# A CASE RECORD OF BORED TUNNELS IN SAND BASED ON THE KAOHSIUNG MASS RAPID TRANSIT SYSTEM PROJECT

Bin-Chen Benson Hsiung [1]

## ABSTRACT

A case study associated with shield-machine bored tunnels in sand is presented in this paper. Observations show that driving the first bored tunnel resulted in up to 10 mm of surface settlement, and the ground between two tunnels seems to have been affected to some extent by the construction of the second, adjacent tunnel. The accumulated maximum surface settlement increases by 12 mm. Back-analyses indicate that excavation of tunnels generates volume loss varying from 0.38 to 0.53%. This volume loss is comparatively smaller than those in cases with the same conditions which might be associated with ground treatment, or performance of the machine, as well as workmanship. Influences on surface settlement from chamber pressure, backfill grout pressure and volume, as well as balance of the volume of materials discharged and inserted into the tunnel were explored. The ground movement might be associated with the imbalance of volume of material discharged and inserted into the tunnel but further data is desired to support the finding.

*Key words:* Bored tunnel, sand, surface settlement.

## 1. INTRODUCTION

Generally, soft ground tunnels are bored using Earth Pressure Balance (EPB) or slurry-type tunnel-boring machines to reduce loss of ground, but unfavourable ground movements induced by the construction of bored tunnels can cause damage to adjacent structures. Ground behaviour induced by the construction of bored tunnels in clay have been widely discussed, (Fang and Chen 1990, Fang, Lin and Su 1994, Hwang *et al*. 1995) but there are comparatively few published studies examining tunnels constructed in sand. Hsiung and Lu (2008) provided a case record of the construction of bored tunnels in sand based on tunnels for one of the Kaohsiung Metro contracts. However, it would be necessary to study more case records in order to further determine the shape and magnitude of ground movements caused by tunnels in sand. In addition, the influence of machine operation on surface settlement warrants further examination.

This paper presents a case record of bored tunnels constructed in sand in a densely populated urban area. It is expected that the results reported here may provide a useful reference for the study of bored tunnels in sand and associated ground behaviour.

## 2. PROJECT BACKGROUND

Kaohsiung is located in southern Taiwan, where the design of a new metro system began in the 1990's, with construction commencing in 2002. Two lines, the Red Line and Orange Line were constructed, and the total route length of the system of 42.8 km, includes 37 stations, 28 of them underground. All underground stations were constructed by using the cut-and- cover method of construction. Stations are linked by a total of 28 twin-bored tunnels throughout the whole system.

There were 10 underground construction contracts in the Kaohsiung Metro project, and Contract CO2 was selected to be presented in this paper, based on the availability and reliability of data. Figure 1 presents the location of CO2. Contract CO2 on the Orange Line is located in the Linya and Sinsing districts in Kaohsiung City with three underground Stations, O6, O7 and O8. The contract comprises two twin-bored tunnels, LUO08 and LUO09, as well as one cross-passage in tunnel LUO09. In general, the tunnels are aligned with one of Kaohsiung City's main east-west roads, being Chung- Cheng Road.

Tunnel LUO08 is located between Stations O6 and O7. The track length of LUO08 is 851.8 m (including both the up and the down tracks). Figure 2 shows the longitudinal profile of LUO08. As indicated in Fig. 2, the twin tunnels remain parallel at the same depth, and the centre-to-centre distance of the two tunnels is approximately 12.0 m at Station O6. However this offset becomes slightly wider (14.0 m) at Station O7. The longitudinal tunnel centre-line is approximately 14 m below the surface level of Station O6 and becomes slightly deeper towards O7, reaching 16 m at Station O7.

Tunnel LUO09, located between Stations O7 and O8, and approximately 15 m beneath the bottom slab of the Chung-Cheng underpass, is 1665.6 m in length. Figure 3 represents the longitudinal profile of tunnel LUO09 as a twin-bored tunnel, where the two tunnels run parallel at the same depth, similar to tunnel LUO08. However, the offset between these two tunnel centrelines is narrower, 7.9 m, at the two stations, (O7 and O8), but widens at the middle (where the cross passage is located). Figure 3 shows that the LUO09 tunnel is situated approximately 16 m below the surface level at Station O7, and gradually increases in depth towards the cross passage and sump location (approximately 26 m below surface level) and rises again toward the direction of O8.

Two EPB tunnel boring machines were employed for the construction of tunnels on Contract CO2. EPB boring machines equalise and maintain the earth pressures on both the outside face of the cutting head and inside the chamber, by maintaining spoil in the chamber under controlled pressure, thus preventing immediate ground losses through the chamber.

Manuscript received September 27, 2010; revised June 14, 2011; accepted June 14, 2011.

[1] Associate Professor (corresponding author), Department of Civil Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung City, Taiwan, R.O.C. (e-mail: benson@cc.kuas.edu.tw).

