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BARRETTE FOUNDATIONS-TWO CASE HISTORIES FROM TURKEY

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ABSTRACT

In the recent decades construction of tower structures in big cities around the world is a new trend that has been followed. As a result, engineers are faced with foundations to be designed and constructed under heavier super structural loads imposed by such structures. Often, poor subsoil conditions, site heterogeneity, variability in geometry, and high seismicity brings further challenge in cost effective and safe foundation design. To overcome such complexities and meet higher load capacity requirements often barrette foundations have been utilized instead of cast in situ circular large diameter piles. In this paper applications of barrette foundations together with the emphasis on key issues controlling their design and construction are presented using two recent case histories from Turkey. The first case history, is a covered sports arena with a capacity of 18,000 thousand people and is constructed at the Asian part of Istanbul. Main lithological units underlying the site are the upper uncontrolled fill of variable thickness and underlying bedrock. The second case history is Folkart Towers, Europe's 5th highest twin towers project in Izmir presently under construction. Subsoil conditions at the site is very poor with alternating layers of alluvium consisting of gravel, sand, silt and clay layers with very high groundwater table. Both sites have very high past seismic activity. In the first case, foundations are designed and constructed by means of socketed barrettes into the underlying bedrock. The design loads of barrettes considering only skin resistance along the socket are estimated using empirical equations proposed by various authors in the past. In the second case, both skin resistances and tip resistance developed are estimated using mechanical modeling of subsoils determined as a result of soil characterization by means of in situ measurements using similar procedures utilized in circular pile design. In both cases, estimated capacities are checked at the design stage by means of O'Cell load testing performed on constructed barrettes at a representative location of the site in order to end up with safe and economical foundation design. Verticality and constructability of barrettes having long lengths are another key issues to be considered during design and construction. Instrumentation and monitoring techniques that could be utilized to ensure verticality are also presented within Folkart twin towers project.

INTRODUCTION

It is well known that one of the major problem faced during the construction of circular cast in situ piles is the achievement of the required socket length in bedrock using rotary pile drilling rigs. The problem is even more pronounced with the increasing diameter of bored piles and increasing hardness and strength of the bedrock In addition, cast in situ individual circular piles become impractical and uneconomical when heavy super structural loads are transferred to the deeper soil layers due to their limited capacity.

In such cases, barrettes offer an alternative deep foundation system to large diameter cast-in-situ piles. Further, utilization of various types of diaphragm wall machines proper for the encountered subsoil condition allows the possibility to construct barrette foundations with optimum time, cost and effort. Diaphragm walls can be implemented with mechanical and hydraulic grabs in soil sediments and cutters with reverse circulation in bedrock. Besides, a rectangular barrette has a higher specific surface[1] than has a circular pile with the same cross section resisting vertical loads by means of skin resistance only.

Occasionally, barrettes are utilized in projects that require utilization of diaphragm wall retaining structure for supporting the basement excavation pit. In such a case, they are constructed using the same equipment, thus substantial savings in total mobilization cost of the equipment could be achieved. In fact, since in general barrettes sustain heavier vertical loads in comparison to circular cast in situ piles,

[1] Specific surface is defined as the ratio between perimeter to the cross section of either barrette or circular pile.

eventually their utilization results in a more compact and cost effective design. (Baker et al., 1994).

Recently, writer has been involved with the design and construction of barrettes in various projects within Turkey. Two of these projects presented in this paper as case histories are in which barrettes are socketed to bedrock, Ulker Sports Arena in Istanbul and Folkart Twin Towers in Izmir in which barrettes are designed as floating deep foundations. In both projects, O'Cell testing is conducted during the design stage to determine the distribution of the unit skin resistance along the skin and vertical displacements under service and maximum test loads providing crucial data for cost effective and safe design. Further, results of monitoring barrette construction for verticality using Taralog recorder and Caliper Sonic Logging tests are discussed in the second case history.

