

COMPONENTS OF VOLUME LOSS INDUCED BY EPB TBM TUNNELLING IN SANDY SOILS – A CASE STUDY IN HO CHI MINH CITY VIETNAM

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Abstract: The 781m twin tunnel in line No 1 Ben Thanh – Suoi Tien was the first tunnels constructed by Earth Pressure Balance Tunnel Boring Machine (EPB TBM) in the urban area in Ho Chi Minh City, Vietnam. Field data on a surface settlement at three sections, measured during the construction period from May 2017 to June 2018, are used for back analyses on the development of surface settlement with the corresponding advancement of the EPB TBM. From there, the contributions of the main components of volume loss are determined which can be a useful reference for similar tunneling projects in the local area.

Keywords: Tunnelling; surface settlement; volume loss; case study.

Classification code: 11.2

Tóm tắt: 781 đường hầm đôi của tuyến số 1 Bến Thành – Suối Tiên là đường hầm đầu tiên được xây dựng bằng máy khoan hầm cân bằng áp lực đất (EPB TBM) trong khu vực đô thị Thành phố Hồ Chí Minh, Việt Nam. Các số liệu lún bề mặt đất ở ba mặt cắt, quan trắc trong quá trình thi công từ tháng 05 năm 2017 đến tháng 06 năm 2018, được sử dụng để phân tích ngược sự phát triển của lún bề mặt đất tương ứng với tiến trình thi công của EPB TBM. Từ đó, xác định được sự phân bố các thành phần chính gây ra thể tích đất mất, làm tài liệu tham khảo hữu ích cho các dự án thi công đường hầm ở khu vực.

Từ khóa: Đường hầm, lún bề mặt, thể tích đất mất, trường hợp nghiên cứu.

Mã phân loại: 11.2

1. Introduction

The total length of line No 1 Ben Thanh – Suoi Tien is 19.7 km which includes 781 m of twin tunnels that connect Ba Son station (chainage km 0+805) with Opera House station (chainage km 1+586). The depth of the two tunnels from the ground surface varies from 15.5 m to 28.4 m. The distance between the two tunnels varies from 6.0 m to 15.15 m. The external and internal diameters of the tunnel are 6.65 m and 6.05 m respectively.

During the twin tunnel excavation, monitoring works were carried out along the tunnel route to measure ground surface settlement. This paper will firstly present the

measurement data at chainages km 0+983, km 1+003, and km 1+403. From there, typical parameters of settlement trough including volume loss (V_L) and the trough width parameter (K) are determined. Then, longitudinal settlement is plotted concerning the advancement of the TBM to investigate the components of volume loss induced during the tunnel excavation.

2. Ground condition

Figure 1 illustrates the ground conditions at the three monitored sections and indicates the positions of the Eastbound (EB) and Westbound (WB) tunnels.

