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Performance of Deep Soil Nailed Walls

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PERFORMANCE OF DEEP SOIL NAILED WALLS

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FOREWORD

Exactly 40 years ago, one sunny September day, I found myself at the secretarial office of Geotechnical Engineering at UC Berkeley. I was very excited because it was going to be the first meeting with my advisor, Professor James K. Mitchell. Although I had previously received a very warm welcome letter from Professor Mitchell, I was convinced the meeting would be a very different experience for a foreign student from Turkey. Upon entering his office, and receiving a warm welcome, my assignment as a Research Assistant at the Richmond Field Station was explained to me and my schedule of classes for the Fall Quarter was identified. Professor Mitchell was apparently not impressed with my "fluent" English! He advised me to add a course entitled "English for Foreign Students" to my schedule. After a successful academic year and the completion of a series of tests to investigate the effect of salt water intrusion on the hydraulic conductivity of aquitard clays in southern California, Professor Mitchell asked me if I would be interested in participating in the NASA Lunar Soil Mechanics research program. I answered "yes" and that was the beginning of my involvement in the development of static penetration testing and analysis for the lunar environment, the topic of my doctoral dissertation under Professor Mitchell's guidance and great motivation.

It is a great privilege for me to present this paper on a very special day honoring my dear Professor. Obviously, it was not easy to decide on the topic. The inspiration for the paper evolved in my mind in the following manner. First, this Conference focuses on case histories in Geotechnical Engineering and, therefore, the paper should be within the theme of the Conference. Second, Jim has been interested throughout his professional life in soil improvement and soil reinforcement. Consequently, the choice of soil nailing would be of interest to him. Third, Jim is also interested in the soil behavior and performance of soil-structures. Therefore, the topic should incorporate performance monitoring. As a result, I have decided to present a summary of my experience during the last decade related to the behavior of deep soil nailed walls in Istanbul, Turkey.

Throughout my academic and professional life in Geotechnical Engineering, I always found Professor Mitchell very willing to share his views and to give advice to solve a myriad of problems with which I was confronted. I could always count on Professor Mitchell. I would like to take this opportunity to thank Jim for his friendship throughout my adult life and his untiring dedication to the advancement of my professional career.

ABSTRACT

Deep excavations and retaining structures are constructed in the city of Istanbul at different locations of the city due to the recent demand for the construction of high-rise structures and shopping malls having various basements. Usually the main lithological unit of Trace Formation, i.e. alternating layers of sandstone, siltstone and claystone are encountered during these excavations especially along the axis of Büyükdere Avenue. The lithological unit is extensively fractured. Consequently, stress relief in horizontal direction as a result of excavations is the main potential hazard that has to be handled with care. Istanbul is located at a very seismically active region and a major earthquake magnitude of $M_w>7.0$ are expected to occur with a 65% probability within the next 30 years. It is well known that flexible earth retaining structures in cuts as soil nailed walls offer a great advantage under the described subsoil and seismic conditions. As a result many deep soil nailed walls have been constructed recently in the city. The performances of these walls are monitored by means of inclinometers. The displacement data for various projects are evaluated in terms of various design parameters of the soil nailed walls and the excavation depth. The basic guidelines for deep soil nailed walls in typical greywacke formation of the city are developed for future applications in the similar subsoil conditions.

INTRODUCTION

The city of Istanbul due to its recent growth in economy caused a great attraction for the construction of high-rise residential and office buildings. In order to obtain parking space, deep excavations are employed to allow great number of basements below these tower structures. The depths of the excavations commonly reach to 25-40 meters below the ground surface. A picture showing recently constructed Canyon project at the left and Büyükdere Avenue at the right is given in Fig. 1.

Istanbul is potentially under the influence area of the Marmara Fault System, located at the south, in the Marmara Sea, which is the western end of the North Anatolian Fault-NAF of Turkey (Fig. 2-right). After the 1999 Kocaeli and Düzce earthquakes occurred on NAF within the Marmara Region in approximately 100-150 kilometers from the city of Istanbul, the structure of NAF system in Marmara Sea attracted worldwide scientific attention. Recent studies conducted after 1999 Kocaeli (M_w=7.4) and Düzce (M_w=7.2) earthquakes indicated about 65% probability for the occurrence of a M_w>7.0 effecting Istanbul within the next 30 years due to the existence of potential seismic gaps (Parsons et al., 2000).

Fig. 1. A picture from Istanbul, Canyon Project

The encountered subsoil formation is soft rock greywacke locally known as Trace Formation, which is lithologically alternating sandstone, siltstone and claystones with various degrees of weathering and fracturing.

Based on the previous positive records of flexible earth retaining structures during earthquakes in Turkey by Mitchell et al. (2000) and Durgunoglu et al. (2003a), soil nailed walls both temporary and permanent in such excavations performed within the city offer great advantage especially for the encountered subsoil and seismic conditions.

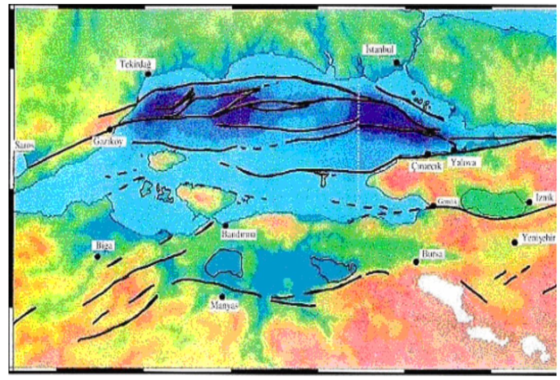

Fig. 2. Western end of North Anatolian Fault in Marmara Sea.

The results of the performance of walls with different heights in various sites having the similar greywacke subsoil formation are compiled. The performances of walls are monitored by inclinometer recordings taken at certain time intervals in parallel to the excavation at various locations. The displacement and normalized displacement (i.e. performance ratio, P_r) data are presented together with some basic parameters of soil nailed walls such as, height of wall (H), area per nail (S), average nail length (L), nail density (η=L/S), length ratio (L_r), bond ratio (B_r) and strength ratio (S_r). As a result the values of performance ratio for soil nailed walls together with nail density in typical greywacke formation of the city of Istanbul are developed based on these extensive case studies as a guideline for future applications in similar subsoil conditions.

CHARACTERIZATION OF MAIN LITHOLOGICAL FORMATION

At location of tower structures, the main lithological unit present is greywacke formation with alternating layers of sandstone, siltstone and claystones with various degrees of weathering and fracturing, Fig. 3. Obviously, the extend of weathering and fracturing controls the mechanical properties and in fact geological observations do well agree with the results of in-situ measurements reflecting mechanical properties of the formation. The geotechnical modeling of formation, weathered zones, extend of fracturing and compressibility modulus of formation are usually obtained by means of integrated seismic survey and Menard pressuremeter testings performed within the predrilled boreholes at various locations and depths. (Durgunoglu and Yilmaz, 2007)

A typical P-wave velocity-depth model at a planned tower site as an example is presented in Fig. 4. The near-surface at the comprises three main units starting from the ground level: (1) top soil and/or fill with v_p velocities varying between 500-1,000m/s and thickness varying between 3-18m; V_s=200-600m/s (2) heterogeneous layer with velocities varying between 1,000-2,500m/s in most parts of the site and thickness varying between 10-35m; V_s =600-1200m/s (3) homogeneous layer with P-wave velocities varying between 2,500-3,500m/s, mostly in the vertical direction, and thickness varying between 10-20m. Below the near-surface layers is the geological bedrock with velocities exceeding 3,500m/s. P-wave velocities generally are 10-20% higher in the NS direction than the velocities in the EW direction, particularly within the third layer and bedrock. Such directional difference in velocities may be attributed to seismic anisotropy caused by fracture surfaces in the EW direction that may be present in the third layer and bedrock. Some dikes and faults can also be inferred from the structural interpretation of the P-wave velocity-depth models based on velocity contrast. The variation of V_s with depth obtained at four stations at this site i.e. S4, S3, S2, S6 is shown in Fig. 5.

