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The effect of back-fill grout characteristics on long-term ground settlement induced by shield tunneling

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ABSTRACT
A 10 km long tunnel of Tehran Metro Line 7 was excavated by a 9.164 m diameter EPB-TBM through an old congested part of the city where ground settlement is one of the main construction challenges. Among different sources of settlement in shield tunneling, the settlement caused by the closure of the annulus gap behind the shield tail was discussed in this paper. This settlement usually takes place over a relatively short period of time from few hours to few days. To minimize this settlement, this gap should be properly filled with grout.
In this project, a two-component grout was considered to fill the gap and the tunnel route was properly instrumented to monitor ground movements and assess the efficiency of grouting on the ground control. The grout mixture was studied by conducting over 40 laboratory tests. Based on the quality control recordings, where the optimized mixture was not properly made during the construction, ground settlement was analyzed that showed relation between the grout characteristics and the ground settlement.

RÉSUMÉ
Un tunnel de 10 km de long de la ligne 7 du métro de Téhéran a été creusé par un EPB-TBM de 9,164 m de diamètre à travers une vieille partie congestionnée de la ville où le tassement au sol est l'un des principaux défis de la construction.
Parmi les différentes sources de tassement dans le tunnelier à bouclier, le tassement causé par la fermeture de l'écart de l'anneau derrière la queue du bouclier a été discuté dans cet article. Ce tassement se déroule généralement dans une période de temps relativement courte, de quelques heures à quelques jours.Pour minimiser ce tassement, cet espace doit être correctement rempli de coulis. Dans ce projet, un coulis à deux composants a été considéré pour combler le vide et le tracé du tunnel a été correctement instrumenté afin de surveiller les mouvements du sol et évaluer l'efficacité de l'injection de coulis sur le contrôle au sol. Le mélange de coulis a été étudié en effectuant plus de 40 tests en laboratoire. Sur la base des enregistreurs de contrôle de qualité, où le mélange optimisé n'a pas été correctement fait pendant la construction, le tassement du sol a été analysé qui a montré une relation entre les caractéristiques du coulis et le tassement du sol.

1 INTRODUCTION

A 10 km long tunnel of East-West lot of Tehran metro line 7 (TML7) is being constructed by a 9.164 m diameter Earth Pressure Balance Tunnel Boring Machine (EPB-TBM) through an old heavily built-up and congested area of the southern part of the city (Figure 1). Table 1 shows general information about the project and the TBM used for tunnel boring. This tunnel passes beneath buildings, different underground structures such as water conveyance tunnels, other metro lines, a series of unforeseeable old underground waterways, called Qanat, and other abandoned man-made cavities. These unusual circumstances have caused few collapses, building damages and other construction problems alongside the tunnel route (Geranmayeh et al., 2012, Forooghi et al., 2012). Some of these challenges caused the surface settlement to be prolonged for a long period of time. As a result, at some areas, the ground level had monitored for more than 7 months once the TBM passed the area. The recorded information was used to interpreting long-term settlements due to shield tunneling.

2 GEOLOGICAL AND GEOTECHNICAL CONDITIONS

The geology of East-West lot of Tehran metro line 7 tunnel is mainly alluvial deposited during the quaternary era. The dominant soils mass along the tunnel were categorized into six Engineering Soil Types (ET) based on their grain size distributions (content of fine and coarse particles). These six zones are ET-1, ET-2, ET-3, ET-4, ET-5 and ET-6 units and their soil descriptions were provided in Table 2. Among them, ET-1, ET-2, ET-3 and ET-4 are granular soils mainly sandy Gravel or gravely Sand with silt and clay. The soils with fine particle size (silt and clay) were categorized in ET-5 and ET-6 units. Figure 2 shows the geological section along the tunnel alignment. The area discussed in this paper consists mainly of fine graded soils categorized as ET-5.