ULKER SPORTS ARENA-CASE HISTORY NO.1

PROJECT

One of the well known sports club, through their sponsor, has decided to implement a complex project containing a covered sports arena with a capacity of 18.000 people, a hotel, an office block and shopping mall located in the Asian part of city of Istanbul, Turkey. The site is located about 15 km north of North Anatolian Fault (NAF) line which is well recognized for its past seismic activities. It is well known that a segment of NAF was responsible for 1999 Golcuk Earthquake of M_w = 7.2 that caused large number of human casualties and great financial loss. It is also known that a segment of NAF located beneath the Marmara sea will create a major earthquake of M_w > 7.0 in near future (a 67% probability within 30 years). Therefore, the earthquake resistant design of every structure, especially the ones that involve public safety such as covered sports arena in this case history are of critical importance to civil engineers

STRUCTURAL SYSTEM AND FOUNDATIONS

Sports Arena is a dome structure about 100.0m in diameter. Dome superstructure contains 208 rectangular columns having circular symmetry as seen in Figure 1. Obviously outside column loads, having maximum value of 1250 tons, are much larger compared to central column loads of 350 tons. In other words, distribution of vertical loads increases from the center to perimeter of the dome.

The structure includes two parking levels beneath the ground surface. It is considered that, foundations of columns socketed into the underlying bedrock with a specified socket length, is a proper choice based on the encountered subsoil conditions, structural system, and seismicity of the site. Cast-in situ barrette foundations under each column were chosen for this purpose. Barrette dimensions were designed as 0.80 m by 2.80 m. Since a single barrette is located under each column, the total number of barrettes was also 208. Barrettes were connected with a structural reinforced concrete mat at the top against heavy lateral loads.

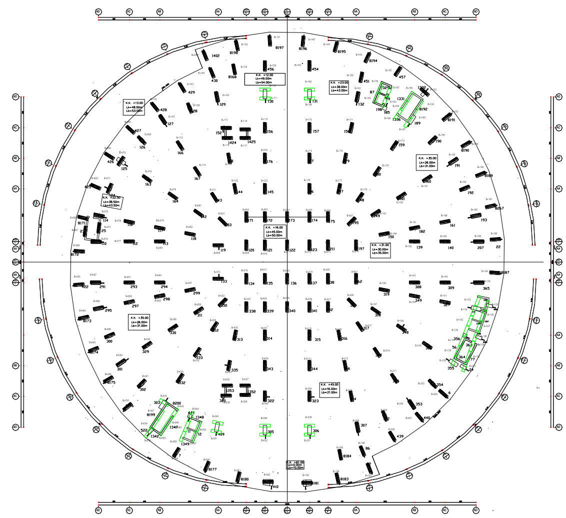

Figure 1. Layout of Columns and Foundations (Durgunoglu, 2013)

Due to heterogeneity in bedrock conditions and due to no redundancy of foundations each barrette was designed based on the maximum column load of 1250 tons for conservatism. Barrettes have offered the following advantages compared to cast-in situ conventional circular piles in this specific project:

- Rectangular configuration having possibility of placement of foundations with circular symmetry offered the possibility of excellent behavior of foundations under seismic loadings. Having circular symmetry in foundations, no torsional moment is expected to be created under earthquake loadings regardless of the direction of the seismic shaking.
- Utilization of both hydraulic grab and reversed circulation cutter technology used in barrette construction offered the confidence and comfort of obtaining desired socket lengths within the bedrock without any problems.
- For the same section, barrette offers 35% larger frictional surface compared to circular piles. In this case each barrette cross section area is A_b = 0.8 x 2.8 = 2.4 m^2, equivalent pile diameter is d_{eq}=1.69 m, skin area of barrette for unit length is a_{sb}=7.2 m^2/m and skin area of pile is a_{sp} = 5.3m^2/m yielding to ratio of a_{sb}/a_{sp}= 1.35. This results 35% higher vertical capacity in skin friction in case of barrettes compare to circular piles having same cross sectional area.
- Combining all barrette foundations together with a concrete mat result in a foundation system much stiffer than isolated barrettes offering large resistance under lateral loadings.

Owing to the above advantages of barrettes over cast in situ circular piles, their implications in recent years have been greatly increased in various countries including Turkey. (Durgunoglu et. al., 2011, Kocak et. al., 2012).

