PERFORMANCE OF SOIL-NAILED AND ANCHORED WALLS BASED ON FIELD-MONITORING DATA IN DIFFERENT SOIL CONDITIONS IN ISTANBUL

Dogan Çetin
Yildiz Technical University,
Civil Engineering Department
Davutpasa Campus, Esenler, Istanbul, Turkey
E-mail: dogancetin56@hotmail.com

Keywords

deep excavation, wall displacement, soil formation, soil-nailed wall, anchored wall

Abstract

In this study, data on the lateral wall displacements of 28 deep excavations in Istanbul soil from over 90 field monitors were collected and analysed. The most commonly used retaining walls for deep excavations in Istanbul are soil-nailed shotcrete walls (SNPWs) and contiguous pile walls (CPWs). Other types of retaining walls include anchored micropile walls (MPWs), diaphragm walls (DWs), concrete walls (CWs) and secantpile walls (SPWs). The analyses were performed under two main headings: analysis of soil-nailed walls' data and analysis of anchored walls' data. The data of $\delta_{h,max}$ *generally range from 0.05%H to 0.35%H with an average value of 0.20%H in the soil-nailed projects. The data of* $\delta_{h,max}$ *generally range from 0.043%H to 0.32%H with an average value of 0.155%H in anchored pile wall projects. Some factors affecting the deformation of deep excavations, such as nail density, embedded wall ratio and wall stiffness, were studied based on field-monitoring data. Wall movements were also compared with observations in some case histories from around the world.*

1 INTRODUCTION

Due to the city's rapid economic growth, a number of deep excavation projects for high-rise buildings, shopping malls and metro systems have been carried out in Istanbul during the past two decades [1]. Estimates of the wall movements and ground deformations induced by deep excavations are critically important in urban areas in order to be able to provide safety for adjacent structures and buildings [2, 3]. Understanding the behaviour of excavation bracing is a complicated issue because of the number of factors affecting the performance of wall systems, such as soil type, base stability, compression and rebound, consolidation, wall-system stiffness, construction procedures, and workmanship [3, 4]. Any of these factors can contribute to the overall movement of a supported excavation. Therefore, great concern has been shown with respect to deep excavations since the report initiated by Peck [5]. Numerous researches have been performed to understand and evaluate the behaviour of retaining walls. Because of the difficulties in making a direct analysis of the performance of wall systems and the behaviour of ground deformation [3,6,7], case studies have been a better way to obtain information about deep excavations and retaining walls. Case studies performed by Ma et al. [3], Hwang and Moh [6], Finno and Bryson [8], Ou et al. [9], Hou et al. [10], Wong and Chou [11] can be given as examples.

Databases prepared by Goldberg et al. [12], Mana and Clough [13], Clough and O'Rourke [14], Ou et al. [15], Wong and Patron [16], Carder [17], Fernie and Suckling [18], Wong et al. [19], Hsieh and Ou [20], Long [21], Yoo [22], Moormann [23] and Leung and Ng [24] present comprehensive information about the performance of in-situ walls constructed in urban areas in terms of different soil conditions, adjacent structures and utilities.

In this study, data from field monitors on the lateral displacement of the walls from some 28 deep excavations in Istanbul soil were collected. The notation for the symbols and parameters used in this study is shown in Figure 1. The magnitudes of the lateral displacement for different types of retaining systems were compared with each other and also compared with relevant case histories worldwide. Furthermore, some factors affecting the deformation of deep excavations were studied.

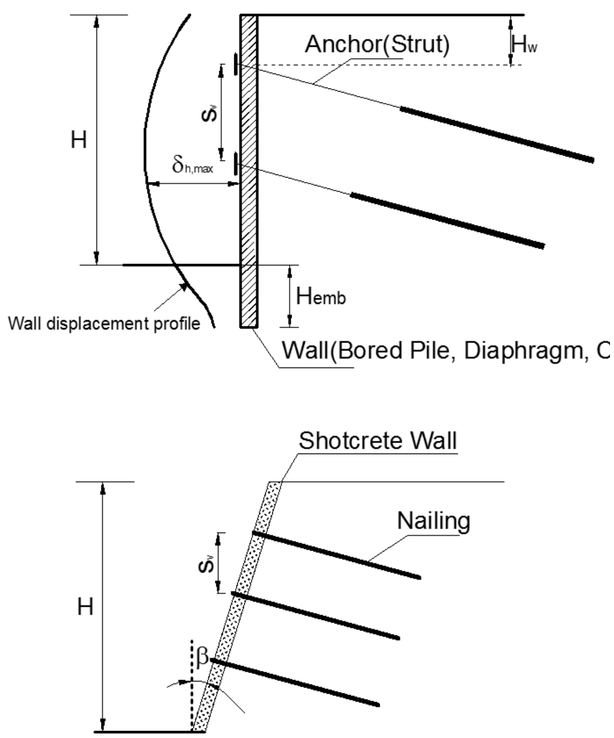

Figure 1. Definition of the wall and support parameters in a deep excavation.

H is the excavation depth, H_{emb} is the embedded wall length, s_v is the vertical distance between the anchors or soil-nailing levels, H_w is the depth of the ground-water level from the surface, $\delta_{h,max}$ is the maximum wall displacement and β is the wall inclination from the vertical in Fig.1.

2 GENERAL SOIL CONDITIONS IN PROJECT FIELDS

A very comprehensive and detailed geotechnical survey carried out by the Metropolitan Municipality of Istanbul between 2005 and 2009 for very large areas of both the Asian and European sides of the city [25, 26] was used to explain the soil profile and general soil properties in the project fields. As a result of that intensive work, 24 different local soil formations were identified on both the Asian and European sides. If the project fields are placed on the map of the microzonation work, it can be seen that 7 of the 24 local formations were encountered in deep-excavation projects. These local formations can be called Fill, Alluvium, Gungoren, Gurpinar, Bakirkoy, Cukurcesme and Trakya. The alluvium in the investigated areas mainly consists of clay-type materials of soft-to-medium stiffness. Sand layers are also present at different depths. The Gungoren formation is composed of clay and sand layers that are very stiff and dense. The over-consolidated clay layers in this formation show claystone properties. The Gurpinar formation generally consists of consecutive clay-claystone and/or sand-sandstone layers. The Bakirkoy formation contains limestone layers, but this formation also has clay-sand layers within the limestone layer. The Cukurcesme formation in the investigated areas is mostly composed of gravel and/or sand of different fractions and forms. The Trakya formation is the general name of the claystone-sandstone-mudstone in Istanbul. The upper level of this formation can be seen mostly as highly fractured and/or weathered. Therefore, the upper levels in the Trakya formation can be defined as clay or sand, depending on the main fraction of the material. Figure 2 shows the borders of the investigation areas. The investigation work can be classified as in-situ tests and laboratory tests.

