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Geotechnical Evaluation of Multi-Layered Simsima Limestone using Bi-Directional Static Load Test (BDSLT)

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ABSTRACT

Static load tests are vital to assess the genuine behaviour of piles to substantiate the geotechnical design parameters and construction approaches. A load testing program was undertaken to determine the working capacity, skin friction, and settlement of drilled shafts in Simsima limestone, the predominant foundation stratum in Doha, Qatar. The weathering profile of the Simsima limestone is complex with the degree of weathering likely to increase with depth. This paper presents the performance of three preliminary instrumented bored cast-in-situ test piles (Type 1, Type 2 and Type 3) by Bi-directional static load test (BDSLT) using sacrificial hydraulic jacks, socketed in the weathering zones of Simsima limestone formation in Lusail FIFA World Cup 2022 stadium project, Qatar. The test piles were instrumented with vibrating wire strain gauge technology and were load tested using the BDSLT loading method to determine the pile-rock interactions within the various weathering zones of Simsima limestone. The unit shaft friction values obtained from the load test are compared with the initial design values. Results indicate that the skin friction was increased from values reported before pile load testing and was used for the optimization of pile design. BDSLT method with strain gauge instrumentation is a modern tool in value engineering of pile design to provide accurate information to the Qatar infrastructure foundation industry.

INTRODUCTION

The occurrence of the Simsima limestone with matrix materials is of concern to researchers and designers, particularly when shallow foundations are designed. As it is difficult to envisage the matrix material behavior, pile foundation has become the favorite choice for most designers dealing with the Simsima limestone. Pile foundation in Simsima limestone is commonly used in Qatar for multistory buildings, bridges, and other structures where there is a limitation of space for using foundations. However, there are inadequate studies in Qatar to quantify the shaft friction capacity of bored piles socketed in Simsima limestone.

Over the last few decades, the static loading test has advanced into bi-directional method of testing, which does provide the required information. BDSLT has become common to evaluate the geotechnical capacity of deep foundations, particularly bored and drilled foundations. The bidirectional static load test (BDSLT) has been around since the early 1970s (Gibson and Devenny, 1973; Amir, 1983). Subsequently, an independent development took place in Brazil (Elisio, 1983), which led to an industrial production, offered commercially, in the Brazil piling industry. Later in the USA (Osterberg, 1998), the test was carried out in full scale for commercial use by hydraulic jack arrangement placed at or near the pile toe to pursue the bidirectional technique. Ogura et al. (1996) showed with full scale tests in which piles were first pushed up with the O-cell and then pushed down, that the ultimate side friction up and down were the same. Schmertmann and Hayes (1997) have mentioned that bidirectional tests using O-Cell were first performed experimentally and commercially. Salem and Fellenius (2017) highlight the different characteristics of the tests to help the foundation industry. This testing method was widely used in the last two decades for cost effective value engineering of foundation piles and barrettes in the Middle East Region (Cherian, 2018, 2020). The ultimate capacity of a deep foundation is often defined with reference to a pile head settlement. A widely used definition of the ultimate resistance of deep foundations installed in the ground is the load that would cause a deep foundation to settle by an amount equal to 10% of its diameter (British Standards Institution, 1986; Randolph, 2003; Jardine et al., 2005; Salgado, 2008). This method is internationally accepted and referred to in the standards (Federation of Piling Specialists, 2006; ICE Manual, 2012; IRC:78, 2014; ASTM D8169, 2018).

BDSLT can be used in both preliminary and working compression/tension, raked, and continuous flight auger piles and also when there is a lack of space and a high magnitude of the load is to be applied for the pile load test. The sacrificial jack assembly is embedded within the pile located deep down in the ground and load will be directly exerted on the rock layer before it is transferred to the upper/lower portion of the stratum. There is no requirement for platform preparation or loading of concrete blocks on the bored pile and this can eliminate the risk of collapse due to soft ground. Moreover, no necessity to extend the pile up to ground level, especially for deep cut off level piles, thereby economical and less time-consuming test method as compared to the conventional static load test. On the other hand, there is a specific limit to the load capacity that can be applied to traditional methods like kentledge, reaction piles, or anchors, and as the load increases, the costs increase proportionally.

