GROUND FREEZING FOR RESTORATION OF DAMAGED TUNNEL

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SYNOPSIS: The presence of an abandoned pumping well led to a serious failure at a tunnel portal when the opening is made on the diaphragm wall of the arrival shaft to prepare for the breakthrough. The well became a path bringing a large quantity of water from an underlying gravelly stratum to spurt at the tunnel invert. A sinkhole of 5,000 cubic meters in volume was made outside the shaft, and as a result, the shaft was flooded and two shield machines were submerged in water. Both of the twin tunnels of the rapid system were seriously damaged. Ground freezing was adopted to seal up the portal so the damaged segments could be replaced. The successful application proves that ground freezing is an effective measure in cases of a similar nature.

INTRODUCTION

The twin tunnels in Construction Contract CP262 of the Panchiao Line of Taipei Rapid Transit Systems (TRTS), refer to Fig. 1 for the layout, were bored by using two earth pressure balancing shield tunneling machines. The first drive of each tunnel proceeded from the crossover at the east end of Chiangtzusui Station to Vent Shaft A and the second drive proceeded from Vent Shaft A to Vent Shaft B where the contract ends.

On July 16, 1995, water spurted at the invert when an opening was made on the western wall of Vent Shaft A to prepare for the arrival of the shield machine upon the completion of the first drive of the Up-Track tunnel. It soon became uncontrollable and the shaft had to be flooded to prevent the situation from deterioration. This incident resulted in a sinkhole with a surface area of 5,000m^2 and a maximum depth of 6m. The last sections of the first drives of both the Up-Track and the Down Track tunnels were severely damaged. At the time the incident occurred, the shield machine in the Down-Track tunnel had already passed through Vent Shaft A and had advanced by 25m in the second drive. This second drive, however, was not damaged. The shield machine in the Up-Track tunnel was irrecoverable and a new machine had to be employed for the second drive. The shield machine in the Down-Track tunnel was repaired and tunneling was resumed for the second drive a few months later.

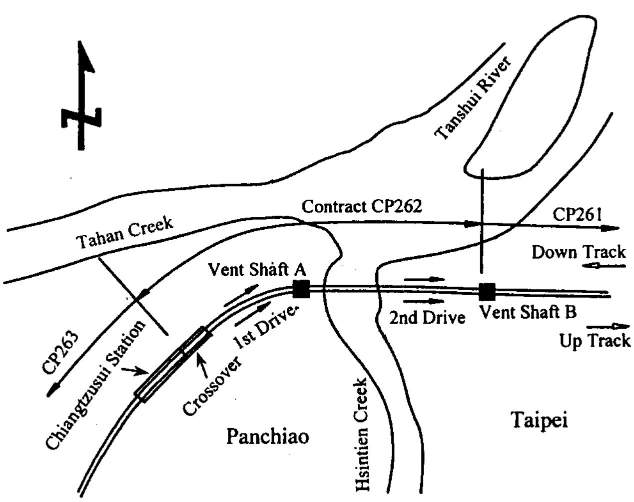


Fig. 1 Location Map

Ground freezing method was adopted to seal up the portal so the Up-Track tunnel could be remedied. It was also used as a precautionary measure to prepare for the launching of the second drive.

SUBSOIL AND GROUNDWATER CONDITIONS

The site is located at a distance of about 70m West of the bank of the Hsintien Creek which separates Panchiao from the City of Taipei. A typical soil profile in this area is shown in Fig. 2. The subsoil at the site comprises alluvial deposits, i.e., the so-called Taipei Silts or the Sungshan Formation, to depths varying from 45m to 55m (Woo and Moh, 1990). Underlying the Sungshan Formation is an extremely permeable and water-rich gravelly layer, i.e., the Chingmei Gravels, with hydraulic conductivity ranging from 0.12 m/sec to 0.18 m/sec and storativity ranging from 0.001 to 0.004 (Moh, Chuay and Hwang, 1996). It was once the primary source of water

