GROUND SETTLEMENTS OVER TUNNELS AFFECTED BY LOSS OF COMPRESSED AIR PRESSURES

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Abstract: A section of twin tunnels was constructed by using the NATM method with compressed air as an auxiliary measure for maintaining face stability. Compressed air pressure was reduced from 1.2 bar to 0.4 bar following an incident in which a sinkhole was made as a result of air leakage and erosion of soil. In a second incident, compressed air dropped to 0.2 bar in 12 hours during a power breakage. Considerable ground settlements were observed in these two events. This paper analyzes the ground settlements incurred and estimates what the ground settlements would be without these two incidents.

Keywords: NATM, Settlement, Compressed air.

1. INTRODUCTION

During the construction of the Initial Network of the Taipei Rapid Transit Systems, a short section of the Hsintien Line was constructed by using the New Austrian Tunneling Method (NATM). This section is 222m in length and is too short for shield tunnelling. The project also served as a pilot test for studying the applicability of the method in soft ground. The twin tunnels were bored through Sublayer 5 of the Sungshan Formation, consisting mainly of silty sand and sandy silts. The crowns of these two tunnels are at depths of 8m to 11m below ground surface with N-values typically in the range of 8 to 15 at this depth. Because ground conditions are very poor, compressed air was used for maintaining face stability during tunneling. Two incidents led to loss of compressed air pressure and resulted in much ground settlements. This paper reports the observations made to see if ground settlements can be correlated to cyclic loadings of compressed air.

2. TUNNELLING

Construction of the two tunnels was carried out in five stages as depicted in Fig. 1. Stage 1 construction involved excavation in free air in a space enclosed by slurry walls for providing a shaft of 30m in length to house the compressed air plant. The remaining sections of the tunnels were excavated by using a backhoe. The soft nature of the ground called for the use of compressed air to a maximum pressure of 1.35 bar. Construction was carried out in such a way that the two tunnels were inter-connected, as shown in Fig. 1, by a cross drift so that both tunnels were able to be pressurized by using a single set of compressed air facility. The soil pillars on both sides of this cross drift were strengthened by high pressure jet grouting for stability.

Tunneling was carried out in two headings as illustrated in Fig. 2. The upper heading was kept at a distance of 2m to 4m ahead of the lower heading. Lattice girders were installed at 1m intervals and the tunnels were protected by shotcrete, 250mm in thickness, and wire mesh as primary lining. For maintaining the stability of the crown, steel lagging sheets, 6mm in thickness, 200mm to 300mm in width and 2m in length, were closely spaced to form a canopy. An average progress of 1m per day was achieved in normal operation. The tunnels were finally lined by 350mm reinforced concrete as permanent lining.

