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Single Bore Multiple Anchored Diaphragm Walls in Deep Soft Alluvial Soils

L'utilisation et performance des parois moulées ancrés par des tirants scellés et précontraints à multiple phase dans de sols alluviaux moux

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ABSTRACT: This paper presents the design, construction and performance of two anchored diaphragm wall projects utilizing Single Bore Multiple Anchor (SBMA) technology within deep alluvial soils; to support deep basement excavations in Turkey. The first project is the Mahall Bomonti Project; where a shoring system composed of 27,500 m^2 diaphragm wall with a total depth of 22 m to 28 m supported by 3-levels to 5-levels of SBMA was designed and constructed in order to support one of the deepest basement excavation of 18.5 m in Izmir, Turkey. The second project is the Ferko Line Project; where a diaphragm wall with a total depth of 20 m supported by 1-level of SBMA was designed and constructed so as to support one of the largest and deepest basement excavations in very soft soil conditions of Kağıthane region in İstanbul, Turkey for the first time. Additionally, 7-rows of jet grout columns were executed in order to improve the soil at the toe of the diaphragm wall. Within the scope of this project, 12,500 m² of diaphragm wall, 8,900 m of SBMA and 62,400 m of jet grout columns were completed. In both projects displacement of the reinforced concrete diaphragm walls were analyzed using finite element methods and compared with measurements of lateral displacements monitored during the course of excavation.

RÉSUMÉ: Ce document présente la conception, la construction et la performance des soutènement à parois moulées ancrées par tirants utilisant la technologie SBMA (Single Bore Multiple Anchor/ Ancrage scellé et précontraint à multiple phase) dans deux projets décrits ci-dessous. Ces projets de soutènement des excavations porfondes dans des sols alluviaux pour la construction des sous-sols ont été récemment achevés avec succès en Turquie. Le premier projet de soutènement conçu pour l'excavation des sous sols de Mahall Bomonti situé a İzmir en Turquie comprend un système de soutènement composé d'une paroi moulée de 27 500 m2 dont la profondeur varie de 22 à 28 m. La paroie est soutenue sur une hauteur de 18,5 m par 3 à 5 niveaux de tirants SBMA. Le deuxième projet est le projet de soutènement excavation de grande superficie pour les fondations et sous sols du project d'habitation "Ferko Style Project" à İstanbul en Turquie ; où un diaphragme de paroie moulée d'une profondeur totale de 20 m est executée complétement dans les argile trés molle de Kağıthane et y est ancrée par un niveau de SBMA . En outre, 7 rangées de colonnes de jet à haute pression ont été exécutées au pied de la paroie afin d'améliorer sa stabilité.

Keywords: Diaphragm Wall; Single Bore Multiple Anchor; SBMA; Deep Excavation; Alluvial Soil

1 INTRODUCTION

Due to the economical growth and urbanisation of Turkey in the 2000s, the increase in the number of large scale investment projects especially in the main cities of Turkey has necessitated the use of special watertight deep excavations for foundation of high rise buildings, mix-used complex and infrastructure projects.

The deep soft alluvial subsoil conditions, the safety of neighbouring structures, high ground water regime, deformation limitations must all be considered for choice of deep excavation support system. Therefore diaphragm wall supported by high capacity anchors, Single Bore Multiple Anchor (SBMA) technology; is selected as the most suitable and economical deep excavation system. The design and performance of deep excavation systems, sequence of works, quality control programs applied during the construction of both projects are summarized.

2 THE MAHALL BOMONTI PROJECT

2.1 General Information

The Mahall Bomonti Project comprises both residential and commercial developments and is being constructed on a land of approximately 45,000 m² in Bayraklı, Izmir in Turkey. In order to improve the social welfare of the region, nine historical buildings are to be restored within the scope of the project. Three new blocks will be constructed; Block-A consisting of a 15-storey podium area and a 57-storey tower, which will be the highest skyscraper in the region, and the Blocks-B and C consisting of three and four storey commercial and office areas respectively.

The maximum depth of foundation excavation is 18.50 m within the soft alluvial soil layers under a high water table. The general layout plan, geometric dimensions of the project and the excavation depth for each block is shown in Figure 1.

