

Interaction of longitudinal surface settlements for twin tunnels in shallow and soft soils: the case of Istanbul Metro

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Abstract Increasing demands on infrastructures increases the attention on shallow soft ground tunneling methods in urbanized areas. Especially, in metro tunnel excavations, it is important to control the surface settlements observed before and after excavation, which may cause damage to surface structures. To solve this problem, earth pressure balance machines (EPBMs) have widely been used throughout the world. This study focuses on surface settlement measurements, the interaction of twin tunnel surface settlement, and the relationship between shield parameters and surface settlement for parallel tunnels using EPBM shields in clay and sand soils. In this study, the tunnels were excavated using two EPBMs. The tunnels were 6.5 m in diameter, as twin tubes with a 14 m distance from center to center. The EPBM in the first tube followed about 100 m behind the other tube. Segmental lining with 1.4 m of length was employed as a final support. The results from this study showed that (1) the most important parameters for the maximum surface settlements are the face pressure and backfill; (2) in twin tunnel excavation with EPBM for longitudinal profile, the settlement rate reached its peak value when the shield came to the monitoring section and this peak value continued until the shield passed the monitoring section; (3) every shield affected the other tunnel's longitudinal surface settlement profile by approximately 35–36.8 %; (4) S_A , S_B and S_C values were found to be 38.0, 35.8 and 26.2 %, respectively for an EPBM, and (5) ensuring good construction quality is a very effective way to control face stability and minimize surface settlement.

Keywords Twin tunnel excavation · Surface settlement · EPBM · Interaction of settlements

Introduction

Unlike motorway tunnels, sewerage tunnels and other infrastructure tunnels, metro tunnels have generally been excavated as twin tunnels. In addition, metro tunnels have a shallow depth. Due to their shallow depth, metro tunnels have generally been constructed in soft soil. For example, independent of the construction method, all metro tunnels in Istanbul have been excavated as twin tunnels, at a shallow depth and generally in soft soils or weak rocks (Ocak 2008a, 2008b, 2009a, 2009b, Ocak and Bilgin 2010). A typical surface settlement basin shape resulting from twin tunnels is seen in Fig. 1.

In metro tunnel excavations, it is important to control surface settlements observed before and after excavation that may cause damage to the surface structures. Otherwise, the metro tunnel cannot perform the expected task and the advantages of the metro tunnel are lost (Ocak 2008a). Independent of the excavation method, the interaction between the twin tunnels should be examined and remedial precautions against any damage to existing structures taken prior to construction. Tunneling cost and project time substantially increase due to damage to structures for surface settlements that result above the tolerable limits. In the Otogar–Kirazli metro project, the damage to the environment that was caused by the EPBM excavation increased costs by 15.8 % and the project schedule by 29.3 % (Ocak 2009b).

The basic parameters affecting the ground deformations may be divided into three main groups (Table 1).

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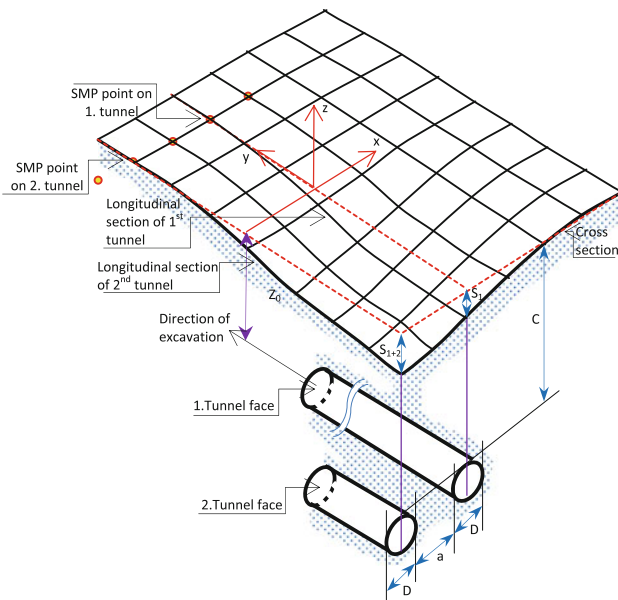


Fig. 1 Surface settlement basin induced by shallow twin tunnel excavation

Table 1 Main factors affecting the surface settlement

Category	Factors
Excavation and support method	Excavation method (NATM, TBM, EPBM, etc)
	Excavation type (full face or sequential mining)
	Support (anchoring, shotcrete, steel sets, lining, etc)
	Shield operation factors for EPBM (F_p , penetration rate, pitching angle, tail void grouting pressure, percent tail void grout filling, etc.)
Tunnel geometry	Worksite conditions
	Depth
	Diameter
	Number of tunnels
Ground properties	Distance between tunnels
	Elasticity modulus
	Unit weight
	Cohesion
	Friction angle
	Poisson's ratio
	Lateral earth pressure coefficient
Groundwater	
Permeability	

Increasing demands on infrastructures increase attention to shallow soft ground tunneling methods in urbanized areas. Many surface and sub-surface structures make underground construction work very delicate due to the influence of ground deformation, which should be definitely limited/controlled to acceptable levels (Ercelebi et al. 2010). For achieving this purpose, compared with

traditional tunnel construction techniques, the EPBM has been widely used in metro tunnel construction throughout the world. Recently, surface settlements in EPBM tunneling have been examined and discussed (Chou and Bobet 2002; Chen et al. 2011; Suwansawat 2006; Migliazza et al. 2009). However, the studies done about the field measurements for parallel tunnels in the literature are still insufficient to understand the interaction of surface settlement between two tunnels. There is no systematic field measurement for surface settlement and EPBM parameters conducted in the same site for parallel tunnels.