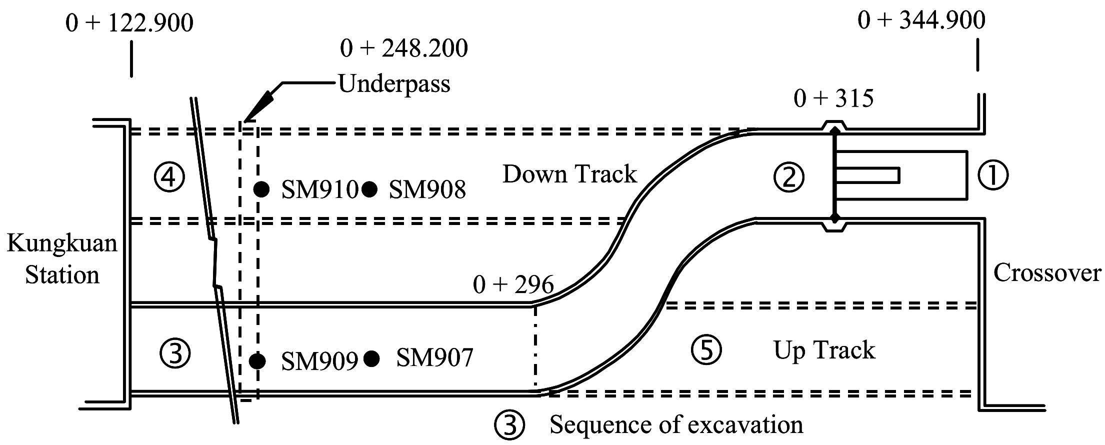


Figure 1. Plan of NATM tunnels in Contract CH221

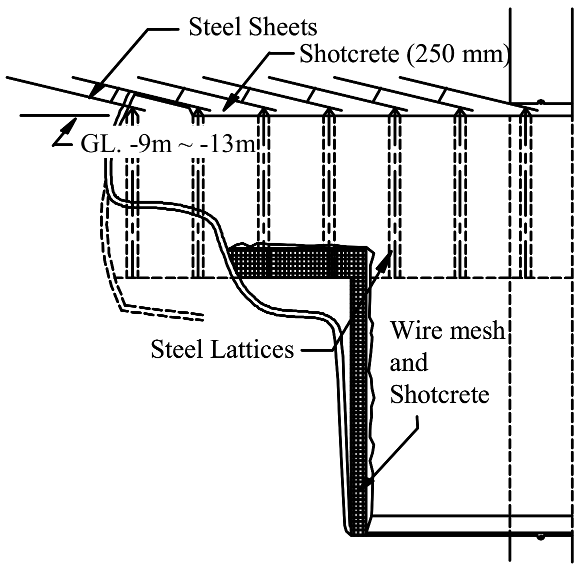


Figure 2. Profile for NATM tunnels in Contract CH221

As depicted in Fig. 3, Stage 2 excavation for the drift shaft started on December 13, 1993 from the western end of the cross drift (Ch 0+315m) in the down-track tunnel and proceeded toward the up-track tunnel (Ch 0+296m). Upon the completion of this cross drift, Stage 3 excavation immediately followed for mining the up-track tunnel. An incident, which will be discussed in detail in a later section, occurred in the beginning of April, 1994, when the upper heading reached Ch 0+238m and a progress of 58m had been made in the up-track tunnel. Excavation was suspended for four months as depicted in Fig. 3 and was resumed on July 25. Stage 3 excavation was completed at the end of November 1994 and Stage 4 excavation for mining the down-track tunnel immediately followed. The occurrence of the second incident, which is again to be discussed later, interrupted the operation for only 12 hours on March 22, 1995 when the upper heading reached Ch. 0+183m in the down-track tunnel. Other than that, tunneling was continuous till the completion of the down-track tunnel. Mining for the section of the up-track tunnel north to the cross drift, i.e., Stage 5 excavation, started on June 8, 1995 and completed on July 22. Compressed air pressure was released, starting on July 25, 1995 at a rate of 2.5 kPa per hour.

The up-track tunnel was lined by in-situ reinforced concrete, starting from the very southern end toward the north, in the period of February 8 to October 28, 1995 and the down-track tunnel was lined in the period of July 3, 1995 to February 15, 1996.

3. INCIDENT ONE – Air Leakage at Underpass

As depicted in Fig. 4, air pressure was maintained at 1.3 bar in the initial stage. An emergency situation was encountered, starting on 29 March, 1994, when air escaped through the fissures, which were left in place after sheet piles were withdrawn, into a pedestrian underpass through the cracks in the base slab, refer to Fig. 5 for details. The escaping air carried much water and soil solids into the underpass and as a result, a sinkhole of 70 cubic meters in volume was created at ground surface. The tunnel, however, was not damaged. Five days later, a minor explosion, presumably, due to the ignition of gas leaking from a gas line, shook nearby houses and broke window glass. At the time this happened, the upper heading reached Ch. 0+238m and had passed the underpass by 10m or so. The gas could have accumulated in a covered box culvert to a sufficient concentration enabling ignition. In fact, the explosion occurred at a location quite far away from the tunnel alignment and the steel covers of a couple

