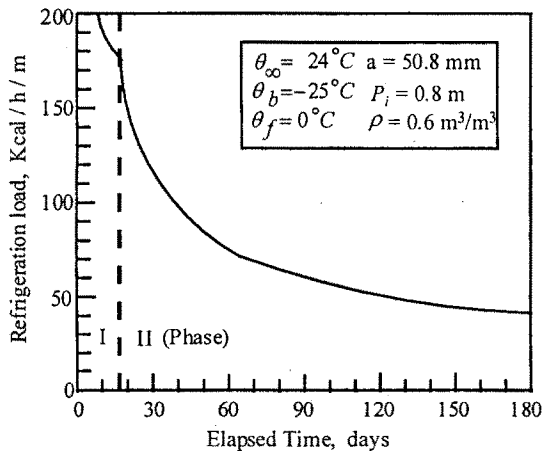


Fig. 11 Refrigeration load

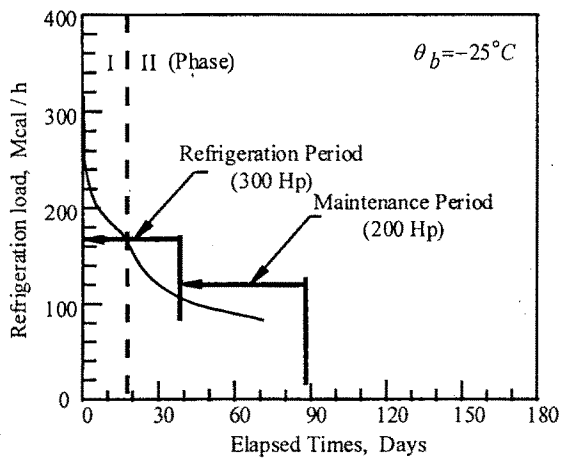


Fig. 12 Estimation of capacity of plant for Stage 1 refrigeration

the figure was developed based on the condition that the temperature of the brine would be maintained at a constant temperature while the input energy would vary with time. This is how the mathematical solutions to the differential equations were obtained. However, this is not how the operation was carried out. It would be difficult to vary the input energy with time. Instead, the refrigeration was carried out in stages with a constant input energy provided in each stage while the temperature of the brine would drop with time. In the case of interest, the operation was divided into two stages: the refrigeration stage and the maintenance stage. An average capacity of 170 Meg-cal/hour was theoretically required in the 39-day period of refrigeration. This converted to 200 kw (1 cal = 4.184 joules and 1 watt = 1 joule/sec) and was provided by one unit of 200 Hp (150 kw) refrigerating machine and one unit of 100 Hp (75 kw) refrigerating machine. During the maintenance period, the capacity required would be less than 100 Meg-cal/hour and the 200 Hp unit alone would be sufficient.

Installation of refrigeration pipes took 54 days (Day 144 to Day 198 following the incident) to complete and refrigeration started on 19 October, 1994 (Day 201). As can be noted from Fig. 13, the brine temperature indeed dropped to below -30°C and the 100 Hp unit was shut down 21 days after the refrigeration started. The 200 Hp unit was in fact running at an efficiency of 66% starting on the 34 day. The temperature of the delivery was maintained at -32°C and the return showed a temperature of about -30°C , giving a temperature differential of 2°C .

Twelve observation holes, of which the locations are shown in Fig. 8, were made for measuring the temperatures in the ground. Basically, these observation holes can be grouped into two categories:

- a) those installed in the central refrigeration zone bound by the two rows of refrigeration pipes, including Holes 928, 902, 914 and 903, and
- b) those installed in the apron outside the central refrigeration zone, including all the rest of holes.

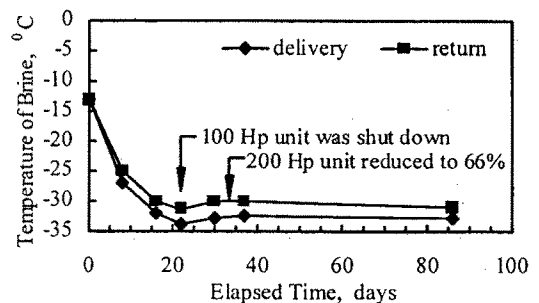


Fig. 13 Brine temperature

All the observation holes in the apron, except Holes 901 and 904, were located at a distance of roughly 0.8m beyond the outer row of refrigeration pipes. Holes 901 and 904 were located beyond the edge of the patching pad.

The temperature readings obtained at the depth of the center of the tunnel, i.e., RL 79.3m or a depth of 28.7m, in the four observation holes in the central refrigeration zone, are shown in Fig. 14(a). As can be noted, the temperatures dropped to the freezing temperature of 0°C within 10 days except at the location of Observation Hole 914. At the end of refrigeration period of 39 days, the temperatures inside the pad were generally below -20°C. Observation Hole 914, compared to others, are closer to the midspan between the two rows of refrigeration piles and are therefore more representative of the temperature readings at the center of the pad.