SUBSOIL CONDITIONS

The site is an old rock quarry and the pit was later used as a landfill. The landfill consists of trash and the excavated surplus material generated at the various construction sites within the Asian part of the city. Consequently, the depth of bedrock from existing ground surface is quite variable beneath the sports arena. In fact, the unpredictable variability of bedrock surface topography brings special uncertainty to handle in foundation design. It is clear from the nature of the planned structure, high structural loads of individual columns, and the existence of trash in varying thickness beneath the structure, that a deep foundation system socketed to bedrock has to be considered. Consequently, to manage uncertainty involved with bedrock surface topography, the elevation of bedrock at every column location was determined at the design stage. For that purpose, a systematic subsoil investigation program was implemented, having one boring at each structural column foundation location. The lengths of borings were specified as having minimum coring of 10.0 m into the underlying bedrock. Consequently, maximum boring lengths of 65.0 m were realized at the bottom of the valley. The thickness of the uncontrolled fill located above the bedrock was quite variable as expected, reaching a value as high as 50.0 m. It was observed that the fill contained all kinds of debris transported and dumped into the site and was quite loosely packed having various size void spaces. As a result, the uncontrolled fill is very susceptible to vertical displacements even without loading due to the probable partial wetting of the deposit during the life time of the structure. Further, the hydraulic conductivity of the fill is quite large due to its loose state of placement which brings a special problem to handle during excavation of cast in-situ barrette foundations to manage the loss of bentonite drilling slurry. As determined from the cores, the bedrock is very heterogeneous in both lithology and mechanical properties, which brings an additional uncertainty in foundation design. Main lithological units observed in bedrock were sandstone, siltstone, shale and limestone.

Systematic core samples taken from the bedrock at various levels in each boring were tested under uniaxial compression to determine unconfined compressive strength in the laboratory. The variation of uniaxial compressive strength, UCS-q_{ucs} with depth is quiet variable as expected due to the heterogeneity in lithology and the depth of the bedrock from the ground surface. Based on the laboratory results, there is a distinct increase in UCS with depth of bedrock at that location. The results could be simplified to a mechanical model for design purposes as below according to depth of bedrock:

Table 1. UCS values according to depth of the top of bedrock (Durgunoglu, 2013)

d_b, m	UCS, MPa
0-15	2.5
15-25	5.0
25^+	7.5

DESIGN OF BARRETTES

Considering the structural system, implications of performance criteria i.e. limiting vertical displacements under static loadings, subsoil conditions and high seismicity of the site, barrettes were designed based on skin friction only along the socket. Low skin friction through the uncontrolled fill and possible low negative skin friction upon partial wetting of the fill both are neglected in estimation of vertical load capacity. Ultimate socket load through the bedrock, Q_{sult} is estimated as; $Q_{sult} = A_s \cdot f_{sult}$, where A_s=socket area which is given as $A_s = p \cdot L_s$ where p = perimeter of the barrette which is 7.2m and L_s is the socket length; f_{sult} is the ultimate unit skin friction along the socket.
Based on the previous studies, f_{sult} could be estimated as;
$f_{sult} = \alpha \cdot q^{\beta}_{UCS}$, where α and β are correlation coefficients recommended by various authors and q_{UCS} is the average uniaxial compressive strength of the bedrock along the socket length. Therefore ultimate skin load, Q_{sult} will be equal to,
$Q_{sult} = \alpha \cdot A_s \cdot q^{\beta}_{UCS}$. Using factor of safety FS, the allowable load will be; $Q_{Ssafe} = \frac{Q_{sult}}{FS} = \frac{\alpha \cdot p \cdot L_s \cdot q^{\beta}_{UCS}}{FS}$. Considering that the minimum socket length of barrettes are estimated based on the maximum service load, Q_{ser} , the socket length, L_s could be estimated from $Qs_{safe} = Q_{ser}$, i.e.

$$L(m) \geq \frac{Q_{ser} \cdot FS}{\alpha \cdot p \cdot q^{\beta}_{UCS}}$$

In this relationship, p= 2(0.8 + 2.8) = 7.2 m, and FS = 2.