According to the soil-investigation works carried out by the related department of the Metropolitan Municipality of Istanbul, the ground-water level is generally between 1 m and 20 m from the ground surface in the investigated area depending on the altitude of the point at which the measurement of the ground-water level was made.

2.1 In-situ Tests

The geological investigation and geophysical measurements were carried out as in-situ tests. The geological investigation consists of normal borehole, deep borehole, liquefaction borehole, landslide borehole and CPT. Table 1 shows the content of the geological survey.

Table 2 shows the content of the geophysical investigation.

Table 1. Content of the geological survey.

Type of investigation work	Number of borehole points for Asian Side	Number of borehole points for European Side	Total quantity of bore-holes for Asian Side (m)	Total quantity of boreholes for European Side (m)
Normal Borehole	4426	2830	98681	86840
Deep Borehole	122	27	11594	4201
Liquefaction Borehole	433	764	6683	12344
Landslide Borehole	10	608	227	18144
CPT Test	?	663	4076	8769

Table 2. Content of the geophysical investigation.

Measurement method	Number points measured for Asian Side	Number points measured for European Side	Total quantity (m)
Seismic refraction	4132	2762	435093
Seismic reflection	-	-	34105
PS-Logging	504	201	10997
Array microtremor	30	30	-
Electric resistance	80	2625	-

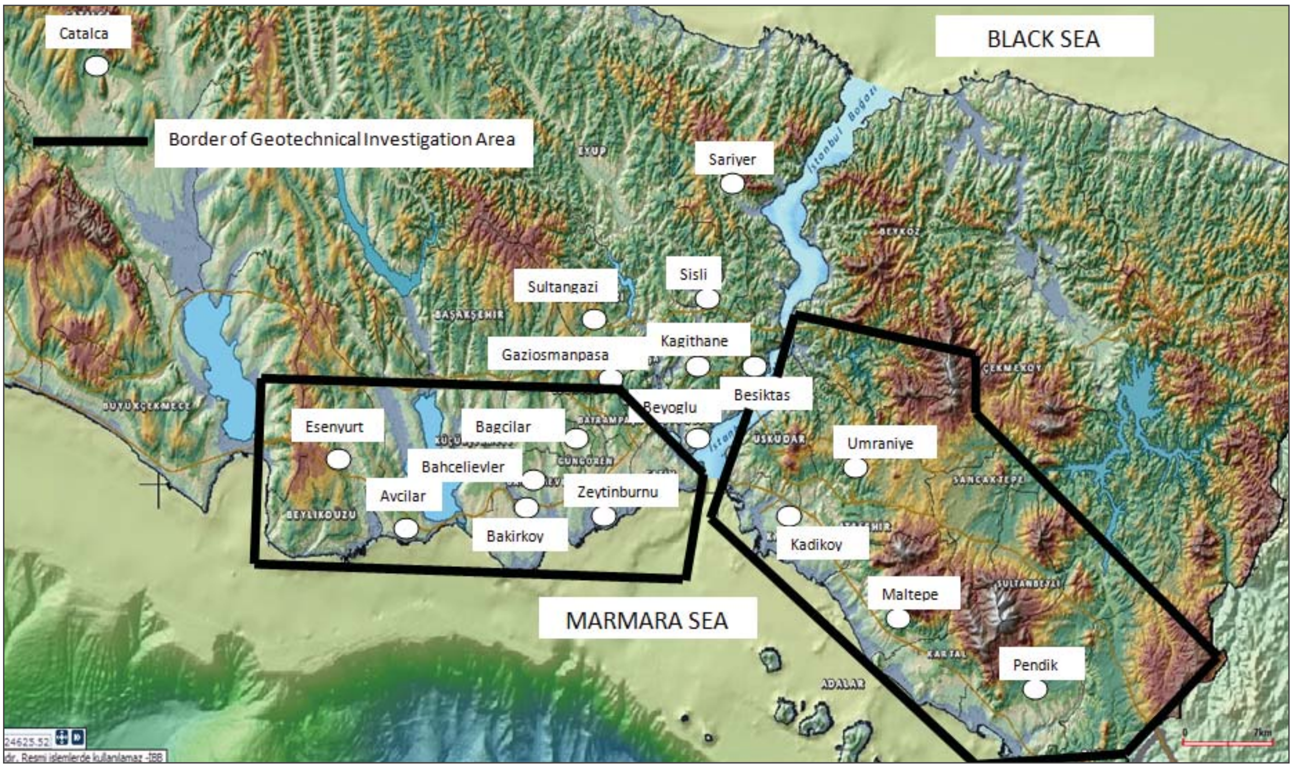

Figure 2. Location of the projects and the border of the geotechnical investigation area in Istanbul.

2.2 Laboratory Tests

Laboratory tests included whole basic soil tests such as Atterberg limits, sieve analysis, unaxial and triaxial compressive strength tests, natural water content tests, hydrometer tests and consolidation tests. According to the reports of the microzonation works [25, 26], for natural water content tests ASTM D2216, for sieve analysis ASTM D422, for hydrometer tests ASTM D4221, for Atterberg Limits tests ASTM D4318, for unconfined compression tests ASTM D2166 and for Triaxial Compression tests ASTM D2850 standards were followed. Table 3 shows the content of the laboratory tests.

Table 3. Content of the laboratory tests.

Side	Natural water content tests	Determination of the grain size distribution		Atterberg Limits	Unaxial Compressive Tests	Triaxial Tests	Consolidation
		Sieve analysis	Hydrometer Tests				
Asian	29072	29071	6867	21608	572	214	1339
European	53938	53938	124	46432	1120	462	2315

Table 4. Average soil properties of the local soil formation.

Local formation name	Definition of the formation	W_n (%)	W_L (%)	W_p (%)	I_p (%)	Particle size distribution			C_u (kPa)
						Clay and Silt (%)	Sand (%)	Gravel (%)	
Fill	New and old fill material	23.8	46.5	13.2	33.3	48.4	28.3	23.3	85
Alluvium	Sandy soft to stiff clay	32.2	50.3	13	37.3	68.1	26.4	5.5	69
Trakya	Mudstone, sandstone, claystone (from fractured to extensively fractured)	14.6	35.5	15.3	20.2	35.2	37.7	27.1	93
Gurpinar	Alternating sandy stiff clay-claystone	24.6	56.1	15.7	40.4	73.6	23.4	3	127
Gungoren	Soft-to-medium sandy clay	28.9	60.6	16	44.5	79.1	17.7	3.2	98
Bakirkoy	Limestone with clay strip	24.1	47.1	15.2	31.9	62.8	18	19.2	78
Cukurcesme	Clayey gravely sand	17.8	41.3	13.5	27.8	36.6	54.2	9.2	164

As a result of a comprehensive geotechnical investigation, 24 different local soil formations were identified on the Asian and European sides of Istanbul. As can be seen from Figure 2, most of the projects were carried out bordering the geotechnical investigation area. Therefore, the soil formations encountered in the project files were identified using the results of the geotechnical investigation. Selected projects were conducted in 7 different local soil formations. The properties of the soil formation and a brief explanation of the local soil formation are given in Table 4.