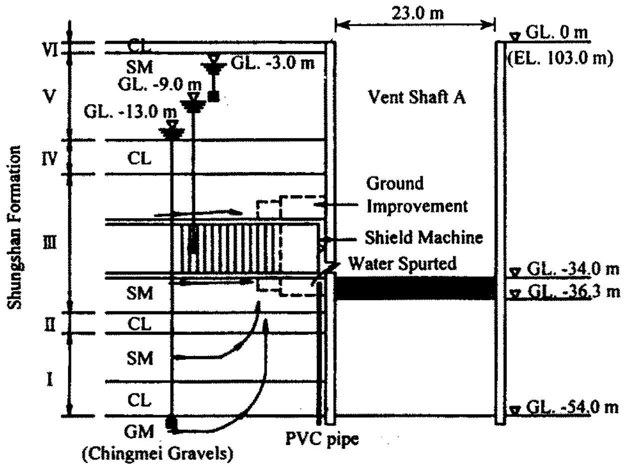


Fig. 2 Soil Profile and Configuration of the Shaft A

supply for the City of Taipei.

Layer IV of the Sungshan Formation is an impervious clayey layer which separates the ground water into two aquifers. The twin tunnels are buried in a silty sand layer, i.e., Layer III in the Sungshan Formation. The inverts of the tunnels are located at a depth of 33.6m below the ground surface and the piezometric head at the inverts of the tunnels was about 200 kPa.

CONSTRUCTION

Vent Shaft A is 23.5m in length and 23m in width. Excavation was carried out to a depth of 36.3m and retained by diaphragm walls of 1.2m in thickness. The diaphragm walls entered the Chingmei Formation by 3m. At the time the incident occurred, the permanent structure of the shaft had been completed.

As shown in Fig. 2, to ensure the safety during the breakthrough, Column Jet Grouting (CJG) was conducted to treat the soils immediately behind the portals to form two grouted tubes, one for each tunnel, to temporarily shelter the shield machines upon arrival. The primary treatment was 6.3m in length, 11.9m in width and 13.5m in height. This treated zone was extended by 3m by using chemical grouting (CW1) to cover the entire length of the shield machine, which is 7.7m long and 6.2m in diameter.

Before the arrival of the shield machines, permeability tests were conducted to check the integrity of the treated ground. Minor leakage were observed and more CJG columns were installed from the ground surface to improve the watertightness of the two tubes. In addition, OH and LW solutions were injected from the shaft to fill up fissures, if any, in the treated ground. After the shield machine entered the tube in each drive, CW1 and Set Foam were injected from the grouting holes inside the shield machine in an attempt to further improve the watertightness of the treated ground.

THE INCIDENT

At 01:30 of July 16, 1995, as the portal was knocked open, water spurted at the invert of the Up-Track tunnel. Within hours, the flow increased from a rate of 200 m^3/hr to a rate of 500 m^3/hr and carried a large amount of sand into the shaft. Eventually a sinkhole of 5,000 m^2 in area and 6m in depth was formed behind the diaphragm wall. In an attempt to stop the situation from deterioration, the shaft was quickly flooded by recharging water from 6 deep wells which were used previously to lower the water table for maintaining the safety against blow-in during the excavation for constructing the shaft. The sinkhole outside the shaft was promptly backfilled by dumping sands and gravels and LW grout was injected to fill up the underground cavities.

As the settlement was arrested, eight check borings, varying from 37m to 45m in depth, were made and SPT tests were carried out to determine the extent of disturbance to the subsoils. The results indicated that all the cavities in the ground had indeed been filled (Lin, Ju and Hwang, 1997).

At the time the incident occurred, the shield machine in the Down-Track tunnel had already passed through Shaft A and had advanced for 25m in the second drive further to the east. The settlements of the two tunnels were estimated by probing the tunnel crowns by drilling to the crowns. The maximum settlements of the tunnels were found to be 1,460mm for the Up-Track tunnel and 340mm for the Down-Track tunnel, respectively. The conditions of the segments were checked by sending divers into the tunnels which were fully flooded by this time. A total of 39 rings in the Up-track and 34 rings in the Down-Track tunnel were found to have been damaged and had to be replaced.