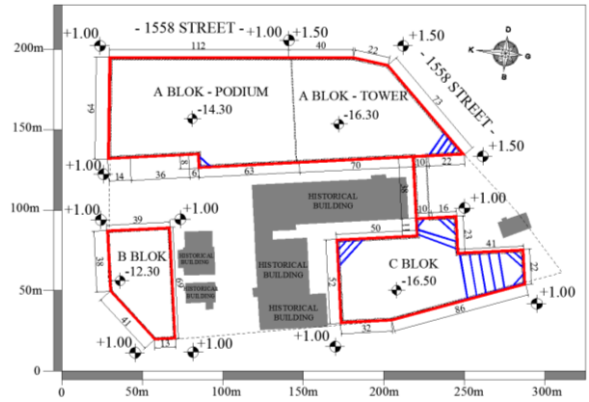

Figure 1. General Layout of the Project

A total of 27,500 m² of 80 cm thick diaphragm wall was constructed; laterally supported by a total of 55,200 linear metres of high capacity SBMAs, with a design load of 650 kN.

As part of the investigation anchor test program; a number of Single Unit Anchor Tests (SUTs) and SBMA test anchors were installed and tested before the commencement of the production anchor works in order to verify and determine the design load of anchors in accordance with the limiting creep criteria.

A maximum anchor load capacity of 1,850 kN was achieved on the test anchors; which were installed by using special drilling and grouting techniques. These test anchors achieved the highest anchor capacities in Izmir region; where the subsoil conditions are composed of very soft deep alluvial layers.

A strict and detailed quality assurance and quality control programs (QA/QC) have been applied so that the registered historical structures, located within the vicinity of the ground support system, were not damaged by anchor drilling, installation and excavation works.

Besides, the performance of the ground support system was continuously monitored and readings from inclinometers and anchor load cells were taken and reported on a weekly basis during excavation works.

2.2 Geological Conditions

The subsoil conditions at the construction site consists of Quaternary alluvial units containing clay, silt, sand and gravel from the surface up to the depth of 24.2 m. These layers were composed of plastic clay, silicate clay, silt, clay sand and non-plastic silt sand units at the top 10 m. Below these layers the subsoil conditions consists of plastic clay containing clayey sand, clayey gravel and silty gravel bands with clay units. The water table is 2 m below the ground level and artesian ground water was observed at the levels of 38 m below ground level in the gravel layers.

It is noteworthy that the project area lies on a tectonic depression. This depression, formed during the collapse of the Aegean Sea, was filled with alluvial materials at the next stage and thus became an alluvial plain. In addition, parts of the plain near the sea were covered with marshes and shallow lakes, indicating that these parts of the deposition have not yet been completed.

The site investigation consists of 26 no. of boreholes and 6 no. of Cone Penetration Tests (CPT). Variation of tip resistance; q_c and friction rato; f_s values taken from CPT tests with depth are shown in Figure 2. The results obtained from both SPT and CPT tests are in good corrroboration of the prevailing subsoil conditions and provided a sound basis for both anchor and deep shoring system design.

2.3 Design of the Shoring System

Due to challenging ground conditions and high ground water table, a 80 cm thick cast-in-place reinforced concrete diaphragm wall was selected as the main retaining element. The depth of the diaphragm wall varied from 22 m to 28 m supported by 3-levels to 5-levels of high capacity SBMA was designed and constructed in order to support one of the largest basement excavation of 18.5 m in deep soft alluvial depost in Izmir, Turkey.

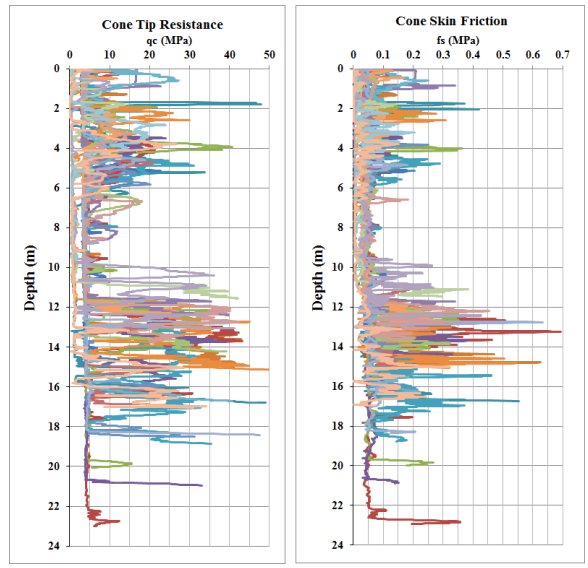

Figure 2. Variation of q_c and f_s values from CPT tests with Depth

The depth of the retaining structure and the close proximity of adjacent historical buildings required the analysis of staged excavation by 2-D finite element analysis software Plaxis to analyze both the wall and surrounding soil and structures. A reinforced concrete design was also undertaken according to structural forces and moments obtained from the computer program.