The readings obtained in the rest of holes are shown in Fig. 14(b). Data are more scattered in comparison with those shown in Fig. 14(a). They can be further classified into three categories, refer to Fig. 8:

- a) those corresponding to holes located near the center of the patching pad, including Holes 907 and 908,
- b) those corresponding to holes located near the edge of the patching pad, including Holes 905, 906, 923 and 909, and
- c) those corresponding to holes located beyond the edge of the patching pad, including Holes 901 and 904.

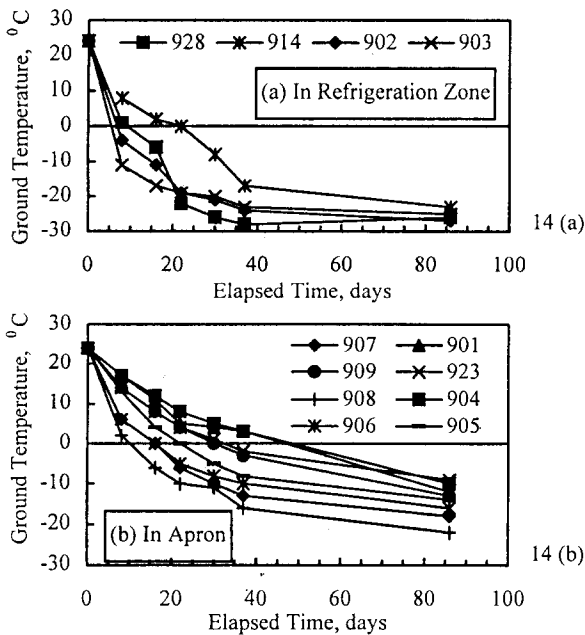


Fig. 14 Temperature readings in Stage 1 refrigeration

It is reasonable to expect the temperatures in the holes located near the center of the pad to show faster rates of decline than those in the holes located near, or beyond, the edge of the pad because of the boundary effects and this expectation was indeed confirmed by the readings given in Fig. 14.

The vertical profiles of the temperature observed in Observation Holes 902 and 914 are shown in Fig. 15. These two holes, refer to Fig. 8 for their locations, were the ones nearest to the center of the pad among all the holes. As can be noted that the temperatures at the mid-height were the lowest as expected. Towards the edge, the temperatures were higher because of the boundary effects. It is therefore expected that the thickness of the pad would be the greatest at the center and the pad would really be a convex iceberg. Based on Fig. 15, this iceberg (i.e., the zone with temperature lower than the freezing temperature of 0°C) would be larger than 14m in height at the end of the refrigeration period of 39 days.

Figure 16(a) shows the distribution of temperature obtained in the observation holes located in the central refrigeration zone bound by the two rows of pipes and Fig. 16(b) shows the same obtained in the observation holes located in the apron outside the refrigeration zone. Data are far from being ideal, presumably, because temperature readings were very sensitive to the proximity of the observation holes to the adjacent refrigeration pipes. Refrigeration pipes were in fact line sources and the temperatures in the pad were expected to vary from one location to another and from one depth to another. Nevertheless, with proper judgement, the distribution of temperatures across the width of the patching pad still can be deduced from the data and the results are shown Fig. 17. Again, the boundary effects at the edge are evident. Based