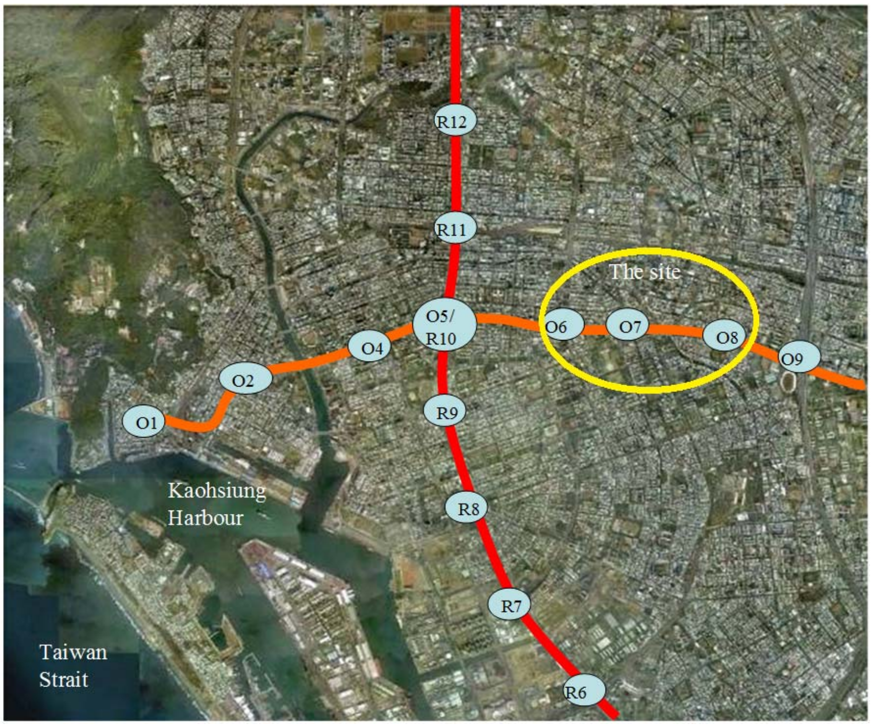



**Fig. 1 Network of Kaohsiung Metro and location of the site (redraw from google map)**

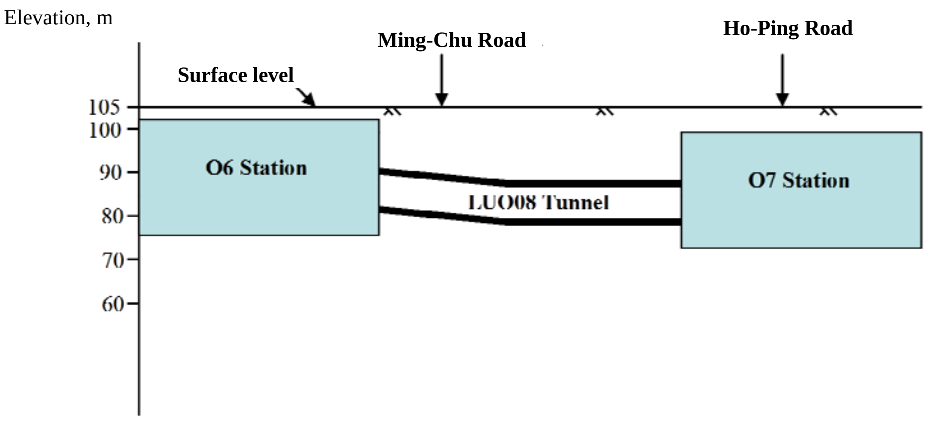



**Fig. 2 Longitudinal section of LUO08**

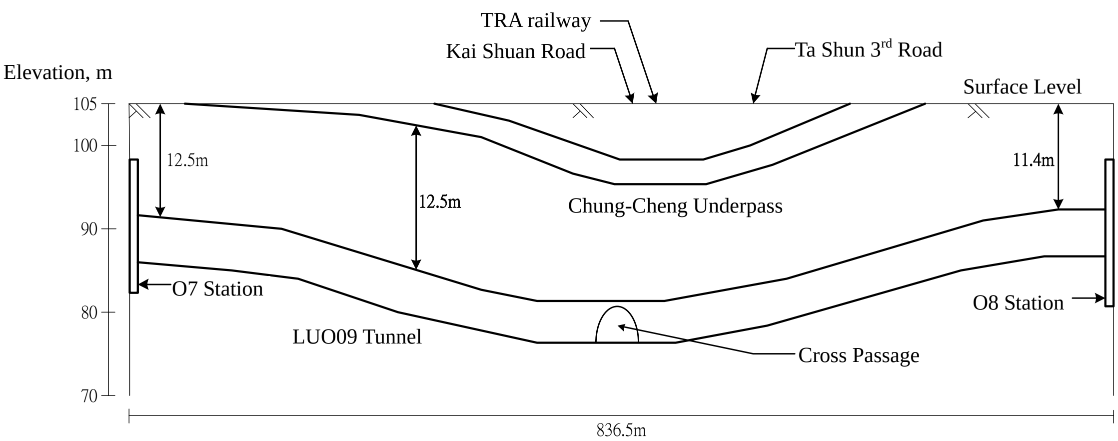



**Fig. 3 Longitudinal profile of LUO09**

The EPB machine shield used was 6.23 m in diameter and the inner and the outer diameter of the tunnel lining are 5.60 m and 6.10 m, respectively. As with other contracts on the Kaohsiung Metro project, the prefabricated tunnel lining rings were 1.2 m wide, 0.25-m-thick, with each ring comprising six segments (three *A*-type segments, two *B*-type segments and one *K*-type segment).

## 3. GROUND CONDITIONS

Kaohsiung City is located in southern Taiwan and the geological strata were formed during either the late Tertiary or Quaternary periods. Figure 4 represents the geology of Kaohsiung City. The city is situated at the mouth of three rivers, Dien-Pao River in the north, Love River in the middle and Chien-Jen River in the south, and as a result the ground conditions in Kaohsiung city are mainly sandy and silty with clay, as depicted in Fig. 4. The CO2 project site is located in the centre of Kaohsiung City, and several field investigations were undertaken to identify the physical properties and strength of the prevailing soils.

Field investigations identified mainly silty sand and occasionally low plasticity silty clay deposits. Soil samples retrieved from the site were selected and tested in the laboratory. Testing programmes included basic soil properties testing, direct shear tests, tri-axial consolidated undrained and drained tests and oedometer tests. A simplified description of the ground profile for project CO2 is presented in Tables 1 and 2.

The effective friction angle measured from the direct shear tests and tri-axial consolidated undrained and drained tests performed on the soil samples was in the range of 31° to 32° for sand and 26° to 27° for clay.

The groundwater level was observed to vary from 2.6 m to 4.8 m below ground level.

## 4. MONITORING RESULTS

The surface settlement points (hereinafter denoted as "SM") were installed at ground level directly above the centre axis of the tunnels and were used to monitor arising surface settlements induced by tunnel excavation. The precision of surface settlement measurement is to the nearest 0.1 mm. Surface settlements were monitored in several sections transverse to the tunnel.

Figure 5 presents the time histories of settlement monitored at the surface directly above the centre-line of each tunnel at LUO08. The locations of settlement points for surface settlement measurement are shown in Fig. 6. Surface settlements varying from 6 to 10 mm were observed during the 1st drive. The settlement was continually monitored during the second drive, up track, and the settlement increased again after passing of the 2nd machine, approximately 120 days after passing of the 1st machine. The ultimate maximum accumulated surface settlement measurements were between 8 to 12 mm.

Hwang *et al*. (1995) suggested that three phases of ground settlement (shield advancing, tail void and consolidation) could be clearly distinguished in Taipei. Based on study of the other case records of tunnel construction in Kaohsiung, Hsiung and Lu (2008) have reached the following conclusions:

1. Driving of the 1st tunnel induced up to 20 mm of surface settlement. The surface settlement might be further affected by construction of a second, adjacent tunnel and the accumulated maximum surface settlement may increase to 40 mm.
2. Ground becomes stable 20 to 40 days after the shield has passed but construction of cross- passages or excavation of adjacent open- cut stations could induce further settlement.
3. No consolidation settlement was observed.