In this paper, the interaction of longitudinal surface settlements resulting from twin tunnel construction is studied. Extensive instrumentation records, consisting of systematic field measurement for longitudinal surface settlement at the same site for the parallel tunnels of the Otogar–Kirazli metro project, were used in this research. In addition to settlement data, important data pertaining to shield like face pressure (F_p) were used. The settlements were analyzed based on the field measurements and shield parameters.

The geology in the study area is composed of fill, sand, very dense sand, clay and hard clay, starting from the surface. The underground water table starts at about 4–5 m below the surface. The tunnel depth varies between 8.8 and 43.2 m in the study area.

General information

General information about the project

The first construction phase of the Istanbul Metro line began in 1992 and was opened to the public in 2000. This line is being gradually extended and additional lines are being constructed in other locations. One of these metro lines is the twin line between Otogar and Kirazli, of 5.77 km. The metro line consists of a 3.87 km tunnel, a 0.62 km cut and cover station and 1.28 km at the grade crossing. The excavation of this section began in May 2006 and was completed in June 2008 (Fig. 2) (Ocak 2009b).

General information about EPBMs and tunnel geometry

Two EPBMs were used for the excavation of the tunnels (Fig. 3), a Herrenknecht EPBM for the left tube and a Lovat EPBM for the right tube. One excavation was kept approximately 100 m behind the other one. Some of the technical features of the machines are summarized in Table 2 (Ocak 2009b).

Since the excavated ground bears water and includes stability problems, the excavation chamber was pressurized

Fig. 2 Main route of Otogar–Kirazlı 1 Metro line and location

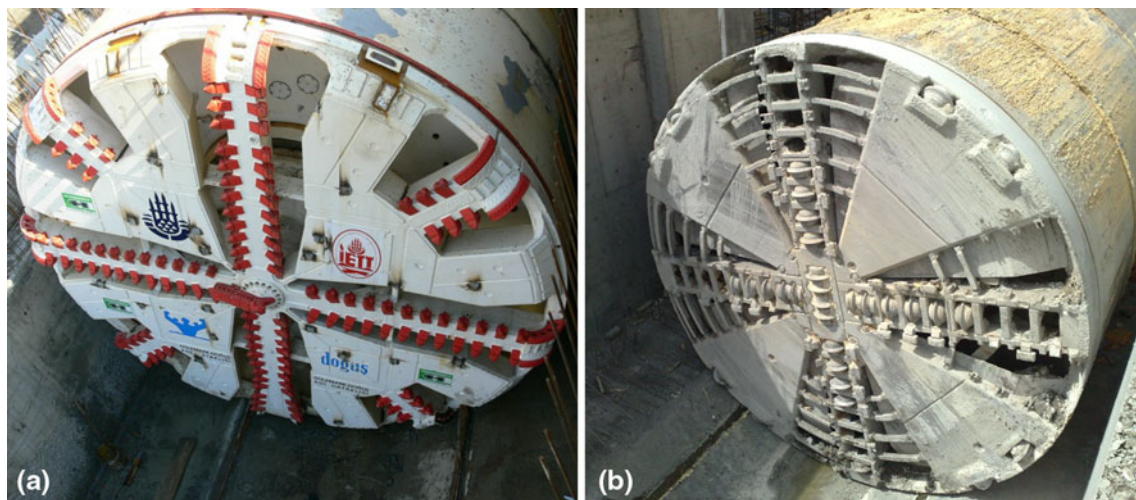


Fig. 3 EPBMs used in the project: **a** left line, Herrenknecht; **b** right line, Lovat

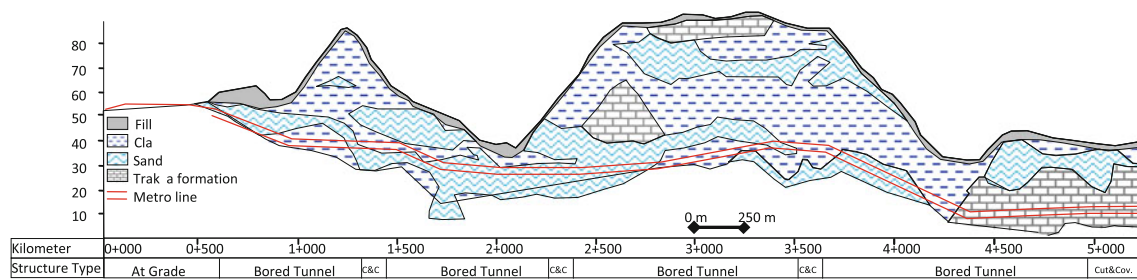
up to 300 kPa and conditioned by applying water, foam, bentonite and polymers through the injection ports. The chamber pressure was continuously monitored by pressure sensors inside the chamber and auger. An installation of a segment ring of 1.4 m in length (inner diameter of 5.7 m and outer diameter of 6.3 m) and 30 cm in thickness was implemented with a wing-type vacuum erector. The ring was configured as five segments plus a key segment. After installation of the ring, the excavation restarted and the gap between the segment outer perimeter and excavated tunnel perimeter was grouted up to 300 kPa of pressure through the grout channels in the trailing shield (Ocak 2009b).