A temporary deep excavation system was designed and calculations were carried out for 3 different block locations and 4 different excavation depths. Excavation depths and details of the anchoring works at each block are summarized in Table 1.

Table 1. Details of the Deep Excavation System

Block Name	Excavation Depth (m)	Number of Anchor Rows (no.)
A Block	15.3	4
A Block (Tower)	17.8	5
B Block	13.8	3
C Block	18.5	5

2.4 Design of Single Bore Multiple Anchor (SBMA)

SBMA technology is a contemporary method for effective mobilization of bond strength of a ground anchor in soils and weak rocks. Barley (1995) and Ostermayer and Barley (2003) explained that as the bonded length of a conventional anchor increases, its efficiency decreases due to the progressive debonding phenomenon. At the ultimate load only a residual bond stress is mobilized along the majority of the bonded length with the peak bond stress mobilized at the distal end of the fixed anchor.

The ultimate load in the anchor, P_{ult}, is a function of the ultimate in situ bond stress and the fixed anchor dimensions corrected by a factor that accounts for the non-linearity of the bond stress distribution and progress debonding within the tendon bond length.

$$P_{ult} = \pi * D * L_f * f_{ult} * f_{eff}$$

Where;
D: Anchor drilling diameter
L_f: Anchor fixed length
f_{ult}: Ultimate bond stress
f_{eff} : Factor of efficiency

By effectively designing the anchor bond length using a series of efficient unit lengths, the SBMA system is able to achieve higher capacities than conventional anchors in soils and weak rocks. It is known that the maximum load, which can be carried by anchor bond, depends on the mobilized in situ bond stress and the effective length of anchor bond. The studies carried out by Ostermayer (1974 and 1977) and later by Barley (1995) show that mobilized anchor capacity does not increase linearly with the increase in bond length. Furthermore, empirical studies have confirmed that anchors constructed with highly efficient bond lengths of 3 m operated at approximately 85% efficiency, whereas conventional anchor bond lengths of 10 m were approximately 50% less efficient for similar magnitudes of applied load.

Prior to the design of the SBMAs, 4 no. of SUT (Single unit test) were performed at the project site with different drilling and grouting techniques; which are pressure grouting (PG), end-of-casing grouting (EoC).

An ultimate test load of 615.6 kN to 720 kN was achieved for a 3 m long single anchor unit having an ultimate bond stress varies between 375 kPa to 460 kPa as shown in Table 2. Therefore, the most appropriate drilling and grouting method was selected in accordance to the ground conditions at the project site.

Table 2. Details of the Single Unit Test (SUT) Results

SUT Test No	Bond Area / Soil Type	Grouting Type	Ultimate Test Load (kN)
SUT-1	Sandy Gravel	EoC	720.0
SUT-2	Sandy Clay	PG	684.0
SUT-3	Sandy Clay	EoC	684.0
SUT-4	Clay	PG	615.6

The number of anchor units and unit bond lengths of the SBMA test anchors were determined and selected by taking into account the unit bond stress obtained from the test results. Investigation tests were performed on 8 no. of SBMA test anchors having three and four anchor units. The SBMA test anchors; which effectively achieved the target design load, whilst satisfying the creep criterion (BS8081; 2015), was used to determine the configuration of the production anchors.

A summary of the result of the SBMA test anchors are suumarized in Table 3. Based on the special installation and grouting techniques; it was possible to reach much higher anchor capacities than previous studies in field experiments (Düzceer 2014, Düzceer, 2015, Mothersille et.al. 2015 and Düzceer et.al. 2017). The maximum anchor capacity achieved in the investigation SBMA tests was 1,850 kN, whilst satisfying the creep criterion.

Table 3. Details of Investigation SBMA Test Results

SBMA Test No	Bond Area / Soil Type	Grouting Type	Unit No	Max. Test Load (kN)
1	Clay	EoC	3	1231
2	Clay	EoC	4	1459
3	Sandy Clay	PG	3	1094
4	Sandy Clay	PG	4	1642
5	Sand	EoC	3	1094
6	Sandy Clay	EoC	4	1850
7	Clay	PG	3	1231
8	Sandy Clay	PG	4	1824

2.5 Performance of the Support System

Some 55,200 linear metres of SBMAs were installed within the scope of the project. All anchors were tested to 1.25 times the design load and locked to 1.10 times the design load of 650 kN. One in every 10 anchors was tested to 1.5 times the anchor design load and performance checked against the creep criteria as stipulated in BS8081.