3. SUMMARY OF INFORMATION FROM COLLECTED DATA

For the database, data from 28 individual projects in Istanbul were collected. Almost all of these projects were carried out in the past two decades. The data were mainly extracted from conference proceedings, PhD theses and a company database that contains a lot of valuable unpublished data. In each case, the measured wall displacement was analysed in terms of the wall type, the support system and its geometric configuration, the embedded wall ratio, the soil-nailing density, the wall stiffness and the soil type.

The most common method for measuring wall deflection is the use of vertical inclinometers, instruments for measuring the relative horizontal displacements through a borehole casing placed behind the wall. The bottom must be embedded to the zero displacement zone. An inclinometer is read using a probe. The probe measures the tilt, which can be converted to a horizontal movement. The inclinometer probe is connected to a power source and readout unit to enable the measurements. The electrical cable linking the probe to the readout device is usually marked in 0.5-m increments so the shape of the casing can be measured at consistent depths. The measurements are taken starting at the bottom of the inclinometer. Subsequent readings are made of the casing as the probe is raised incrementally, usually at 0.5-m intervals, to the top of the casing. This process is conducted shortly after the casing is installed to determine the initial shape of the casing, i.e., to obtain the zero reading. The difference between the zero and the subsequent readings is used to determine the change in the shape and position of the initially vertical casing [27].

Two sets of casing grooves allow the inclinometer probe to be oriented in either of two planes set at 90° to each other. Therefore, the horizontal components of movement, both transverse and parallel to any assumed direction of movement, can be computed from the inclinometer measurements [28]. The measurement accuracy is generally to hundredths of a mm.

The most commonly used retaining walls for deep excavations in Istanbul are soil-nailed shotcrete walls (SNPWs) and contiguous pile walls (CPWs). Other types of retaining walls include anchored micropile walls (MPWs), diaphragm walls (DWs), concrete walls (CWs) and secant pile walls (SPWs). Summarized information about the projects is given in Table 5.

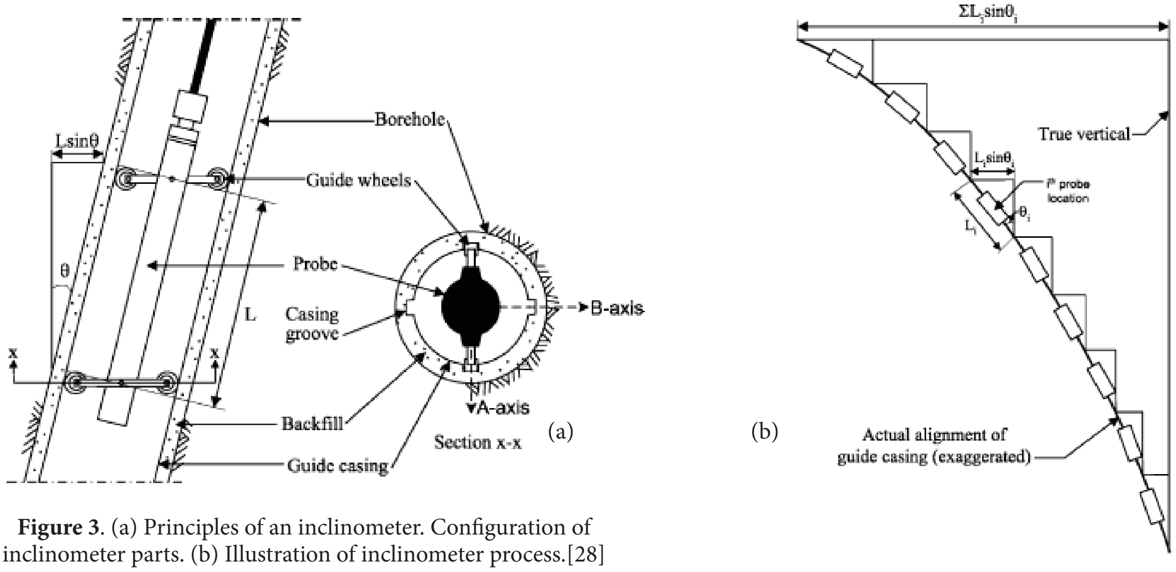

Figure 3. (a) Principles of an inclinometer. Configuration of inclinometer parts. (b) Illustration of inclinometer process.[28]

Table 5. Summary information of the projects.

No.	Project Name	District	Support System	Wall type	Soil profile	Soil formation name	H (m)	H_w (m)	H_{emb} (m)	S_v (m)	S_h (m)	η (m/m^2)	EI (kNm^2/m)	n	$\delta_{h,\,max}$ (mm)	Reference
1	Baumax AVM	Avcilar	Multi anchored	80 cm diameter bored pile	Clayey sand-Hard clay	Gung-oren	15.8	-	6.7	2.4	1	-	312500	4	7.9 25.3 18.9 36.3	Unpub-lished data
2	Karabulut Textile Factory Project	Kagith-ane	Multi an-chored+ strut	65 cm diameter secant pile	Silty soft clay	Alluvium	8	-2	6	2	1.2	-	172300	2	18.4 30	Unpub-lished data
3	Busi-nessPort AVM	Bahce-lievler	Multi anchored	65 cm diameter bored pile	Clayey sand-clay	Gung-oren	21.6 21.6 21.6 19 18	-	3.7 3.7 3.7 4.1 4.5	2.5	1.8	-	115000	5	49.7 68.5 43.2 34.2 19.8	Unpub-lished data
4	Taksim Residence	Sisli	Multi anchored	25 cm diameter micro pile	Mud-stone-sandstone	Trakya	19.65 18.70	-14		?	?	-	1070	2	19.65 16.8	Cetin et al. [29]
5	Bomonti	Sisli	Multi anchored	25 cm diameter micro pile	Fractured sandstone	Trakya	26 22.8	-	2.5 2.1	2.5	1.5	-	2350	2	43.3 42.5	Unpub-lished data
			Soil nail-ing	Shotcrete wall	Fractured sandstone	Trakya	22	-		1.5	1.5	5.5		1	14.60	
6	Tekfen Towers	Levent	Soil nail-ing	Shotcrete wall	Highly fractured gray-wacke	Trakya	25 24 20 19.50 24	-	-	1.5	2	2.85	?	5	45 14.4 10 9.75 19.2	Yilmaz et al. [30]
7	Otoport	Esenyurt	Multi anchored	80 cm diameter bored pile	Clayey sand-san-dy clay	Gung-oren	25 21	-6	7.2 6	2.3	2		312500	2	51.7 22.1	Unpub-lished data
8	Setat 2002	Levent	Soil nail-ing	Shotcrete wall	Dense fill	Fill	9.50 10 10 13	-	-	1.5	2	2.4	?	4	7.6 10 10 22.1	Yilmaz et al. [30]

Table 5. Summary information of the projects (Continued).