Fig. 3. Features of Typical Greywacke Formation in Istanbul

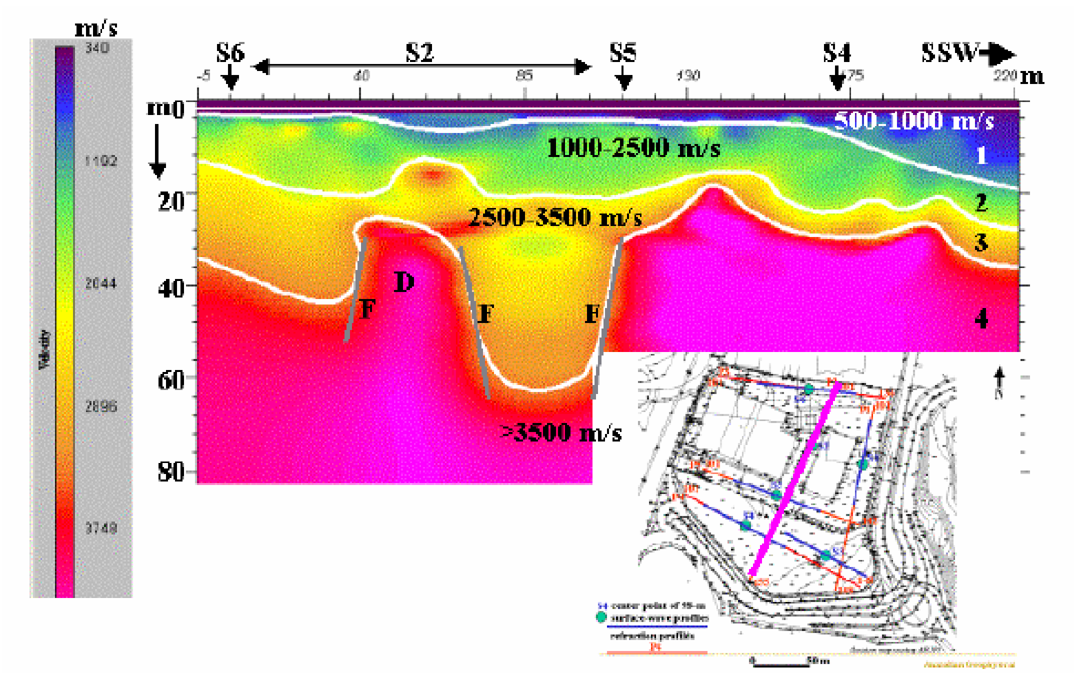

Fig. 4. An Example of structural interpretation of the P-wave velocity-depth model at a Tower Site (Durgunoglu and Yilmaz, 2007)

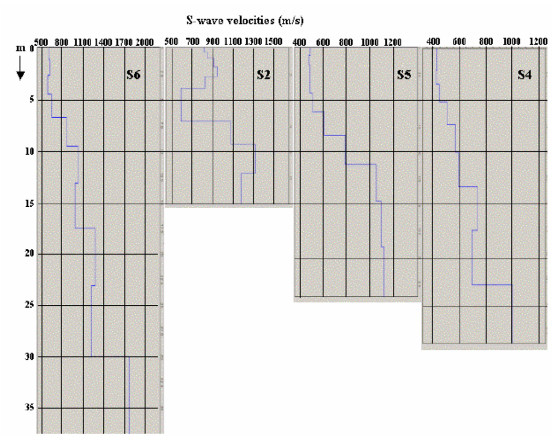

Fig. 5. An example of the S-wave velocity-depth profiles from a Tower Site(Durgunoglu and Yilmaz, 2007)

It may be seen that V_s values are typically in the range of 200-1200m/s depending on the depth of the greywacke formation. The V_s values for many strong-motion recording sites used in various ground-shaking regression attenuation relationships is poorly established. Usually, the mean shear wave velocity in the upper 30 meters V_s^* m/s is used. However, appropriate V_s^* m/s values for various subjective site descriptions currently are being debated as shown at the Table 1.

Table 1. Definition of Soil Formation Based on V_s^* Values (Durgunoglu and Yilmaz, 2007)

Reference	Vs^* (m/s)				
	Weak Soil	Firm Soil	Soft Rock	Firm Rock	Hard Rock
Borcherdt, 1994	150	290	540	1050	1620
Boore et al., 1997	<180	180-360	360-750	>750	-
BSSC, 1998	<180	180-360	360-760	760-1500	>1500
Willes and et al., 2000	-	289	372	724	-
Frankelet et al., 2000	-	-	-	760	-
Campbell and Bozovgnia, 2003	163	301	372	718	-

In general, the greywacke is alternating fractured sandstone, siltstone and claystone formation having some degree of weathering close to surface. They are classified as soft rocks having average shear wave velocities in the range of V_s^*=400-800 m/sec depending on the extend of fracturing for the top 30 meters according to Table 1.

The range of shear modulus values for small strains for greywacke formation, G_0 (300-1200 MPa) determined based on Vs (400-800 m/sec) values are great. Typical G_0 values, $G_0=\rho V_s^2$ for various soil types as comparison is presented in Table 2.

Table 2. Typical Range of G_0 for Various Soil Types (FHWA Circular no 5, 2002)

SOIL TYPE	G_0 (MPa)
Soft Clays	3 – 14
Hard Clays	7 – 35
Silty Sands	30 – 140
Dense Sand and Gravel	70 – 350
Soft Rocks (Durgunoglu and Yılmaz, 2007)	300 – 1200

For numerical analysis of soil nailed walls the modulus degradation values to be utilized under various strain levels has to be determined. The modulus degradation values have been estimated for the soils in the past by various authors. However, almost no data exists for the rock conditions. The modulus ratios for the three greywacke tower sites in Istanbul are presented in Fig. 6. It may be seen that closer to ground surface 0-30m for pertinent soft rock conditions the ratio is about 30 to 50, on the other hand, for deeper layers, 30+ m, pertinent firm rock conditions the ratio is about 50-200.

It is seen that the degradation ratios for greywacke formation to obtain G_m for loading to be utilized in prediction of lateral displacement of soil nailed walls are large as well. Therefore the modulus value of greywackes of Istanbul to be utilized in numerical models such as PLAXIS to predict the displacements do vary in a very big range. Consequently, the displacements of soil nailed walls based on selected modulus values for loading and unloading are only indicative. Therefore, direct measurement of lateral displacements of deep soil nailed walls in Istanbul is compulsory in order to follow performance of such structures during and after construction.