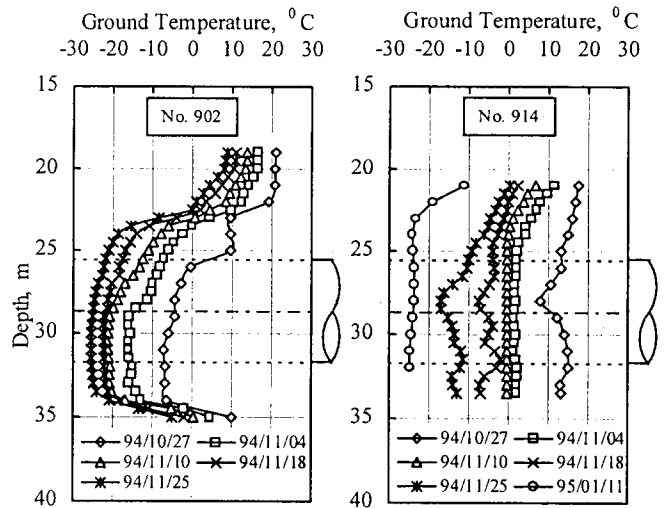


Fig. 15 Temperature profiles near the center of the pad

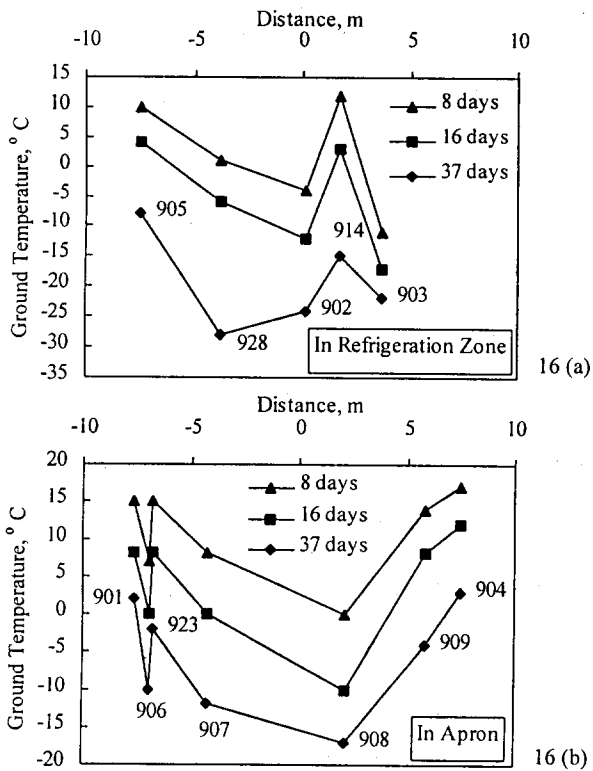


Fig. 16 Distribution of temperature across the width of the pad

on this figure, the iceberg is estimated to be at least 16m in width at the end of the refrigeration period of 39 days.

The distribution of temperatures across the thickness of the pad is shown in Fig. 18. The "iceberg" is estimated to be 5.2m in thickness at the end of the refrigeration period. If the iceberg was symmetrical to its center, it would fully fill the opening on the diaphragm wall and intrude into the shaft by, theoretically, 0.2m, as illustrated in Fig. 19. This was proved to be the case as the shaft was drained and the portal was exposed.

It is interesting to note from Fig. 18 that the temperatures at the center of the pad, i.e., the mid-span between the two rows of pipes, were not necessarily the lowest. At an elapsed time of 8 days, the two rows of pipes functioned independently and the temperature profiles were more or less symmetrical on the two sides of each row of the pipes. The same can be said for the readings taken on the 16th day. The readings taken on the 37th day, however, showed much faster rates of decline at the center in comparison with that at the same distance away from the pipes in the apron indicating interaction effects between the two rows of pipes. It is evident that the design curves given in Figs. 10 and 11, which do not take such interaction effects into consideration, are conservative.

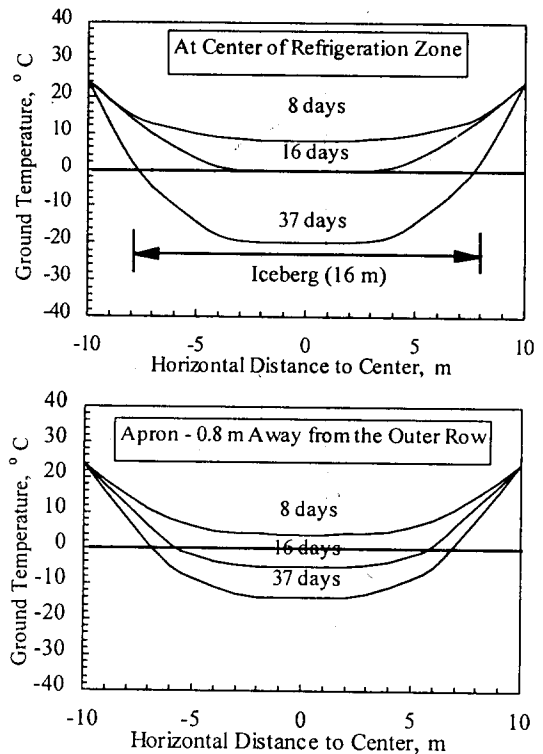


Fig. 17 Idealized temperature distribution across the width of the pad

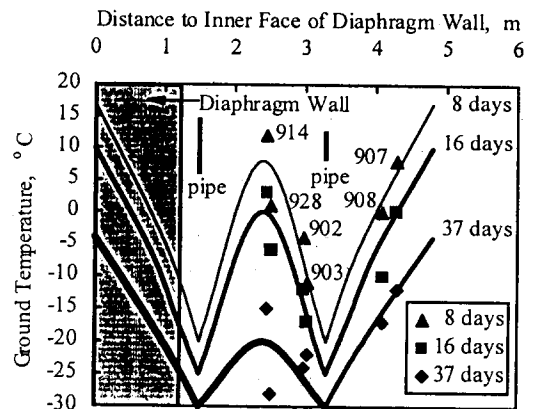


Fig. 18 Distribution of temperature across the thickness of the pad

In summary, a convex iceberg of about 14m in height, 16m in width and 5.2m in thickness was formed at the end of the refrigeration period of 39 days. The volume of the iceberg is estimated to be about 900 cubic meters. It can also be concluded with confidence based on the temperature readings that within the extent of 9m in width and 7m in height and 2.7m in thickness, as originally designed, the temperatures in the pad were all below the design temperature of -10°C .