No.	Project Name	District	Support System	Wall type	Soil profile	Soil formation name	H (m)	H_w (m)	H_{emb} (m)	S_v (m)	S_h (m)	η (m/m²)	EI (kNm²/m)	n	$\delta_{h,\ max}$ (mm)	Reference
9	Ideal Hospital	Gazios-manpasa	Multi anchored	100 cm diameter bored pile	Gravely sand overlying sandstone	Cuku-rcesme Trakya	29.2	-	4.4	2.9-2.5-2	1.2	-	699850	1	18.9	Unpub-lished data
10	Metal Co. Factory Project	Catalca	Multi anchored	65 cm diameter secant pile	Sandy gravely clay	?	9.25 5.25	-	6.75 3.75	2.5 1.7	1.8 2	-	123240	2	16.2 4.1	Unpub-lished data
11	BJK Fulya Complex	Besiktas	Soil nail-ing	Shotcrete wall	Exten-sively fractured sandstone	Trakya	18.50 25 32.5	-	-	1.5	1.8	3.4 5.3 4.9	?	3	14.8 22.5 52	Keskin [1]
12	Saglık Group Hotel Project	Beyoglu	Single prop	65 cm diameter secant pile	Alluvium	Alluvium	6.1	-7	5.9	-	-	-	172300	2	7.4 7.9	Unpub-lished data
13	Erdem Hospital	Gunesli	Multi anchored	65 cm diameter bored pile+ reinforced concrete wall	Medium-hard clay	Güng-oren	16.3 16.3	-	3 3	1	0.9-1.8	-	122570	2	45.5 13.7	Unpub-lished data
14	Filiz Con-struction Co.	İkitelli	Multi anchored	80 cm diameter bored pile	Medium-hard clay	Gung-oren	18.2	-	3	-	-	-	312500	4	7.95	Unpub-lished data
15	Besler Co. Ware-house	Pendik	Soil nail-ing	Shotcrete wall	Exten-sively fractured grey-wacke	Trakya	14.7 16.2 18.4	-	-	2 2	2 1.8	2.3 2.4 2.7	-	3	10.3 17.8 12.9	Keskin [1]
16	Ozbas Cons. Co. Residence Project	Kadikoy	Multi anchored	25 cm diameter micro-pile+ 40 cm con-crete wall	Highly fractured sandstone overlying Highly fractured limestone	Trakya Bakirkoy	22.9 25.9 25.9 22.7	-	-	2.1	1.8	-	233940	4	9.1 30.7 40.3 35.7	Unpub-lished data
17	Isti-nyepark	İstinye-Sariyer	Soil nail-ing	Shotcrete wall	Exten-sively fractured gray-wacke	Trakya	10 10 12 12 14 16 18 20 22	-	-	1.5	2	1.7 2.8 2 2.9 3 2.7 3.1 3.2 3.4	?	9	27 22 37.2 25.2 19.6 44.8 55.8 80 96.8	Keskin [1]
18	Kanyon	Levent	Soil nail-ing	Shotcrete wall	Exten-sively fractured gray-wacke	Trakya	14 15.7 18.8 21.3 25.3 26.3 28.3 28.3 28.3	-	-	1.5	2	3.1 3.1 4 4.3 4.7 4.9 5.0 5.0 5.1	?	9	28 45.5 31.9 68.2 58.2 86.8 53.7 67.9 96.2	Keskin [1]

Table 5. Summary information of the projects (Continued).

No.	Project Name	District	Support System	Wall type	Soil profile	Soil formation name	H (m)	H_w (m)	H_{emb} (m)	S_v (m)	S_h (m)	η (m/m^2)	EI (kNm^2/m)	n	$\delta_{h,\,max}$ (mm)	Reference
19	Zeytinburnu Municipality Underground Parking Lot Project	Zeytinburnu	Multi anchored	45 cm diameter bored pile	Limestone with clay layers	Bakirkoy	11.3		3.7	2.6	2.1	-	29240	6	28.5 34 6.9 8.8 26.6 20.1	Unpublished data
20	Alper Co. Company Residence Project	Umraniye	Soil nailing	Shotcrete wall	Fractured Sandstone	Trakya	15.2 15.2			1.6	1.4	-		2	24.9 34.5	Unpublished data
21	Mashattan Residans	Maslak	Soil nailing	Shotcrete wall	Extensively fractured graywacke	Trakya	18.3			1.5	1.6	2.8		1	58.6	Keskin [1]
22	Terrace-Mix	Esenyurt	Multi anchored	80 cm diameter bored pile	soft-medium clay	Gurpinar	11.5 11.5 13.4 13.4		12 12 9.6 9.6	2.2	1.25	-	312500	4	10.4 15.3 26.9 17.2	Unpublished data
23	Tepe Shopping Mall	Maltepe	Soil nailing	Shotcrete wall	Extensively fractured graywacke	Trakya	7 9 9 10			1.5	1.8	2.4 5.3 3.1 5.3		4	5.6 16.2 15.3 24	Keskin [1]
24	Cultural Center	Sultangazi	Multi anchored	65 cm diameter bored pile	Fill -Sandstone	Fill Trakya	17.6 17.6		3 3	2	1.7	-	146000	2	4.5 6.7	Unpublished data
25	Hotel Radisson	Kucukcekmece	Soil nailing	Shotcrete wall	clay-sand-limestone-over consolidated clay	Gungoren Bakirkoy	7.5 7.5		-	2	2	-		2	15.4 38.4	Durgunoglu and Olgun [31]
26	Axis Shopping Mall	Kaigthane	single anchored +multi propped	Diaphragm wall	Soft clay overlying	Gungoren Trakya	17		-			-	1280000	1	100	Durgunoglu et al. [28]
27	Faco Medicine Factory Project	Levent-Besiktas	Multi anchored	65 cm diameter bored pile 25 cm diameter micropile	Graywacke	Trakya	22 18		1.5 1.5	3.2 2.7	1.95 2.1	-	115000 2350	1 1	45 36	Adatepe et al. [33]
28	Siyavuspasa Underground Parking Lot Project	Bahcelievler	Multi anchored	80 cm diameter bored pile	Fill overlying Hard clay	Fill Gurpinar	11		3	2.25	1.7	-	312500	4	10.1	Unpublished data

H is the excavation depth, H_w is the depth of the underground water level from the surface, H_{emb} is the embedded wall length, S_v is the vertical distance between the anchor or soil-nailing levels, S_h is the horizontal distance between the anchor or the soil nailing, η is the nail density (m/m^2), EI is the wall stiffness, n is number of the inclinometers in a project, $\delta_{h,max}$ is the maximum lateral wall displacement in Table 5.