Table 1. General project information of East-West lot of Tehran metro line 7

Item	Amount
Boring diameter	9.164 m
Total route length	10,000 m
Precast segmental lining:	
Outer diameter	8.850 m
Inner diameter	8.150 m
Type	Universal ring
Number of pieces	6+1key+1invert
Thickness	0.35 m
Length	1.5 m

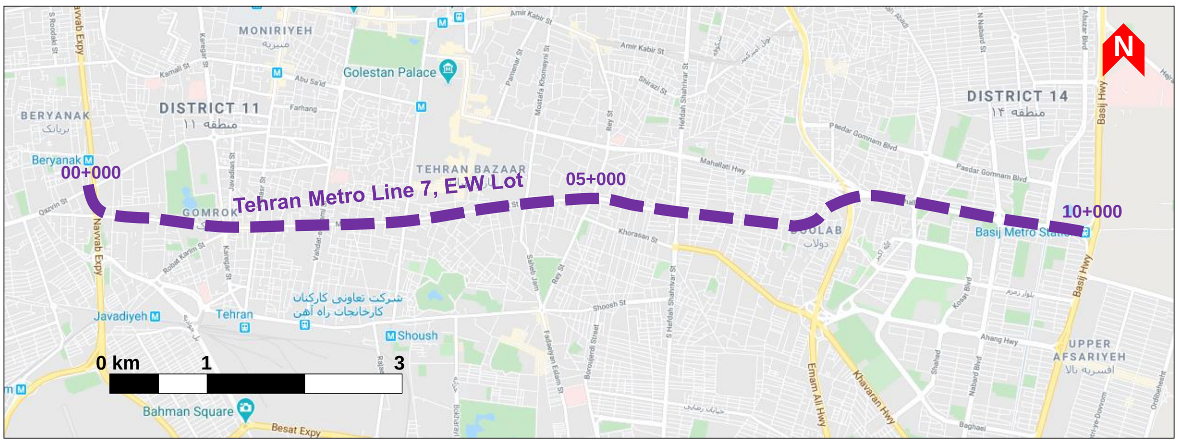

Figure 1. Tehran metro line 7 route in southern part of the city

Table 2. Geological description and geotechnical parameters of soil units

Soil Types	ET-1	ET-2	ET-3	ET-4	ET-5	ET-6
Soil description	Sandy GRAVEL & gravely SAND	Very gravely SAND with silt & clay	Very silty clayey SAND with gravel, very sandy CLAY (or silt) with gravel	Clayey silty SAND with gravel	Clayey SILT & silty CLAY with sand, very sandy CLAY (or silt)	Very soft clayey sandy SILT
Passing the no. 200 sieve	3-12%	12-30%	30-60%	22-34%	>60%	>60%
Soil type (USCS)	GW, GW-GM, GP-GC, SW, SP	SC, SC-SM & GC	SC, SM & CL	SC, SM	CL, ML & CL-ML	ML

3 LONG-TERM SETTLEMENT

Since ground settlements induced by tunneling may drag on for a very long period of time, it is essential to evaluate ground settlements in different cases with a consistent time scale. Hwang et al. (1995 & 1996), Hwang and Moh (2006), Kao et al. (2009) categorized the ground settlements into 3 phases with the passing of the shield as the beginning of timeline:

- Phase 1: due to face movements, overcutting and shield advancing,
- Phase 2: due to the closure of tail void after the passing of the tail,
- Phase 3: due to long-term consolidation.

The logarithmic model as depicted in Figure 3 was adopted as idealized settlements curve. Settlements occur during the phase 1, mainly depend on the amount of applied face pressure. The face pressure is applied to prevent face movements and also filling the annulus space behind the shield body which created for easy steering of TBM with bentonite paste or similar thixotropic materials. These materials are used to reduce the friction between the shield machine and ground and, in turn, minimize the settlements around the shield (BTS 2005, JSCE 2007). Main settlement would occur during phase 2 when the tail passes and the surrounding soils fill the annulus gap around the segments. To minimize ground settlement at this phase, grout is injected to fill up the voids behind the segmental rings. The sooner and more efficient the grout in injected, the better result is achieved to minimize the ground settlement. In this respect, backfill grouting is considered simultaneously as the shield machine is advanced. The backfill grouting material should have good filling and early strength (JSCE 2007). Phase 1 and phase 2 settlements usually take place in few hours or days until hardening of grouting materials behind segmental lining. In general, settlement magnitude during these two phases depends on the construction quality and is considered as “short-term settlement” or “ground loss”.