Deep-foundation designers, academic researchers, and consultants have many tools and data available to them, including numerous formulas, computer software, basic and sophisticated laboratory testing, and past experience. Often, several of these resources are used to estimate nominal resistances, to which a safety resistance factor is applied to determine an allowable load. However, this rapid method of sophisticated automatized high load testing provides an improved estimate of nominal resistances, and thus allows the use of a higher resistance factor for providing an economically feasible design to reduce the geotechnical risk in the foundation industry.

BDSLT has become prevalent to evaluate the geotechnical capacity of deep foundations, particularly bored and drilled foundations. The use of an embedded hydraulic jack/cell assembly to apply loads upward and downward aids to better understanding of the foundation's internal force distribution, as well as the shaft and base resistances activated during the testing. In an instrumented BDSLT, strain measurements are obtained using strain gauges installed along with the foundation element, and the measured values are used to calculate foundation internal forces. The upward and downward movements can be measured at the level of the jacks (bottom and top) with tell-tale rods

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in conjunction with displacement transducers. With BDSLT, pile load tests on deep piles can be conducted economically, compared to the conventional testing method. The conventional method generally requires the use of reaction piles, which are not needed when using BDSLT method. This method utilizes reaction from shaft friction above the jacks and from end bearing and shaft resistances below the jacks. Geokon concrete embedded type vibrating wire strain gauges installed along the pile length measure strains and thereby determine the internal load distribution associated with each applied load. This data aid to further calculate shaft friction and end bearing along with the different segments of the pile thereby has no effect on the reaction friction component. The load applied by using the sacrificial hydraulic jacks within the pile implicitly is the true load in the pile distributed over the pile section and can be established from the strain gauges installed along the pile length. In a traditional load test, it is difficult to describe the ultimate shaft friction and end bearing of the rock socket in a bored pile, as the amount of top down load diminishes before it reaches the pile toe to fully mobilize the bored pile. In order to optimize the design of a rock socketed bored pile, designers are profound to identify the ultimate shaft friction and end bearing of the rock layer. This can be achieved relatively easier in a BDSLT as the jack can be placed in the specific rock layer. The load will be directly exerted on the rock layer before it is transferred to the upper/lower portion of the soil layer.

In Qatar, not much study has been carried out about the geotechnical behaviour of Simisima limestone (Fourniadis, 2010; Nikolaos et al, 2016). The presence of weathering zones and different inclusions in the Simsima limestone can affect the strength and quality considerably. Apart from these basic studies, barely any study has been undertaken to understand the multilayer properties of Simsima limestone using BDSLT. The present study intended to understand the skin friction characteristics of multi-layered Simisima limestone in the Lusail Stadium Project (Fig.1) using BDSLT to validate the pile design and to aid future foundation designers and researchers in the region.

Fig.1. Location map of study site (Lusail Stadium, Qatar)

GEOLOGY OF QATAR

The Qatar peninsula is geologically part of the Arabian Gulf basin, which has been accumulating carbonate and evaporitic sediments since the Cambrian age with a thickness of the sedimentary succession estimated to be over 10 km (Cavellier et al. 1970; Fourniadis, 2010). Geologically, Qatar belongs to the relatively stable Arabian interior platform. The country's rocks have been subjected to a gentle but long lasting tectonic activity. The folding along with erosion processes have determined the topography of the peninsula, which is governed by the Qatar Dom anticline structure. This broad anticline has a north–south axis and is gently dipping towards the east and west. Doha is situated on the eastern basin of the anticline stretching from sea level to the east and reaching a maximum elevation of about 30 m above sea level to the west towards the anticline axis. Smaller scale gentle folds are found within the anticline structure, while no faults at depths relative to construction activities have been identified. At these depths, the geological units are of Palaeogene to Quaternary age. Quaternary units are found on or close to the surface and, in Doha, are mainly marine sediments, and residual soil. The underlying bedrock units are largely horizontal to gentle dipping marine carbonates and evaporites comprising limestones, shales, siltstones, claystones, marls, and gypsum.

The Simsima Limestone member of the upper Dammam Formation outcrops over 80% of the land surface of Qatar, including the Doha area, and, due to its thickness and geotechnical properties, has been the main founding stratum for most developments in the area. The upper Dammam Formation is underlain by the lower Dammam Formation, which is in turn underlain by the Rus Formation (Fourniadis, 2010). This stratigraphic succession is consistent throughout Doha since it has not been disturbed by the gentle tectonic movements. Nevertheless, there is spatial variance in the thickness and geological characteristics of these formations owing to depositional, diagenetic and erosion factors.