Site geology

The study area is located between the Otogar and Kirazlı 1 stations in Istanbul (Fig. 2). The geology of the study area is given in Fig. 4 (Ocak 2009b). The relevant geotechnical properties of the layers are summarized in Table 3. The Gungoren formation of Miocene age was found in the study area. The fill layer consisted of sand, clay, gravel and some pieces of masonry. The sand layer, brown at the upper levels and greenish yellow in color at the lower levels, consists of clay, silt and mica. The very dense sand is greenish yellow and contains mica. The clay layer is

Table 2 Technical features of the EPBMs (Ocak 2009b)

	Herrenknecht (left line)	Lovat (right line)
Excavation diameter (m)	6.500	6.564
External diameter (m)	6.30	6.30
Internal diameter (m)	5.70	5.70
Segment thickness (m)	0.30	0.30
Average segment length (m)	1.40	1.40
Configuration of segment	6 (5 + 1 keystone)	6 (5 + 1 keystone)
Shield outside diameter (m)	6.45	6.52
Cutter head rotational speed (rpm)	0–2.5	0–6.0
Total installed power (kW)	1,100	1,622
Face pressure (kPa)	300	400
Cutter head type	Mixed ground	Mixed ground
Cutter head power (kW)	630	900
Maximum torque (tm)	435 (2.5 rpm)	445 (1.9 rpm)
Maximum thrust (kN)	35,200	54,000
Grout output	Grouting the trailing shield	Grouting the trailing shield

**Fig. 4** Geology of the study area**Table 3** Geotechnical properties of the study area

Strata	γ	E	c	n	$\varphi(^{\circ})$	W	K	SPT
Fill	18.0	5	1	0.30	10	–	–	10
Sand	18.3	25	1	0.25	35	–	10^{-5} – 10^{-4}	40
Very dense sand	18.5	30	1	0.30	30	31	10^{-7} – 10^{-6}	45
Clay (Gungoren fr.)	16.5	20	20	0.35	14	–	10^{-9} – 10^{-8}	60
Hard clay (Gungoren fr.)	17.2	28	25	0.40	20	35	10^{-11} – 10^{-9}	70

γ unit weight, E modulus of elasticity, c cohesion, n Poisson ratio, φ internal friction angle, W water content, K permeability, SPT standard penetration test

grayish green in color and includes gravel and sand. The base layer of the tunnel consists of sand and dark green hard clay containing shell. The underground water table is variable, but is generally located 4–5 m below the surface.

Construction parameters of EPBMs

While all the EPBMs were excavated through the tunnel route, a lot of parameters regarding earth pressure balance (EPB) process were collected (Table 4). The F_p , the most

important parameter for EPB tunneling, changes from 0.5 bar to 2.7 bar for both EPBMs; the average values were 1.63 bar for Lovat and 1.13 bar for Herrenknecht, respectively. Another important parameter affecting surface settlement is the amount of tail grouting. This parameter changed from 4 to 6.5 m³/lining for both EPBMs; the average was a 4.47 m³/lining for Lovat and a 4.14 m³/lining for Herrenknecht, respectively. The tail void was a 2.813 and a 3.732 m³/lining for Lovat and Herrenknecht, respectively. Therefore, the grouting ratio (the ratio

Table 4 Some important parameters pertain to EPBMs during excavation

	Lovat (RL)			Herrenknecht (LL)		
	Min.	Max.	Mean	Min.	Max.	Mean
Face pressure (bar)	0.7	1.9	1.63	0.5	2.7	1.13
Advance speed (mm/min)	0	100	46.8	0	100	46.7
Excavation time per lining (min)	14	140	46.3	14	280	37.7
Cutter head operating pressure(bar)	180	395	344.8	63	309	172.1
Cutter head rotational speed (rpm)	1.4	2.2	1.96	0.6	1.8	1.23
Screw conveyor rotation speed (rpm)	8	16	14.1	8	18	16.3
Screw conveyor torque (kNm)	90	130	99.4	80	180	96.2
Excavated material per lining (carriage)	5	6	5.54	5	6	5.55
Amount of tail grouting per lining (m ³)	4	6.5	4.47	3.5	6.5	4.14
Amount of foam used (lt)	20	220	82.5	10	230	46.9

Table 5 Content of grouting material used as backfill

Material type	Amount (kg/m ³)
Water	220
Cement	160
Ash	300
Natural sand	1200
Additive 1	5
Additive 2	3
Bentonite (with water)	43.5

between the volume of grouting material and the volume of tail void) changed from 142 to 213 % for Lovat, and from 94 % to 174 % for Herrenknecht. The content of the grouting material used as a backfill is presented in Table 5.