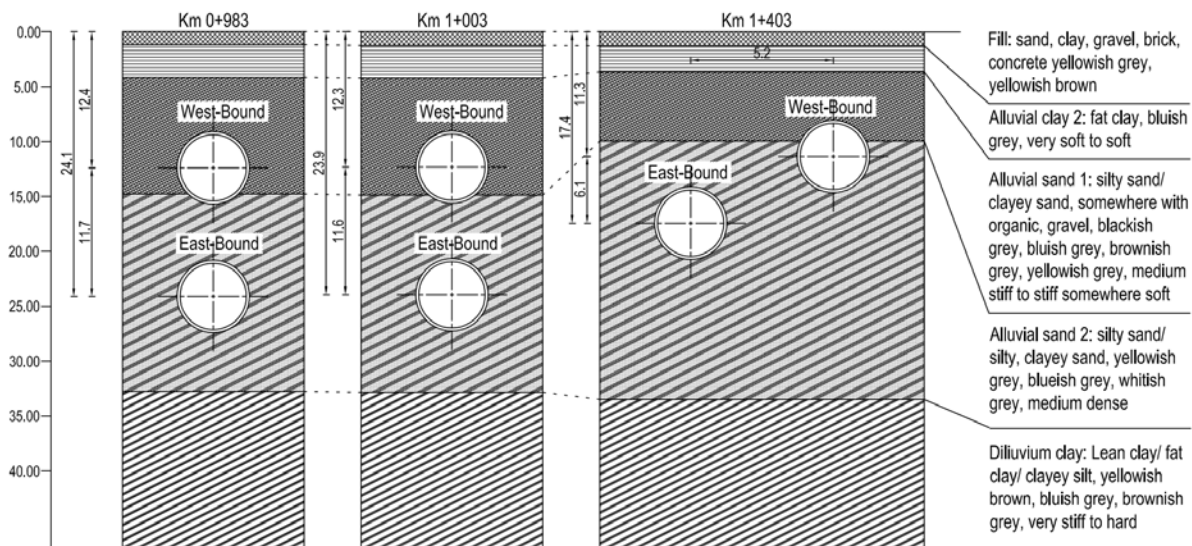


Figure 1. Cross section at km 0+980, km 1+003, km 1+403.

The soil at those sections from the ground surface comprises of: Fill layer, Alluvial clay, Alluvial sand, and Diluvium clay. The EB tunnel, which lies completely in the AS2 layer, was constructed first while the WB tunnel lies in AS1 and AS2 layers, was constructed later. Details of the layers AS1 and AS2 are provided below:

- AS1 layer has non-homogeneous to a homogeneous material. The silty content ratio decreases with depth and changes to fine sand with silt. The soil layer is encountered at all boreholes. The thickness varies from 3.2 m to 13 m;

- AS2 layer is lowermost in alluvium deposit and above hard clayey silt of Diluvium. The main component of this layer is medium-grained to coarse-grained sand. This sand layer is mainly medium dense to dense sand with occasional loose pockets. This sand layer encountered at all boreholes. The thickness varies from 16.9 m to 27.8 m.

3. Construction method

According to the ground condition along the tunnel route which is mainly alluvial sand, the Earth Pressure Balance Tunnel Boring Machine (EPB TBM) was chosen to construct the tunnels which are known for effective control of ground settlement for tunneling in sandy soils. The key feature of an EPB TBM is its provision of substantial support to the excavation face at all times which is important in minimizing ground movements. The

excavation process can be summarised as follow. The cutter head, powered by the drive motor, excavates soil in front of the TBM. The excavated soil passed into the pressurized chamber head which is immediately behind the cutter head. A key feature of the EPB TBM is the extraction of the soil from the pressurized chamber head by means of a screw conveyor, which is an Archimedian screw within a cylindrical steel casing (Mair, 2008). The EPB TBM in line No 1 Ben Thanh – Suoi Tien has an excavation diameter of 6.82 m and the diameter of the shield is 6.79 m. The length from excavation plate to tail is 8.5 m and the total length of the machine is 12.9 m (figure 2). There is a copy cutter in the cutter head that creates adequate space and reduces forces applied to the shield skin of the EPB TBM when it passes through a curve or changes the excavation direction. The tunnel lining segments are erected within the TBM tail skin by an erector arm. The precast concrete tunnel lining rings were formed of 5 segments plus a key piece which all had a thickness of 300 mm and a nominal length of 1.2 m. As the tail skin leaves the tunnel lining, grout is injected under high pressure to fill the annular void between the extrados of the tunnel lining and the excavated ground to minimize radial soil movements, one of the components causing ground settlement.

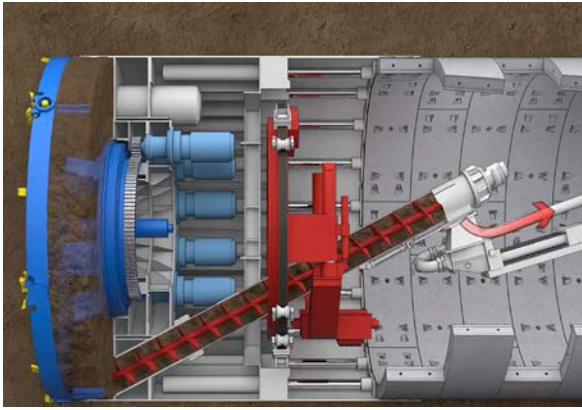


Figure 2. Details of EPB TBM.