The anchor properties in the anchored wall projects are given in Table 6.

4 DATA ANALYSIS

4.1 Analysis of soil-nailed wall data

Soil nailing is a useful technique for constructing excavations by reinforcing with fully bonded steel bars. The reinforced surface is stabilized with sprayed concrete, which creates a zone similar to a conventional gravity retaining wall. However, this sprayed concrete face does not play a vital role in the structural stability of the soil-nailed wall system. The inclination to the vertical of the wall, the soil condition, the excavation depth and the nail density per unit length of the wall (m^2/m) can be considered important factors affecting the performance of the wall system. Figure 4 shows the relationship between the maximum lateral displacement of the wall ($\delta_{h,max}$) and the excavation depth (H) for soil-nailed shotcrete wall systems. The data shown in Figure 4 are from projects 5, 6, 8, 11, 15, 17, 18, 20, 21, 23 and 25.

There is a clear relationship between $\delta_{h,max}$ the maximum lateral displacement and the excavation depth. The data of $\delta_{h,max}$ generally range from 0.05%H to 0.35%H

Table 6. Anchor Properties for anchored walls.

Project No	Project Name	Excavation Depth (m)		Number of Anchor Rows	Anchor Length (m)		Tendon Diameter (")	EA (kN/m)	Allowable Tensile Capacity (KN)
		Min.	Max.		Min.	Max.			
1	Baumax AVM	15.80		6	20	25	0.6	112000	728
2	Karabulut Textile Factory	8		3	20	14	0.6	84000	545
3	BusinessPort	18	21.60	5-8	12	22	0.6	84000	545
4	Taksim Residence	18.7	19.65	?	?	?	0.6	84000	545
5	Bomonti Hotel and Congress Center	22.8	26	11	12	28	0.6	84000	545
7	Otoport	21	25	10	35		0.6	84000	545
9	Ideal Hospital	29.2		11	18	32	0.6	140000	910
10	Metal Co. Factory	5.25	9.25	3-4	13	19	0.6	84000	545
13	Erdem Hospital	16.3		7	19	30	0.6	84000	545
14	Filiz Co. Factory	18.2		6	14	25	0.6	84000	545
16	Ozbas Residence	22.7	25.9	12	13	35	0.6	84000	545
19	Zeytinburnu Parking lot	11.3		4	14	20	0.6	84000	545
22	Terramix	11.5	13.4	4-5	14	26	0.5	59200	385
24	Cultural Center	8-17.6		3-8	12	19	0.6	84000	545
27	Faco Medicine Factory	18	22	7-9	13	22	0.6	84000	545
28	Siyavuspasa Parking lot	11		4	14	21	0.5	59200	385

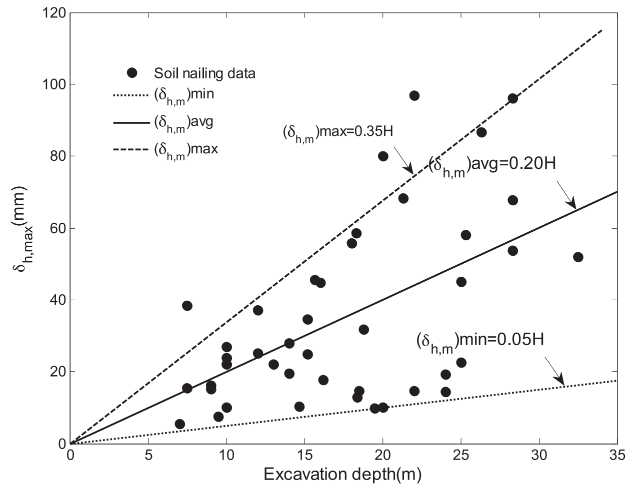

Figure 4. Relationship between maximum wall displacement and excavation depth for soil-nailing data.

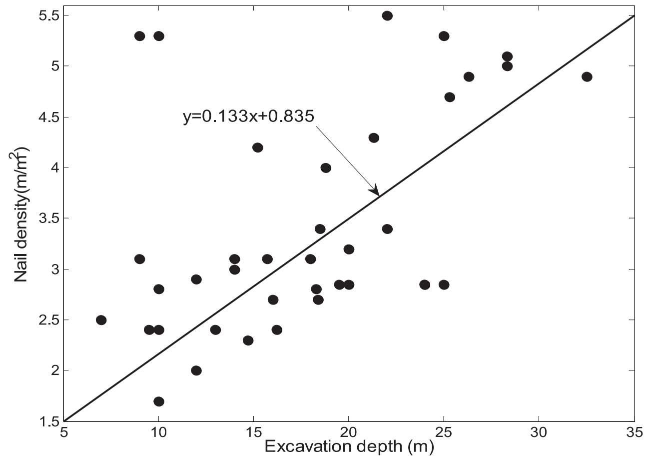

Figure 5. Relationship between nail density and excavation depth.

with an average value of 0.20%H. Except for projects 8 and 23, all the data shown in Figure 4 were obtained from projects carried out in the Trakya formation that is mainly composed of claystone-sandstone-mudstone, from extensively fractured to highly fractured. With a few exceptions, it can be said that the distribution of the data is within very reasonable limits. The data outside the limit are from Projects 17 and 25. Project 17 was conducted in the Gurgoren formation, which, composed of soft clay layers, is a weak soil formation in comparison to the Trakya formation. The excavation depth and the maximum wall displacement as a percentage of excavation depth were 7.5 m and 0.51%H, respectively, for project 17. It can be said that the wall movement beyond the maximum limit was due to the weak soil condition. In project 25 there were 9 inclinometers. The data from 7 inclinometers are within the limits, while the data from only 2 inclinometers are outside the limits. Sometimes, unexplained, excessive wall movement can be seen in projects that have very long facades.

Generally, the inclination of the wall varies between 5° and 11° to the vertical in soil-nailing projects. This inclination has some positive effects on the performance of the wall, such as a lower earth pressure, a lower soil density and a better safety factor in comparison with the condition of a zero wall inclination to the vertical. Mittal [34] conducted a study on the effects of the variation of some design parameters, such as the nail length, the nail inclination and the wall inclination, on the safety of the wall. It was found that the safety factor of the wall system increases uniformly with an increasing wall inclination up to 20° to the vertical. Beyond this angle, the dimension of the increase of the safety factor of the wall system is very high.