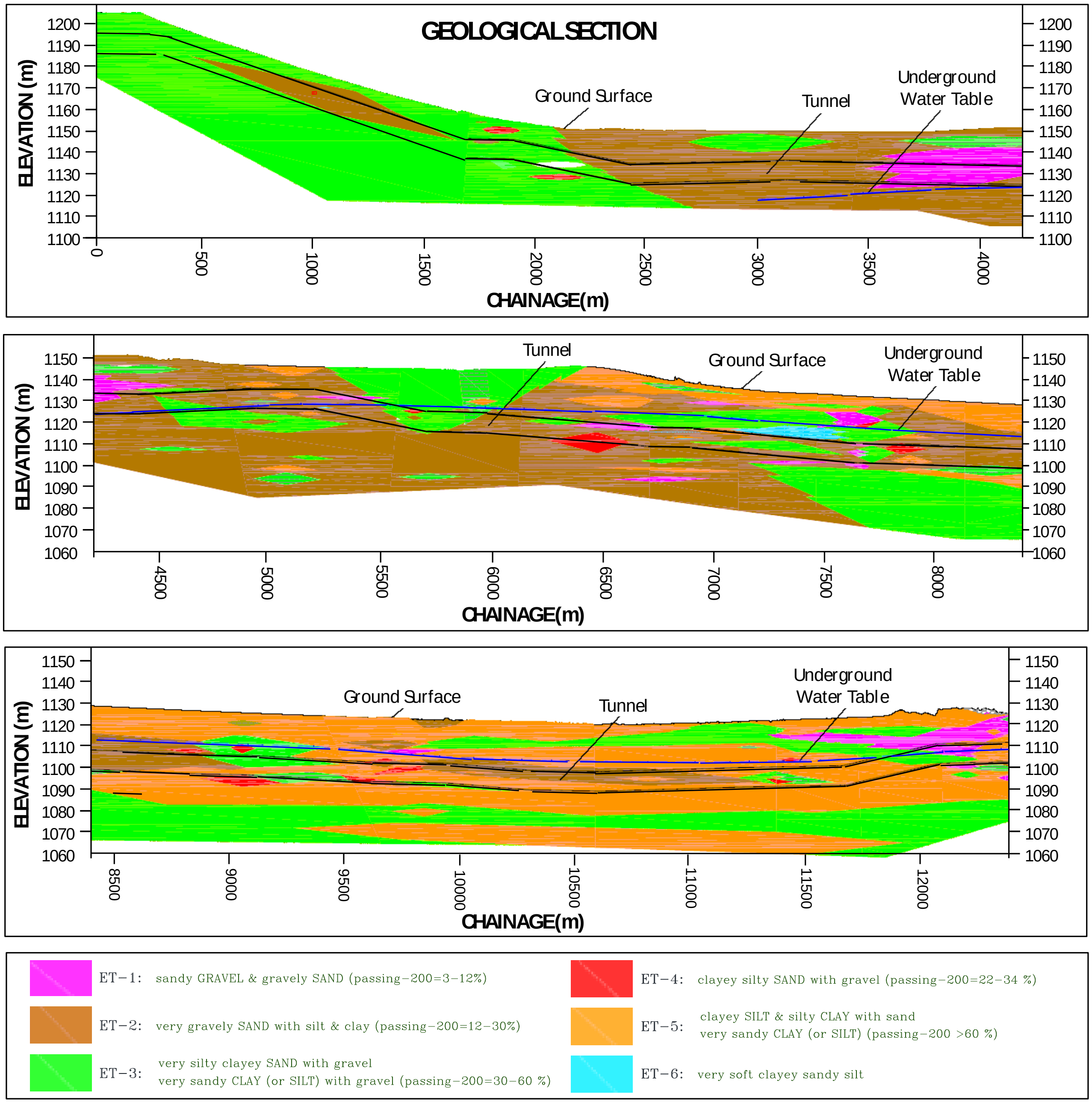

Figure 2. Longitudinal section details of geological information of bored tunnel

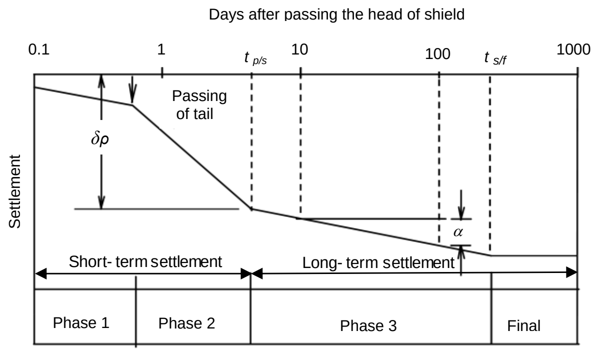

Figure 3. Logarithmic Curve for Ground Settlement over Tunnel (Kao et al. 2009)