4. Transverse and longitudinal ground surface settlement due to epb tmb tunnelling

4.1. Empirical transverse settlement trough

Base on previous researches such as Martos (1958), Peck (1969), O'Reilly and New (1982), Nyren (1998), Dimmock (2003), Wan et al (2017), Le and Taylor (2018), the transverse ground surface settlement trough induced by tunneling has a shape of an inverse Gaussian distribution curve. The equation of transverse settlement trough is described below:

$$S_T = S_{max} e^{\left(\frac{-y^2}{2i^2}\right)} \quad (1)$$

$$S_{max} = \frac{V_L \pi D^2}{i \sqrt{2\pi}} \quad (2)$$

Where: S_T is the surface settlement, S_{max} is the maximum settlement, y is the horizontal distance from the tunnel center-line, i is the horizontal distance from the tunnel center-line to the point of inflection of the settlement trough, D is the tunnel diameter, V_L is the volume loss (figure 3).

The volume of the surface settlement trough (per meter length), V_s , can be evaluated by integrating equation (1), (2) to give:

$$V_s = \sqrt{2\pi} \cdot i \cdot S_{max} \quad (3)$$

$$V_L = \frac{4V_s}{\pi D^2} \quad (4)$$

Many researchers have investigated similar relationships between settlement through width i and tunnel depth. O'Reilly and New (1982) showed that i is an approximately linear function of the tunnel depth, z_0 , and is broadly independent of the tunneling method

and tunnel diameter. They proposed a simple approximation relationship as below:

$$i = Kz_0 \quad (5)$$

Where K is a trough width parameter that depends mainly on the soil type. K value varies from 0.4 to 0.7 for tunnels in clays and 0.25 to 0.45 for tunnels in sand and gravels.

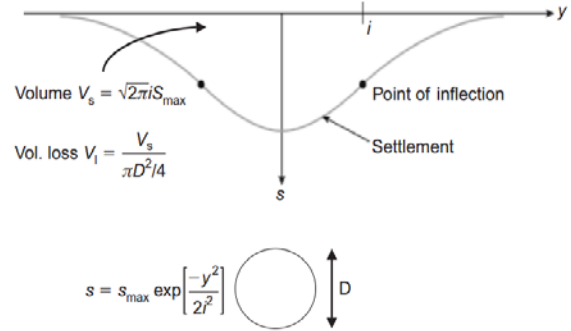


Figure 3. Transverse settlement trough [1].

4.2. Longitudinal settlement trough

In the longitudinal direction, the shape of the settlement trough is well represented by the cumulative probability function (O'Reilly & New 1982; Attewell & Woodman 1982).

$$S_L = S_{max} \Phi(x) \quad (6)$$

$$\Phi(x) = \frac{1}{i\sqrt{2\pi}} \int_{-\infty}^x e^{\frac{-x^2}{2i^2}} \quad (7)$$

Where x is the distance ahead of the tunnel face parallel to the tunnel axis, ix is the trough length parameter in a longitudinal direction, and $\Phi(x)$ is the cumulative probability function. For tunnels constructed in stiff clays without face support, the surface settlement directly above the tunnel face generally corresponds to about $0.5S_{max}$. However, for tunnels constructed in soft clays with face support, the surface settlement directly above the tunnel face tends to be considerably less than $0.5S_{max}$ (figure 4).

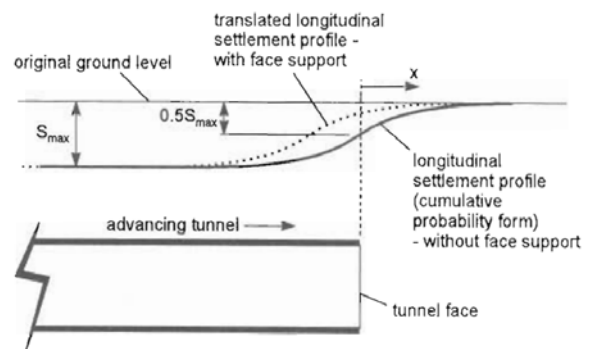


Figure 4. Longitudinal settlement trough [11].

4.3. Volume loss

The volume loss, V_L , is the amount of ground lost in the region close to the tunnel. The magnitude of volume loss defined in equations (3), depends on the type of ground, tunneling method, quality of workmanship which is difficult to predict. A common approach to estimate V_L value is to use reference data from other tunneling projects with similar soil conditions and tunnel construction techniques.

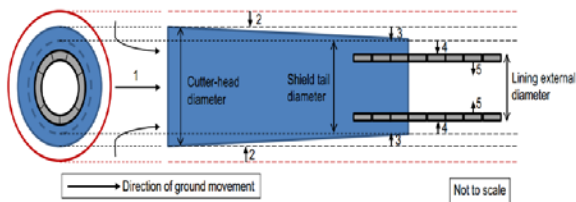


Figure 5. Components of volume loss in TBM tunneling [8].