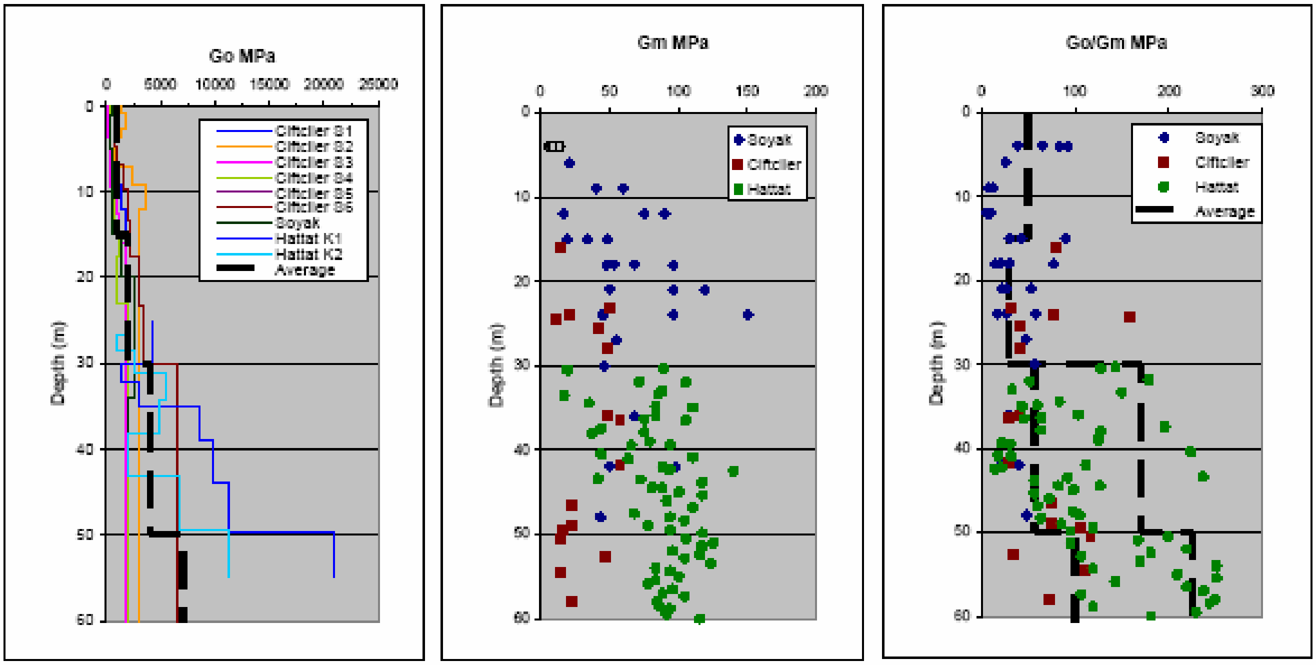

Fig. 6. The variation of shear modulus with depth of typical greywacke in Istanbul (Durgunoglu and Yilmaz, 2007)

CASE STUDIES

During the last ten years soil nailed walls have been extensively constructed within the city of Istanbul generally as temporary retaining walls to support the basement excavations of various structures. According to recent compilation by Zetas (2006) about 160,000 m2 of wall had been constructed in 60 different projects and the performances of some of these soil nailed wall structures have been reported previously by Ozsoy (1996), Durgunoglu et al. (1997) and Yilmaz (2000). In this study six major case of deep soil nailing walls constructed in Istanbul in locally well-known Trace Formation–greywacke are presented based on the recent study performed by Keskin (2008).

These six case studies of soil nailed walls having total surface area of 63,000 m2 are BJK Fulya Complex, Istinye Park Complex, Kanyon Complex, Mashattan Residence, Tepe Shopping Mall and Besler Warehouse as presented in Table 3. BJK Fulya Complex, planned to be erected in Fulya, Istanbul by Besiktas JK, consists of two residential towers, one office building, hospital and shopping mall. Due to the variations of soil formation of the entire project area, different retaining methods in accordance with the subsoil conditions are applied at different sections. In the 6,500 m2 out of the total 15,000 m2 of retaining area, soil nailed walls were constructed. Istinye Park Project, erected in Istinye, Istanbul, is a complex of residences, shopping mall and social facilities. Soil nailed walls were applied in the total 20,000 m2 of retaining area. Kanyon Complex, situated in Levent region of Istanbul, has shopping mall, residences and a multi-storey office building. The project has 16,000 m2 retaining area, all soil nailed walls, with maximum height of 28.3 m. Mashattan Residence in Maslak is a housing estate with eight apartment blocks each 30-storey with total retaining structure area of 10,000 m2 which 6,500 m2 of that was soil nailed walls. Tepe Shopping Mall in Maltepe region of Istanbul, has 6,000 m2 of retaining area with all soil nailed walls application. The last case, Besler Warehouse in Kurtköy, Istanbul with 8,000 m2 soil nailed walls and the maximum height was 28.7 m.

Table 3. Six Major Case Studies of Soil Nailed Walls in Istanbul

CASE STUDIES	SURFACE AREA, m2
BJK Fulya Complex	6,500
Istinye Park Complex	20,000
Kanyon Complex	16,000
Mashattan Residence	6,500
Tepe Shopping Mall	6,000
Besler Warehouse	8,000
TOTAL	63,000

In the case studies evaluated, the maximum height of soil nailed walls varied between 10.0 m to 32.5 m. Since it is known from the previous studies that a small inclination from the vertical has a great advantage in the performance of the walls (French National Research Project Clouterre, 1993; Elias and Juran, 1989), the slope angle β for the studied cases were 85° except for Case No. 2, Istinye Park having β=80°. Nail orientation with the horizontal were adopted as ω=10° in all the cases together with a common nail diameter of D=105 mm. The main lithological features of the greywacke formation are given together with other geometrical data; the maximum excavation height, H, slope angle, β, nail orientation, ω and the nail hole diameter, D in Table 4.

Table 4. Geometrical Data and Soil Conditions of Case Studies of Soil Nailed Walls

No.	Project Name	H_{max}(m)	β (°)	ω (°)	D (mm)	Subsoil Conditions
1	BJK Fulya Complex	32.5	85	10	105	fractured silicified **sandstone**
2	Istinye Park Complex	22.0	80	10	105	extensively fractured **siltstone, claystone**
3	Kanyon Complex	28.3	85	10	105	extensively fractured **sandstone, siltstone, claystone**
4	Mashattan Residence	24.9	85	10	105	extensively fractured **siltstone, claystone**
5	Tepe Shopping Mall	10.0	85	15	105	extensively fractured **sandstone, siltstone, claystone**
6	Besler Warehouse	28.7	85	10	105	extensively fractured **sandstone**

H_{max} (m) : Maximum soil nailed wall height
β (°) : Slope angle
ω (°) : Nail orienation
D (mm) : Nail hole diameter

Lateral displacement readings of the above mentioned six projects studied and evaluated in detail, are given in Fig.'s 7 through 12 respectively. A picture view and the cross-section where the inclinometer readings made are also provided for reference.