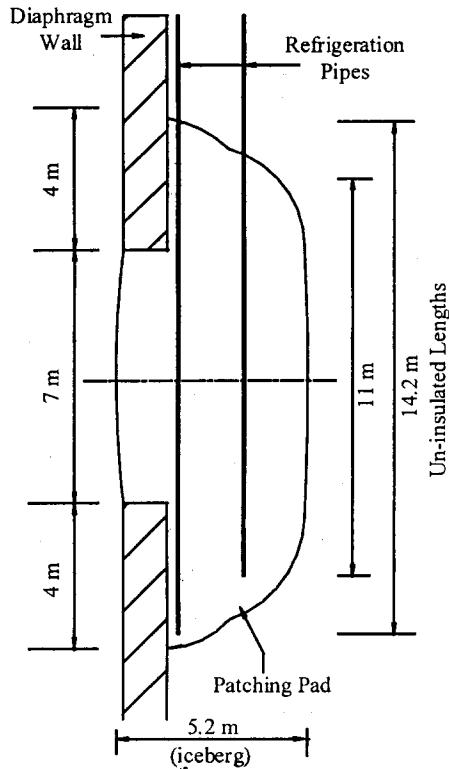


Fig. 19 Prospective of the iceberg formed

Draining of the shaft started on 28 November, 1994 (Day 241 following the incident, or the day after the end of refrigeration period). As the water level in the shaft was lowered below the crown, rectangular refrigeration pipes (refrigeration plates), refer to Fig. 7(c) for layout, were mounted on the diaphragm wall at the portal as an additional safety measure. This became necessary because, otherwise, as the portal was exposed and subsequent works were carried out, the temperature in the patching pad might rise and endanger the integrity of the pad.

7 Stage 2 Refrigeration and the Shelter

Stage 2 refrigeration was rather more complicated in comparison. Basically, a hollow cylindrical shelter was to be formed to enclose the damaged segments for them to be dismantled and replaced safely. First of all, most of the vertical refrigeration pipes and refrigeration square pipes installed in Stage 1 refrigeration were in the way and had to be removed for the installation of horizontal pipes. This was possible because the portal had already been sealed off by the steel bulkhead. The remaining pipes and plates, of which the quantities are given in Table 2, continued to function till all the tunnel segments were replaced.

This hollow cylindrical shelter, as depicted in Fig. 20, essentially behaved as a shield and was subjected to

earthpressures all around its outer perimeter. The stresses in the wall can be expressed as follows:

$$\sigma = \frac{N}{A} \pm \frac{M}{Z} \quad \text{Eq.2}$$

where

N : normal force

M : bending moment

A : sectional area across the thickness

Z : sectional modulus

The normal force, N , and the bending moment, M , were obtained in the same way as the tunnel segments were designed. For simplicity, they will not be discussed herein. For a design temperature of -12°C , the strengths of the frozen soils were assumed to be 2.05 MPa against tension and bending and 3.45 MPa against compression. Accordingly, the thickness of the cylinder required was found to be $t = 2.36\text{m}$ with a factor of safety of 2 applied on the material strength. The design wall thickness of the cylinder was decided to be 2.8m to allow for deviations from the intended alignments of pipes.

The shelter was irregular in shape. It was in fact made of four parts as illustrated in Figs. 20 to 22:

- a half of circular tube formed by using horizontal refrigeration pipes running parallel to the longitudinal axis of the tunnel (Figs. 20 and 21). For convenience, this part of the shelter will be referred to as the "tubular section" hereinafter. Pipes were spaced roughly 0.8m apart.