Since freezing was applied to the Up-Track tunnel only, what has happened to the Down-Track tunnel is irrelevant to the theme and the following discussion is limited to the Up-Track tunnel.

RESTORATION OF THE FIRST DRIVE

As depicted in Fig. 3, the portal was first sealed by a concrete gravity wall erected in water so the shaft could be drained in preparation of subsequent operations. A plug was formed behind the tail of the shield by grouting the soils which entered the tunnel. A steel bulkhead was erected at a distance of 700m away from the shaft (not shown in the figure). The ground surrounding the section of damaged tunnel was treated by using CJG grouting. With all these measures taken, compressed air with pressures of, upto, 2.1 bars was applied to pressurize the tunnel so the water in the tunnel could be drained and the dirt removed. Subsequently, the damaged segments were replaced in

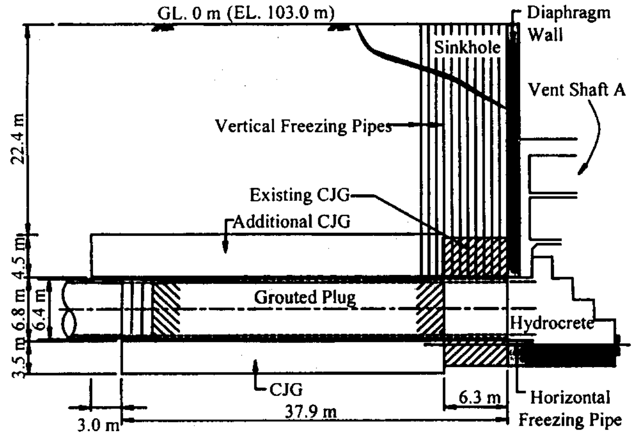


Fig. 3 Remedial Measures

compressed air. More details on the incident and the remedial measures taken can be found in Lin, Ju and Hwang (1997).

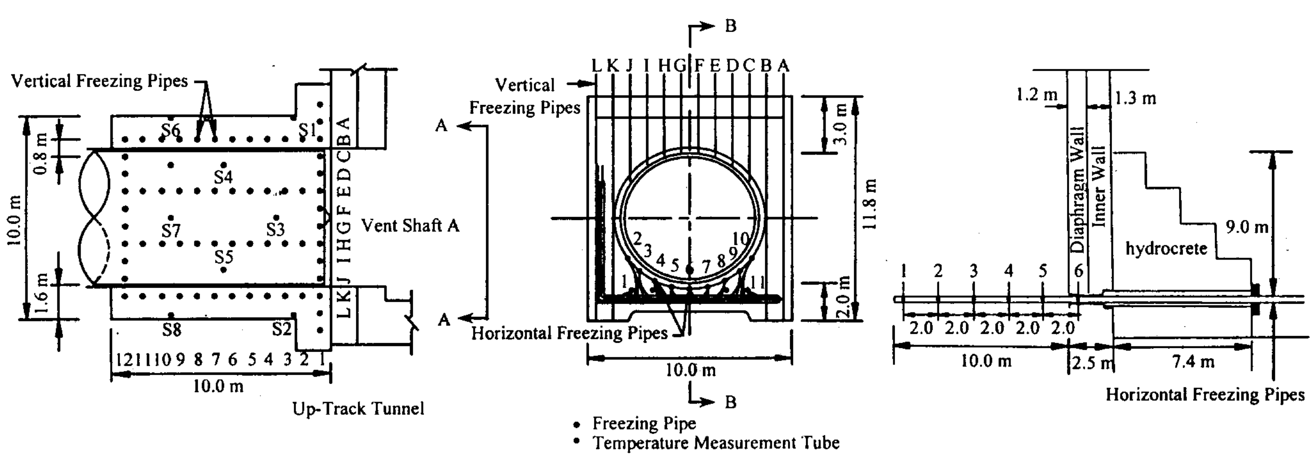
Freezing was conducted, refer to Fig. 3, to solidify the soils surrounding the shield machine and to seal off the water path so the concrete retaining wall and the grouted plug, which served the purpose of sealing the portal, could be removed and the final connection to the shaft could be made. A total of 66 vertical freezing pipes, refer to Fig. 4 for layout, were installed from the surface. They were double-tube steel pipes of 90mm in diameter and were installed at spacings of 0.8m apart, center to center. The pipes in the middle 8 rows (C to J) stopped at the tunnel crown while the outer 4 rows extended to a depth of 2m below the invert. To complete the enclosure, 11 freezing pipes were installed underneath the invert to a length of 10m, measured from the outer face of the diaphragm wall. Freezing was carried out to a height of 3m above the crown. The portion of pipes outside the refrigerated zone was insulated with foam of 25 mm to 50 mm in thickness.