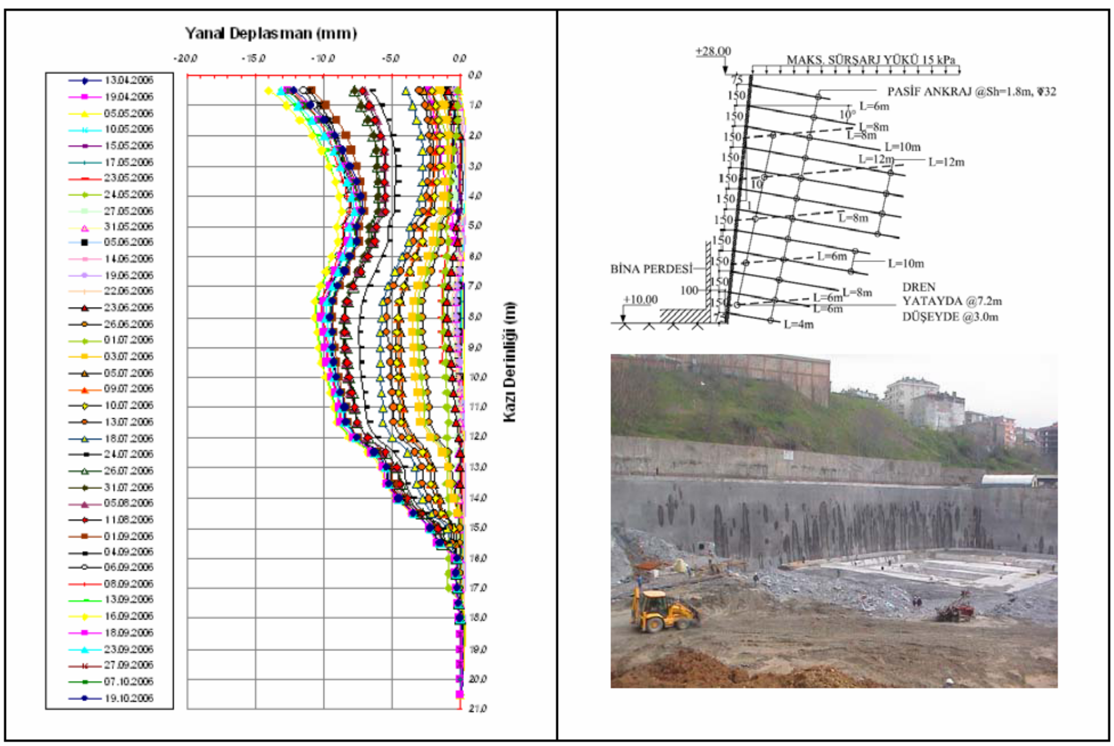

Fig. 7. BJK Fulya Complex, Inclinometer No.1 Readings, Cross-Section and a View

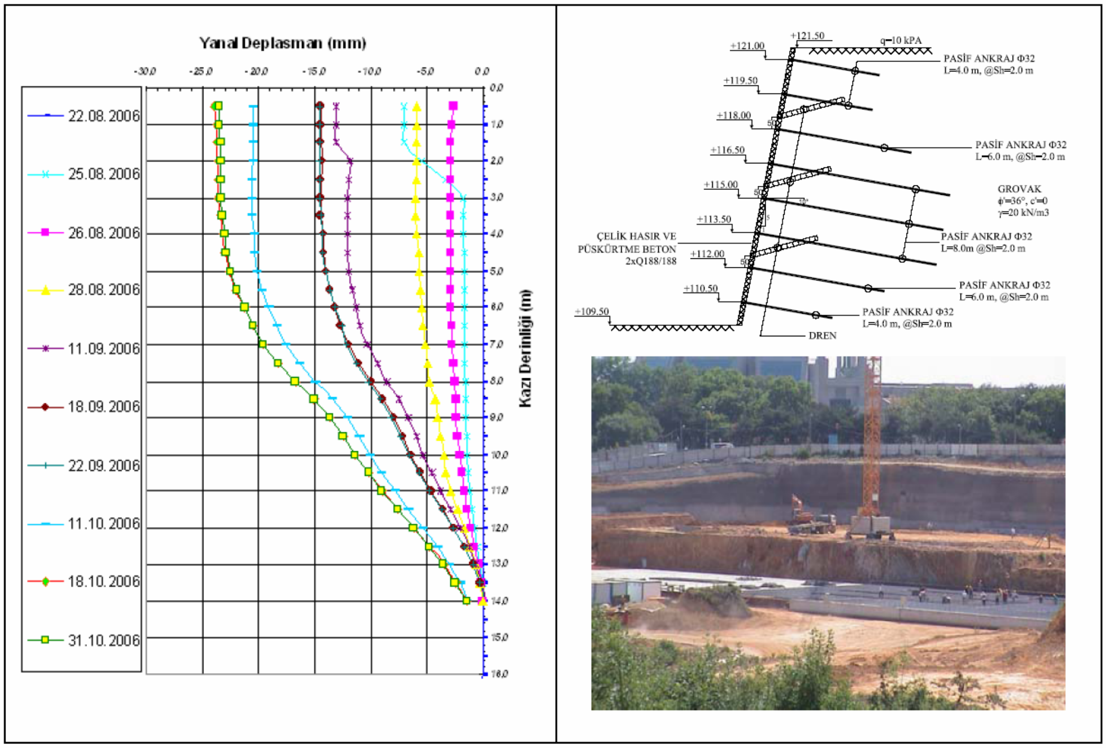

Fig. 8. Istinye Park Complex, Inclinometer No.4 Readings, Cross-Section and a View