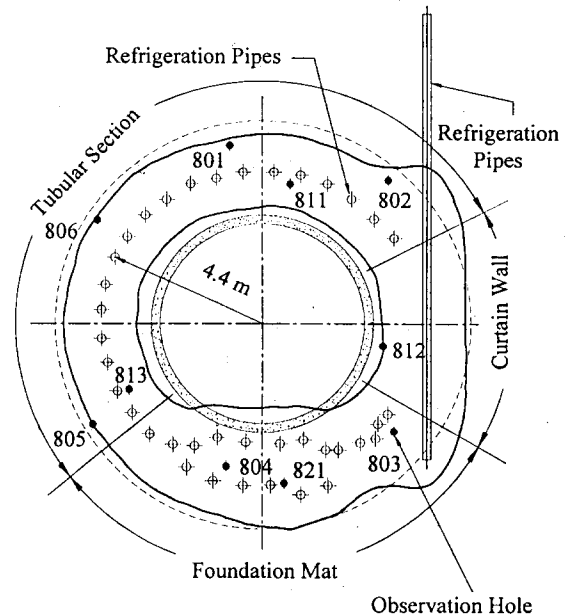


Fig. 20 Front view of the shelter in Stage 2 refrigeration

- b) a curtain wall formed by using a single row of vertical refrigeration pipes installed alongside the tunnel to the east of the tunnel at a spacing of 0.8m (Figs. 20 and 22). Vertical pipes were used because, refer to Figs. 4 and 22, the diaphragm wall to the east of the portal would obstruct the installation if horizontal pipes were to be used.
- c) a foundation mat below the tunnel invert formed by using two rows of inclined refrigeration pipes to separate the tunnel from the Chingmei Gravels (Figs. 20 and 21). The presence of the base slab made it impossible to install horizontal pipes at the desired positions and inclined pipes were therefore installed. Because of the different inclinations of the two rows of pipes, the spacing between these two rows of pipes varied along their lengths.
- d) at the rear end of the shelter, refrigeration plates were mounted on Rings No. 25 to 28 from the inside of the tunnel(Figs. 21 and 22).

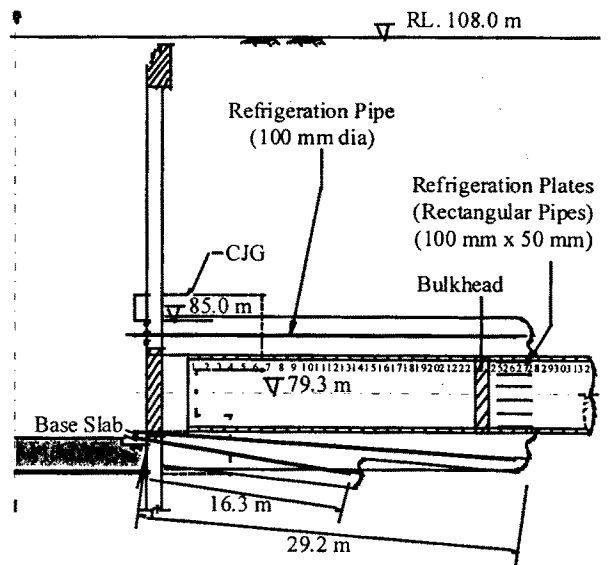


Fig. 21 Longitudinal profile of the shelter

It was suspected that the ground below the tunnel invert was much disturbed, therefore, compensation grouting was carried out first to stabilize the ground before refrigeration was carried out.

The time required for the wall of this cylinder to grow to the design thickness of 2.8m was estimated from Fig. 23. The radius of pipes was increased from 50.7mm to 57.2mm in comparison with Stage 1 refrigeration. Refrigeration pipes in the tubular section and those in the curtain wall were installed roughly 0.8m apart and it would still take 18 days for the individual columns to grow into plates. Subsequently, it would take 71 more days for these plates to grow to the required thickness of 2.8m. A total of 89 days would thus be needed. It would take a shorter time for the foundation mat to grow to the desired thickness because

there were two rows, instead of one, of pipes.

The capacity of the refrigeration plant was estimated by using Fig. 24 and it was found that the capacity of 300 Hp provided in the Stage 1 refrigeration would be adequate for a refrigeration period of 89 days in the Stage 2. However, in addition to the two units of refrigeration machines used in Stage 1, a 37 kw refrigeration machine (50 Hp) was added, mainly, for circulating the brine to the refrigeration plates mounted on the segments at the rear end of the shelter. It took 60 days to complete the installation of pipes and freezing started on 18 April, 1995 (Day 382). The temperature of the brine was continuously monitored and the readings are shown in Fig. 25. The 100-Hp unit was shut down one month after the operation started.