To resist the earth and water pressure, the frozen ground on the two sides of the tunnel had to be at least 1.4 m in thickness for a design compressive strength of 6 MPa and a factor of safety of 2. In order to achieve this compressive strength, the temperature in the frozen ground had to be lowered to −12°C or below. Ground temperatures were measured in 8 vertical holes (S1 to S8 in Fig. 4a) and 2 horizontal holes (S9 and S10 in Fig. 4b). Thermometers were installed at 9 depths in the vertical observation holes and 6 locations in the horizontal observation holes.

Installation of the freezing system started in late November, 1995 (about 4 months subsequent to the incident), and freezing started in January, 1996. Figures 5 and 6 show the distribution of temperatures obtained in May. It can be noted that the frozen soil was as much as 3m thick above the crown and 1.5m thick on the two sides and below the invert. The design assumptions appeared to have been satisfied.

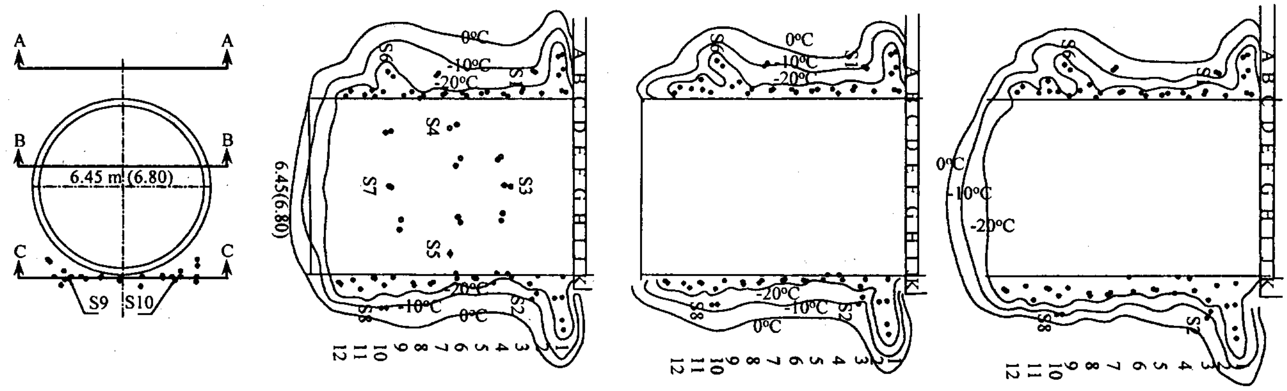
In January, 1997, all the damaged segments were replaced and the voids between these segments and the wall of tunnel backfilled. On May 20, 1997, the compressed air was released. The tunneling equipment in the shield machine was dismantled leaving only the shell in-place. The use of torch for dismantling the equipment did cause the temperature in the ground to rise by, roughly, 3 to 5 degrees.