Based on the settlement graph shown in Figure 3, the beginning of long-term settlement can be considered as transmission of Phase 2 to Phase 3. The slope of the line corresponding to Phase 3 settlements, denoted as α, is called "index of Phase 3 settlement" and can be used to predict future settlements based on previously recorded data. This index can be defined as the settlement over one full cycle in a semi-log plot, or, simply the difference between the settlements obtained on the 100th and 10th day after the passing of the shield machine. Such a definition has the merit that settlement increases, roughly, by 0.5α each time the elapse time increases by a factor of 3. For example, from 10 days to a month, from a month to 100 days, from 100 days to a year, so on and so forth. Accordingly, long-term settlements beyond the observation period can be obtained by extending this straight line and can be expressed as follows:

$$\delta_t = \delta_p + \log\left(\frac{t}{t_{p/s}}\right).\alpha \qquad [1]$$

where

- δ_t is settlement on the t-th days after the passing of the shield,
- δ_p is Phases 1 and 2 settlement,
- t elapse time after the passing of shield,
- $t_{p/s}$ is time corresponding to the transition of Phase 2 settlement and Phase 3 settlement,
- α is index of Phase 3 settlement, and
- $t_{s/f}$ is time corresponding to the transition of Phase 3 settlement and final settlement.

The distinction between Phase 2 and Phase 3 settlements is ambiguous because the transition takes place gradually. Observations indicate that the transition between these two phases occurs, in general, at elapse time between 4 days to 10 days after the passing of the shield.

Long-time monitoring of ground settlements can be very useful to identify other factors rather than tunneling that cause to the suddenly occurrence of unusual long-term settlements (Forooghi et al., 2015). It should be noted that beside tunneling quality and geotechnical characteristics of ground other reasons such as leakage of lining, lowering of ground water table, heavy traffic on surface, cutting and/or filling of the ground, existence of cavities above the tunnel and etc. may contribute in long-term consolidation (Hwang and Moh 2006).

4 BACKFILL GROUTING IN SHIELD TUNNELING

According to the dimensional difference between the excavation diameter and the outer diameter of the segmental lining, a space called "annular gap" remains behind the segmental ring. This annular gap must be filled by backfilling material to minimize ground settlement (Harrison, 2000). In fact, one of the vital and integral parts during the advancement of shield tunneling, especially in urban areas, is to how fill the annular gap by grouting materials achieved. Usually, single- or two- component grouting methods are used to fill this gap. The main objectives of injection behind the segments are as follows (Novin et al., 2015):

- Filling the annular gap and minimizing ground loss and its subsequence ground surface settlement.
- Avoiding point loads on the segmental lining by creating a uniform contact area between the tunnel lining and the surrounding ground.
- Fixation and holding of the segment ring in its place after passing the shield.
- Bearing the loads imposed by TBM Backup and transportation system on the invert segment.
- Completion of tunnel sealing.
- Inhibition of ring distortions.

Selecting a suitable backfilling grouting method for the annulus gap depends on various parameters such as ground conditions, TBM penetration rate, applied grouting pressure, transporting methods, interaction with the lining, materials availability and economic considerations. For Tehran metro line 7 project, a "two-component grout" consisted of cement, bentonite, water, and retarder as the first component, and accelerator as the second component was practiced for fill the annulus gap. Proper selection of admixture has great importance from both technical and economical points of view that was discussed with more details the following sections.