For the purpose of pile testing and design, the Simsima Limestone was characterized into three site-specific grades (zones) of rock quality or weathering, grades A through C, with grade A being the most intact/competent rock and grade C representing the lowest quality rock. The Unconfined Compressive Strength (UCS), skin friction and weathering zones are summarized in Table 1.

METHODOLOGY

Bi-directional static load tests are performed for three piles (Type 1, Type 2 and Type 3) using sacrificial hydraulic jack assembly embedded within the pile foundation element. Each jack assembly consists of two hydraulic jacks located between upper and lower bearing plates (Photograph 1). As hydraulic pressure is applied, the jack assembly can expand in both directions, and loads are applied to the foundation in an upward and downward direction. Hydraulic cell positioning is determined based on soil data. This is used as a basis to compute the expected skin friction and end-bearing capacities of the piles. The main aim of positioning the assembly will be to equalize

Table 1. Initial Geotechnical Parameters

Simsima Weathering Zone	Average Depth (mQNHD)	Grades of Simsima Limestone	Average UCS (MPa)	RQD	Ultimate Skin Friction (kPa)
A	+ 3.00 to -5.50	Weak to medium strong, light to dark grey, dolomitic, slightly to moderately weathered and occasional lenses of chert.	15	50-75	970
B	-5.50 to -10.00	Weak, dark greyish brown, dolomitic, slightly to moderately weathered.	13	25-50	900
C	-10.00 to -17.00	Highly weathered to completely weathered with inclusions and patches of stiff to firm, yellowish brown silt/clay.	11	<25	830

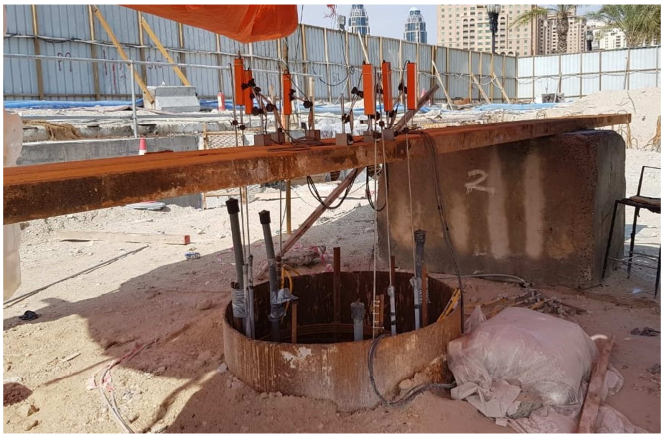
Photograph 1. BDSLT pile installation

the bi-directional forces in the pile so that failure in one direction does not occur prematurely. This requires not only the knowledge of geotechnical parameters, but also the local experience gained from various projects. From the initial geotechnical report, unconfined compressive strength (UCS) of borehole near to pile load test is extracted. The unit shaft friction calculated from UCS using the equation given by Horvath and Kenney (1979) as follows.

$$r_s = b\sqrt{q_u}$$

where r_s = unit shaft resistance; b = empirical coefficient (0.25); q_u = UCS of rock

From unit shaft friction obtained, the total shaft friction of the pile is calculated and the mid-value of the shaft friction is used as the position of the hydraulic cell assembly. To further observe and analyze the behavior of a foundation element under loading conditions, the foundation is instrumented using four levels of strain gauges, telltales, and displacement transducers. Strain gauges installed along the foundation measure strains associated with each applied load, and aid to further determine the foundation internal load distribution. Telltales and displacement transducers measure displacement at cell top and cell bottom. Pile top movement under load will be measured directly from the shaft using two displacement transducers that are installed at the testing platform level. The main types of instrumentation used during the tests were, concrete embedment vibrating wire strain gauges, to allow measurement of axial strains at four levels along the pile shafts and hence estimation of the axial load distribution. Telltale extensometers along with displacement transducers, to measure the embedded jack opening, vertical movement at the pile head and pressure gauge to monitor the load applied to the pile via the sacrificial jacks (Photograph 2). The bidirectional static load test was carried out when the concrete strength of the pile was adequate to sustain the maximum required test load.