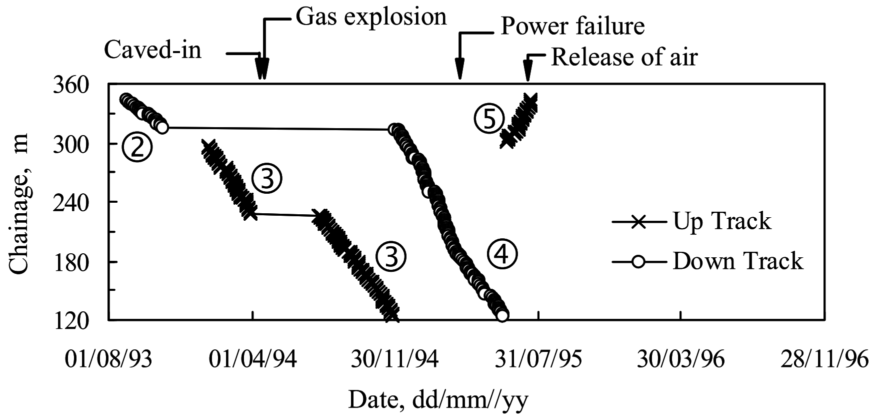


Figure 3. Progress of NATM tunnelling

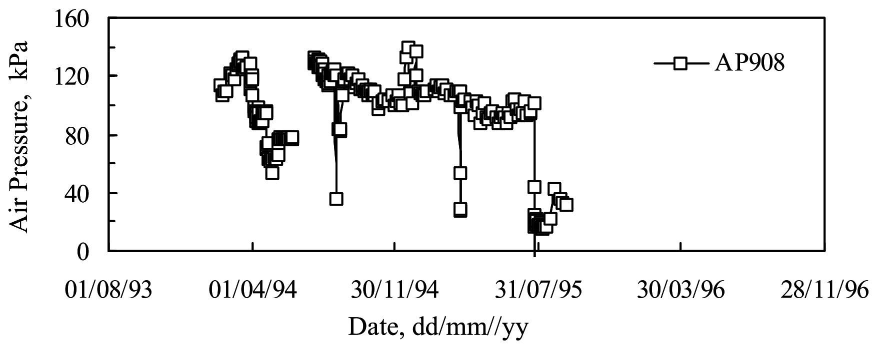


Figure 4. Compressed Air pressure

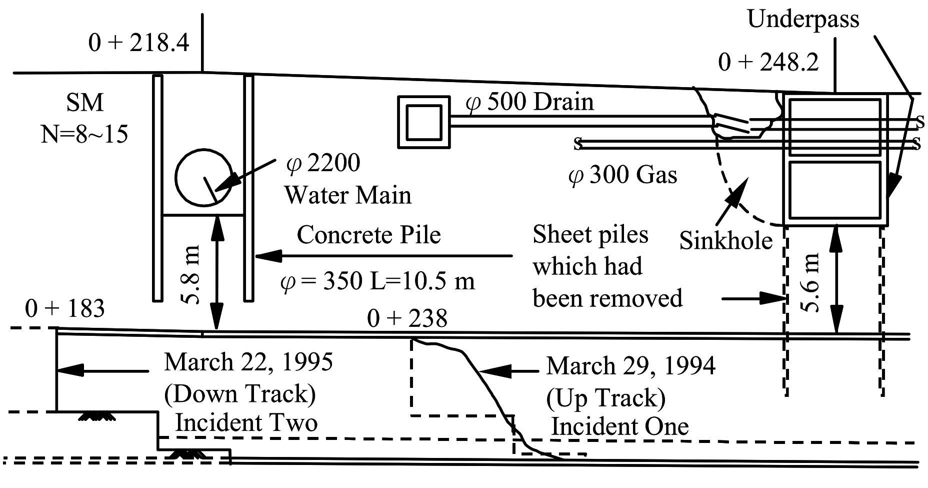


Figure 5. Incidents occurred along the route of NATM tunnels

manholes were blown off as a result of explosion. Although damages were minimal, it did cause panic of local residents. As a precaution, the pressure of compressed air was gradually lowered from 1.2 bar to 0.4 bar and maintained at that level for nearly half a month before returning to the normal level of 1.2 bar.

Excavation was suspended and grouting was carried out on both sides of the underpass to seal off fissures. The method of construction was carefully reviewed. Excavation was resumed 4 months later after the situation was judged to be stable and the safety of the works was assured.