Surface settlement measurements on the surface

Contractors performed surface settlements with intervals of approximately 20–30 m, depending on building situations on the surface. For readings of surface settlements, surface monitoring points (SMPs) were installed at suitable points on the surface. The surface settlement measurement readings started before the excavation at that section and continued up to the allowed limits. The accuracy of SMP measurements was typically 0.025 mm per meter for precise leveling. Generally, the surface settlement measurements are performed at five points on the surface including both tunnel sections in Istanbul Metro studies (Fig. 5).

Investigation of longitudinal surface settlement profile

The main source of settlements induced by shield tunneling can be divided into four main factors (ITA/AITES 2007):

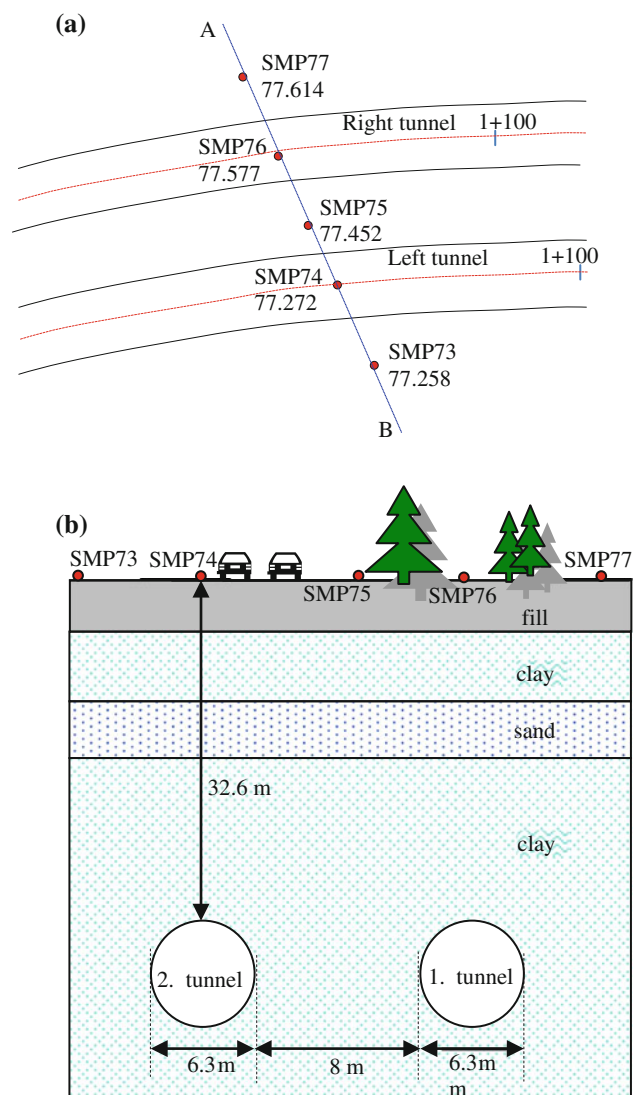


Fig. 5 Typical SMP layout above tunnels. **a** Plan view **b** A–B section

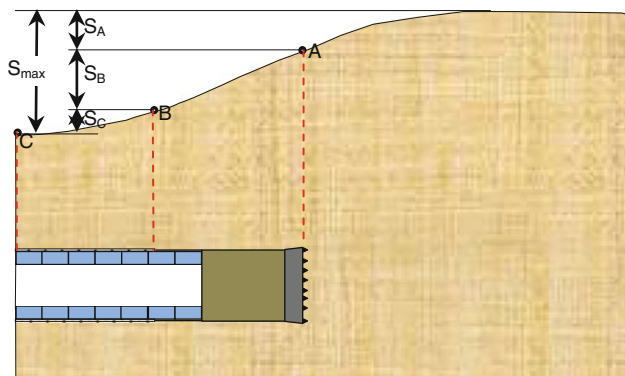


Fig. 6 A typical longitudinal surface settlement profile along a shield

- settlements ahead and above the face,
- settlements along the shield,
- settlements at the shield tail skin,
- settlements due to liner deformations.

A typical shape of a twin tunnel surface settlement is given in Fig. 1. The evolution of the longitudinal profile of the surface settlement in a TBM/EPBM tunnel was previously investigated by various researchers (Pantet 1991; Mroueh and Shahrouh 2008; ITA/AITES 2007). However, these investigations could not encompass the effect of the interactions of the twin tunnels. A typical longitudinal surface settlement profile occurring along a shield is shown in Fig. 6. As seen from Fig. 6, the surface settlement occurring during the excavation process can be divided into three parts (ITA/AITES 2007):

- settlement on A point (S_A): observed by the face intake,
- settlement on B point (S_B): observed along the shield,
- settlement on C point (S_C): observed at the tail skin (Fig. 6).

The important parameters for SMP and EPBMs used in this research are reported in Tables 6 and 7. The SMPs in Tables 6 and 7 are on the first tunnel (right line, RL) and on the second tunnel (left line, LL), respectively. Because of the similarities in the longitudinal surface settlement, only six of the SMP graphs are given in Figs. 7 and 8. While the graphs in Fig. 7 are based on the data in Table 6, those in Fig. 8 are based on the data in Table 7 (on the second tunnel). Both the first tunnel SMP and second tunnel SMPs are situated exactly along the longitudinal axis. The tunnel cover depth (C), rate of tunnel cover depth to tunnel diameter (C/D) and average F_p applied during excavation below the monitoring point (F_p) are given in Figs. 7 and 8. All figures given in Figs. 7 and 8 are aligned according to C/D values which change from 1.35 to 4.97 and from 1.12 to 4.97 for the first tunnel and second tunnel, respectively.