Photograph 2. Pile load test setup.

The displacement data obtained from the test (Fig.2) is analyzed to obtain the Equivalent Top-Loading Curve (ETL). The ETL curve (Fig.3) is an estimation of the foundation head load-displacement behavior which would result from a top-loading static compression test. Since bi-directional test loads are applied at some depth within the foundation, such load-displacement relationships are not measured but must be constructed (Osterberg, 1998). BDSLT initial results are typically reported in a butterfly-shaped plot presenting load-displacement behavior of the jack assembly's upper and lower bearing plates (Fig.2). Upper bearing plate load- displacement behavior is governed by shaft resistance developed in the foundation upper portion; lower bearing plate load-displacement behavior is governed by shaft and base resistances developed in the foundation lower portion. The Jack movement data obtained from the test is analyzed using an equivalent top loading method to identify the elastic settlement curve (Hoyoung et al. 2016). The equivalent top load curve is constructed by selecting a displacement value. This selected value will be used for both the top and bottom cells because the pile is assumed a rigid pile. For bored concrete piles, the compression of the pile is typically 1 to 3 mm at ultimate load (Osterberg, 1998). Draw a line from the selected value until it meets the load-displacement curve, thus the o-cell load will be obtained for both the "up" and "down" curve. Sum the corresponding loads to obtain the total load which is equivalent to the load on the pile head. Repeat those procedures to construct the equivalent top-load curve and modify the curve to account for the elastic shortening of the pile.

The unit shaft resistance obtained from the load test results was compared with the install geotechnical parameters. Eurocode 7 (2013) describes the procedures for obtaining the characteristic compressive resistance of piles using the results of load tests and ground soil tests. Eurocode 7 provides correlation factors to convert the measured pile resistances or pile resistances calculated from profiles of test results into characteristic resistances. The design pile resistances derivation

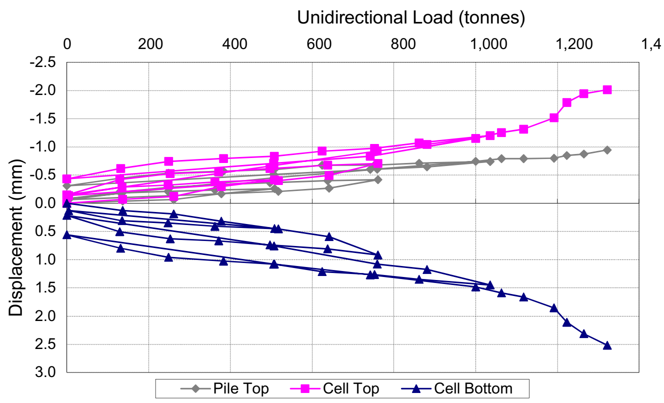


Fig.2. Typical BDSLT site test data (Type 1 pile).

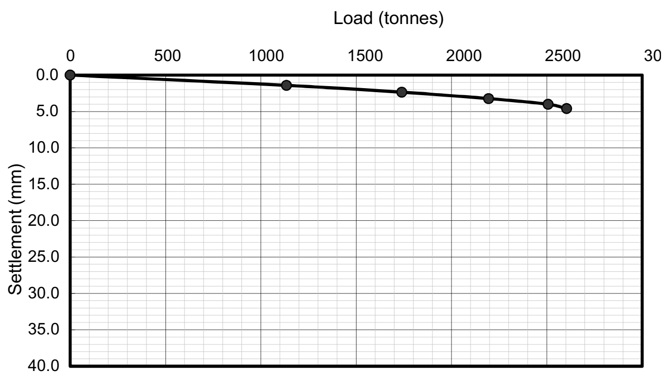


Fig.3. Equivalent top load - settlement plot (Type 1 pile).

Table 2. Lusail Stadium test pile details

Pile type	Zone	Diameter (mm)	Cutoff level (mQNHD)	Toe level (mQNHD)	Pile length (m)	150% load (kN)	Ultimate load (kN)
Type 1	A	900	+2.50	-5.50	8.00	15000	26000
Type 2	B	900	-5.50	-10.00	4.50	7500	11500
Type 3	C	900	-10.00	-17.00	7.00	15000	20000

requires applying the resistance partial factors to the characteristic values. The combinations of partial factor values that should be used for Design Approach I are as follows:

DAI.CI: A1 + M1 +R1

Following partial factors are from the Eurocode 7, 1.35 for A1, 1 for M1, 1 for R1, 1.28 for the correlation factor, based on pile load tests.