According to different α and β values recommended by various authors Horvath and Kenny, 1979, Carter & Kulhawy, 1988, Williams et. al., 1980 and Meigh and Wolski, 1979, estimated average values of f_{sult} (MPa) for depths greater than 25m are within the range of 0.55 to 0.91 MPa. (Durgunoglu, 2013).

Under these circumstances, the average ultimate unit socket skin friction values are utilized in estimation of minimum socket lengths as proposed by various authors. The values of L_s=7.5 m, 5.0 m and 4.0 m are determined based on the three depth ranges of the bedrock surface from ground surface at the column locations. At most of the barrette locations, the depth of the bedrock is greater than 15 m, as a result utilization of a specific single value of L_s = 5.0 m is considered to be appropriate and practical to be implemented during construction for design purposes. It should be further emphasized that the socket length of barrettes has a very slight influence on cost of foundations, considering that barrette length is directly influenced by the depth of bedrock from the base of foundation mat, and the thickness of the debris is much greater than the considered socket length. In foundation design, geotechnical engineers often consider cost vs. benefit relations in making decisions. Since the cost of the additional meter of socket length is so minor compare to the additional safety and practicality obtained by doing it, it was wise to be generous in deciding the socket length to be utilized in this specific case history.

O'CELL TESTING OF BARRETTES

It is also known from practice that the estimated socket lengths using the empirical relations proposed by various authors are often conservative. In fact, this dilemma inspired Professor Osterberg to develop O-Cell testing which allowed utilization of very high vertical loads in in-situ testing of deep foundations including piles and barrettes. (Osterberg, 1998).

The estimated vertical load capacity of a barrette constructed with 5.0 m socket length was tested using O-Cell procedure in order to verify the design socket length and estimate the vertical displacement under the service load prior to the construction. The test barrette had 0.8 m x 2.8 m dimensions, as in the design, and an average length of 30.0 m. A maximum test load of 2500 tons, which is twice of the maximum column load of 1250 tons, was applied during the test, since F.S. of 2.0 was utilized in design. Test location had a bedrock depth of about 30.0 m from the surface in order to reflect a representative fill thickness condition. Load cells are located in the middle of the socket length considering very low skin resistance to be developed along the fill, and 2x700 tons load cells (hydraulic jacks) are used in testing. In addition, sixty strain-gauges at ten different elevations are used to measure the skin friction distribution with depth along the surface of the barrette.

Using the procedure recommended by Osterberg (1998), the real load-displacement relationship for the case of barrette loaded at the top is estimated as in Figure 2.

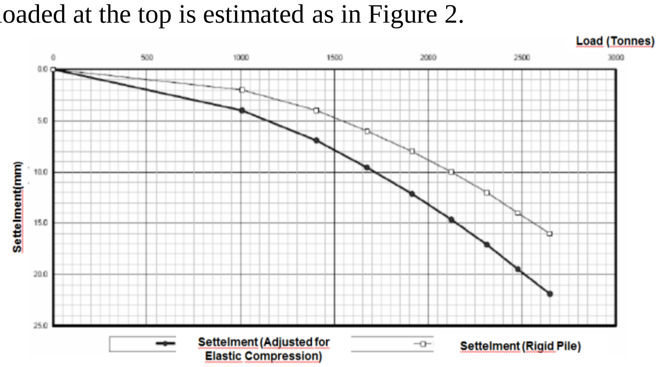

Figure 2. Load vs. Vertical Displacement, (Durgunoglu, 2013)

It is seen from Figure 2 that, vertical displacement under service load is δ = 5.8 mm and vertical displacement under maximum test load is δ_{max} = 19.8 mm. It is interesting to note that, the maximum displacement to develop the maximum unit skin resistance is in good agreement with the value of δ_{max}=20.0 mm given for granitic saprolites. (Charles and Lei, 2003).

The O-Cell vertical displacement measurement results also indicate that the selected socket length of 5.0 m was quite effective, i.e. not over design because of the fact that the load-displacement relationship was not linear throughout the test, in other words, displacement under the maximum test load (twice the service load) was as much as 3.4 times greater than the displacement measured under the service load. It is also seen that f_{smob} along unweathered bedrock along lower part of socket is within the range of values previously estimated based on empirical relations utilized in design.