During the first and second shield advancement for the first tunnel (Fig. 1), the variations in surface settlements

Table 6 Study points' properties on the right line (first tunnel)

No.	SMP no.	Km	Lithology	Depth of tunnel cover (C)	Water table level (m)	Rate of C/D	SPT	Face pressure (F_p) (bar)	First EPBM S_A	First EPBM S_B	First EPBM S_C	Second EPBM S_A	Second EPBM S_B	Second EPBM S_C
1	SMP01	0 + 754.56	Hard sand	11.4	0	1.74	>50	0.00	0.6	0.7	1.0	1.3	-0.3	-0.9
2	SMP02	0 + 759.57	Hard sand	11.6	0	1.77	>50	0.00	-4.0	-6.3	-10.6	-11.8	-12.6	-14.5
3	SMP03	0 + 768.16	Hard sand	11.9	0	1.81	>50	0.87	-4.4	-10.5	-13.6	-15.5	-17.1	-18.7
4	SMP11	0 + 842.42	Hard sand	9.5	0	1.45	>50	1.50	-10.5	-22.8	-32.1	-39.4	-42.3	-49.4
5	SMP12	0 + 847.47	Hard sand	9.1	2	1.39	>50	1.60	-6.0	-11.0	-17.3	-23.0	-25.0	-31.1
6	SMP28	0 + 869.34	Hard sand	8.8	2	1.35	>50	1.40	-16.2	-30.9	-37.3	-40.5	-43.1	-46.1
7	SMP29	0 + 875.11	Hard sand	8.9	2	1.35	>50	1.40	-16.5	-21.0	-29.3	-50.6	-53.5	-59.0
8	SMP35	0 + 903.91	Clay + sand	10.5	3	1.60	45	1.40	-1.6	-5.0	-8.3	-9.0	-11.9	-14.3
9	SMP49	0 + 950.02	Clay	13.1	4	2.00	33	1.40	-4.3	-8.9	-10.0	-11.1	-12.5	-14.3
10	SMP59	1 + 016.00	Hard clay	19.7	5	3.00	40	1.60	-2.1	-4.1	-4.8	-5.9	-7.0	-8.0
11	SMP71 ^a	1 + 074.60	Hard clay	27.1	6	4.13	>50	1.40	NA	NA	NA	-0.3	-1.7	-2.1
12	SMP76	1 + 126.54	Hard clay	32.6	12	4.97	>50	1.50	0.2	0.3	-3.7	-6.3	-6.7	-6.9
13	SMP81 ^a	1 + 175.43	Clay + sand	37.9	14	5.77	>50	1.57	NA	-13.9	-45.7	NA	-50.4	-55.1
14	SMP87 ^a	1 + 241.87	Clay + sand	43.2	11	6.59	>50	1.30	NA	NA	NA	10.5	NA	10.5

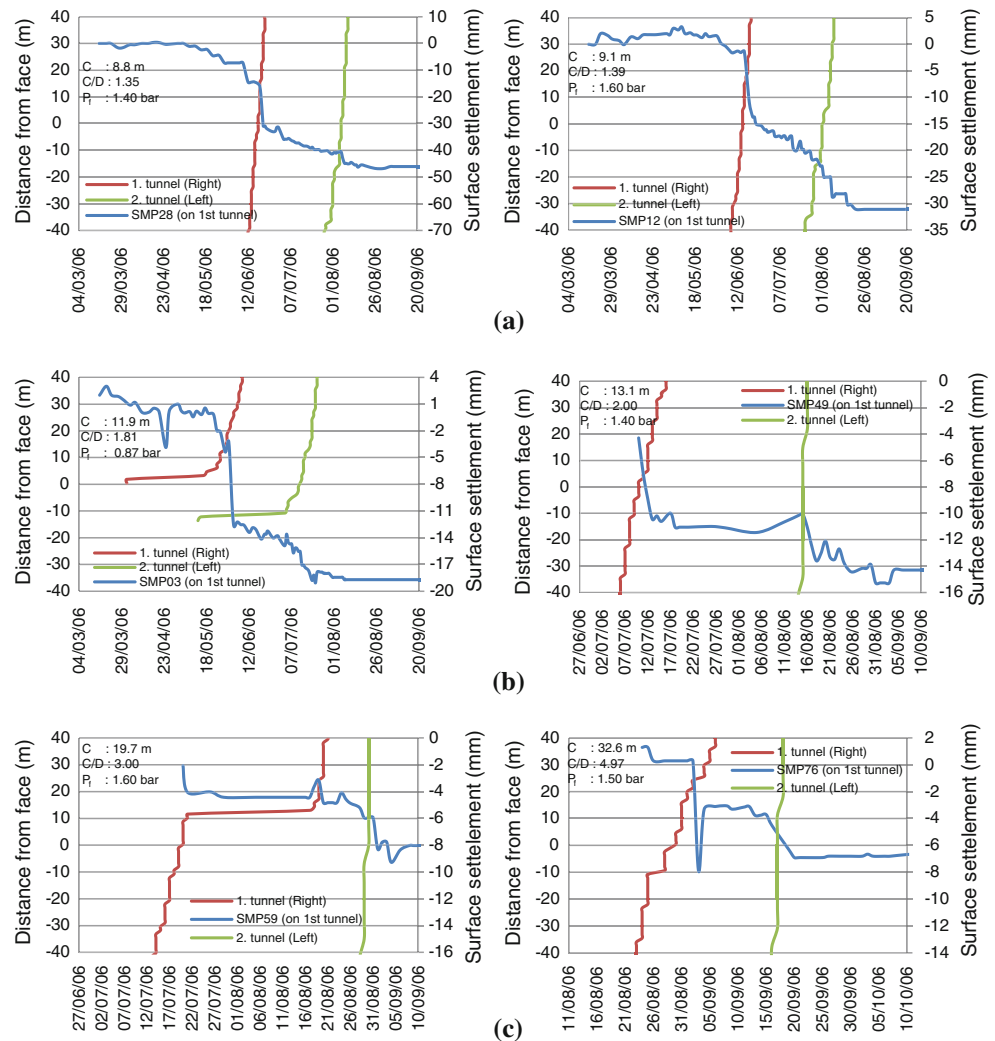
^a Monitoring is not read on time, so these points are excluded