To ensure that historical adjacent structures were not adversely affected by the construction works, a detailed quality control program was implemented. The behaviour of the anchored structure was checked on a weekly basis by observing 21 inclinometers, 9 anchor load cells and 6 piezometer wells. In addition, the water level behind the diaphragm wall was also controlled. The close corroboration between calculated and measured deformations, for four different selected sections, used in the design of the deep excvataion system is shown in Figure 3.

It is noteworthy that during drilling of anchors at the lower rows, high artesian water pressure was encountered within the gravel bands between the clayey layers. This challenging site condition was overcome by using special drilling tools and by implementing exclusive grouting techniques and this ensured that the anchors were installed satisfactorily so that target anchor loads were successfully achieved.

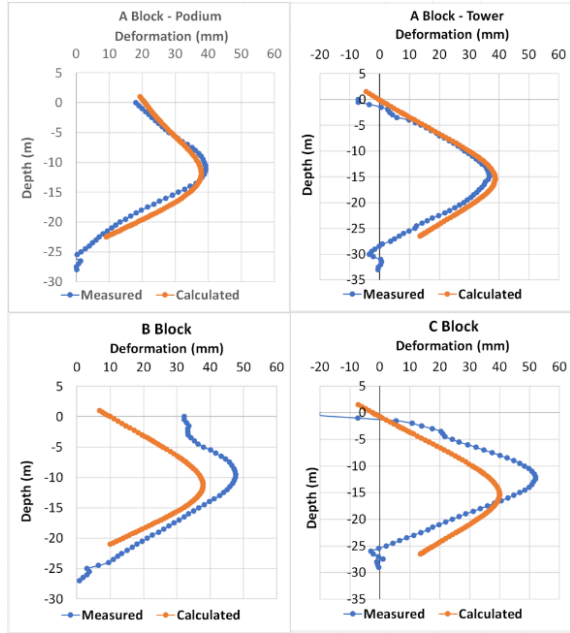

Figure 3. Calculated and Measured Deformations

3 FERKO LINE PROJECT

3.1 General Information

The project site is located on the Cendere Street and in the middle of Kağıthane; one of the largest regeneration and real estate development areas of Istanbul, Turkey. It is located on the European side and extends over the shores of Cendere, the stream that discharges into the Golden Horn. Due to its central location, especially its connections with the new intra-city transport networks, and the entry into force of urban regeneration legislation, the Kağıthane district will serve as a hub after the completion of the construction of the third airport (new airport), third bridge and three-storey under water tunnel.

Ferko Line Project, is a vibrant mix-use complex comprising a hotel, a business park, offices, residential, restaurants, leisure facilities and two levels of basement for car parks, storage and utilities; with a total construction area of 105 thousand square meters. (Figure 4)

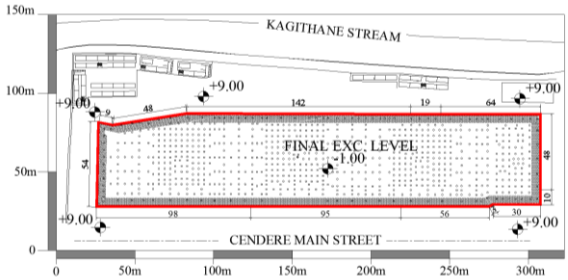

Figure 4. General Layout of the Project

3.2 Geological Conditions

Two separate site investigations, undertaken in November and December 2015, confirmed that the site is comprised 4 to 6.5 m of man-made fill underlain by a deep alluvial deposit of 35 m thickness; consisting of mixed soil stratum of very soft-soft clay with interbedded loose sand; loose sand with fine gravel and soft clay with interbedded sand layers; underlain by a 12 m of impervious stiff clay layer of hard consistency with interbedded sand and a 16-18 m of medium dense sand layers.

The groundwater level was about 5-8 m from the surface of the ground. The clay-sand strata are intertwined and sand bands were encountered in the clay layer.