**Table 1 The soil strata of LUO08 at CO2**

| Layer | Description of ground | Soil classification | Depth | Total unit weight (kN/m$^3$, Approximately) | SPT-N value |
|---|---|---|---|---|---|
| I | Grey silty sand | SM | Surface to 6.5 m below; groundwater level observed at GL 2.9 m | 19.6 | 5 to 6 |
| II | Grey silty clay with sandy silt | CL | GL 6.5 m to 8.5 m | 18.9 | 6 |
| III | Grey silty sand occasionally with sandy silt | SM | GL 8.5 m to 23.0 m | 20.0 | 6 to 15 |
| IV | Grey silty clay with sandy silt | CL | GL 23.0 m to 25.0 m | 19.3 | 12 |
| V | Grey silty sand with sandy silt | SM | Beneath 25.0 m below the ground surface | 19.8 | 12- 19 |

**Table 2 The soil strata of LUO09 at CO2**

| Layer | Description of ground | Soil classification | Depth | Total unit weight (kN/m$^3$, Approximately) | SPT-N value |
|---|---|---|---|---|---|
| I | Yellow silty sand. Backfill materials are observed on surface in some locations. | SM | Surface to 2.0 m below; groundwater level observed at GL 3.2 m | 18.0 | 2 |
| II | Yellow silty clay | CL | GL 2.0 m to 3.3 m | 20.2 | 7 |
| III | Yellow and grey silty sand | SM | GL 3.3 m to 6.8 m | 20.9 | 6 to 9 |
| IV | Grey silty sand occasionally with organic material | SM | GL 6.8 m to 8.0 m | 18.0 | 3 |
| V | Grey silty sand | SM | GL 8.0 m to 20.4 m | 19.0 | 11 to 15 |
| VI | Grey sandy silt | ML | GL 20.4 m to 23.1 m | 18.9 | 8 to 11 |
| VII | Grey silty sand with clay | SM | GL 23.1 m to 29.3m | 18.9 | 15 to 20 |
| VIII | Grey sandy silt with clay | ML | GL 29.3 m to 32.0 m | 19.1 | 15 to 16 |
| VIII | Grey silty sand occasionally with clay | SM | Beneath 32.0 m below the ground surface | 19.0 | 17 to 28 |

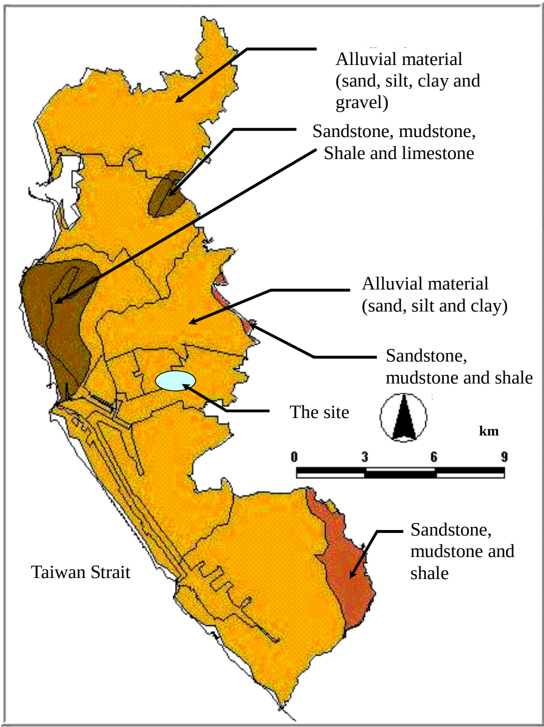
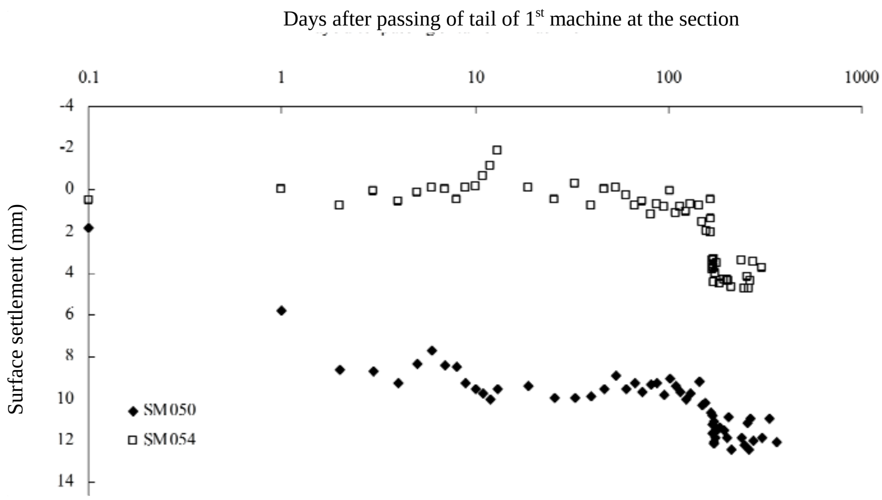
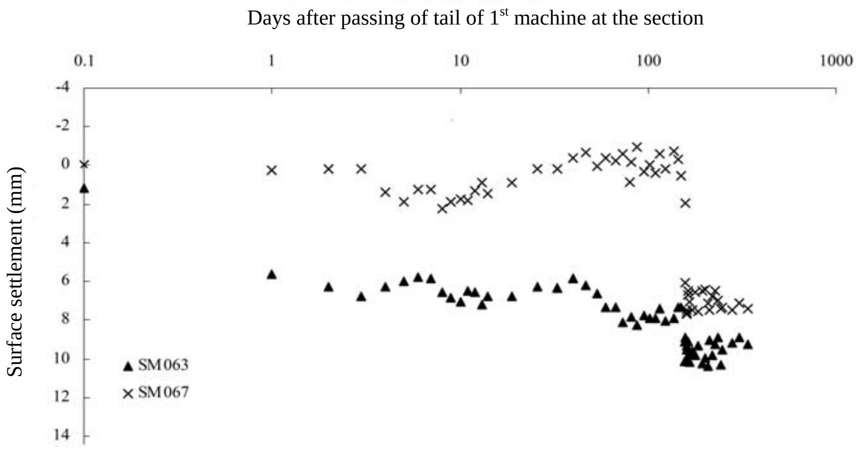