The concrete retaining wall was demolished and the portal re-opened in July, 1997. A PVC pipe was found right next to the diaphragm wall as the invert was exposed. This pipe is believed to have been responsible for the



(a) Plan (b) Front View A -A (c) Section B-B (Tunnel and vertical pipes are omitted)

Fig. 4 Arrangement of Freezing pipes and Locations of Thermometers



(a) Front View (b) Section A-A (c) Section B-B (d) Section C-C

Fig. 5 Temperature Distribution at Horizontal Sections

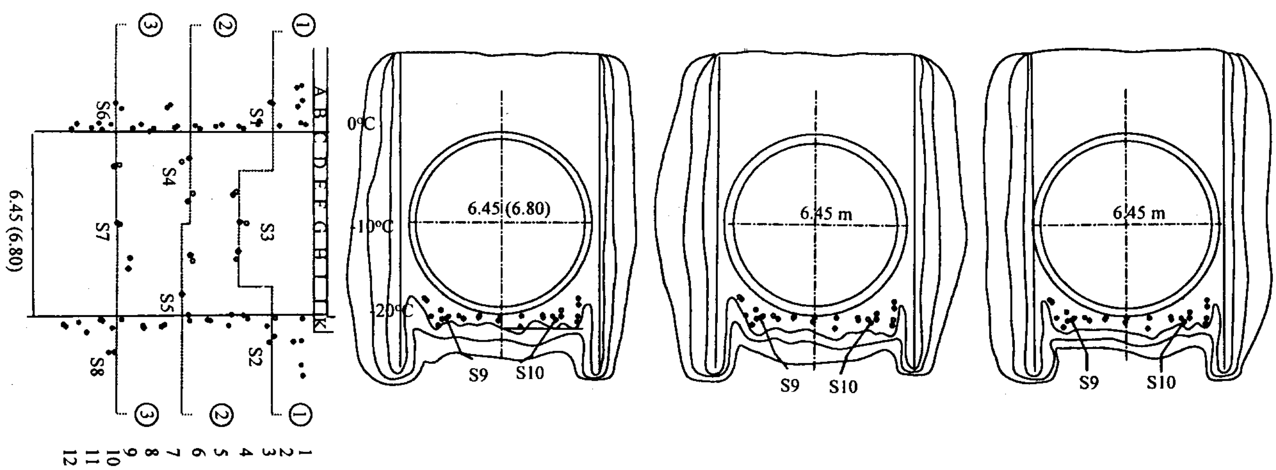
occurrence of the incident. It was an abandoned well, about 200mm in diameter, which was used to pump water from the Chingmei Gravels for the purpose of irrigation. The pipe was cut by the shield machine and formed a water path connecting to the Chingmei Gravels which is extremely permeable and water-rich.

As a final step, a flexible joint was constructed to complete the connection to the shaft in accordance with the original design. Freezing ended at the end of August, 1997 and the freezing pipes were removed in September.