CONSTRUCTION OF BARRETTES

Mechanical and hydraulic grabs were utilized in excavation of uncontrolled fill located at the top using bentonite slurry. Special precautions by means of pre-grouting at some locations were taken to prevent the seepage of the slurry through the surface skin area of the each segment of barrette towards the loose uncontrolled fill during excavation. At lower elevations, hydrofraise cutter is utilized with reverse circulation as well as using bentonite slurry to excavate the bedrock to achieve the required socket length of 5.0 m encountering no special problems during construction.

FOLKART TWIN TOWERS –CASE HISTORY NO.2

PROJECT

Folkart towers are Europe's 5th tallest twin towers with a floor area of 27.000 m^2 located in city of Izmir, Turkey. The height of the twin towers is 190 m. Seismic vulnerability of the site is very high under the influence of various active fault systems in the Aegean region. Due to the high super structural loads the foundation system of the towers is designed with combination of barrettes. On the other hand circular cast in situ piles are used in podium area as seen in Figure 3. (Kocak, et.al., 2012). In order to increase the lateral stiffness of the barrettes and circular piles under the earthquake loads soil improvement was implemented by means of jet grouting technique between them only within liquefiable zone. Because of the high ground water table (approx. 2.0m-5.0m below the ground surface which is above the foundation bottom level of -8.40 m from the ground surface) a dewatering system was also installed at the site. With the help of mentioned dewatering system, the water level was lowered and maintained at below the desired foundation bottom level of -8.40m. The barrettes are 50.0 m in length and have dimensions of 0.80 m by 2.80 m.

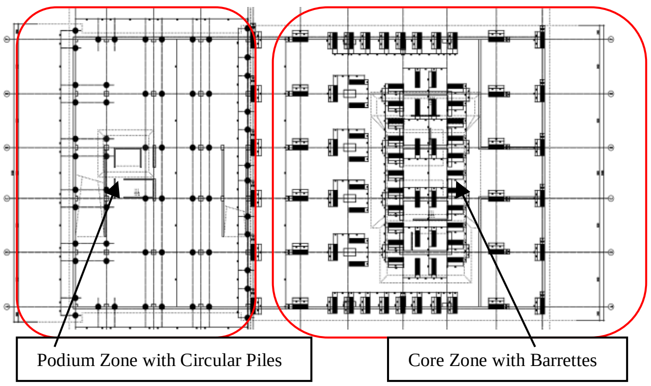

Figure 3. Plan of Barrette/Circular Piles under the each Tower (Kocak, et al., 2012)

SUBSOIL CONDITIONS

The subsoil conditions are very poor and heterogeneous alluvium of Gediz stream consisting of alternating layers of silt, clay, sand and gravel. The major part of the soil layers is fine grained. According to SPT and pressuremeter test results, the general soil profile could be interpreted as loose and soft till the depth of 37.0m beneath the ground surface. Below the depth of 37.0 m hard and dense zones are encountered as shown in Table 2.

Table 2. Mechanical Properties of Alluvium

Depth, m	**SPT(N)**	**p_l (kPa)$^{(1)}$**	**E_P (MPa)$^{(1)}$**
0 - 12	5	480	4.0
12 - 21	12	750	7.0
21 - 37	18	900	10.0
37 +	35 +	-	-

(1) p_l and E_P are Pressuremeter net limit pressure and modulus respectively

BARRETTE VERTICAL CAPACITY

The necessity of a deep foundation system has been emphasized in order to transfer the high super structural loads below the depth of 37.0 m (Kocak, et. al., 2012). Because of the high vertical load capacity requirement, especially below the towers, 0.80 m of 2.80 m sized barrettes are selected in order to achieve maximum skin friction capacity with minimum number. It was estimated that the ultimate capacity of a single barrette having length of 50.0 m is about 2700 tons using conventional methods as in case of in situ piles utilizing mechanical model of subsoil given in Table 2.