**Fig. 4 Geological Map of Kaohsiung City (redraw from Wang, 1997)**

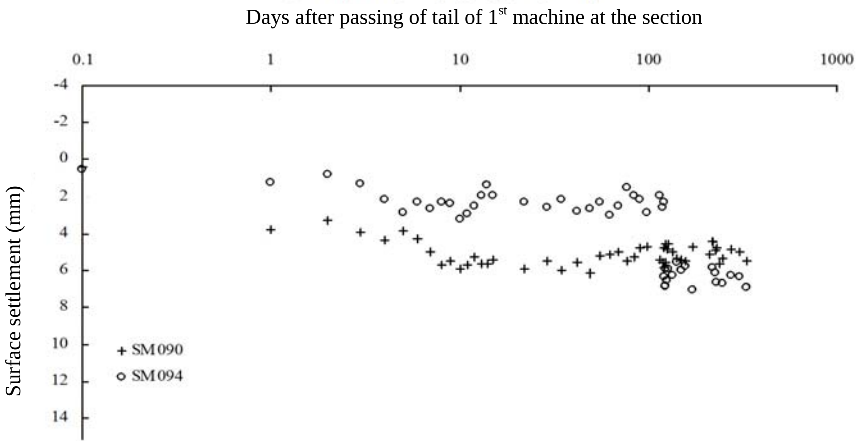



(a) Section A




(b) Section B

**Fig. 5 Time history of surface settlement measured at LUO08**




(c) Section C

**Fig. 5 (continued)**

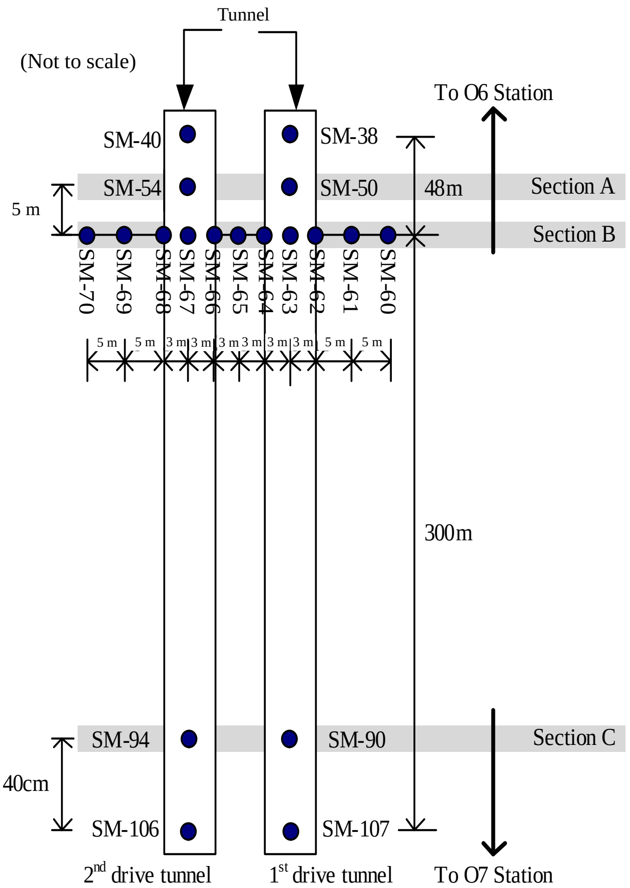



**Fig. 6 Location of monitoring array and settlement points of surface settlement**

As shown in Fig. 5, ground settlements induced during the phases of shield advance and tail void were observed, but there was no consolidation settlement in the Kaohsiung tunnels. This is consistent with the observations that Hsiung and Lu (2008) reported. The ground is sandy, consolidation settlement are small so differing ground conditions is likely the main reason for the different settlement results.

Figure 5 also shows that the ground sometimes heaved for several days immediately after the boring machine passed, and back grouting is the presumed cause since grout was injected almost at the same time. Limited heave was noted at point SM067 for 40 to 120 days after passing of the tail of the 1st machine, and the error in the measurements might be connected.

Similarly, observations from tunnel LUO09 were examined. Significant settlement was seen at places located outside the working shaft, and they are not far away from the place where the machine was launched. At the time of these measurements the workers were still adjusting the machine that establishes the earth pressure balance. In contrast, limited settlement was observed at places located at the central part of the tunnel, and there are two possible explanations for the small settlements there: (1) The tunnel is located much deeper at the central section than at the two ends. (2) The Chung-Cheng underpass is located exactly above LUO09, and the greater stiffness of its concrete reinforcement box might significantly reduce the settlement measured at the surface level.

As described above, tunnel LUO09 is located directly beneath the Chung-Cheng underpass, and the measurement of surface settlement may have been influenced by the presence of the Chung Cheng underground box structure so therefore this is not a ‘green-field’ site. As a result, only data taken from tunnel LUO08 was used in this paper.

As indicated in Fig. 5, in all sections the ground attained a stable condition in less than 20 days after the shield had passed through. It appears that the time for stabilisation was shorter than observations from other contracts in Kaohsiung, which were reported by Hsiung and Lu (2008). The very limited presence of clayey material is considered to be is the likely reason for this discrepancy in stabilisation time.

Peck (1969) stated that if two tunnels are driven adjacent to one another, the construction of the 2nd tunnel will generate significantly greater movements because of the stress relief of the ground resulting from the construction of the 1st tunnel. However, this situation does not seem to apply to most locations in CO2, and it appears that experience in operating the machine in similar ground conditions helped reduce surface settlement.

A transverse surface settlement trough was also measured at CO2, and, as explained previously, only data from LUO08 were selected for further analyses. There were three survey monitoring arrays in LUO08, *i.e.*, LUO08-1, LUO08-2 and LUO08-3, and their locations are shown in Fig. 7 together with the ground profile. Generally, since twin-bored tunnels run parallel horizontally, the centre of the array is defined as the midpoint between each tunnel. Two settlement points in an array were installed above the centreline of each tunnel, and the array extended up to 30 m from the centre of the array perpendicular to the line of the tunnel.

Methods recommended by Peck (1969) and O'Reilly and New (1982), which are similar to those employed by Hsiung and Lu (2008), were used for the back-analyses, and the surface settlement measurements in the transverse direction were interpreted and mapped to surface settlements induced by a single tunnel. Two parameters, the width factor ($k$) and volume loss rate ($V$), could thus be interpreted. Volume loss rate ($V$) is determined by

$$V = \frac{\delta_{\max}\, i}{0.0126 R^2} \tag{1}$$

where $\delta_{\max}$ is the maximum surface settlement, $R$ is radius of tunnel and $i$ is a inflexion distance and can be defined by

$$i = kZ_0 \tag{2}$$

in which $Z_0$ is the depth to the centre of the tunnel. Figures 8, 9 and 10 present the interpreted surface settlement induced by individual tunnel drivings. The inferred maximum surface settlement ($\delta_{\max}$) of the individual tunnel driving reaches 3.8 to 10.0 mm for the down track tunnel (the 1st drive) and 5.9 to 7.0 mm for the up track tunnel (the 2nd drive).

The parameters $k$ and $V$ associated with the back-analyses of data for tunnel LUO08 are shown in Tables 3 and 4. In order to perform the analyses, $\delta_{\max}$ was fixed, but the $k$ and $V$ values on the analytical curve were adjusted to fit the rest of the observed data points on the plot. Volume loss, $V$, of 0.38% to 0.53% was interpreted from the back-analyses of tunnels at CO2. Bhogal (2005) reported that $V$ could be reduced to 0.5% if polymer was used as a soil conditioning agent. The interpreted results of $V$ obtained for CO2 appear consistent with values reported previously.

## 5. MACHINE OPERATION

As described previously, two EPB machines were used for the tunnel drives on Contract CO2, and the details of the EPB machine used in tunnel LUO08 are listed in Table 5. The operation parameters of the EPB shield-machine, such as chamber pressure, volume and pressure of backfill grout used and the spoil excavated and transported in tunnel LUO08 were also fully recorded. The main purpose of the chamber is to create pressure behind the cutting head so that the earth pressure on the cutting head can be equalised with the pressure inside the chamber in order to reduce the earth movements during tunnel excavation. The applied pressure in tunnel LUO08 remained in the range of 180 to 210 kPa during construction of both running tunnels but was significantly reduced in the ground treatment zone near the launching and docking shafts.