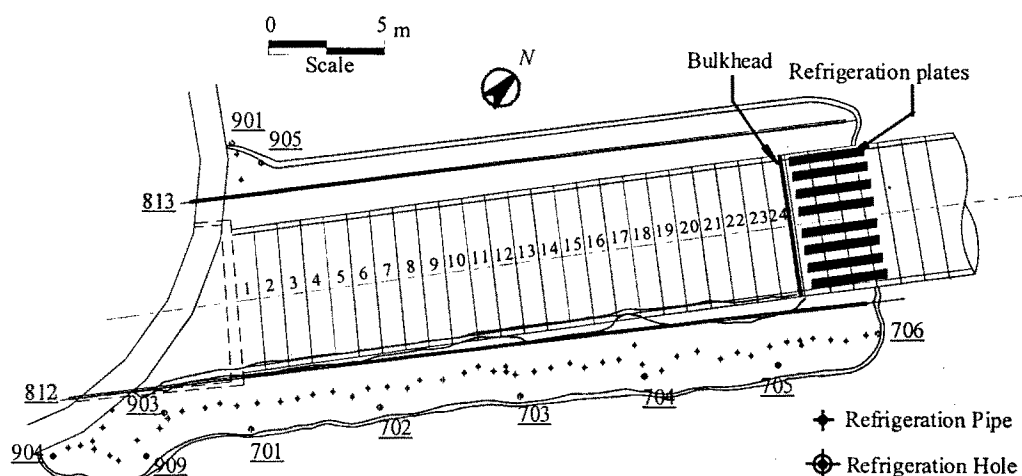


Fig. 22 Plan view at depth of tunnel axis

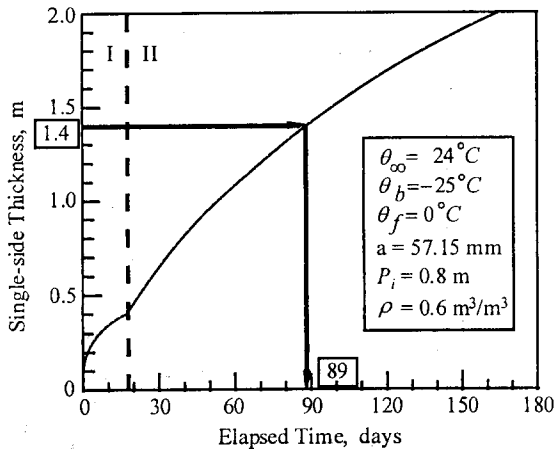


Fig. 23 Estimation of period for Stage 2 refrigeration

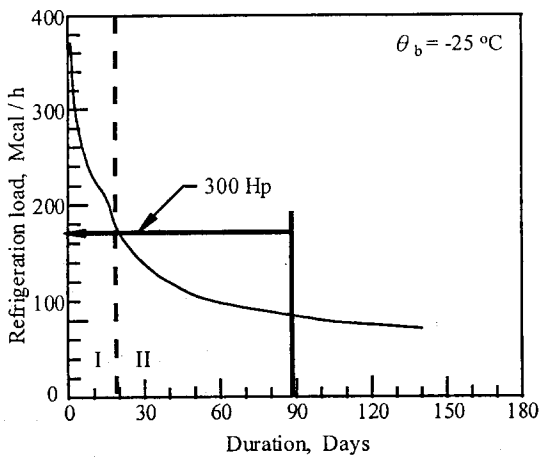


Fig. 24 Estimation of capacity of the plant for Stage 2 refrigeration

A total of 10 horizontal observation holes and 11 vertical holes were available for measuring the temperatures in the ground. For convenience, they are listed in Table 4. In the tubular section, there were 6 holes of which Hole 802 was too close to the vertical pipes (refer to Fig. 20) to be representative and the readings obtained in this hole are thus excluded in the following analysis. The time histories of temperatures obtained in the remaining 5 holes at the location of Ring No. 14 are shown in Fig. 26. As can be noted that in the two holes which were near the refrigeration pipes, i.e., Holes 811 and 813 (refer to Fig. 20 for locations), the temperature dropped to the freezing point in less than 20 days. In all other holes which were located near the perimeter of the tube, freezing was achieved in 40 to 50 days. The distribution of temperatures alongside the tunnel are shown in Fig. 27. The readings are quite erratic. One reason for this to be the case is that both refrigeration pipes and observation holes could have significantly

deviated from their theoretical alignments and readings were affected by the proximity between the refrigeration pipes and observation holes.

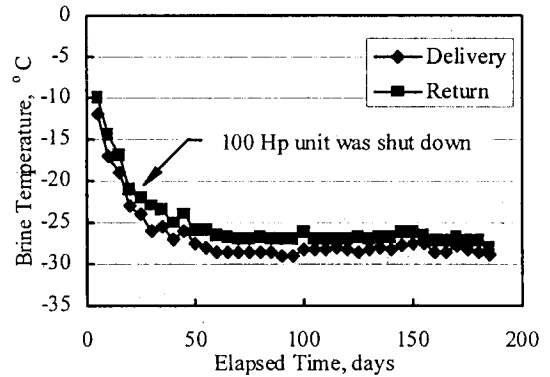


Fig. 25 Temperature of the brine in Stage 2 refrigeration

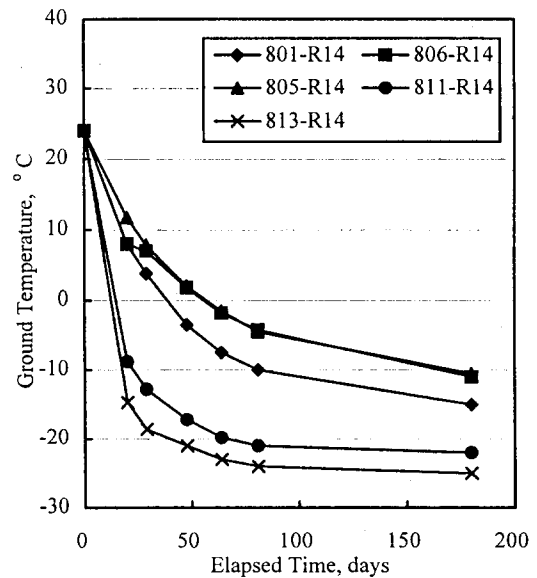


Fig. 26 Temperature readings at Ring No. 14

Table 4 Observation holes in Stage 2 refrigeration

	Horizontal Holes	Vertical Holes
Patching Pad		901, 903, 904, 905, 909
Tubular Section	801, 802, 805, 806, 811, 813	
Vertical Curtain Wall	812	701, 702, 703, 704, 705, 706
Foundation Mat	803, 804, 821	