PREPARATION FOR LAUNCHING THE SECOND DRIVE

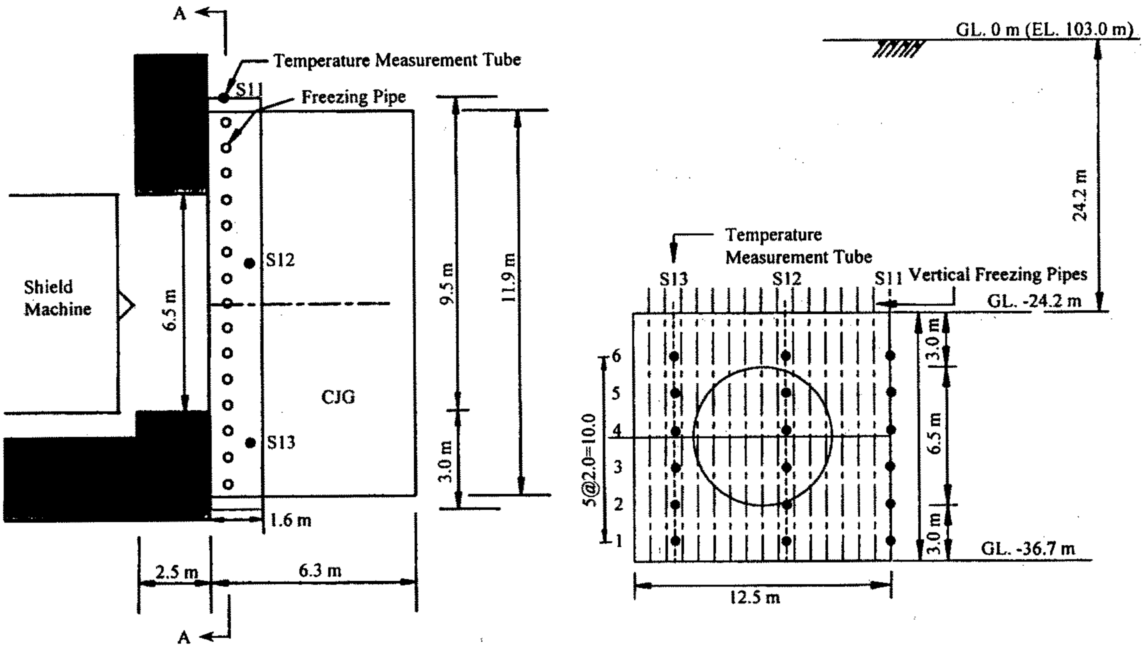
At the time the incident occurred, the eastern diaphragm wall, which is 1200mm in thickness, of the shaft had already been knock down to the last 100mm in thickness to prepare for the launching of the shield machine for the second drive. Although there were no signs of danger, to play safe, the portal was also sealed by a concrete retaining wall of a similar design as the one for the first drive but to a height of 7.5m instead of 9m. In addition, as shown in Fig. 7, freezing was carried out in a single row of 15 vertical freezing pipes installed at 0.8m spacings and to a depth of 3m below the invert. Also shown in these figures are the locations of three observation holes, i.e., S11, S12 and S13, and the locations of the thermometers installed in these holes for measuring ground temperature.

The readings obtained in these observation holes are shown in Fig. 8. As can be noted that the observation hole S12 registered the fastest rate of freezing while S11 registered the slowest, obviously due to boundary conditions. Another fact worthy of mentioning is that the ground temperatures at the bottom appeared to be a few degrees lower than those recorded at the top. This could be attributed to the fact that the inner rod which carried the



(a) Top View (b) Section ① - ① (c) Section ② - ② (d) Section ③ - ③

Fig. 6 Temperature Distribution at Vertical Sections



(a) Plan

(b) Section A-A

Fig. 7 Ground Freezing for Launching the Second Drive

fresh brine supply extended all the way down to the bottom and therefore the temperature of the brine was the lower over there. The brine picked up the heat from the ground on its return and the temperature rose with the height.

As indicated in Fig. 9, for a water content of 0.6 m^3/m^3, a brine temperature of -25°C, an ambient ground temperature of 24 °C, a spacing of 0.8m between pipes and a pipe diameter of 90mm, it was expected that the frozen ground would grow into a plate with the design thickness of 1.6m (0.8m on single side of axis in 30 days). As can be observed from Fig. 8 that the soils at the location of S12, which was 0.8m away from the center of the row, was not frozen till 40 days, or ten days later than what was expected. This could be due to the error in locationing the observation hole. A minor error in distance could affect the temperature readings significantly.

Freezing started in early March, 1996. On August 1, 1996, the shaft was flooded for the second time because Typhoon Herb brought in heavy rains. In fact, the flood reached a level of 2m above the ground and even the freezing plant was submerged. Freezing was resumed 10 days later and it was found that the ground temperature rose by, roughly, 3 to 5 degrees in the 10-day period of suspension, giving a rate of thawing of 0.4 degree per day. However, the frozen plate was estimated to reduce by only 300mm in thickness.

Based on the inclinometer readings, the eastern diaphragm wall moved by 13mm maximum inward as a result of freezing and 7mm outward upon thawing. It should be noted that, however, the permanent shaft structure had been completed before the incident occurred and the 1.3m thick inner wall presumably reduced the wall movements significantly. The ground surface movement caused by the ground freezing was practically nil for the reasons that the freezing was applied at depths exceeding 25m and the treated soil was granular. Strain gauges mounted on rebars in the diaphragm wall registered increases of, up to, 10 Mpa in stresses.