4. INCIDENT TWO – Power Failure

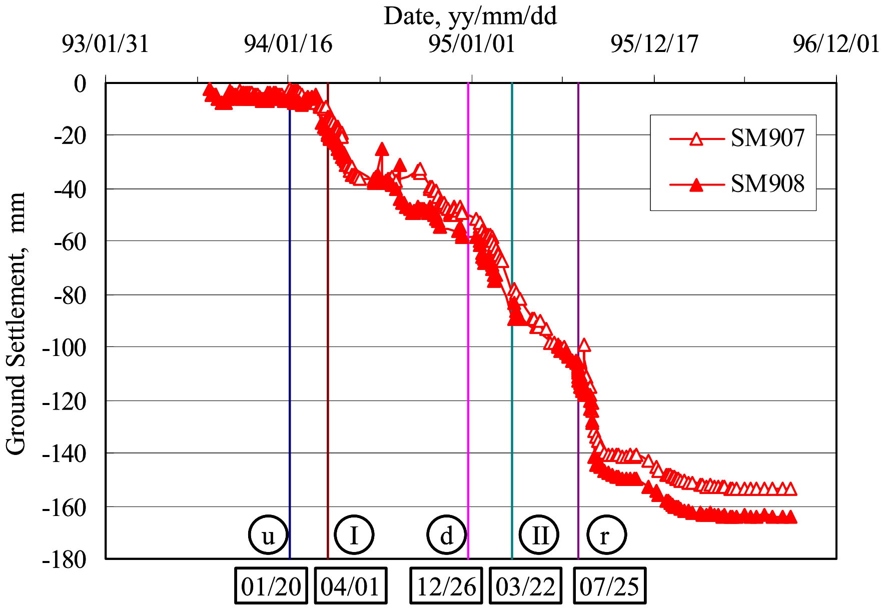
The most scary incident, psychologically, occurred when a transformer malfunctioned and disrupted the electrical power supply during Stage 4 excavation for mining the down-track tunnel. Air pressure in the two tunnels dropped from 1.1 bar to 0.2 bar in 12 hours before the transformer was replaced and the power supply was back to normal. At that time, Stage 3 excavation had already been completed and the heading reached Ch 0+183m in the down –track tunnel. In other words, there was a total length of 305m of tunnel (173m in the up-track and 132m in the down-track tunnel) already been driven. Although the primary lining was designed to hold the tunnels even without compressed air, the face did rely on compressed air to stand up. A 2200 mm diameter water main ran across the two tunnels and supplied water to the entire Taipei City. Should it rupture, the consequence would be disastrous. Fortunately the ground in front of the face had been previously stabilized by grouting for reducing the loss of compressed air and the face was thus stable. The contractor was able to replace the transformer promptly and the crisis was resolved without even minor damages.

5. GROUND SETTLEMENTS

Settlements at three sections are analyzed. Figure 6 shows the settlements obtained in Section 1 which was located at Ch 0+293m, or about 3m from the end of the drift shaft. Naturally, ground started to settle as the upper heading in the up-track tunnel passed. The settlements accelerated as the air pressure was reduced following the gas explosion (Incident One). They tended to tail off in December, 1994 and a new phase of settlement was triggered by the passing of the heading in the second drive, i.e., the down-track tunnel, on December 26. When the second incident occurred, both tunnels had been lined by steel lattices girders and shortcrete and therefore the effects of pressure drop were minimal. Maximum settlements obtained were of an order of 160mm at the end of construction.

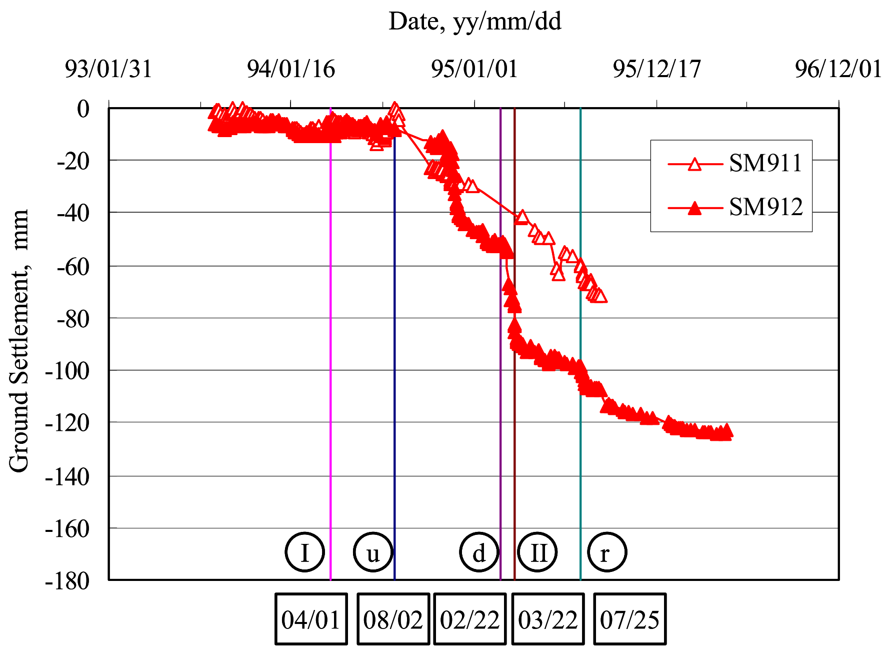
Figure 7 shows the settlements obtained in Section 2 which was located at Ch 0+221m. Little settlements were observed during Incident One because the heading was 17m away when it happened. Records show that, the excavation for the invert at this section in the down-track tunnel started on February 27, 1995, therefore, when the second incident occurred on March 22, this section was newly lined. A settlement of about 13mm was observed at SM912 on that day. The settlement above the up-track tunnel was little as observed by SM911.