Wan et al. (2017) suggested that short-term ground loss induced by EPB TBM excavation can be divided into five primary components:

Component 1 – Face movement: deformation of the ground towards the face resulting from stress relief. The ground movement at the front of the face due to the imbalance of any tunnel support pressure with the earth or water pressures at the tunnel face. This component can be very small if the face pressure is carefully controlled;

Component 2 – Over-cutting by a cutter head;

Component 3 – Shield body tapering;

Component 4 – Tail void closure: the existence of a gap between the tail skin of the shield and the lining means that will be a tendency for further radial ground movements in the gap;

Component 5 – Lining deformation.

In this case study, the EPB TBM was not tapered and the settlement measurements are short-term. Therefore, component 3 and long-term ground surface settlement are not considered.

4.4. The non-linear regression method

In order to determine the best-fit Gaussian curve, Jones & Clayton (2013)

suggested a non-linear regression method that varies both V_L and i or K . In this case, the “best-fit” Gaussian curve is found when the values of K and V_L provide the smallest sum of absolute errors (SAE). SAE is defined as the difference between the measured monitoring data and the empirical settlement at the same offset from the tunnel centerline, y . These errors are also known as “residuals” in regression analysis. The equation used to calculate SAE is expressed below:

$$SAE = \sum_{j=1}^n \left| \frac{V_s}{i\sqrt{2\pi}} e^{-\frac{y^2}{2i^2}} - S_j \right| \quad (8)$$

Where n is the number of monitoring points in the transverse direction and S_j is the corresponding empirical settlement value.

However, this method does not indicate the reliability and quality of the obtained values. Le et al (2019) suggested using a factor called the goodness of fit, G , to assess the reliability of the SAE method which is defined as follow:

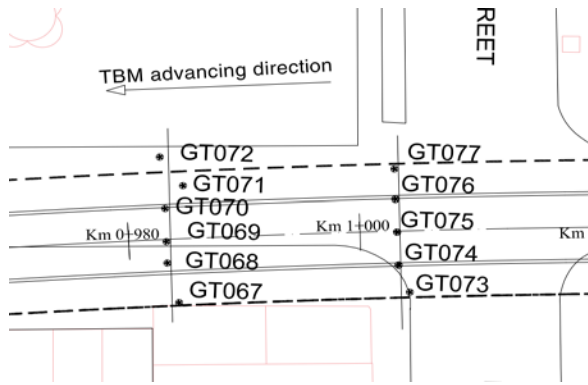
$$G = \left(1 - \frac{SAE}{|SoS|} \right) 100\% \quad (9)$$

Where SoS is the sum of the settlement. High values of G imply a good fit between the empirical and measured ground surface settlement troughs whereas low G indicates poor fit.

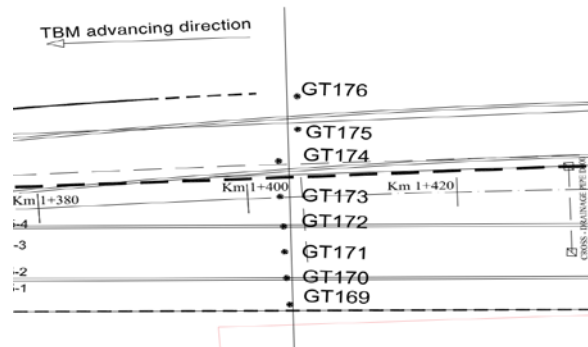
5. Results

5.1. Ground surface settlement monitoring

The ground surface settlement monitoring points were installed along the tunnel route and their locations are depicted in figure 6. Ground surface settlements were measured using precise leveling techniques once a day when TBM was within +100 m to +10 m from the measurement section and twice a day when the TBM was within +10 m to -40 m of the section. (“+” when TBM face was approaching the measure section and “-” when TBM passed the measured section).



(a) Monitoring points layout at km 0+983 and km 1+003.



(b) Monitoring points layout at km 1+403.

Figure 6. Ground surface monitoring layout.