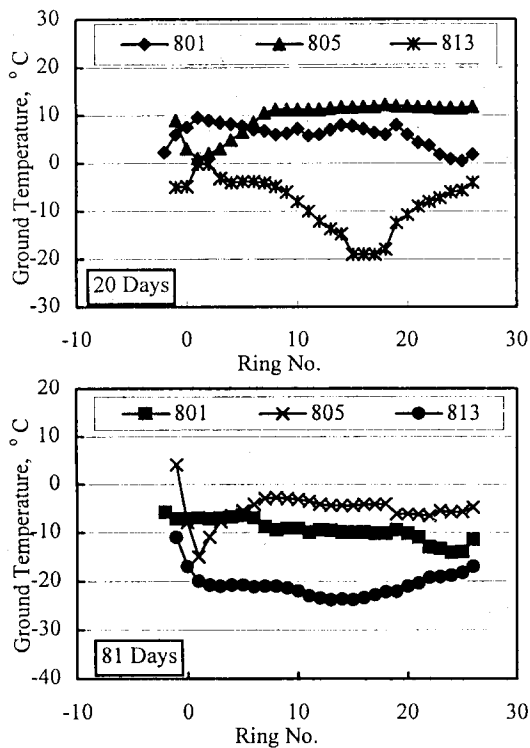


Fig. 27 Temperature readings along the length of the tubular section

The distribution of temperature across the wall of the tubular section is shown in Fig. 28. The refrigeration pipes were roughly 4.4m off the center of the tunnel, however, the temperatures were found to be the lowest at a distance of 4.2m from the center as shown in the figure, giving an offset of about 0.2m. One of the possible reasons is that the heat confined by the cylindrical shelter was limited in quantity while the heat drawn from the outside was unlimited. Before, the distribution was not symmetrical. Based on Fig. 28, it is estimated that the “ice tube” would be about 2.8m in thickness, as designed, at the end of the refrigeration period of 89 days and the average temperature in the wall was very close to the design temperature of -12°C .

In the curtain wall which was formed by refrigeration using a single row of vertical pipes, temperatures were monitored in 6 vertical observation holes as shown in Fig. 22 and one horizontal hole, Hole 812, of which the location is shown in Fig. 20. The readings obtained in the vertical holes at the depth of tunnel axis are shown in Fig. 29. As can be noted that freezing was achieved in 60 days or so in all these holes which were roughly 0.8m away from the line in which refrigeration pipes were aligned. The distribution of temperature alongside the tunnel in the horizontal hole 812 is shown in Fig. 30. In all, the performance of these