RESULTS AND DISCUSSION

A program of pile load testing was undertaken, consisting of three 900mm diameter piles (Type 1, Type 2 and Type 3), compression test loads of 26000kN, 11500kN and 23000kN and lengths of 8.0m, 4.50m, and 7.00m at the three zones (A, B and C) of the Simsima limestone (Table 2).

The instrumentation was placed to measure either the load distribution along the pile lengths within specific grades of the Simsima Limestone. The jack assembly was installed at the mid-height of the test pile section, then a soft-toe of 300 mm thick expanded polystyrene was installed to curtail the contribution of the base resistance. The details of test piles with jack level and strain gauge instrumentation levels are provided in Table 3.

The characteristic resistance is calculated by applying a certain correlation factor and partial factor. Based on Eurocode 7, unit shaft resistance along the length of the pile in different zones of Simsima limestone from load test results is presented in Table 4. The skin friction values have been improved from those calculated from theory. The average skin friction obtained in Simsima limestone Zone A was 1335 kPa, in Zone B was 1269 kPa and in Zone C was 1197 kPa based on the load test. The factored unit skin friction based on Eurocode 7 were 758 kPa, 703 kPa, and 649 kPa for Zones A, B, and C Simsima Limestone, respectively.

The decrease in skin friction from top to bottom zones of the Simsima limestone indicates the intensity of weathering and shift of rock quality from fair to poor. The measured values exceeded the design values and yet still do not represent ultimate values as any of the piles reached the ultimate state during testing. The Simsima Limestone in this area of Qatar was capable of supporting high skin friction loads. The results from the preliminary pile tests indicate that the ultimate skin friction has not been mobilized, and as such none of the piles were tested to failure. Hence proposed skin friction values adopted for the production pile design based on the present study were 842 kPa, 786kPa, and 729 kPa for Zones A, B, and C Simsima Limestone, respectively (Fig.4). Based on the recommended values, the skin friction was increased after the pile test from values used for preliminary pile design by 11%. This ultimately indicates 11% reduction of the pile length and thereby saving cost.

Figure 4 shows the settlement curve obtained during the load tests. The maximum pile settlement of 9.70 mm was observed at the test load of 20000 kN. The theoretical settlement value of 9.00mm as compared with the settlement at 150% load, indicates that the settlement values (2.00mm, 2.10mm, and 7.00mm) were within the permissible limit (less than 1 % of the pile diameter). The settlement values increased from top to bottom zones of the Simsima limestone indicates the intensity of weathering and poor quality of rock. The calculated settlements from the theoretical analysis were considerably greater

Table 3. Instrumentation details of test piles

Test Pile Type	Type 1	Type 2	Type 3
Diameter (mm)	900	900	900
Jack level (mQNHD)	-1.75	-8.00	-13.50
Strain gauge levels (mQNHD)	2.00, 0.38, -3.38, -5.00	-6.00, -6.75, -8.75, -9.50	-10.50, -11.88, -15.13, -16.50
Ultimate Test load (kN)	26000	11500	20000

Table 4. Recommend unit skin friction values

Elevation (mQNHD)	Rock	Load test (kPa)	Ground test value based on Eurocode (kPa)	Recommended Value (kPa)
3.00 to -5.50	Simsima A	1335	758	842
-5.50 to -10.00	Simsima B	1269	703	786
-10.00 to -17.00	Simsima C	1197	649	729