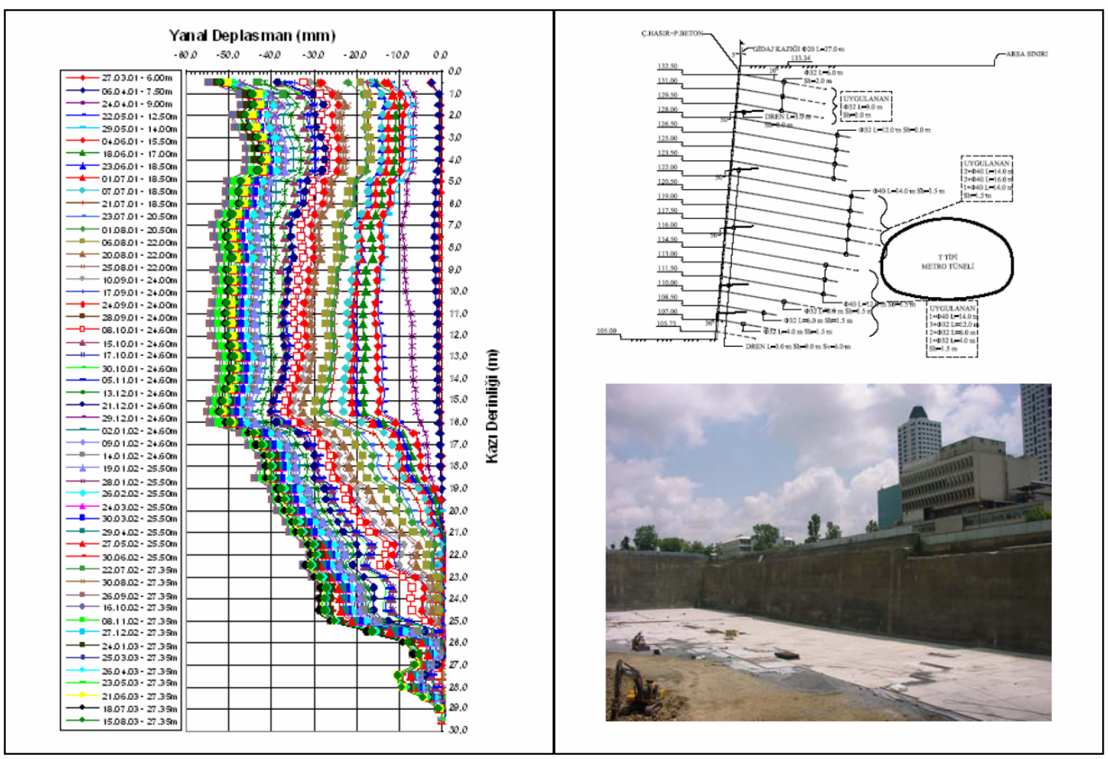

Fig. 9. Canyon Complex, Inclinometer No.7 Readings, Cross-Section and a View

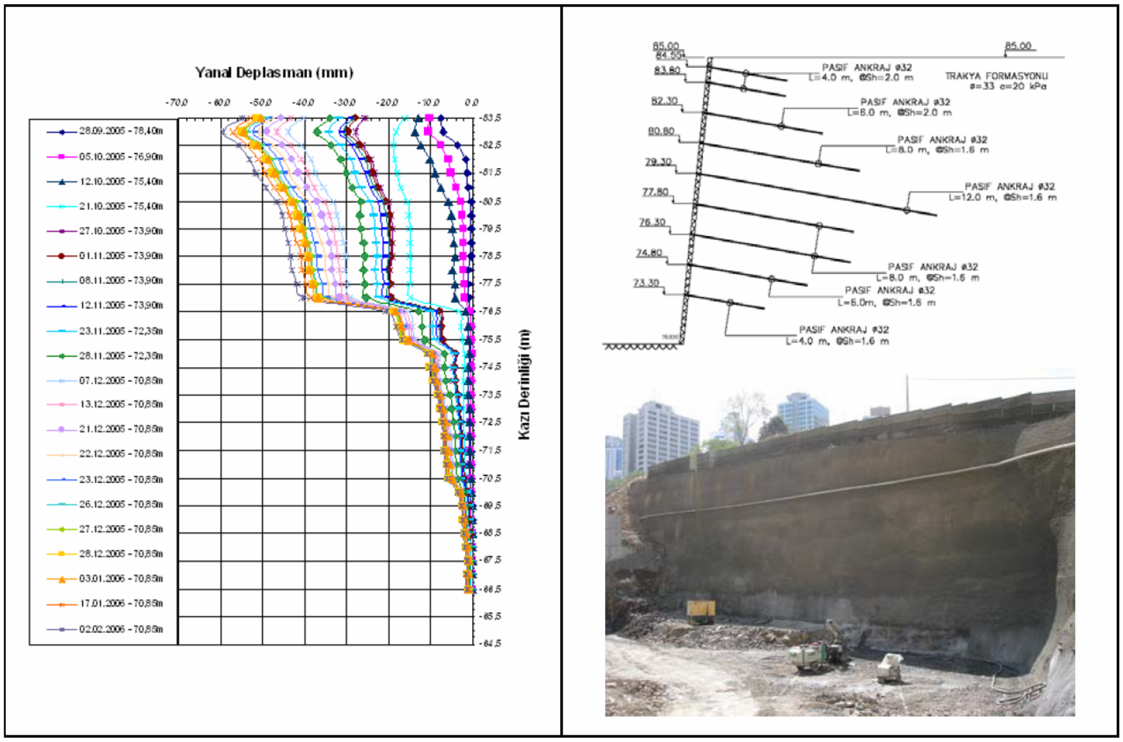

Fig. 10. Mashattan Residence, Inclinometer No.1 Readings, Cross-Section and a View

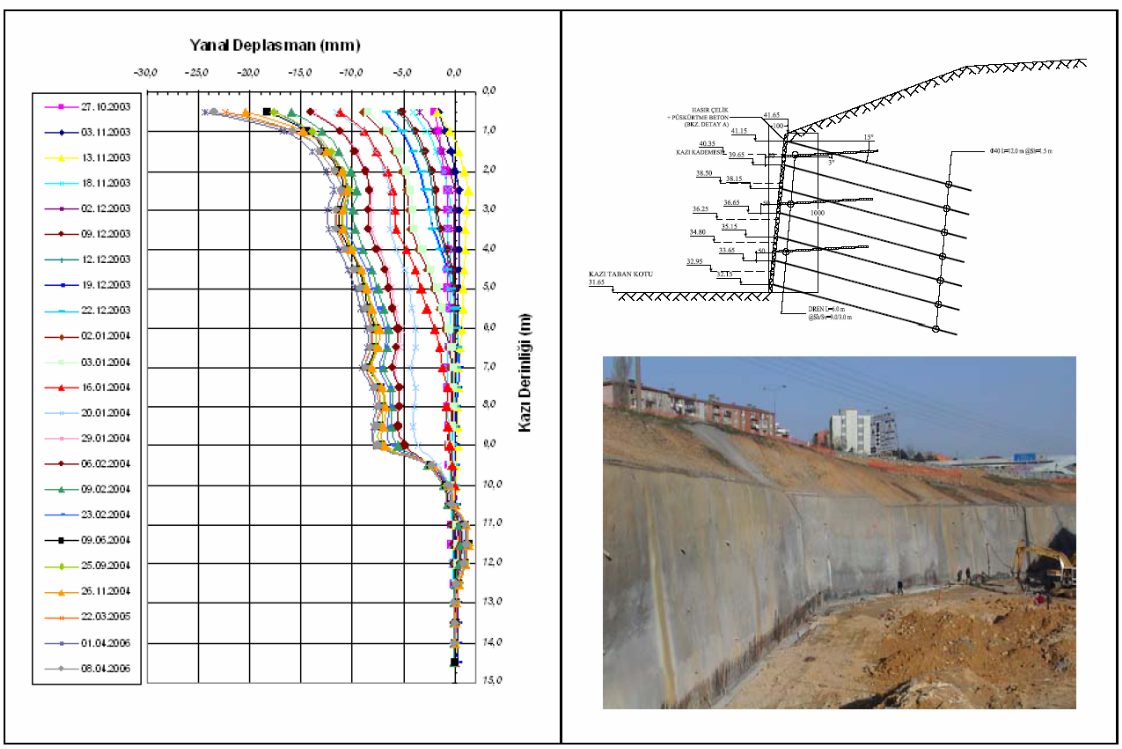

Fig. 11. Tepe Shopping Mall, Inclinometer No.4 Readings, Cross-Section and a View