4.1 Experimental Tests and Acceptance Criteria for Two-Component Grout

Two-component grout should be tested in the laboratory to approve workability criteria and grout pumpability and resistance properties. Experimental tests of two-component grout are divided into two sets. Some of these tests, such as bleeding test and Marsh funnel time, are related to Part A while another set of tests, such as gelling time (regard to the amount of part B) and compressive strength of hardened grout, are related to the time that Part B is added to Part A (Figure 4). The criteria, experimental tests and acceptance values were presented in Table 3. The optimized admixture plan was selected by making more than 40 admixture schemes in laboratory and obtaining of the effective parameters, such as 4 hours bleeding, marsh viscosity, gelling time and 7-day compressive strength of cubic specimens as reported in Table 3.

Figure 4. Some measuring sets for two-component grout test (Novin et al. 2015)

Table 3. Acceptance level for some tests of two-component grout (Novin et al., 2012, Novin et al., 2015)

Parameters		Standards	Unit	Acceptance level min	Acceptance level max	Optimized amount
Marsh funnel (A)		ASTM C 940	Sec	33	38	38
Bleeding (A)		ASTM D 6910	%	2	6	2.4
Gelling time		Other projects	Sec	6	12	8-11
Compressive Strength	24 hr	ASTM C 109	MPa	0.3	0.8	0.5-0.8
	7 day			1.0	2.5	1.92

4.2 Quality Control Aims and Procedure

The goals of a quality control program for shield tunnels backfill grouting are to assume that:

- mixes are properly designed and implemented;
- appropriate equipment and injection procedures are used;
- proper volume with appropriate injection pressure for complete void filling is achieved;
- detailed tests based on the acceptance levels indicated by designer are done; and
- related records are maintained for all advance cycles.

In practice, some quality control tests of two-component grout should be carried out in the laboratory such as material properties and hardened cubic strength test. However, some tests such as bleeding test, Marsh funnel and gelling time also can be done at site in the TBM backup system during tunnel excavation. Therefore, QC experts obligated to iterative execution site tests for each advance cycle as indicated by Inspection and Test Plan (ITP) of TML7 project. Documentation of the test results, beside the grouting volume and pressure recordings by TBM PLC (Programmable Logic Controller), forms the QC/QA documents of backfill grouting.

5 GROUND MONITORING AND QC RESULTS

At the beginning of the project, few collapses were occurred due to an unidentified Qanat at the area that caused minor damage to the buildings near the tunnel route. To avoid such surprises, more instruments were considered for the remaining of the tunnel route. In addition, as the tunnel was being bored below Tehran Grand Bazar, the reading intervals were decreased form once a day to once in an hour at the sections near the TBM.

Various instruments such as Standpipe Piezometer, Extensometer, Strain Gauge, Tiltmeter, Crackmeter, Ground Leveling Point (GLP) and Building Leveling Point (BLP) were considered for this project to monitor various parameters to understand the tunneling effect on surrounding structures. Among them, GLPs and BLPs were extensively used for further back-analysis of TBM tunneling condition. Collecting such valuable monitoring data allowed resident engineers to optimize TBM operation parameters and perform ground-tunnel interaction analysis faster and more efficient.

5.1 Monitoring sections and recorded settlements

The data used in this study were selected among more than 400 monitoring sections. These sections were selected based on operation reports where TBM contractor deviated from proposed grout mixture. In such cases, the tunnel QC inspector reported such deviations for further actions by resident engineers.

Monitoring sections and instrument point situation were provided in Table 4 and shown on Figure 5. The geological parameters of soil units were presented in Table 5, Table 6 and the short- and long-term settlements graphs were shown in Figure 6.

Table 4. Monitoring sections

Instrument Section	Instrument Point	Distance from Tunnel Axis (m)	Chainage	Ring No.
CS.LP.104	CS.LP.104.L	-3.7	3+514	2343
	CS.LP.104.C	2.8		
	CS.LP.104.R	9.9		
CS.LP.108	CS.LP.108.L	-3.7	3+613	2409
	CS.LP.108.C	2.9		
	CS.LP.108.R	10.2		
CS.LP.112	CS.LP.112.L	-3.7	3+717	2478
	CS.LP.112.C	2.6		
	CS.LP.112.R	9.8		
CS.LP.175	CS.LP.175.C	0.4	4+989	3326
CS.LP.180	CS.LP.180.C	0.5	5+049	3366
CS.LP.182	CS.LP.182.C	-0.3	5+072	3381
CS.LP.187	CS.LP.187.L	-3.8	5+117	3411
	CS.LP.187.C	-0.7		