Most of the settlement occurring during the construction of the tunnel may have been caused by closure of the void at the tail of the shield, so grout was used to backfill the tail void. The functions of the backfill grout are to: (i) ensure a uniform contact between the ground and the segment, (ii) limit the surface settlement over the tunnel; (iii) support the ring in place during shield advance, (iv) take up the load transferred to the lining by the shield back-up, and (v) reduce seepage and loss of fine particles (Shirlaw and Boone 2009). The grout was to be injected under adequate pressure. Table 6 presents the matching of the grout used. Contract CO2 aimed to maintain the grout pressure in the range of 100-300 kPa, based on the construction plan. In reviewing the construction records, it was found that the pressure of backfill grout was kept at 300 kPa throughout the construction work on both the down track tunnel and up track tunnel at LUO08.

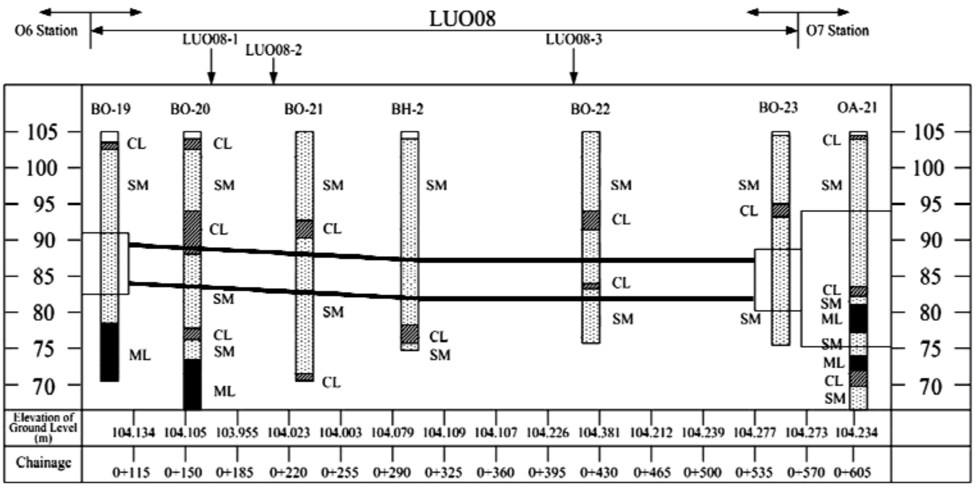



**Fig. 7 Soil profile and locations of monitoring sections**

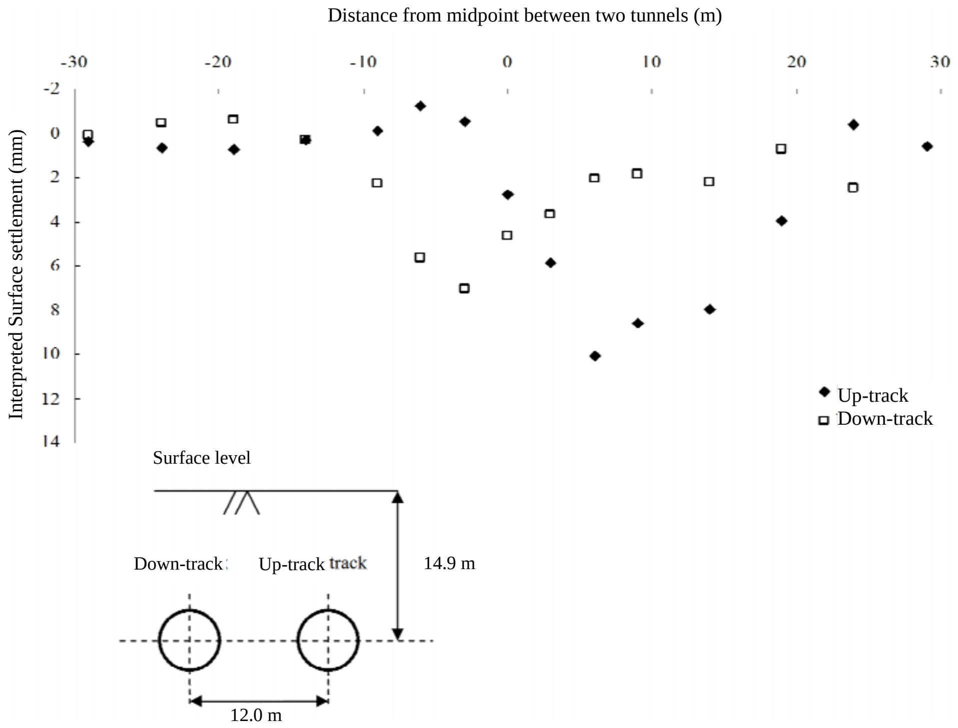



**Fig. 8 Transverse surface settlements at Section LUO08-1**

**Table 3 Estimated *k* and *V* for the up track tunnel at LUO08**

| Section | Range of *k* | Average *k* | Range of *V* (%) | Average *V* (%) |
|---|---|---|---|---|
| LUO08-1 | 0.31-0.65 | 0.48 | 0.27-0.57 | 0.42 |
| LUO08-2 | 0.29-0.83 | 0.56 | 0.25-0.71 | 0.48 |
| LUO08-3 | 0.23-1.26 | 0.78 | 0.12-0.64 | 0.38 |

**Table 4 Estimated *k* and *V* for the down track tunnel at LUO08**

| Section | Range of *k* | Average *k* | Range of *V* (%) | Average *V* (%) |
|---|---|---|---|---|
| LUO08-1 | 0.24-0.61 | 0.43 | 0.30-0.76 | 0.53 |
| LUO08-2 | 0.30-0.62 | 0.46 | 0.30-0.61 | 0.46 |
| LUO08-3 | 0.27-0.97 | 0.62 | 0.21-0.75 | 0.48 |

**Table 5 Details of TBM**

| Number of machine | 30 (for LUO09) | 31 (for LUO08) |
|---|---|---|
| Type of TBM | Earth pressure balance | Earth pressure balance |
| Outer diameter of machine | 6240 mm | 6230 mm |
| Cutter head configuration | Close type | Close type |
| Hydraulic jacking-maximum thrust | 34320 kN | 33000 kN |
| Hydraulic jacking speed | 5.0 cm/min | 7.0 cm/min |
| Maximum torque of cutter head | 4932 kN·m | 4228 kN·m |

Furthermore, the volume of backfill grout used at LUO08 was interpreted using an index called the "backfill rate ($R_b$)", which is calculated by

$$R_b = \frac{V_{\text{grout}}}{V_{\text{tail}}} \tag{3}$$

where $V_{\text{grout}}$ is the volume of backfill grout used and $V_{\text{tail}}$ is the volume of the tail void.