Freezing pipes were removed on December 12, 1996 to make way for the shield machine and the portal was opened on December 15. A new shield machine was installed to replace the one which was damaged and was launched on December 19. Tunneling was finally completed in May 8, 1997.

CONCLUSIONS

The case history presented herein leads to the following conclusions:

1. Making openings on underground constructions can be very dangerous if the ground is permeable and the water head is high.
2. Ground freezing is a reliable method in sealing underground openings. It can be effectively applied to a space in the ground which is inaccessible by other means.

The technical information given above is believed to be

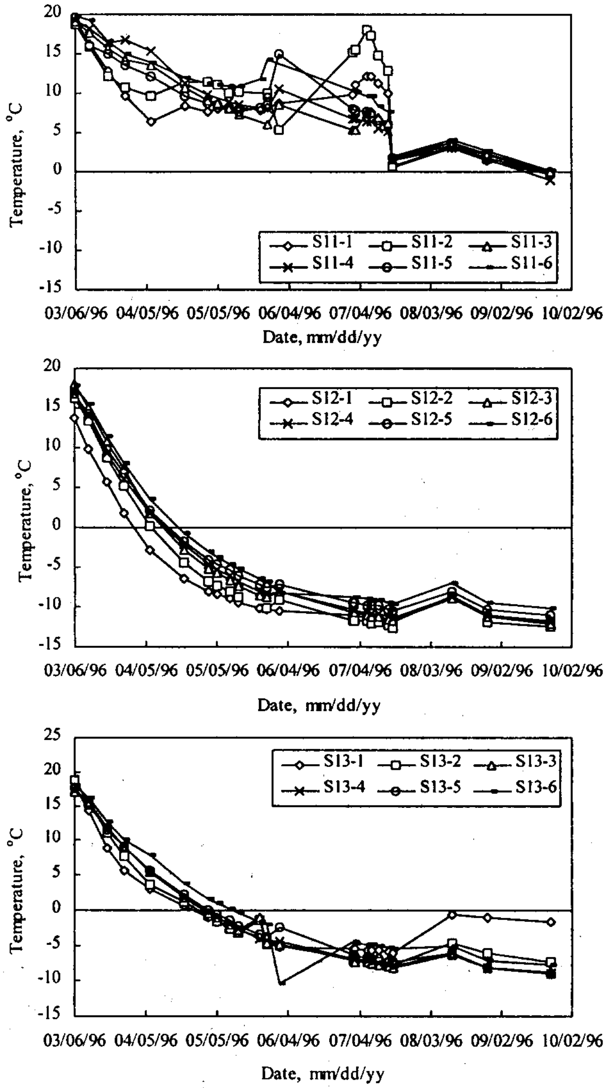


Fig. 8 Time History of Temperature

helpful to designers as well as contractors in dealing with incidents of a similar nature.

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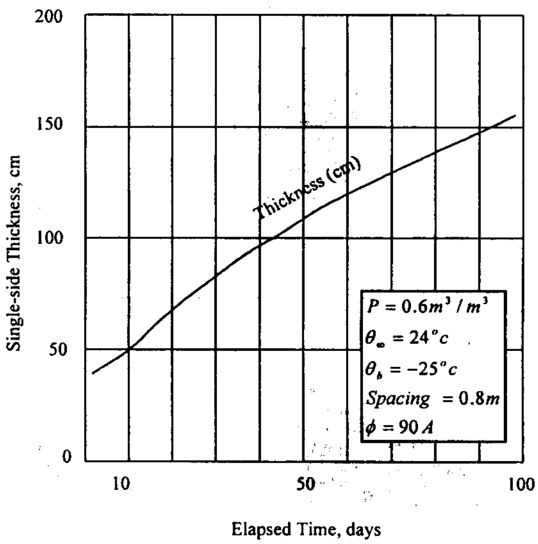

Fig. 9 Estimation of Required Period for Refrigeration

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