5.2. Back-Analysis

5.2.1. Transverse settlement trough

The ground settlement monitoring results obtained at 3 chainages along the tunnel route (Figure 7a, 7b) show that the settlement

during EB tunnel construction with $S_{max} = -3.4\text{mm}$ is smaller than that in WB tunnel construction with $S_{max} = -26.2\text{mm}$.

In figures 7a and 7b, along with the field measurement data, the best-fit Gaussian curves, determined using the non-linear regression method with the Goodness of fit factor (tables 1 and 2), are also plotted.

Most G values were found greater than 60% which indicates that the Gaussian curves fit well with the measured data. Besides, some G values were smaller than 60% hence corresponding K and V_L values of these cases are not accurate and not provided in this paper.

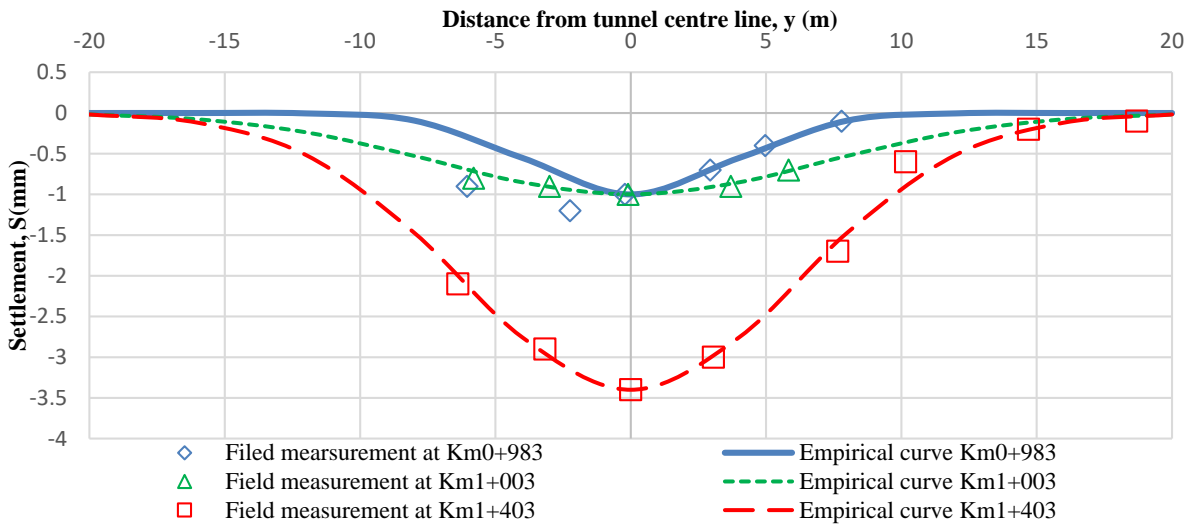
During the EB tunnel construction period, the tunnel lied in sand layer AS2, the K values were found to be within the range from 0.24 to 0.37, and V_L values were very small (less than 0.1% except at chainage Km1+403 with $V_L \text{ max} = 0.152$) (table 1). During WB tunnel construction, the tunnel depth was shallower than the EB tunnel with major part lied in silty sand layer AS1 at chainages Km0+983, Km1+003 and in AS2 at chainage Km1+403. The K values were found to be within the range from 0.30 to 0.41. The V_L values were larger than that for EB tunnel but still less than 1% (table 2).

Table 1. Values of K and V_L during EB tunnel construction.