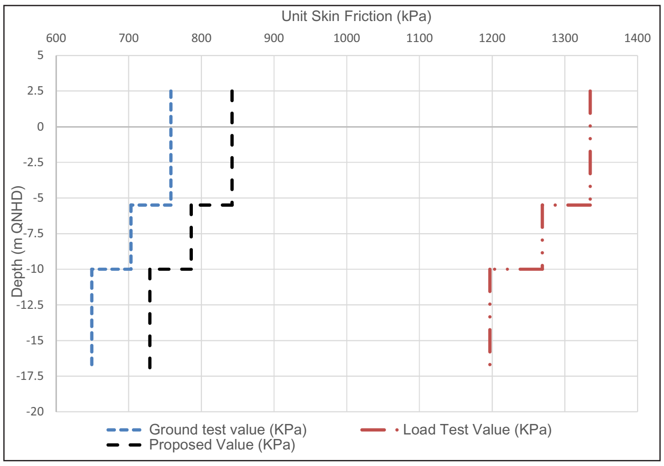


Fig.4. Proposed unit skin friction values for pile design

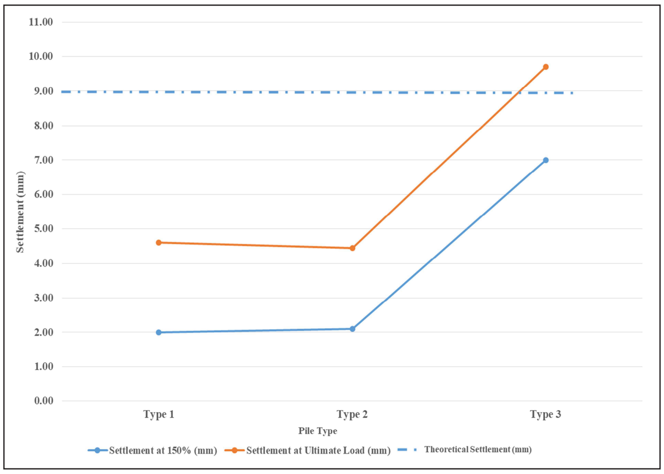


Fig.5. Comparison of settlement values.

Table 5. Geotechnical values adopted for pile design

Test Pile Type	Type 1	Type 2	Type 3
Diameter (mm)	900	900	900
Ultimate Test load (kN)	26000	11500	20000
Prevalent Simsima Zone	A	B	C
Settlement at 150% load (mm)	2.00	2.10	7.00
Permissible settlement at 150% load (mm)	9.00	9.00	9.00
Settlement at Ultimate load (mm)	4.60	4.45	9.70
Ground test value based on Eurocode (kPa)	758	703	649
Mobilized skin friction from load test (kPa)	1335	1269	1197
Proposed skin friction values (kPa)	842	786	729
Percentage of increase of unit skin friction from preliminary pile design (%)	11	11	11

than those obtained from the load test results. The main reason for these larger design settlements was that the settlements were for both dead and live load acting, conservative values of Young's modulus as well as ground stiffness were used in these analyses by the designer. Moreover, it was hard to estimate the possible differential settlement, its decreased strength upon wetting, and possible cemented structural collapses when undergoing different loading forces and water exposure. Hence, there was no recommendation given to reduce the settlement values after load test results as some additional settlement would be expected after the completion of the superstructure. Based on the skin friction values obtained, 11% reduction of pile length was adopted for optimizing the pile design in an economically feasible manner in the Simisima limestone, due to its weathering processes and property variation over quite a small depth.

The preliminary test piles, which were carried out prior to the installation of the working piles, checked the pile capacity, skin friction, and load–settlement behavior, confirmed the effectiveness of the piling, and provided greater assurance of the satisfactory performance of the foundations. The results of the preliminary pile-testing program were compared with those obtained from theoretical predictions between the skin friction and settlement. On the basis of the above information, recommended unit skin friction values were used for the execution of production piles in the project (Table 5).

CONCLUSION

A comprehensive preliminary pile load testing program was conducted to confirm the geotechnical parameters and provide confidence in the foundation design. Preliminary load tests must be performed far in advance of the installation of the production piles to optimize the design. Biaxial load test results and subsequent analysis indicate that the pile length can be further reduced to 11% by maintaining a sufficient factor of safety. The permissible settlement values are in good agreement with the induced values from the load tests. Therefore, any reduction in socket length decreases foundation costs by reducing drilling costs, material costs, construction time, labor, and less expensive to load test. Based on the load test results, it was identified that the BDSLT method with strain gauge instrumentation was an effective contemporary tool in optimizing the design and providing valuable information to foundation designers. The application of such innovative testing methods and analysis approaches has resulted in a cost-effective and optimized foundation design solution for foundation constructions in the region.

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