4.1.1 Influence of nail density

The nail density can be calculated as follows:

$$\eta = L/s_v\, s_h \;\; [1, 35] \qquad (1)$$

where η is the nail density, L is the average nail length, s_v is the vertical distance between the nail levels and s_h is the horizontal distance between the nails.

Figure 5 shows the relationship between the nail density and the excavation depth. The nail density increases with the height of the soil-nailed wall. With the exception of a few points, the data are evenly distributed on both sides of the slope line.

Figure 6 (next page) shows the relationship between the nail density and maximum wall displacement.

The data are scattered over a wide range. Increasing the nail density is a natural consequence of increasing the excavation depth. Therefore, the nail density should be considered in conjunction with the excavation depth. It can be said that increasing the nail density is not a decisive factor solely on the performance of the wall.

4.2 Analysis of anchored wall data

The data for five different wall types were collected and analysed. Figure 7 shows the relationship between the maximum wall displacement and the excavation depth depending on the type of wall.

Similar to the soil-nailing data, there is a clear relationship between the maximum lateral displacement and the excavation depth. The data of $\delta_{h,max}$ generally range

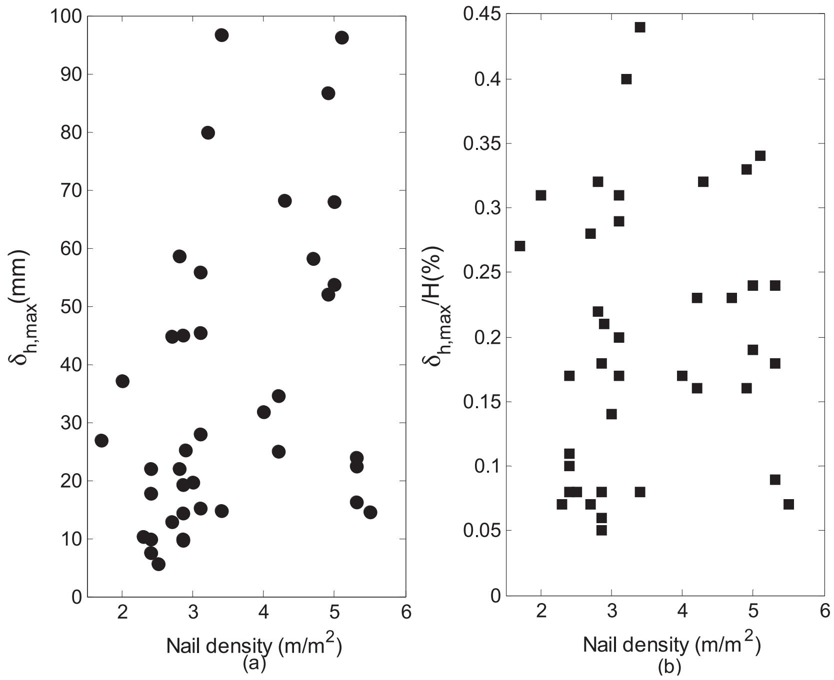

Figure 6. Relationship between nail density and maximum wall displacement.

from 0.043%*H* to 0.32%*H* with an average value of 0.155%*H*. With a few exceptions, it can be said that the distribution of the data is within very reasonable limits. The data from project 26 were obtained from soft clay overlying sandstone. The excavation depth was 17 m, which can be considered as a large depth. Although the wall type was a diaphragm wall, which has a high wall stiffness, the weak soil conditions combined with the large excavation depth may have caused high wall movements in practice.

The secant pile wall and the diaphragm wall systems are used to prevent water flow into the excavation site if the underground water level is above the final excavation depth. Although the data for the secant pile wall (SCW) and the diaphragm wall (DW) are

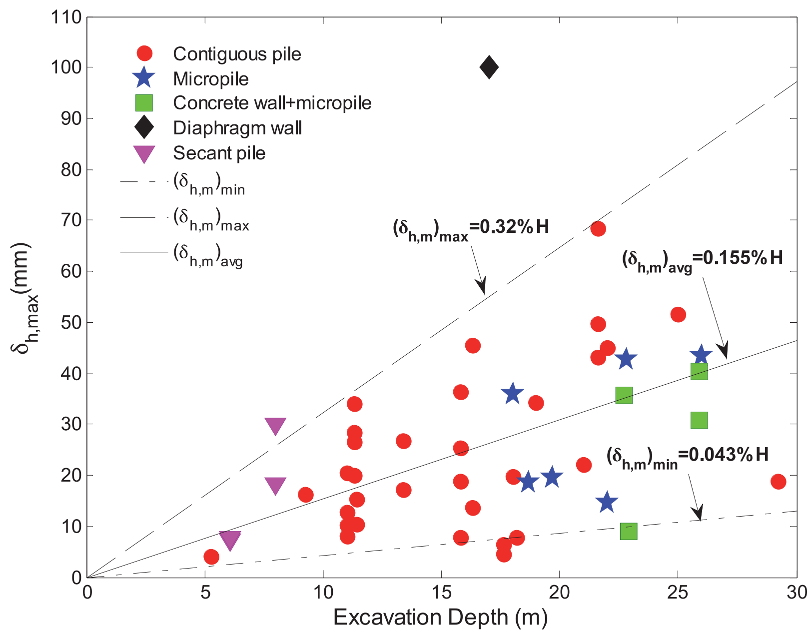

Figure 7. Relationship between maximum wall displacement and excavation depth depending on the type of wall.

very limited, it can be seen in Fig. 7 that the $\delta_{h,max}$ values from the SCW and DW projects are close to or over the max line. This limited data indicate that the underground water level should be taken into account very carefully in the design stage of the wall. MPW and MPW+CW data show that this type of wall has a very good performance in the soil conditions mentioned. As for contiguous pile walls (CPW), the data are generally between the maximum line and minimum line up to an excavation depth of H=20 m. However, for excavation depths greater than H=20 m, the data are above the average line and below the maximum line. An excavation depth of 20 m can be considered as a threshold for a CPW.

Table 7 shows the results obtained from projects 1, 2, 7 and 13 and the results given by some researchers for soft clay soil conditions regardless of the construction method or wall type.

Table 7. Comparison of this study's results with other studies for soft-to-stiff clay condition.

Study	$\delta_{h,max}$ / H			Soil Condition	Note
	Min.	Avg.	Max.		
This study (project 2, 7, 13, 22)	0.09	0.18	0.37	Soft-to-stiff clays	Four different project results
Goldenberg et al. [20]		0.90		Soft-to-stiff clays	Case histories collection
Bentler [37]		0.452		Soft-to-stiff clays	Case histories collection
Wang et al. [36]		0.452		Soft-to-stiff clays	Case histories collection
Kung et al. [38]		0.39		Taipei clay	Case histories collection
Ou et al. [15]		0.40		Taipei soft soil	Case histories collection

As can be seen in Table 7, the average limit of lateral movement for soft-to-stiff clays is 0.18%H. This is smaller than the values given by Goldenberg et al. [20], Bentler [37], Wang et al. [36], Kung et al. [38] and Ou et al. [15].