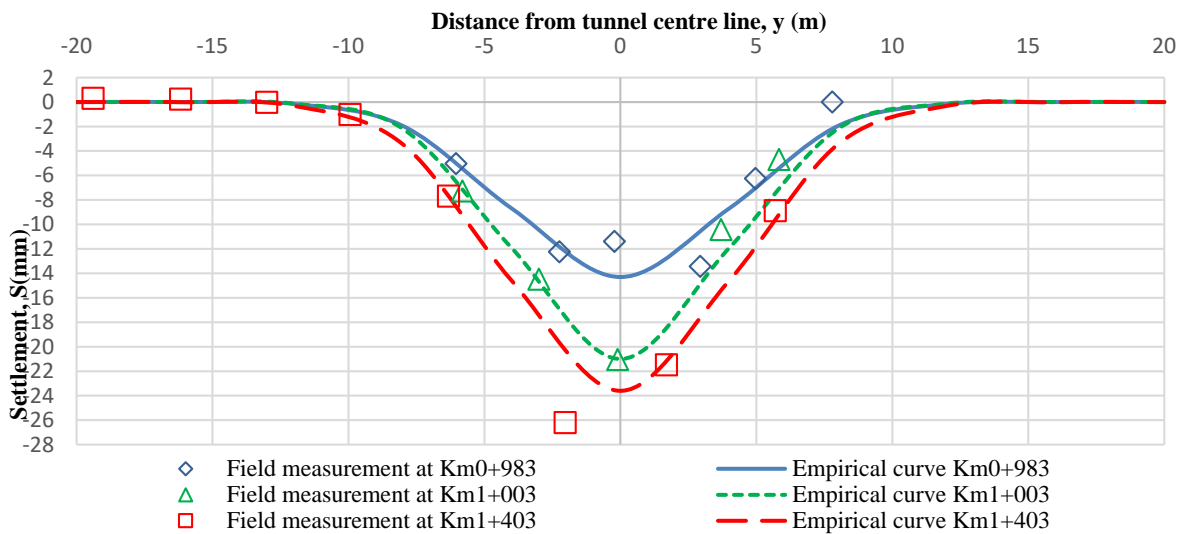
Chainage	Position of TBM	i	V_L	K	G
	(m)	(m)	(%)		(%)
Km0+983	+12.30	6.62	0.009	0.28	62.6
	-8.61	6.62	0.027	0.28	91.9
	-19.97	5.99	0.029	0.25	82.1
Km1+003	+10.45	5.77	0.020	0.24	87.5
	0.00	8.73	0.030	0.37	95.2
	-7.70	7.08	0.034	0.30	90.6
	-20.89	7.66	0.042	0.32	92.0
	-47.86	7.08	0.049	0.30	97.3
Km1+403	2.79	6.50	0.009	0.37	78.0
	-6.81	4.93	0.034	0.28	74.5
	-14.00	5.93	0.090	0.34	90.7
	-28.45	6.50	0.152	0.37	94.1
	-40.41	6.18	0.144	0.35	95.3

Table 2. Values of K and V_L during WB tunnel construction.

Chainage	Position of TBM	i	V_L	K	G
	(m)	(m)	(%)		(%)
Km0+983	-17.00	4.06	0.376	0.40	78.5
	-26.58	4.07	0.402	0.33	83.3
	-34.98	4.01	0.393	0.32	82.6
Km1+003	-10.58	3.66	0.344	0.30	90.7
	-19.00	3.64	0.502	0.30	88.3
	-27.40	3.68	0.523	0.30	87.7
	-46.58	3.76	0.542	0.31	86.9
Km1+403	-1.39	4.66	0.016	0.41	66.3
	-13.03	3.60	0.548	0.32	88.6
	-24.18	3.95	0.686	0.35	90.7
	-32.60	4.08	0.661	0.36	89.3



(a) Best-fit Gaussian curve with measured data at the end of the passage of EB tunnel construction.



(b) Best-fit Gaussian curve with measured data at the end of the passage of WB tunnel construction.

Figure 7. Transverse settlement troughs.