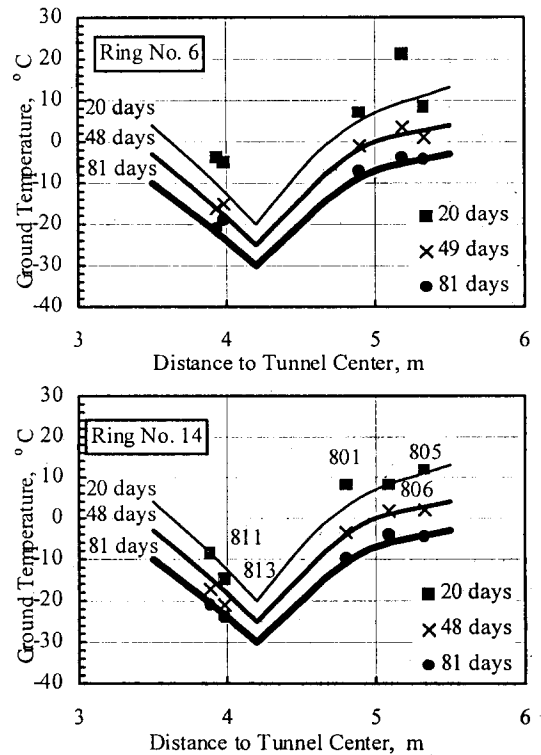


Fig. 28 Distribution of temperature across the wall of the tubular section

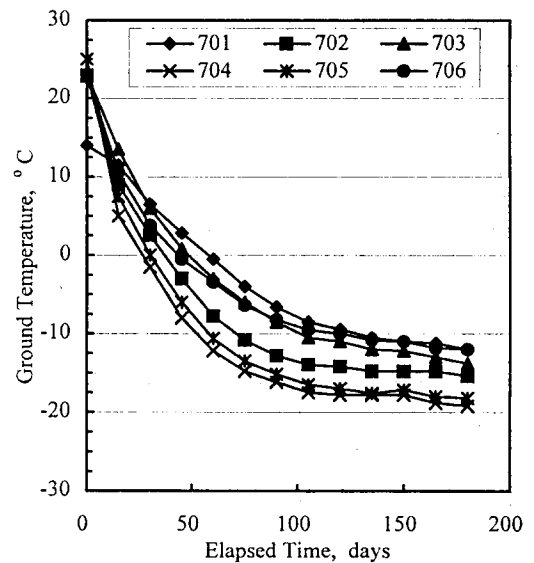


Fig. 29 Temperature readings at depth of tunnel center along the curtain wall

vertical pipes was not any different from what was expected and the design thickness was believed to have been achieved by the end of the refrigeration period.

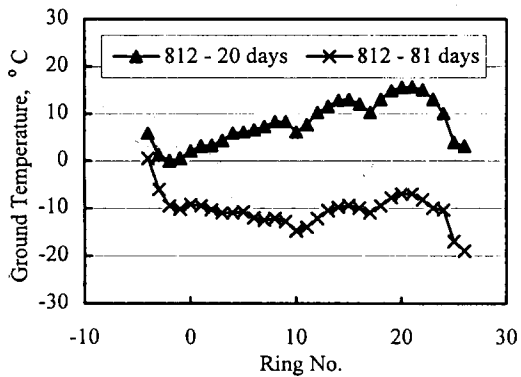


Fig. 30 Temperature readings in the curtain wall at the foundation mat

In the foundation pad formed by refrigeration using two rows of inclined pipes, temperatures were monitored in 3 horizontal observation holes as shown in Fig. 20. The distribution of temperatures alongside the tunnel is shown in Fig. 31. Because of the different inclinations of the two rows of pipes and also because of the fact that the observation holes were parallel to neither row, it would be difficult to estimate the thickness of the mat based on these temperature readings. In any case, there is no reason to doubt that the design thickness was achieved by the end of the refrigeration period of 89 days.

8 Restoration of Tunnel

With this frozen shelter in place, 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 first and then pulled into the tunnel ring by ring. They were bolted together after their

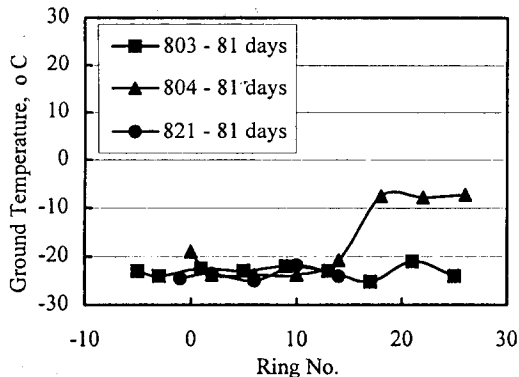


Fig. 31 Temperature readings in foundation mat

positions were properly adjusted. Once all the rings were in place, the voids outside these rings were grouted. The restoration work was completed and refrigeration plants were shut down on October 24, 1995 (Day 571 following the incident).

9 Summary

Experience indicates that a majority of failures in underground constructions could be attributed to groundwater problems. The case history presented herein fully demonstrates how dangerous groundwater could be and it is by no means an isolated case. In evaluating options for groundwater control during design, freezing usually is the last one considered for the reasons that: a) it is costly, and b) it is time consuming. As a general rule, for typical project lasting for 3 months or so, freezing is 5 to 10 times more expensive than other types of ground treatment, such as grouting, in terms of the cost per unit volume of soil to be treated.

It however should be noted that freezing is superior, among all the measures, in that,

- a) A very high strength of frozen soil can be achieved. For a temperature of -10°C , an unconfined compressive strength of, as much as, 3 MPa can be obtained.
- b) Frozen soil is perfectly impermeable and can be in a perfect contact with structures to seal off all the possible water paths.
- c) The safety of construction is ensured as long as refrigeration is ongoing. The rate of thawing is slow and short power failure has little effects.
- d) Once defrosted, the soil will return to its original state leaving no obstacles in the ground.
- e) The extent of the frozen ground and the quality of the product can easily be confirmed by using thermometers.
- f) The operation is pollution free.

Freezing is particularly useful in sealing off openings which are difficult to be sealed by other means because of the presence of obstacles.

Acknowledgment

The authors are deeply indebted to the Contractor of Contract CH221, Aoki/New Asia Joint Venture, and to the Specialist Subcontractors, Seiken Co. Ltd., for providing detailed information and instrument readings. The permission from the Department of Rapid Transit Systems of Taipei Municipal Government for publishing the data presented herein is also appreciated.

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