Long [21] presented a database consisting of about 300 case histories collected from different soil conditions with different wall and support types. As a result of an intensive analysis, it was found that the normalized maximum lateral movement values, $\delta_{h,max}$, are mostly between 0.05%H and 0.25%H, where H is the excavation depth. In this paper, for soil-nailing data, the maximum lateral movement values range from 0.05%H to 0.35%H with an average value of 0.20%H, and for anchored wall data, the maximum lateral movement values range from 0.043%H to 0.32%H with an average value of 0.155%H. The maximum lateral values presented by Long [21] and the maximum lateral values presented in this study differ only slightly from one another.

Tomlinson [40] reviewed 34 case histories of deep excavations conducted with different methods. The results were grouped into three major categories of ground condition. For soft-to-firm NC clays, $\delta_{h,max}$ ranges from 0.08%H to 0.58%H with an average value of 0.30%H, for stiff-to-hard OC clays, $\delta_{h,max}$ ranges from 0.06%H to 0.30%H with an average value of 0.16%H and for sands and gravels, $\delta_{h,max}$ ranges from 0.04%H to 0.46%H with an average value of 0.19%H. Projects 1, 10, and 14 were conducted in hard clay. For these projects, $\delta_{h,max}$ ranges from 0.04%H to 0.23%H with an average value of 0.12%H, which are close to the values reported by Tomlinson [40] for hard clays.

A total of 536 case histories were collected and analysed by Moorman [23]. These case histories were classified into five categories in terms of the ground condition. For stiff clays in Moorman's database, the upper limit of the maximum lateral movement is 1%H and most of the data are under the 0.5%H limit. These values are higher than the values obtained from projects 1, 10 and 14 in this study. For very limited data from a deep excavation conducted in rock, the upper limit of the maximum lateral movement is 0.5%H and most of the data are under the 0.25%H limit. In this study, most of the data for the maximum lateral movement obtained from projects conducted in a rock formation are under 0.20%H, which is very close to the value for a deep excavation conducted in a rock formation presented by Moorman [23].

4.2.1 Influence of embedded depth ratio

The embedded depth ratio can be expressed as follows,

$$R_{emb} = H_{emb} / H \qquad (2)$$

where H_{emb} is the embedded depth of the wall and H is the excavation depth (m). This ratio is an important factor that reflects the economy of the wall [36]. Figure 8 shows the relationship between the maximum wall displacement and the embedded depth ratio of the wall.

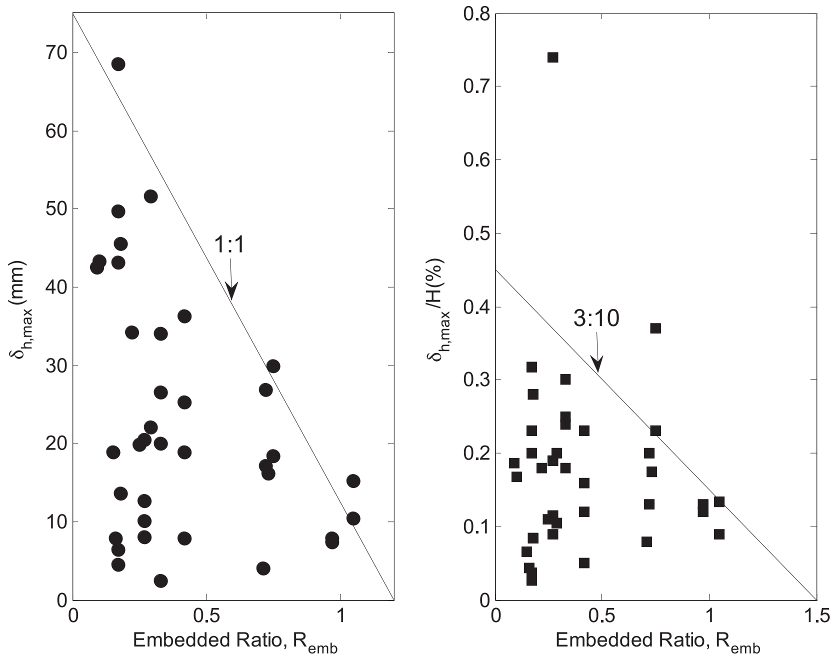

Figure 8. Relationship between maximum wall displacement and the embedded depth ratio of the wall.

The dimensions of the maximum wall displacement are shown in mm units in Fig. 8(a), while they are shown as a percentage of $\delta_{h,max}/H$ in Fig. 8(b). Although the dimensions of the maximum wall displacement were expressed in two different ways, it can be seen that there is a clear trend that the embedded ratio increases while the lateral displacement, or $\delta_{h,max}/H$ ratio, decreases in accordance with the inclination line (Fig.8 (a) and (b)).

Projects 2 and 22 have a higher embedded ratio. Project 2 was conducted in very soft clay soil conditions. There was a risk that the anchors would not work because of the soft soil conditions. Therefore, the embedded ratio selected was very high. Similarly, project 22 was conducted in clay soil that had a landslide risk. Thus, the embedded ratio selected was more than 1. According to the displacement value of the wall, it can be said that a

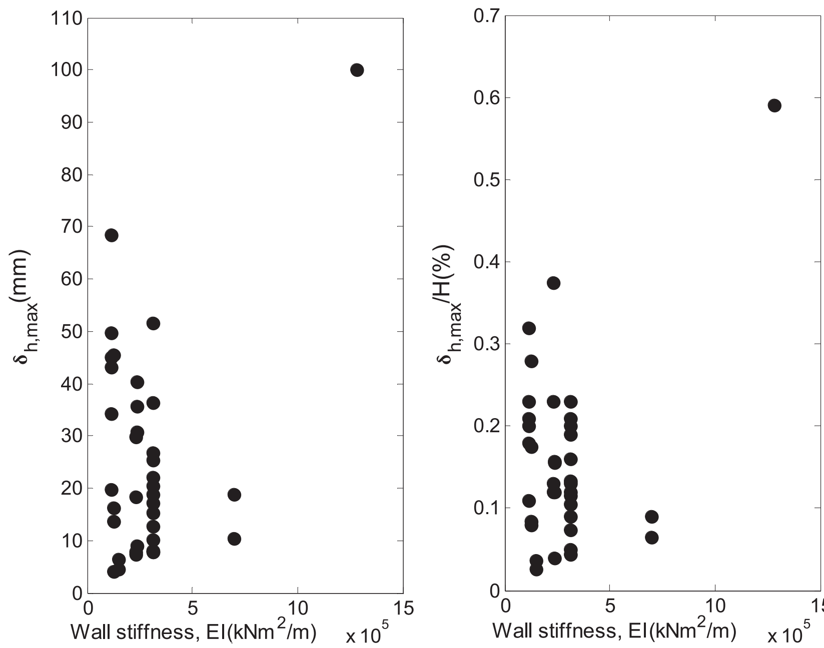

Figure 9. Relationship between maximum wall displacement and wall stiffness.

high embedded ratio is a strong parameter to prevent excessive displacements provided that selection of high wall stiffness in soft soil conditions.