The contractor's plan was to maintain $R_b$ in the range of 1.3 to 2.0 but less than 2.0. $R_b$ varied from 1.3 to 1.8 for the down track tunnel and from 0.9 to 1.3 for the up track tunnel. $R_b$ of the down track tunnel was close to what the contractor targeted, but $R_b$ of the up track tunnel was lower.

Finally, Kao *et al*. (2009) recommended that an imbalance between the spoil discharged and material inserted into tunnel is the key factor leading to ground movements, so this imbalance was also studied. As explained previously, the material discharged was spoil caused by the excavation of the tunnel, and the volume of material inserted into tunnel included the volume of the shield tube, the slurry of soil conditioning and the backfill

**Table 6 Mix proportions of backfill grout and soil conditioning**

(a) Backfill grout-mix proportions

| Material | Cement | Bentonite | Stabiliser | Water | Sodium silicate solution |
|---|---|---|---|---|---|
| Proportion (per m$^3$) | 230 kg | 36 kg | 3 kg | 828 litres | 100 kg in 74 litres |

(b) Soil conditioning-mix proportions

| Material | Water | Algin* | Tackiness Agent D2* |
|---|---|---|---|
| Specific gravity | 1.0 | 0.8 | 1.1 |
| Proportion (per m$^3$) | 982 litres | 14.7 kg | 0.04 litres |

* Polyester materials

grout. Ground shall heave if the volume of material inserted is greater. A reference index ($I_{im}$) for further study was thus designed, and it is defined as

$$I_{im} = \frac{V_{in}}{V_{dis}} \tag{4}$$

where $V_{in}$ is the volume of material inserted into the tunnel and $V_{dis}$ is the volume of spoil discharged.

The use of soil conditioning slurry could reduce the permeability of the spoil, stabilise the excavation face and improve the serviceability of the conveyer. The volume of soil conditioning slurry used was 30% of the shield tube at LUO08, and Table 6 also shows the materials and their matching the slurry. Given the volumes of spoil, shield, backfill grout and soil conditioning slurry used at LUO08, $I_{im}$ estimated at LUO08 was in the range of 0.95-1.04.

## 6. DISCUSSION

Analyses of the transverse surface settlement troughs were undertaken for comparison with similar works in Kaohsiung. In Kaohsiung, Hsiung and Lu (2008) reported that 0.31% to 1.85% of *V* was induced by driving of the tunnels, which seems to be higher than *V* interpreted for the tunnels at CO2. There are two possible explanations for this discrepancy:

1. Some sections selected by Hsiung and Lu (2008) were located in a ground treatment zone and greater volume loss might thus be induced.
2. The difference might be associated with the performance of the machine and workmanship.

In addition, unlike the case which Hsiung and Lu (2008) observed, the driving of the 2nd tunnel did not significantly affect the settlement exactly over the 1st tunnel. It is possible that the ground is very sandy so the influence zone is smaller.

The parameters used for the construction of tunnels using Tunnel Boring Shield Machines at LUO08, such as the chamber pressure, back-grout pressure, grout backfill rate and difference in spoil discharged and inserted the tunnel, are shown together with surface settlement occurred, measured at central axis of tunnel in Figs. 11 to 14. The ring length is 1.2 m. It should be noted that numbering of ring starts from O6 Station side.

In order to successfully retain the soil in front of the cutting head, the chamber pressure must be kept in the range of the earth pressure at rest (lower bond) and the passive earth pressure (upper bond). As shown in Fig. 11, chamber pressure remained near the lower bound of the pressure.

Figure 12 indicates that the backfill pressure remained at 300 kPa during most of the construction of both the up track and down track tunnels, but the settlement measured directly above the tunnel varied widely. It seems that no firm relationship between backfill pressure and surface settlement can be found.

The backfill rate was estimated based on the ratio of the volume of grout used and the volume of the tail void. Figure 13 presents the backfill rate ($R_b$) used for the construction of tunnel LUO08. The rate mainly remained in the 1.3-1.8 range for the 1st drive tunnel, but it was lower for the 2nd drive tunnel (0.9 to 1.3 of $R_b$). It appears that both the amount of settlement and the average volume loss tended to be smaller in the 2nd drive tunnel than in the 1st one, and it is thus recommended that higher $R_b$ may not be able to reduce settlement and volume loss successfully, though it is presumed that the backfill grout should fill the tail void as quickly as possible and thus reduce both settlement and volume loss.

As explained above, $I_{im}$ was determined by the imbalance between the volume of spoil discharged and the volume of the materials inserted into the tunnel. The relationship between the surface settlement measured above the tunnel and $I_{im}$ is plotted in Fig. 14. Although much of data in the present agrees to the finding of Kao *et al*. (2009), further data (mainly ground heave with relative $I_{im}$ value) is desired or needed to support the results.

## 7. CONCLUSIONS

This paper presented a case record of tunnels bored in sand. Observations showed that driving the first bored tunnel induces up to 10 mm of surface settlement. The ground between twin tunnels appeared to be slightly affected by the construction of a second, adjacent tunnel but the accumulated maximum surface settlement remained at 12 mm. The ground became stable after 20 days once the shield had passed, and no consolidation settlement was observed.

The transverse surface settlement trough was also measured and discussed. Back-analyses indicated that excavation of the tunnels generated approximately volume loss of 0.38 to 0.53%. In addition, the driving of the 2nd tunnel did not induce significantly more movement than the 1st tunnel at some places, which is not consistent with the observations of Peck (1969). This discrepancy might be due to the improved operation of the shield-machine.

Volume loss was comparatively smaller than those in cases with the same conditions, which might be associated with the ground treatment, performance of the machine and workmanship.

The influences of the chamber pressure, pressure and volume of backfill grout as well as the imbalance of volume of materials discharged and inserted into the tunnel were explored. The ground movement might be caused by the imbalance of volume of material discharged and inserted into the tunnel but further data is desired to support the finding.

## ACKNOWLEDGEMENTS

The author would like to thank Maeda Construction Corporation and Mr. Teruo Sakai for providing the necessary data for this paper. The paper preparation by Mr. Hsien- Hui Yeh, Mr. Chao-Chun Kao, Mr. Di-Yang Tseng, Mr. Chin-Hao Chang, Mr. Fong-Chen Hsieh and Mr. Chien-Yuan Wang are appreciated. The author would also like to express his sincere appreciation to Mr. Anthony Umney and Mr. Nigel Schofield for their suggestions concerning the technical content of the paper and English correction.