Table 5. Geological condition in the monitoring sections

Instrument Section	Tunnel Section Geology	Tunnel Section Fine Content (%)	Tunnel Overburden Geology
CS.LP.104 CS.LP.108 CS.LP.112	Mostly ET2, with ET3	42	ET2 & ET5
CS.LP.175 CS.LP.180 CS.LP.182 CS.LP.187	ET2 & ET3	28	ET2, ET3, ET5, ET6

Table 6. Short-term and long-term settlement measured in the monitoring sections

Instrument Point	Ring No.	Short-term Settlement (mm)	Settlement After 60 Days (mm)
CS.LP.104.C	2343	23.3	29.3
CS.LP.108.C	2409	42.9	44.3
CS.LP.112.C	2478	22.9	24.7
CS.LP.175.C	3326	29.9	37.5
CS.LP.180.C	3366	37.4	42.0
CS.LP.182.C	3381	23.7	33.2
CS.LP.187.C	3411	25.8	49.9

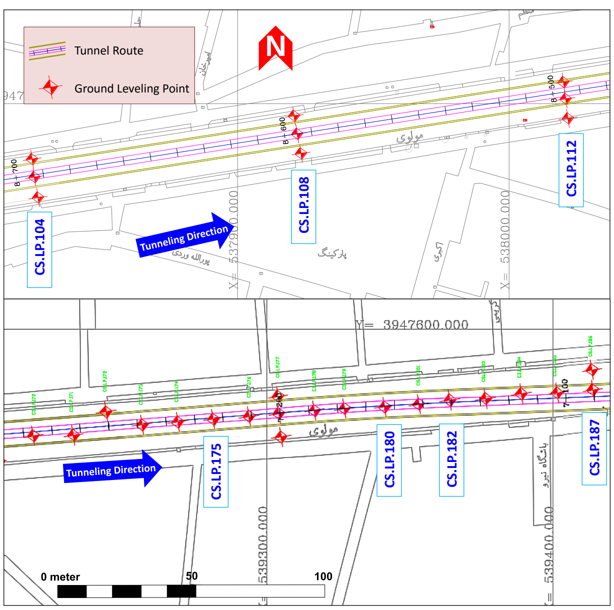

Figure 5. Monitoring (Ground Leveling Point) plan in the study area

5.2 Backfill grouting QC tests result

In addition to the lab QC tests, physical property and workability condition of grout were defined based on Inspection and Test Plan (ITP) using bleeding and gelling time tests. These tests were completed for each TBM advance on Backup system on the backfilling material prepared in the batching planet. The test results performed at the site lab were presented in Table 7. As shown, 4hr bleeding tests resulted in up to 10% increase on rings 2409, 3326 and 3366, while the optimal amount bounded up to a quarter of that. As well, inspector encountered a long gelling time of grout in advance #2478 and #3382 that resulted in rejection of undesirable materials (B Component) provided by supplier and used in practice, without passing the QC acceptance tests.

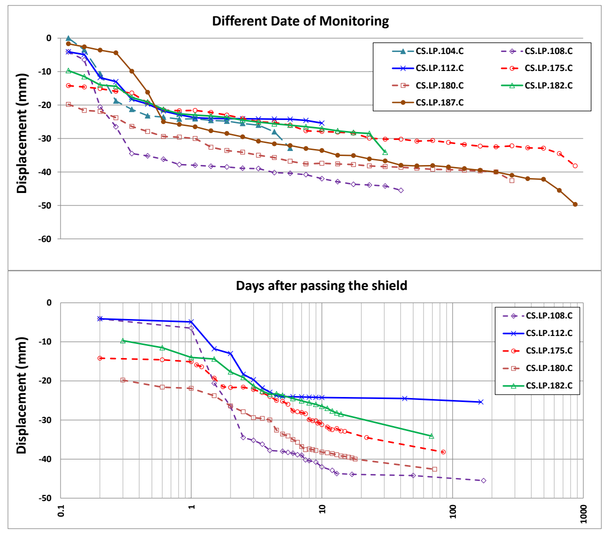

Figure 6. Short-term and long-term settlement measured in the monitoring sections

Studies on the results of more than 400 monitoring sections of GLP and BLP showed that the third phase (consolidation) settlement starts 3-7 days after passing the shield with respect to the geological condition of tunnel route (Forooghi et al., 2015). In order to have a good comparison, the graph in Figure 7 presented the trend of long-term settlement in two normal sections (regarding to backfill grouting tests) CS.LP.104 and CS.LP.187.