O'CELL TESTING

O'Cell static loading test is implemented to verify and optimize the estimated ultimate capacity of 2700 tons (1.5 x DWL, Design Working Load). During the execution of the barrettes two hydraulic jacks with the capacity of 2 x 900 tons were placed into the barrette at a depth of approx. 34.00 m. Six displacement transducer and forty strain-gauges were used at different depths to instrument and monitor the barrette during loading. Test results giving the equivalent top loading vs. displacement curve is given in Figure 4, (Kocak, et.al., 2012). Regarding the load-settlement behavior of the barrette, it was determined that vertical displacements are δ_{vser}=10 mm and δ_{vmax}=26 mm indicating that test barrette is able to carry the maximum load of 2700 tons and as well as the design working load of 1800 tons within tolerable vertical displacements. Further, measured unit skin friction values in various layers are in good agreement with the estimated unit values during design stage, (Kocak, et. al., 2012).

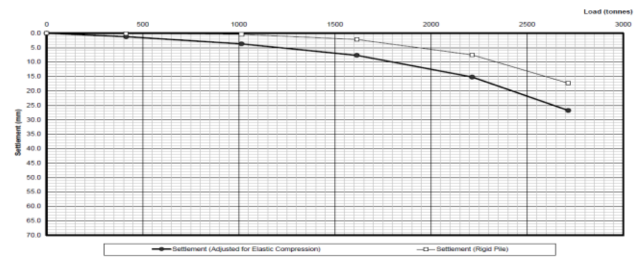

Figure 4. Load vs.Vertical Displacement Curve (Kocak, et al., 2012).

CONSTRUCTION MONITORING OF BARRETTES

Due to alluvial soil deposits encountered, throughout site high capacity hydraulic grab is used in barrette construction. The length of barrettes required to achieve service loads are 50.0 m, therefore achievement of the verticality of each barrette and minimum deviation of excavated trench from rectangular cross section at various elevations are prime importance during construction. In order to produce a straight long barrette with a minimum deviation from vertical, the hydraulic grab was instrumented with a Taralog recorder. Taralog recorder combines the data from depth indicator and wireless gyroscope to show the graphical illustration of grab deviations and rotations with depth during drilling. Besides the Taralog device, the barrette straightness and deviation was also monitored and checked with Caliper Sonic Logging test. The tests were done at ten different excavated barrette trenches which had been determined previously on random basis. In each test, before the replacement of the reinforcement cage the ultrasonic sensor unit was lowered with a constant speed. During lowering of the sensor unit the geometry of excavated trench was determined precisely with the help of the echoes which were created by the sensor unit and also reflected by the trench walls. The unit comprises mainly three major parts: a winch unit in order to lower the senor unit, an ultrasonic sensor unit and a reading unit which controls the winch unit and prints data from the sensor unit versus depth. The sensor unit has the ability of measuring in both directions simultaneously. It was determined that deviations from the verticality and exact positions based on these recordings were within tolerable limits given in technical specifications.

CONCLUSIONS

Various advantages of barrettes including cost effectiveness, compact foundation design, low construction time and constructability in every subsoil conditions including bedrock over cast in -situ circular piles are explained.

Their use is especially superior below heavy structures such as high towers and similarly in bridge piers having very high single column loads. Furthermore, introduction and the extensive use of O'Cell testing allow the pertinent data at design stage for optimum and safe design even under very high test loads. Design procedures and verification of estimated service loads using O'Cell testing, are presented and evaluated having completely different subsoil conditions with the aid of two case histories. In sports arena, barrettes are socketed to underlying bedrock to achieve the required service loads. Therefore, proper estimation of required socket length using unit socket frictional resistance was prime importance. On the other hand in twin towers, barrettes are designed as floating foundations getting their major resistance from the unit skin resistances developed along the various alluvial layers. It was concluded that implications of O'Cell testing at design stage were very effective for estimation of service loads of barrettes in both cases leading to a safe and economical foundation design.

The constructability of barrettes using mechanical and hydraulic grabs in various sediments and hydrofraise cutter in achieving any socket length within various lithological units of bedrock brings a great comfort and reliability in foundation construction. The verticality of barrettes during drilling and prior to concreting especially in construction of long barrettes could be monitored and verified using various modern instruments as demonstrated in twin towers project.

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