These layers were underlain by rock units composed of greywacke, claystone-siltstone-claystone alternations belonging to Trakya Formation were observed. Due to the tectonic deformation of the formation, although the rock units were very strong, highly weathered rock formations were also observed in some areas of the site. Variation of tip resistance; q_c and friction rato; f_s values taken from CPT tests with depth are shown in Figure 5.

3.3 Design of the Shoring System

The unique feature of the construction is the shoring system; which supports a maximum 9 m deep foundation excavation within very soft alluvial soil conditions of Kağıthane under high groundwater level. The perimeter of the rectangular shoring system of the project site is approximately 680 m. In order to facilitate a safe excavation; which is located along the Kağıthane Stream with a minimal impact to surrounding structures and utilities, a 60 cm thick and 20 m deep cast-in-place diaphragm wall with one level of pre-stressed temporary ground anchors were constructed within a heavily urbanized location.

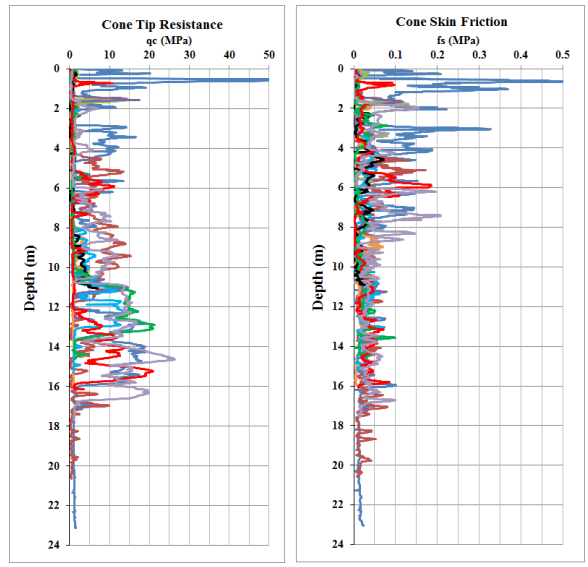

Figure 5. Typical Soil Profile

The shoring design required an anchor working load of 300 kN, which exceeded what could be achieved by conventional anchors in the same founding soil stratum. Therefore, the well-documented single bore multiple anchor (SBMA) technology was implemented. In addition, 7-rows of jet grout columns were also executed in order to improve and strengthen in-situ subsoil at the toe of the diaphragm wall as shown in Figure 6.

Within the scope of this project, a total of 12,500 m² of diaphragm wall, 8,900 m of SBMA and 62,400 m of jet grout columns were successfully completed. Prior to the shoring design, 10 no. of SUT (Single Unit Test) were performed at different locations of the project site with different drilling and grouting techniques; pre-grouting (P) and secondary grouting (SG).

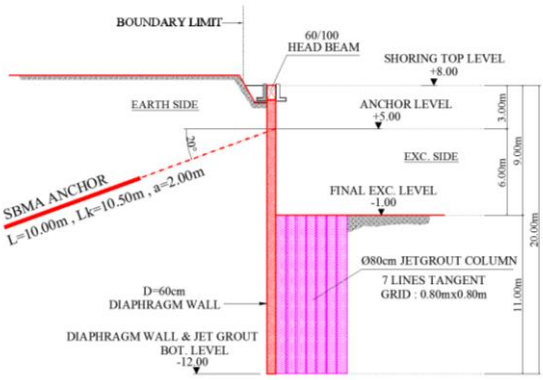

Figure 6. Typical Shoring Section

An ultimate test load of 500 kN to 738 kN was achieved for a 3 m long single anchor unit having an ultimate bond stress varies between 300 kPa to 450 kPa as shown in Table 4. Thus, the most appropriate drilling and grouting method was selected in accordance to the ground conditions at the project site.

Table 4. Details of the Single Unit Test (SUT) Results

SUT Test No	Bond Area / Soil Type	Grouting Type	Ultimate Test Load (kN)
SUT-1	Silty Clay	P-SG	600.0
SUT-2	Silty Sand	P-SG	738.0
SUT-3	Sand	P-SG	600.0
SUT-4	Silty Clay	P-SG	650.0
SUT-5	Silty Clay	P-SG	738.0
SUT-6	Silty Clay	P-SG	550.0
SUT-7	Sandy Clay	P-SG	738.0
SUT-8	Silty Clay	P-SG	650.0
SUT-9	Silty Clay	P-SG	500.0
SUT-10	Silty Clay	P-SG	650.0

Based on the unit bond stress obtained from the SUT test results, SBMA test anchors with 2 no. and 3 no. of unit anchors were selected as the investigation test anchors. The SBMA test anchors, effectively achieved the target design load, whilst satisfying the creep criterion, (BS8081; 2015) was used to determine the configuration of the production anchors as shown in Table 5 and in Figure 7.