As shown in Fig. 8, a similar situation occurred in Section 3, the excavation for invert in the down-track tunnel started on March 14 and the lining probably was incompleted when the second incident occurred. A settlement of 16mm was observed above the down-track tunnel and the settlement above the up-track tunnel was minimal.



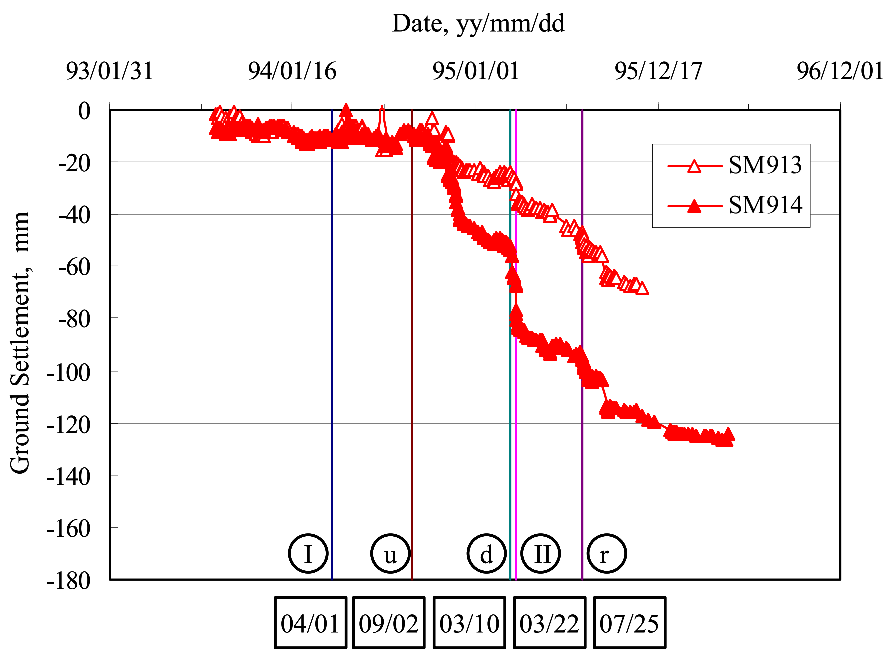
I : Incident I
u : heading reaching in up-track
r : releasing air
II : Incident II
d : heading reaching in down-track

Figure 6. Settlements in Section 1 (Ch 0 + 293m)



I : Incident I
u : heading reaching in up-track
r : releasing air
II : Incident II
d : heading reaching in down-track

Figure 7. Settlements in Section 2 (Ch 0 + 221m)



I : Incident I
u : heading reaching in up-track
r : releasing air
II : Incident II
d : heading reaching in down-track

Figure 8. Settlements in Section 3 (Ch 0 + 195m)

CONCLUSIONS

The successful completion of these two tunnels proves the fesibility of adopting the NATM tunneling method in soft ground and the use of compressed air is an effective auxiliary measure for maintaining the stability of tunnels.

The data presented above indicate that ground settlements would have been in the range of 70mm to 80mm as observed by SM911, SM913 without the two incidents. The loss of cmpressed air pressure in these two incidents increased the final settlements by 70mm to 90mm as observed by SM907 and SM908.

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