4.2.2 Influence of wall stiffness

Wall stiffness can be expressed as *EI*, where *E* is the elasticity modulus of the concrete and I is the moment of inertia of the wall. Figure 9 shows the relationship between the maximum wall displacement and the wall stiffness.

There is no definite information about the thickness of the shotcrete walls. The wall stiffness of the anchored walls was considered in this analysis. Figure 9 shows the data obtained from projects with large-diameter pile walls. Except for projects 9 and 26, the wall stiffness of the anchored pile walls is less than 500,000 kNm^2/m and the data from anchored pile walls vary from 0.05%*H* to 0.45%*H*. There is a large scatter in the data. It can be said that there is no direct or no linear relationship between the wall stiffness and the movements. Hence, it can be interpreted that the wall movements are mainly independent of the wall stiffness. This result is consistent with those reported by Moormann [23], Moormann [39] and Long [21].

This study is the first attempt to prepare a deep-excavation database for Istanbul. Although there are limited data for some analyses, this database provides a good idea about the dimensions of wall movement. This database can be improved by collecting additional data in the future.

4.2.3 Influence of soil type

All the anchored wall data were plotted in Figure 10 in terms of the main soil type in which the projects were conducted.

The data for the Gungoren formation are around the average line up to an excavation depth of 20 m, after which the data are between the maximum and average lines. For the alluvium data, although the excavation depths are low, the data are between the maximum and average lines. The data for the Gurpinar formation are around the average line. The data from the Trakya formation are far from the maximum line even though the excavation depths are greater than 20 m. Because the data for the fill overlying Trakya formation and the Trakya-Bakirkoy formation are very limited, no interpretation can be made. However, it can be said that the data for the Trakya formation are the best results, regardless of soil type, wall type and support type.

5. CONCLUSIONS

On the basis of the results from this study, the following conclusions can be drawn:

- The results obtained show that successful wall performance can be obtained under a wide variety of soil conditions provided that suitable wall and/or support systems are chosen in the design phase.

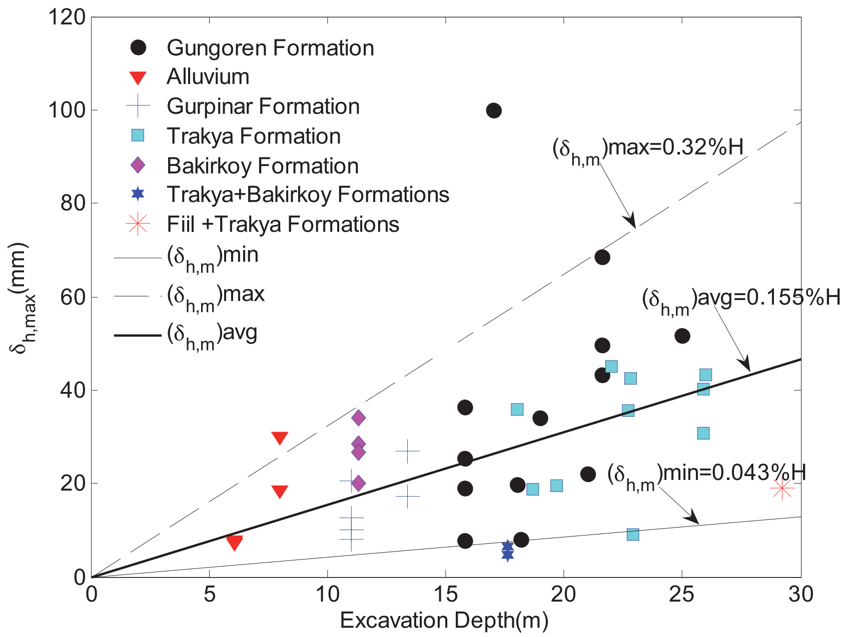

Figure 10. Relationship between maximum wall displacement and excavation depth depending on soil type.

- The maximum lateral displacement of the wall increases with an increasing excavation depth for all types of walls. The data for the SCWs and DWs are close to or over the max line. These limited data show that the underground water level should be taken into account very carefully in the design stage. The data for the MPWs and MPWs + CWs show that these types of walls perform well. The data for CPWs are generally between the max line and min line up to a H=20 m excavation depth. However, for an excavation depth over H=20 m, the data are above the average line and between the average and maximum lines. An excavation depth of H=20 m can be considered as a critical excavation depth for CPWs.
- The data for $\delta_{h,max}$ generally range from 0.05%H to 0.35%H with an average value of 0.20%H in soil--nailed projects. The data for $\delta_{h,max}$ generally range from 0.043%H to 0.32%H with an average value of 0.155%H in anchored pile wall projects
- The nail density increases with the height of soil--nailed walls. It should average 2.2 m/m^2 for H=10 m, 3.5 m/m^2 for H=20 m and 4.8 m/m^2 for H=30 m, according to the data obtained from projects conducted in Istanbul.
- With regard to soil-nailing shotcrete wall systems, it can be said that a soil-nailed shotcrete wall system is a very suitable system in rock conditions if there is no adjacent structure or infrastructure.
- Wall inclination to the vertical is an important factor to be able to obtain good performance for soil--nailing projects.
- In light of the analysis, there is a clear trend that the maximum wall displacement decreases with an increasing embedded ratio. Especially in soft soil conditions, a high ratio should be chosen to be able to prevent excessive soil and wall movements. However, this ratio is also related to the economics of the project. Therefore, this ratio should provide both safety and economy at the same time.
- There is no linear relationship between the wall stiffness (EI) and the wall movements ($\delta_{h,max}$). A number of different $\delta_{h,max}$ values can be seen for the same EI values. In this case, the excavation depth is a more important parameter than the embedded ratio.
- Soil type has an important influence on the dimensions of wall movement. The project conducted in the Trakya formation had the best results in terms of wall movement. Down to an excavation depth of 20 m, the wall movements for the projects conducted in the Gungoren formation are around the average line. However, beyond an excavation depth of 20 m designers should be careful in the design process for projects in the Gungoren formation.

Acknowledgements

The author would like to thank C.E. Mahmut Candan and Geoform Engineering and Consultancy Company for their help with the data collection.

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