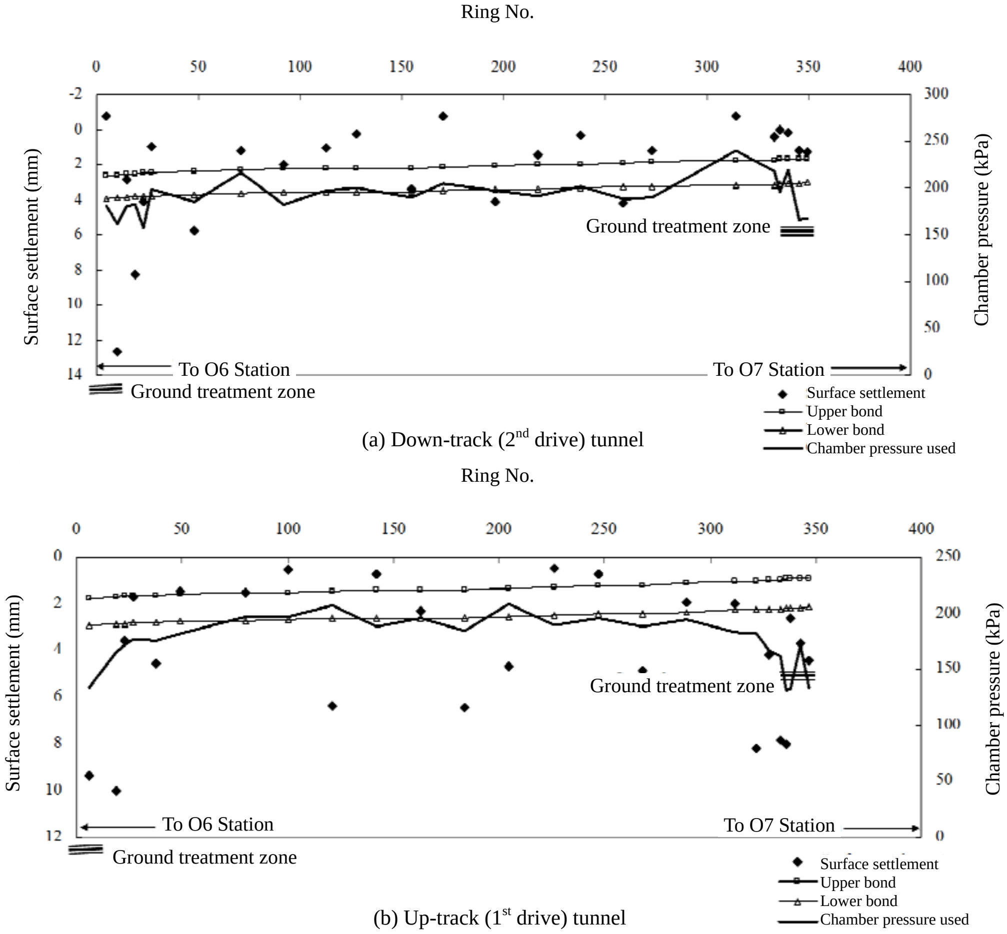



**Fig. 11 Correlation of chamber pressure and surface settlement for construction of single tunnel at LUO08**

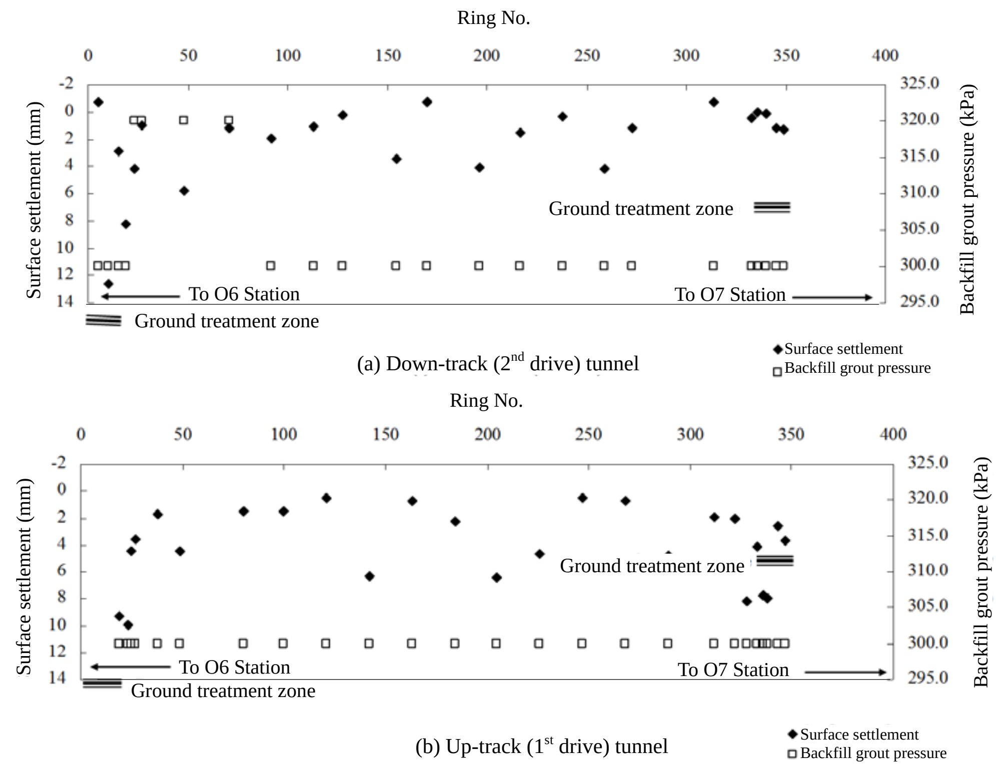



**Fig. 12 Correlation of backfill grout pressure and surface settlement for construction of single tunnel at LUO08**

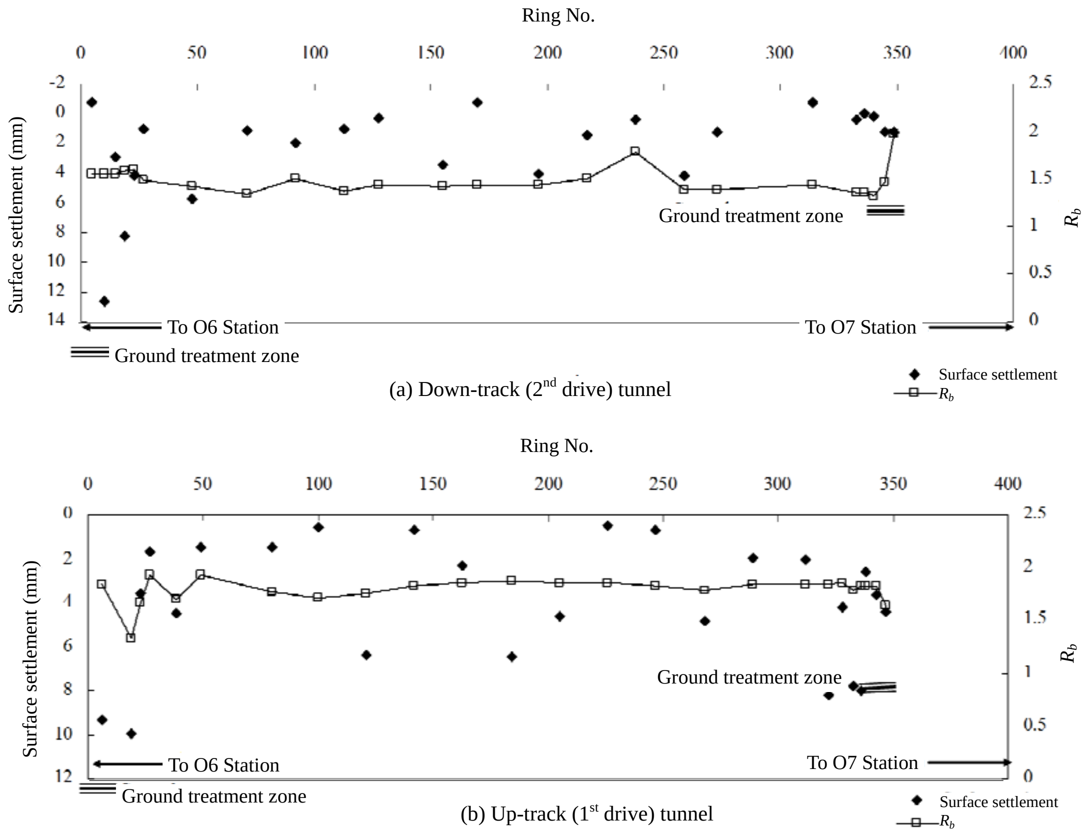



**Fig. 13 Correlation of backfill grout rate ($R_b$) and surface settlement for construction of single tunnel at LUO08**

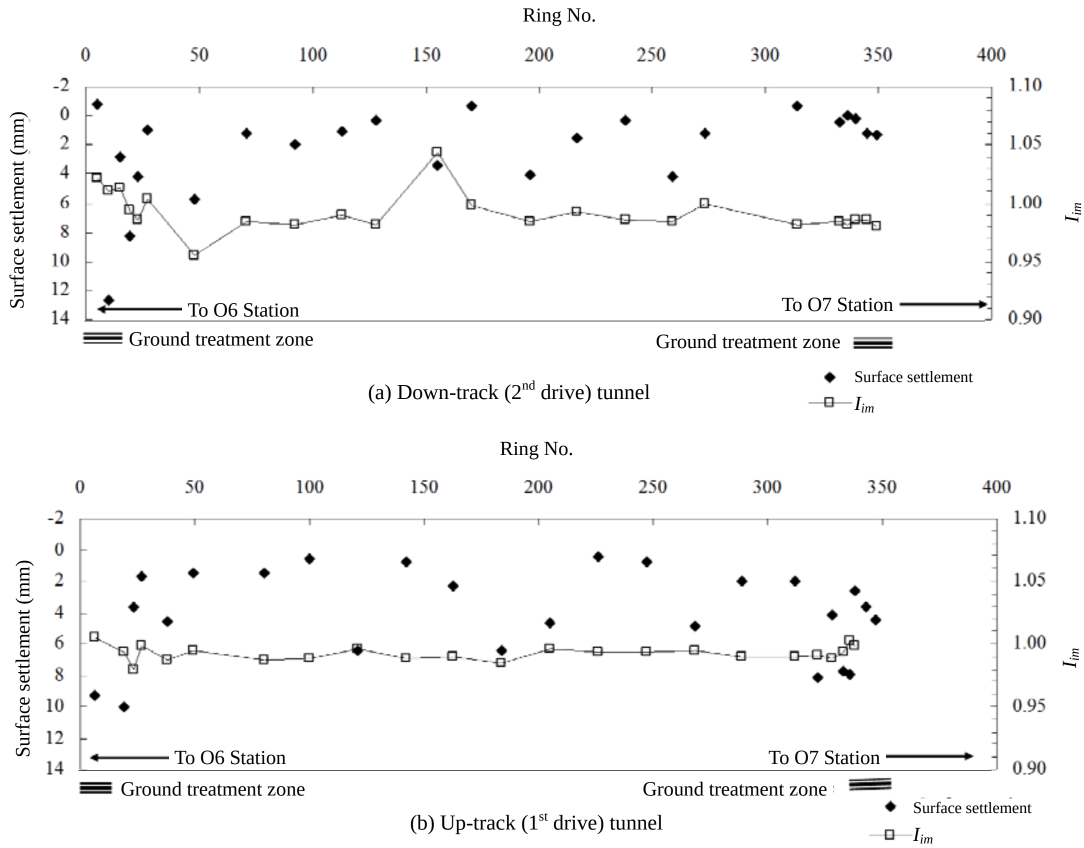



**Fig. 14 Correlation of $I_{im}$ and surface settlement for construction of single tunnel at LUO08**

## REFERENCES

Bhogal, S. (2005), "Quick decision." *Ground Engineering*, August issue, 24-25.

Fang, Y. S. and Chen, C. T. (1990), "Subsidence in Taipei basin due to shield tunnelling." *Proceedings of 10th Southeast Asian Geotechnical Conference*, 501-506.

Fang, Y. S., Lin, J. S., and Su, C. S. (1994), "An estimation of ground settlement due to shield tunneling by the Peck-Fujita Method." *Canadian Geotechnical Journal*, **31**(3), 431-443.

Hsiung, B. C. Benson and Lu, K. L. (2008), "Case record of a bored tunnel on Kaohsiung rapid transit system, Contract CR2." *Journal of GeoEngineering*, Taiwan Geotechnical Society, **3**(1), 33-40.