Table 5. Details of Investigation SBMA Test Results

SBMA Test No	Bond Area / Soil Type	Grouting Type	Unit No	Max. Test Load (kN)
1	Silty Clay	P-SG	3	600
2	Silty Clay	P-SG	3	1200
3	Silty Clay	P-SG	3	1050
4	Silty Clay	P-SG	3	960
5	Silty Sand	P-SG	3	1200
6	Silty Clay	P-SG	3	960
7	Silty Sand	P-SG	2	600
8	Sandy Clay	P-SG	2	600
9	Silty Sand	P-SG	2	600
10	Silty Sand	P-SG	2	900

By utilizing SBMA technology, a record breaking anchor test load of 1,200 kN was achieved in very soft soil conditions in Kağıthane region of Istanbul for the first time. Based on the special installation and grouting techniques developed, it was possible to reach higher anchor capacities in field experiments as documented in Mothersille D., Düzceer R., Gökalp A. (2015)

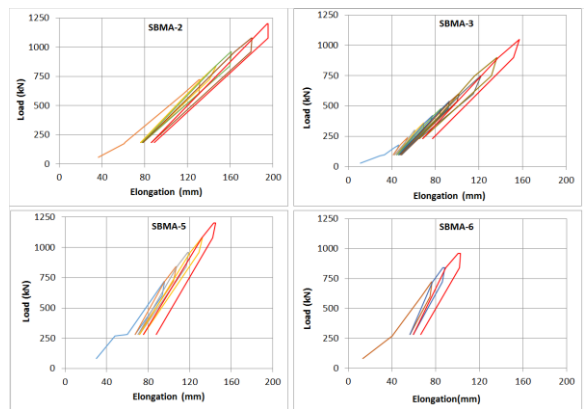

Figure 7. Test Results of SBMAs

3.4 Performance of the Support System

Due to the challenging target work schedule, construction works were completed in 4 separate sub-areas of the site in a successive manner. Therefore, all works; such as diaphragm wall, bored piles, jet grout columns, SBMA anchors,

head beam construction and excavation works were carried out one after another by allocating a large number of machinery and equipment within limited working areas.

Before the commencement of excavation works and as per the quality control program pursued in the project, prism reflectors, 10 no. of inclinometers and anchor load cells were placed and used; all readings were recorded and evaluation reports were also prepared on a weekly basis during excavation works as shown in Figure 8.

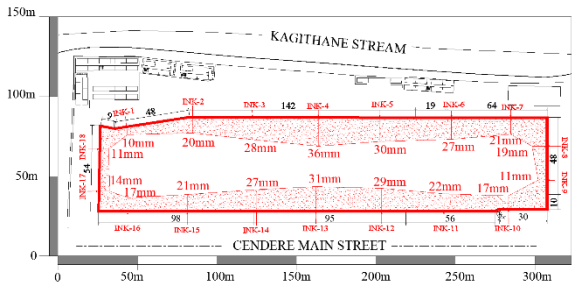

Figure 8. Final lateral displacement of the diaphragm wall at its highest section

Some 8,900 linear metres of SBMAs were installed within the scope of the project. All anchors were tested to 1.25 times the design load and locked to 1.10 times the design load of 300 kN. One in every 10 anchors was tested to 1.5 times the anchor design load and performance checked against the creep criteria as stipulated in BS8081.

4 CONCLUSIONS

This paper presents the design, construction and testing of two recently completed deep excavation projects in Turkey. Within the content of on-going Mahall Bomonti Project and Ferko Line Project, diaphragm walls; laterally supported by record breaking high capacity temporary ground anchors. By utilizing the special ground anchor technology; Single Bore Multiple Anchor (SBMA) was used effectively within challenging soft Alluvial soil deposits in order to support the shoring system for one of the deepest and largest basement excavations in Izmir and Kağıthane, Istanbul respectively.

This paper also describes relevant aspects of diaphragm wall design with particular reference to aspects concerning overall stability and design loads, the extensive investigation test programme presents performance data on the ground anchors and the effectiveness of the installations with respect to limiting wall displacements. The success of this technology in realizing and providing the target design anchor load has paved the way for further applications in Turkey.

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