Table 7 Study points' properties on the right line (second tunnel)

No.	SMP no.	Km	Lithology	Depth of tunnel cover (C)	Water table level (m)	Rate of C/D	SPT	Face pressure (F_p) (bar)	First EPBM S_A	First EPBM S_B	First EPBM S_C	Second EPBM S_A	Second EPBM S_B	Second EPBM S_C
1	SMP09	0 + 787.66	Hard sand	10.3	0	1.59	>50	1.20	-12.1	-15.2	-29.2	-35.8	-50.9	-63.1
2	SMP10	0 + 813.76	Hard sand	6.8	0	1.05	>50	0.87	0.8	1.0	0.8	-5.9	-13.9	-14.1
3	SMP17	0 + 835.82	Hard sand	7.3	0	1.12	>50	1.20	-10.9	-14.8	-23.5	-27.3	-47.0	-59.1
4	SMP18	0 + 841.39	Hard sand	7.7	0	1.18	>50	1.00	-10.6	-13.7	-21.1	-33.2	-47.4	-54.9
5	SMP19	0 + 846.42	Hard sand	7.8	0	1.20	>50	1.25	-2.0	-4.7	-15.0	-23.4	-45.1	-51.9
6	SMP22	0 + 861.14	Hard sand	8.5	2	1.30	>50	1.07	-3.7	-4.9	-21.8	-31.8	-54.3	-62.0
7	SMP21	0 + 855.58	Hard sand	8.2	1	1.26	>50	0.90	-6.1	-8.7	-20.6	-34.2	-49.4	-54.5
8	SMP23	0 + 867.39	Hard sand	8.8	2	1.35	>50	1.83	-4.5	-6.7	-26.9	-38.6	-53.4	-56.9
9	SMP25	0 + 880.27	Hard sand	9.3	3	1.43	>50	1.77	-1.2	-7.8	-8.8	-10.6	-27.4	-27.9
10	SMP38	0 + 907.69	Clay + sand	10.7	4	1.64	45	1.55	-0.3	-1.9	-5.2	-8.4	-11.0	-11.8
11	SMP50	0 + 947.57	Clay	13.0	4	2.01	33	2.20	-2.8	-3.9	-4.9	-11.1	-13.9	-15.9
12	SMP57	1 + 004.46	Clay	19.4	5	2.98	43	2.45	NA	-0.7	-3.1	-5.3	-9.1	-10.5
13	SMP66 ^a	1 + 066.57	Hard clay	26.9	6	4.14	40	1.60	NA	NA	NA	-2.3	-4.7	-7.1
14	SMP74	1 + 121.48	Hard clay	32.3	12	4.97	>50	1.80	-0.8	-0.8	-2.4	-6.1	-8.3	-9.9
15	SMP79 ^a	1 + 173.00	Clay + sand	37.8	14	5.81	>50	1.60	NA	-1.6	-1.7	NA	-6.7	-7.0
16	SMP85 ^a	1 + 243.02	Clay + sand	43.2	11	6.65	>50	1.80	NA	NA	NA	-0.2	-0.2	-0.2

^a Monitoring is not read on time, so these points are excluded

Fig. 7 Interaction of surface settlements during excavation of the two EPBMs



measured on six points are shown in Fig. 7. The surface settlements during the first and second shield advancement have similar trends. The surface started to settle when the distance between the first shield and the monitoring section was approximately less than -20 m (about $3D$). At some points (SMP12 and SMP03), the surface showed a slight upheaval when there was a close distance between the first shield and the monitoring section, as seen in Fig. 7a and b. The maximum upheaval was 3.3 mm in SMP12 (Fig. 7a). As expected, the peak of the settlement rate occurred when the first shield reached to monitoring section. This peak value continued to rise until the shield passed the monitoring section. After the shield had passed through the monitoring section by approximately 20 – 30 m, the surface settlement partly stabilized. It can be concluded that, in clay and sand soil, most of the settlement occurred while the cutter advanced from approximately -20 m before the monitoring section to 20 m past the monitoring section, and that subsequent surface settlement due to soil consolidation after the cutter advanced about 20 m through the

monitoring section was relatively small. After the first shield operation for the first tunnel, the second shield arrived in the monitoring section in the second tunnel. When the second shield arrived at the monitoring section, the surface started to settle again. However, this settlement effect was smaller than the first shield. On average, the second shield had a 35% effect on the first tunnel in this study. After the second shield passed through the monitoring section by about 20 – 30 m, the surface settlement on the first tunnel stabilized. The distribution of the two shields' S_A , S_B and S_C values for the first tunnel is presented in Table 8.