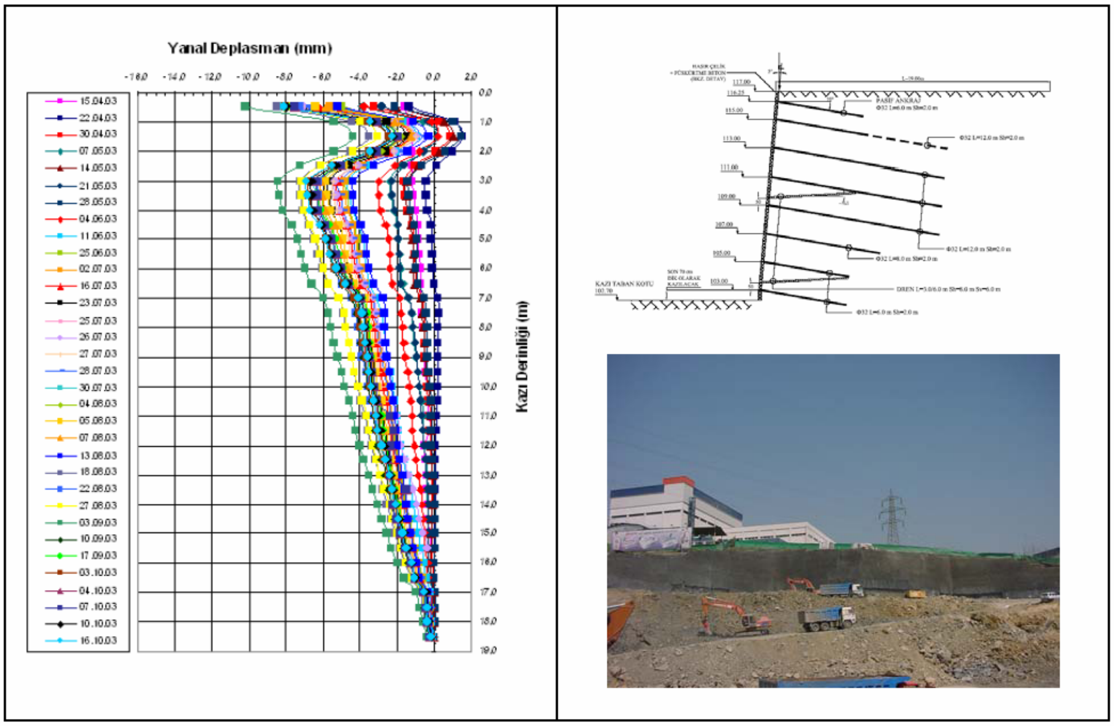

Fig. 12. Besler Warehouse, Inclinometer No.1 Readings, Cross-Section and a View

TYPICAL LATERAL DISPLACEMENT DATA

A typical lateral displacement data for the Case No. 3 (Kanyon Complex, Istanbul), Inclinometer 7 is presented in Fig. 13, (Durgunoglu et al. 2003b). At the top the excavation depth vs. date, in the middle lateral displacement vs. date and at the bottom lateral displacement vs. depth are provided. Inclinometer readings, detailed cross-section and a picture from this site is also given in Fig. 9.

Although the major height of the soil nailed wall was completed within six months, the excavation was kept open for almost another two years due to delay in final design of the upper structures to be constructed and obtaining related building permit from the municipality. It is interesting to note the followings:

- The lateral displacement has increased linearly with depth up to an excavation depth of approximately 18.0 m. For greater depths the rate of increase in the lateral displacement was increased considerably.

- Although the temporary excavation with soil nailed retaining structure left open for more than two years, almost no additional lateral displacement was observed in spite of heavy rain and snow within that period indicating that the drainage system designed and implemented which is given in Fig. 9 were performed satisfactorily. Subhorizontal drains, in length of ld=3 m, were implemented at Sh = 8 to 9 m horizontal spacings with an inclination of 3˚ to the horizontal. The typical vertical spacings were Sv = 4 to 6 m.

PERFORMANCE OF SOIL NAILED WALLS

For each case study, some of the basic design parameters for the soil nailed walls, (Phear et al., 2005) are determined from the final design drawings and are given in Table 5. In Table 5 following parameters are calculated and summarized:

Design Parameters:
H = excavation height, m
S = S_h x S_h, area per nail, m^2
L = average nail length, m
η = L/S, nail density, ave. nail length per area, m/m^2
L_r = L/H, length ratio
B_r = DxL/S, bond ratio
S_r = D^2/S, strength ratio

Performance Parameters:
δ_h = lateral displacement at top, mm
$P_r = \delta_h /H$, performance ratio

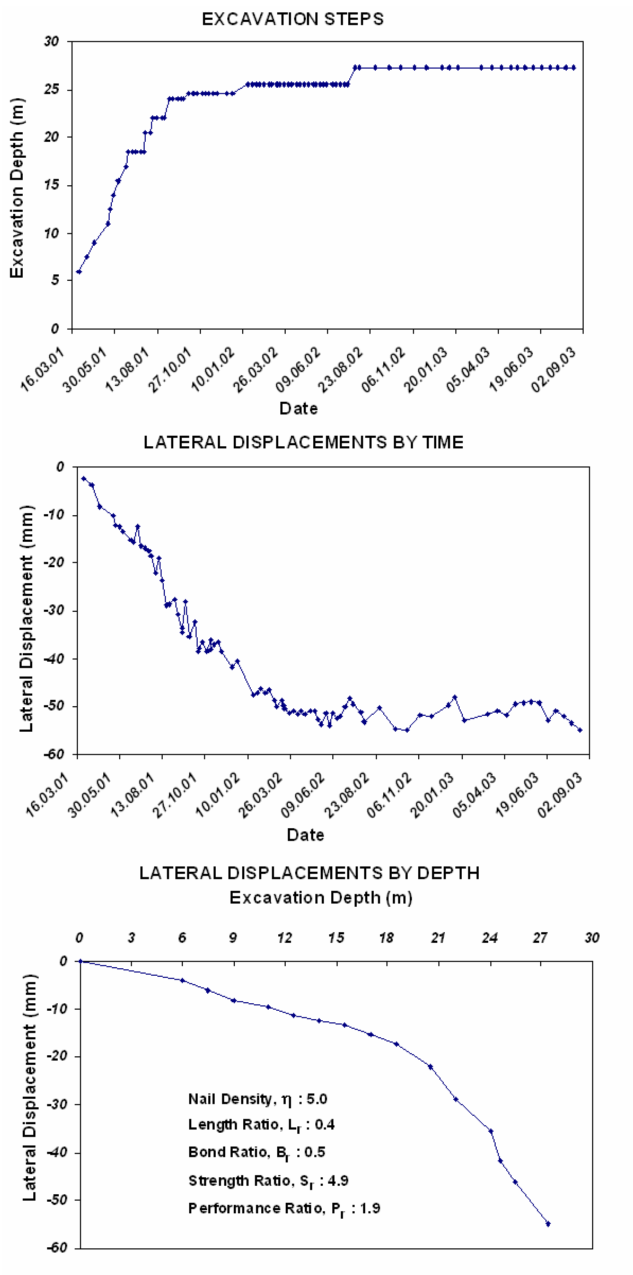

Fig. 13. Lateral Displacements for Case No.3, Canyon Complex, Inclinometer 7

By the analysis of the data given in Table 5, lateral displacements, δ_h, performance ratio, P_r, average nail length, L, and nail density, η versus the height of the soil nailed wall, H were developed and presented in Fig.'s 13 through 16. From these figures the following observations and evaluations are done for the soil nailed walls constructed in greywacke formation of the city Istanbul.