Hwang, R. N., Ju, D. H., Tsai, M. S., and Fang, Y. S. (1995), "Soft ground tunneling in Taiwan." *Proceedings of US/Taiwan Geotechnical Engineering Collaboration Workshop*, 13-16.

Kao, C. C., Chen, C. H., and Hwang, R. N. (2009), "Mechanism of ground settlements and heaves due to shield tunnelling." *Journal of GeoEngineering*, Taiwan Geotechnical Society, **4**(2), 63-72.

O'Reilly, M. O. and New, B. M. (1982), "Settlements above tunnels in the United Kingdom, their magnitude and prediction." *Proceedings of Tunnelling '82*, Brighton, 173-181.

Ou, C. Y., Hwang, R. N., and Lai, W. J. (1998), "Surface settlement during shield tunneling at CH218 in Taipei." *Canadian Geotechnical journal*, **35**(1), 159-168.

Peck, R. B. (1969), "Deep excavations and tunnelling in soft ground." *Proceedings, the 7th International Conference on Soil Mechanics and Foundation Engineering*, Mexico City, State-of-the-Art Volume, 225-290.

Shirlaw, J. N. and Boone, S. (2009), "Geotechnical engineering for TBM tunnelling in soft and mixed ground." *Geotechnical Engineering Journal*, SEAGS & AGSSEA, **40**(2), 117-126.

Wang, K. H. (1997), "Geotechnical characteristic and design of Kaohsiung Metro." *Seminar of Kaohsiung Construction and Underpinning* (in Chinese).