During the first and second shield advancement for the second tunnel, the variations in the surface settlements measured at six points are shown in Fig. 8. The surface started to settle, just as in the first tunnel, when the distance between the first shield and the monitoring section was approximately less than -20 m (about $3D$). There was no important upheaval during advancement of the first shield. The settlement rate reached an important value when the

Fig. 8 Interaction of surface settlements during excavation of the two EPBMs

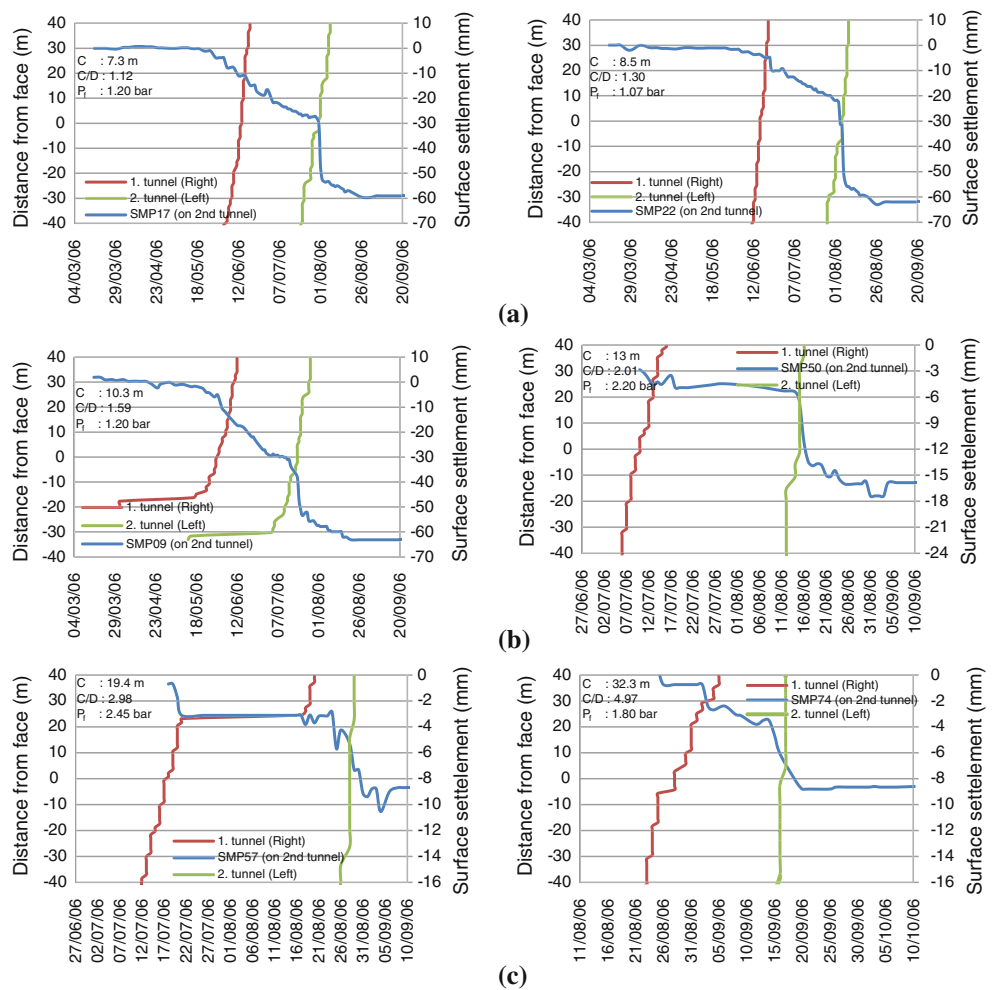


Table 8 Distribution of two shields’ S_A , S_B and S_C values for the first tunnel

	Mean	Cumulative
First shield S_A (%)	24.7	24.7
First shield S_B (%)	23.3	48
First shield S_C (%)	17	65
Second shield S_A (%)	13.4	78.4
Second shield S_B (%)	9	87.4
Second shield S_C (%)	12.6	100

Table 9 Distribution of two shields’ S_A , S_B and S_C values for the second tunnel

	Mean	Cumulative
First shield S_A (%)	10.8	10.8
First shield S_B (%)	7	17.8
First shield S_C (%)	19	36.8
Second shield S_A (%)	20.6	57.4
Second shield S_B (%)	30.7	88
Second shield S_C (%)	12	100