- It is seen that the linear increase in lateral displacement with the height of the wall is valid up to a certain height. The change in slope occurs at various heights and sooner for the weaker claystone than the stronger silicified sandstone case. Similar observation was made by Durgunoglu et al. (2003b) Using conventional methods of design, Federal Highway Administration (2003) and previously developed charts for estimating lateral displacements or performance ratio may be misleading in deep soil nailing applications.

- The performance ratio, P_r, for the greywacke formation is within the range of $1x10^{-3}$ to $3x10^{-3}$, depending on the nature of the lithological unit of the formation. For the strongest silicified sandstone with a typical value of E_m=250 MPa, $P_r \sim 1x10^{-3}$, on the other hand for the weakest claystone $P_r \sim 3x10^{-3}$ with E_m=50 Mpa where E_m is equal to $2(1+\nu)G_m$ and for ν=0.25, E_m=2.5 G_m. It is seen that these values tend to increase after 25 m for the case of sandstone and 15 m for the case of claystone.

- Average nail length, L, increases linearly with the height of soil nailed wall. The average nail length that could be utilized is about L=5 to 8 m for H=10 m and L=8 to 11 m for H=20 m.

- Nail density, L/S (m/m^2) also increases linearly with the height of the soil nailed wall. It is about 1.6 to 3.2 m/m^2 for H=10 m and 2.8 to 4.4 m/m^2 for H=20 m.

- From Figures 16 and 17 it is seen that two sections from Case No. 5, Tepe Shopping Mall, are overdesigned since they have noticeably long average nail lengths considering the small soil nailed wall heights. However, excessive nail lengths implemented on these sections have no or little effect on the lateral displacements or performance ratios as can be seen from the Fig. 14 and Fig. 15.

Table 5. Design and Performance Parameters for Soil Nailed Wall Case Studies – Greywacke

Case 1: BJK Fulya Complex, Fulya,Istanbul									
Inc. No.	H (m)	S (m^2)	L (m)	δ_h (mm)	η (m/m^2)	L_r	B_r	S_r (10^{-3})	P_r (10^{-3})
1	18,5	2,7	9,2	14,0	3,4	0,5	0,4	4,1	0,8
2	25,0	2,1	11,2	22,7	5,3	0,4	0,6	5,3	0,9
3	32,5	2,1	10,2	50,6	4,9	0,3	0,5	5,3	1,6

Case 2: Istinye Park Complex, Istinye, Istanbul									
Inc. No.	H (m)	S (m^2)	L (m)	δ_h (mm)	η (m/m^2)	L_r	B_r	S_r (10^{-3})	P_r (10^{-3})
1	10,0	3,0	5,1	26,6	1,7	0,5	0,2	3,7	2,7
2	10,0	3,0	8,3	22,0	2,8	0,8	0,3	3,7	2,2
3	12,0	3,0	6,0	36,7	2,0	0,5	0,2	3,7	3,1
4	12,0	3,0	8,8	24,7	2,9	0,7	0,3	3,7	2,1
5	14,0	3,0	9,1	19,9	3,0	0,7	0,3	3,7	1,4
6	16,0	3,0	8,2	45,3	2,7	0,5	0,3	3,7	2,8
7	18,0	3,0	9,3	56,7	3,1	0,5	0,3	3,7	3,1
8	20,0	3,0	9,7	80,8	3,2	0,5	0,3	3,7	4,0
9	22,0	3,0	10,1	96,5	3,4	0,5	0,4	3,7	4,4

Case 3: Kanyon Complex, Levent, Istanbul									
Inc. No.	H (m)	S (m^2)	L (m)	δ_h (mm)	η (m/m^2)	L_r	B_r	S_r (10^{-3})	P_r (10^{-3})
1	14,0	2,7	8,4	27,8	3,1	0,6	0,3	4,1	2,0
2	15,7	3,0	9,4	45,1	3,1	0,6	0,3	3,7	2,9
3	18,8	2,4	9,5	32,5	4,0	0,5	0,4	4,6	1,7
4	21,3	2,7	11,6	69,2	4,3	0,5	0,5	4,1	3,2
5	25,3	2,4	11,2	57,5	4,7	0,4	0,5	4,6	2,3
6	26,3	2,4	11,8	85,7	4,9	0,4	0,5	4,6	3,3
7	28,3	2,3	11,3	54,8	5,0	0,4	0,5	4,9	1,9
8	28,3	2,3	11,3	69,2	5,0	0,4	0,5	4,9	2,4
9	28,3	2,3	11,6	97,0	5,1	0,4	0,5	4,9	3,4

Case 4: Mashattan Residence, Maslak, Istanbul									
Inc. No.	H (m)	S (m^2)	L (m)	δ_h (mm)	η (m/m^2)	L_r	B_r	S_r (10^{-3})	P_r (10^{-3})
1	18,3	2,4	6,7	59,3	2,8	0,4	0,3	4,6	3,2

Case 5: Tepe Shopping Mall, Maltepe, Istanbul									
Inc. No.	H (m)	S (m^2)	L (m)	δ_h (mm)	η (m/m^2)	L_r	B_r	S_r (10^{-3})	P_r (10^{-3})
1	7,0	2,7	6,4	5,6	2,4	0,9	0,2	4,1	0,8
2	9,0	2,3	12,0	15,8	5,3	1,3	0,6	4,9	1,8
3	9,0	2,4	7,3	15,4	3,1	0,8	0,3	4,6	1,7
4	10,0	2,3	12,0	24,3	5,3	1,2	0,6	4,9	2,4

Case 6: Besler Warehouse, Pendik, Istanbul									
Inc. No.	H (m)	S (m^2)	L (m)	δ_h (mm)	η (m/m^2)	L_r	B_r	S_r (10^{-3})	P_r (10^{-3})
1	14,7	4,0	9,3	10,2	2,3	0,6	0,2	2,8	0,7
2	16,2	4,0	9,6	18,3	2,4	0,6	0,3	2,8	1,1
3	18,4	3,6	9,6	13,4	2,7	0,5	0,3	3,1	0,7