Table 7. Backfill grouting QC tests results

Ring No.	Instrument Section	4 hours Bleeding (%)	Gelling time
2343	CS.LP.104	3	12 Sec.
2409	CS.LP.108	10	10 Sec.
2478	CS.LP.112	4	2 Days
3326	CS.LP.175	11	8 Sec.
3366	CS.LP.180	10	13 Sec.
3381	CS.LP.182	3	2 Days
2343	CS.LP.187	3	10 Sec.

Long-term settlement in the sections where the back-fill operation had deviations from proposed optimized grout mixture (Table 8, Figure 8 and Figure 9), showed that increasing in bleeding of “A

Component" of grout would lead to a postponed consolidation. Unlike bleeding, excess gelling time would not delay consolidation settlement, where other parameters were in optimal range.

Table 8. Long-term settlement initiation day versus QC tests results

Ring No.	Instrument Section	Bleeding test	Gelling time test	Long-term Settlement Initiation Day
2343	CS.LP.104	Ok	Ok	3
2409	CS.LP.108	N. Ok	Ok	12
2478	CS.LP.112	Ok	N. Ok	4
3326	CS.LP.175	N. Ok	Ok	9
3366	CS.LP.180	N. Ok	Ok	9
3381	CS.LP.182	Ok	N. Ok	4
2343	CS.LP.187	Ok	Ok	3

6 CONCLUSION

Ground settlements induced by tunneling may drag on for a very long period of time after the shield passage. The "long-term settlement" or "consolidation settlement" initiation stars from 3 to 7 days after passing the shield. With respect to the long life of instruments used and the project condition, recording the third phase (consolidation) of settlement became possible. So, prediction of ground response could be done based on the linear portion of settlement graph. Any deviation from linearity can be identified as a result of external factor.

Long-term settlement recordings and quality control inspections were analyzed to understand the effect of improper grout mixture on the ground settlement. The results showed that increasing of grout bleeding would delay consolidation phase while excess gelling time of grout would not.

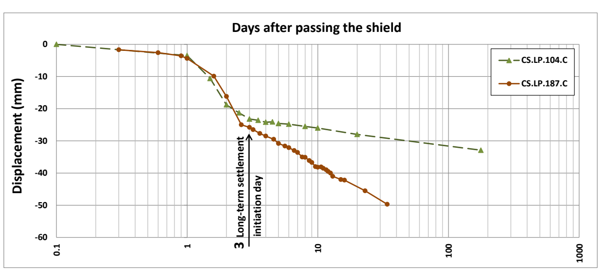

Figure 7. Start of long-term (consolidation) settlement in normal sections in the study area after 3 days

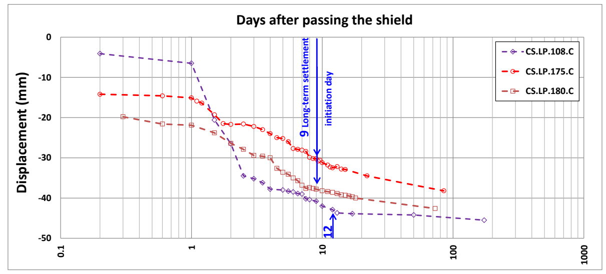

Figure 8. Late initiation of long-term settlement due to excess in bleeding test results

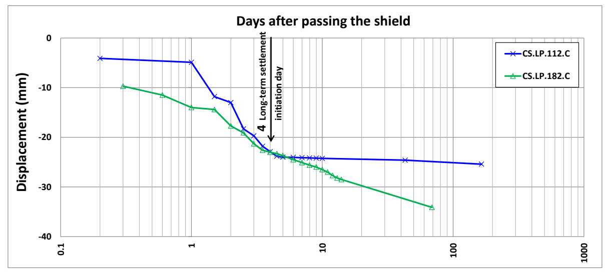

Figure 9. Normal initiation of long-term settlement regardless of excess in gelling time test results

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