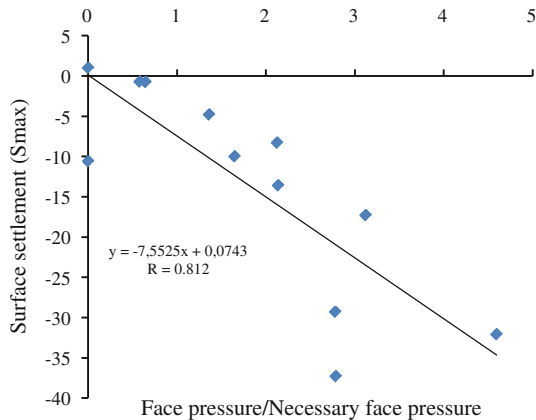
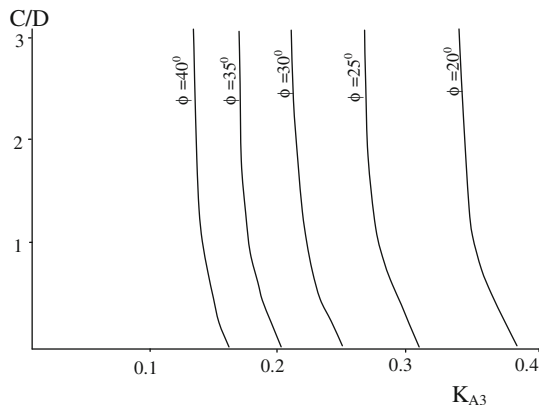
first shield came to the monitoring section. This settlement value continued to rise until the shield passed the monitoring section. However, on the second tunnel, the first shield had a little effect, 36.8 %. After the first shield had passed through the monitoring section, by about 20–30 m, the surface settlement stabilized. The main important surface settlement occurred when the second shield came to a monitoring point. Due to the disturbance of soil from the first shield, when the second shield arrived at a monitoring point, a very big surface settlement occurred on the second

tunnel. After the second shield passed through the monitoring section, by about 20–30 m, the surface settlement on the second tunnel stabilized. The distribution of the two shields’ S_A , S_B and S_C values for the second tunnel is presented in Table 9.

The magnitude of surface settlement was found to highly depend on the operational parameters, such as the F_p used to operate EPB shields. As can be seen from Figs. 7 and 8, at low C/D ratios at close F_p high surface settlements occurred (Figs. 7a and 8a). If the C/D ratios

Table 10 Distribution of surface settlement along the longitudinal axis with EPBM according to various literature

Source	S_A (%)	S_B (%)	S_C (%)
Pantet 1991	27	48	25
ITA/AITES 2007	10–20	40–50	30–40
Mroueh and Shahrour 2008	46	31	23
This study	38.0	35.8	26.2

**Fig. 9** Correlation between S_{max} and F_p/NF_p **Fig. 10** Coefficient of K_{A3} (Jancsecz and Steiner 1994)

increased, surface settlements decreased (Figs. 7b and 8b). But at low F_p at the same C/D ratios, high surface settlements occurred (Fig. 8b). At high C/D ratios at close F_p , a little surface settlement occurred (Figs. 7c and 8c).

There are different opinions with regard to S_A , S_B and S_C for only one shield in the literature. These percentage values from literature are given in Table 10. As seen from Table 10, the S_A , S_B and S_C values were found to be 38.0, 35.8 and 26.2 %, respectively (the surface settlement values caused by the second shield were eliminated from the measured results).

This study also showed that F_p was a very important parameter affecting the face stability. The change in the surface settlement versus face pressure/necessary face pressure (NF_p) is given in Fig. 9. As seen from Fig. 9, if F_p/NF_p ratio is close to one, a little surface settlement occurs. If this ratio rises, the surface settlement tends to rise. NF_p is computed in a blow formula:

$$P_{min} = K_{A3} \cdot 3\sigma_v + P_w \text{ (Jancsecz and Steiner 1994).}$$

where P_{min} is the necessary minimum face pressure (NF_p) for a stable face, K_{A3} is a coefficient which can be obtained with Fig. 10, σ_v is the vertical soil load and P_w is the water table load.

Conclusions

Thirty longitudinal sections consisting of a lot of SMP monitoring with EPBM tunneling in sand, hard sand, clay and hard clay, some of them below the water table and others above the water table, were used to determine the interactions of the longitudinal surface settlement profiles in shallow twin tunnels. The following conclusions are obtained:

- Two of the most important parameters for the maximum surface settlements are the F_p and backfill parameters.
- Good construction quality is very effective in controlling the face stability and minimizing surface settlement.
- In the twin tunnel excavation with EPBM for a longitudinal profile, the settlement rate reached its peak value when the first shield came to the monitoring section for the first tunnel. This peak value continued until the shield passed the monitoring section. After the shield passed through the monitoring section, by about 20–30 m (about 3D), the surface settlement substantially stabilized.
- The second shield's settlement effect on the first tunnel is less than that of the first shield. On average, the second shield has a 35 % effect on the first tunnel for a longitudinal profile.
- For the second tunnel settlement, the first shield had a slight effect similar to that of the first tunnel settlement. This had a 36.8 % influence on the second tunnel.
- In this study, S_A , S_B and S_C values were found to be 38.0, 35.8 and 26.2 %, respectively for an EPBM (surface settlement values caused by the second shield were eliminated from the measured results).

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