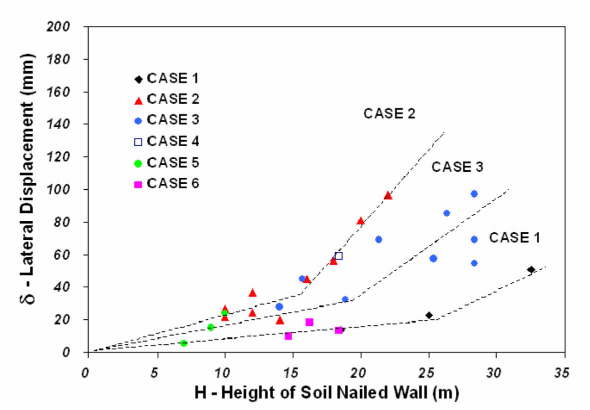

Fig. 14. Lateral Displacements, δ vs. Height of Soil Nailed Walls – Greywacke

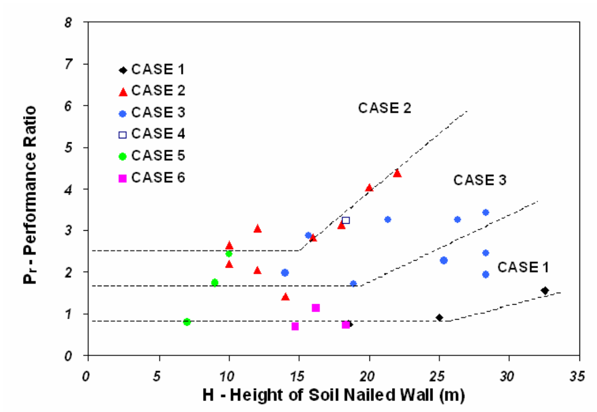

Fig. 15. Performance Ratios, P_r vs. Height of Soil Nailed Walls - Greywacke

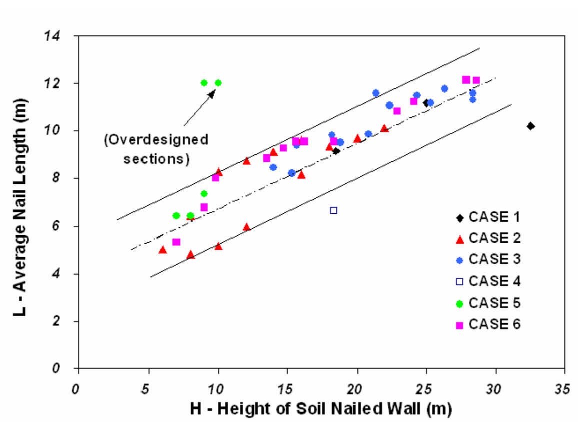

Fig. 16. Average Nail Lengths, L, δ vs. Height of Soil Nailed Walls – Greywacke

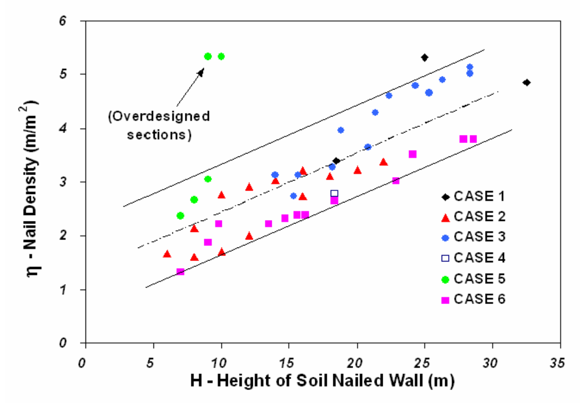

Fig. 17. Nail Density, η vs. Height of Soil Nailed Walls - Greywacke

INCLINATION OF THE WALL

It is known that the effective slope angle of the soil nailed wall has a great influence in the design and the performance of soil nailed walls. In other words, slope angle, nail density and the resulting performance ratio are interrelated. Based on the results of behavior of an approximately 37.0m deep soil nailed wall in similar subsoil conditions, it is shown that the lateral displacements decrease greatly with decreasing effective slope angle for similar nail densities used in the previous case studies, Icoz et al. (2008).

In this study, the wall height was about 37.0m which are divided to three stages by means of two horizontal berms. The width of the berms were respectively 5.0m and 2.0m with a common slope of 5:1 (5 vertical by 1 horizontal) for each stage. With the above geometry the effective slope angle for the complete nailed wall becomes equal to 69 degrees. The typical cross section and the picture of the subject wall is given in Fig.'s. 18 and 19.

Fig. 18. Soil Nail Retaining Wall

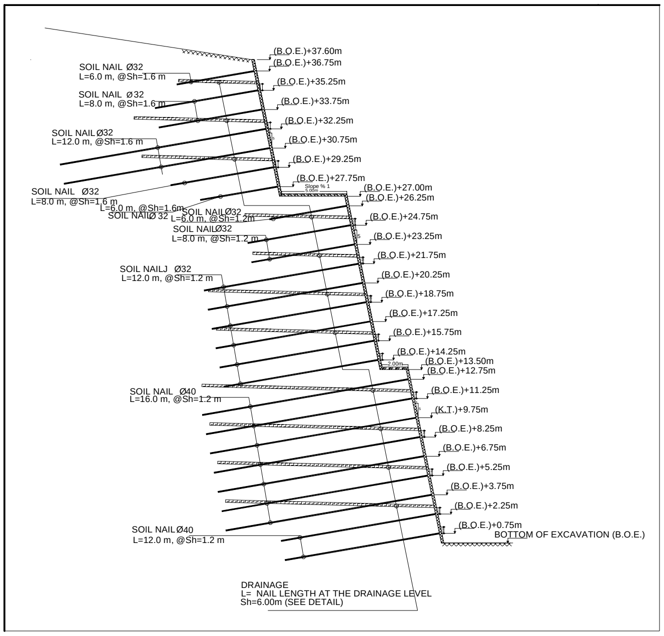

Fig. 19. Detailed Design Cross Section

The horizontal displacements recorded by two inclinometers are presented in Table 6 with nail densities.

Table 6. Summary of the Design and Performance of the Soil Nailed Wall at two Inclinometer Locations

	inclinometer-8	inclinometer-9
Wall Height, H (m)	37.1	37.5
Nail density, η (m/m^2)	5.7	5.6
Wall perf., P_r (10^{-3}, design)	0.23	0.23
Wall perf., P_r (10^{-3}, actual)	0.45	0.32

It is seen that the performance ratio is about P_r=(0.3-0.5)x10^{-3} for the average slope angle of β=69º. This ratio is much smaller than the performance ratio reported earlier for slope angle of 85º indicating the strong influence of slope angle to horizontal displacements under the similar nail densities given in Fig. 17 for H=37.0m.

CONCLUSIONS

Soil nailing is a very versatile excavation retaining system for deep excavations in urban areas surrounded by major structures and infrastructures provided that limiting lateral displacements are not exceeded.

Based on the previous positive records of flexible earth retaining structures during earthquakes in Turkey soil nailed walls in such excavations performed within the city of Istanbul whether temporary or permanent offer great advantage especially for the encountered greywacke unit and described seismic conditions.

It is shown that the modulus values and degradation ratios for greywacke formation do vary in a big range. Therefore, the predicted lateral displacements for such formations are only indicative regardless of the advanced numerical techniques applied in analysis.

As a result the values of performance ratio for soil nailed walls together with nail density in typical greywacke formation of the city of Istanbul are developed based on the lateral displacements that are monitored throughout the construction of various deep soil nailed walls as a guideline for future applications.

It is shown that average slope angle has great influence in resulting horizontal displacements and performance ratios.

For future applications performance of soil nailed walls are recommended to be monitored similarly and to be compared with provided range of performance parameters based on the lithological description of the greywacke formation and the height of the wall.

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