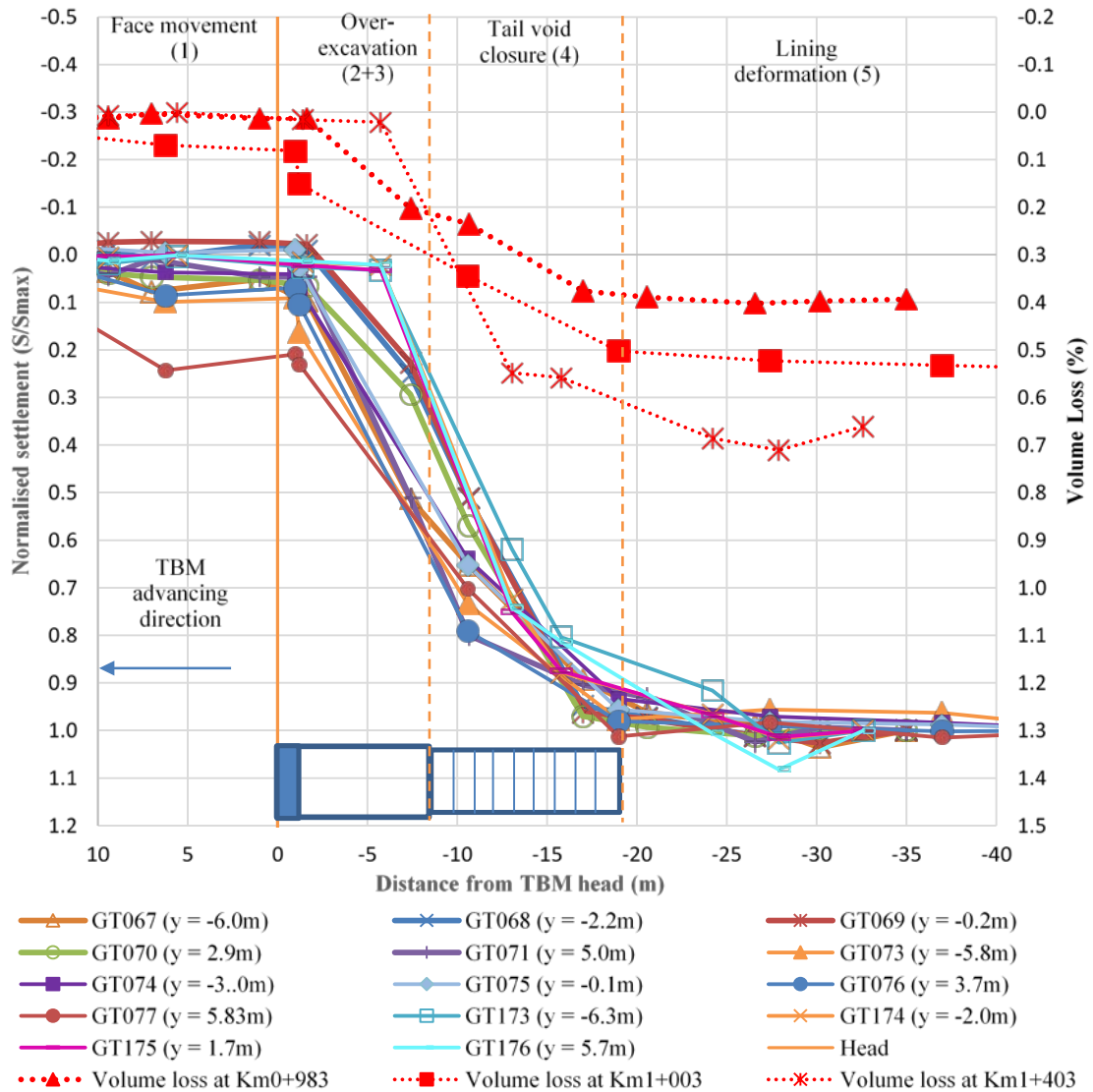


Figure 8. Longitudinal profiles of normalized surface settlement and volume loss during TBM driving.

5.2.2. Longitudinal surface settlement

In addition to the transverse settlement trough, the longitudinal settlement was also plotted in figures 8 to assess the contributions of different components of volume loss to ground surface settlement.

Before the TBM arrived at the measured chainages, ground surface settlement and VL values were very small (less than 0.1%), which means good support pressure in front of the TBM face was provided during the excavation hence the first component of volume loss was controlled well.

While TBM passed the measured sections, the VL values increased considerably. At Km0+983 and Km1+403, VL values increased from under 0.05% to

0.2% while the TBM advancing and continue increasing to 0.4% (Km0+983) and 0.7% (Km1+403) when TBM passed the monitoring a distance of 18m. Meanwhile, at Km1+003, VL values increased from under 0.1% to 0.3% while TBM advancing and became stable at 0.5% when TBM passed 18m behind the monitoring section.

Based on the VL contribution at 3 chainages, it indicates that the significant increase of VL and ground settlement are due to components 2 and 4 (over-cutting by cutter head and tail void closure). These components are the main contributors to the surface settlement.

6. Conclusion

Based on the back – analysis results from field measurement data during twin tunnel construction, the following observations can be made:

- During the twin tunnel construction, the first component of volume loss, caused by face movement, was very small and under 1% of total volume loss. This means good control of face support pressure was achieved;

- The main components of volume loss came from over-excavation and tail void closure in which volume loss of over-excavation accounts for from 28% to 47% and void closure accounts for from 42% to 57% of the total volume loss;

The volume loss of the fifth component, the lining deformation, was less than 15% □

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