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Characterization of Simsima Limestone for Foundation Design in Qatar: A Case Study

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ABSTRACT

Multilayered Simsima limestone is considered as the main formation in Qatar. It is widely spread across the country from around 1.50m below the ground level to a maximum of 20m depth and considered for critical depth for most of the civil and foundation engineering building projects. The weathering pattern of the Simsima limestone is complex, increases with depth due to presence of multilayer dissolution cavities. Thus, from geotechnical investigation viewpoint, the shallow rock mass is deceiving and hence geotechnical investigation of the deep-seated rock mass is required for deep foundation designs. In order to identify the multilayer disparity, a geotechnical study was undertaken to determine the properties of Simsima limestone. Some of the methods used for the study are diagraphy profiling, laboratory tests, and the bidirectional static load test (BDSLT). The involvement in the geotechnical and pile design studies of several Simsima limestone projects, from its initiation to completion, motivated the author to conceptually share some benefits of the classification of this complex Simsima limestone to ease stakeholders in designing economically viable building projects in the future.

Keywords: Simsima; Limestone; Solution cavity; Diagraphy; Skin Friction; Qatar

1. INTRODUCTION

The State of Qatar situated on the southern shores of the Arabian Gulf has experienced an extraordinary construction boom in the last two decades. Construction projects of high-rise buildings, World cup stadiums, infrastructures, etc. have been on the increase. Much of the Qatar landmass comprises of relatively thin unconsolidated desert soil overlying calcareous limestones, elsewhere, and particularly along coastal margins, saline soils occur extensively. Traditional geotechnical investigations performed over the last twenty years have permitted construction of most existing buildings on shallow foundations into the relatively shallow weathered limestone, thought to be sufficiently competent to provide adequate foundation support. An overview of the geotechnical properties of rock layers in Qatar was carried out by different researchers (Alkili and Jackson, 1998; Stypulkowski et al, 2014).

The occurrence of the Simsima limestone with matrix materials is of concern to designers and contractors, particularly when shallow foundations are designed. The presence of weathering zones and different inclusions in the Simsima limestone can affect the strength and deformability significantly. The quality of the limestone considerably varies over quite small horizontal and vertical distances. In order to avoid such issues during construction, it is suggested to have systematic field experiments and laboratory studies of these materials on undisturbed samples to correctly use limestone as a foundation material. Based on the experience from different projects, it is revealed that constructing shallow raft foundations must be avoided, especially when inclusions and highly weathered rock appear during the excavation process. As it is difficult to envisage the matrix material behavior, pile foundation has become the favorite choice for most of the designers dealing with the Simsima limestone rocks in Qatar.

In the nearby location, high-rise buildings such as Lusail Plaza Towers, the pile was constructed deep below Rus formation to avoid the effect of Simsima limestone. In fact, the lack of systematic studies in analyzing the specific rock characteristics of Simsima limestone of Qatar from a geotechnical engineering perspective has encouraged the author to make an effort to try to fill this gap. The study is to characterize the different zones of Simsima limestone from 2022 Lusail World Cup Stadium. The project site located in Lusail City, northeast of Qatar consists of the Lusail Stadium, and other mixed-used, which covers an estimated area of 20 hectares.

2. GEOLOGY OF QATAR

2.1 Regional Geology

The regional geology consists of quaternary and tertiary deposits. The residual soil has sand, gravel or clay as its predominant component and can be described as light brown, sandy, silty, gravelly, clayey, fine to coarse sand/clay/gravel with gravels that are fine to coarse sub-angular to sub-rounded fragments of limestone. Residual soils are generally derived from the physical and chemical breakdown of the underlying limestone bedrock. These materials are directly overlying the Simsima member of the Eocene (upper Dammam Sub-Formation), Midra Shale, and Rus Formation. Dissolution cavities can be occasionally encountered. Other small voids and fissures are also encountered in the limestone strata.

2.2 Structural Setting

The geological history of the state of Qatar was mainly controlled by the development of the Western Salt Basin, which is believed to be the critical factor in the formation of the western anticlines of Qatar, such as the Dukhan Oil Field (Dill et al., 2003), and the Eastern Salt Basin which occupies more than half of the Arabian Gulf. Three major trends of basement faulting control the structural evolution of the Arabian Gulf and adjacent areas of the Arabian and Asian plates. These are the NW–SE, N–S and NE–SW trends. The N–S and NE– SW Arabian Trends are the oldest and are observed in several reactivated basement uplifts like the Qatar Arch and the Hail-Rutbah Arch. The Qatar Arch has migrated southwest-ward from a position in the middle of the present-day Arabian Gulf in the Cretaceous, to north of the Qatar Peninsula in the Eocene, and ultimately to its present position as a structural high. The NE–SW fault trend is a major structural alignment along which occur many Hormuz salt diapers. Diapiric movement of the deep-seated Neo-Proterozoic salt was initiated by repeated extensional and strike-slip movements in the Arabian Shield and their deep subsurface extensions in the Arabian Gulf region and overall salt instability as a result of density contrast and lithological loading (Edgell, 1991).

2.3 Geomorphology

The presence of two major facies for the Rus Formation in Qatar are calcareous facies termed as the "depositional carbonate facies" and gypsiferous facies termed as the “depositional sulphate facies". The boundary between the two facies was supported by geomorphological and drilling evidence (Eccleston, 1981). The difficulty in recognition of the boundary between the two facies is related to the post-depositional dissolution of gypsum, which results in the development of a "residual sulphate facies". The virtual absence of gypsum in the northern part of Qatar was considered to be the result of non-deposition over the broad structural high at the northern end of the Qatar peninsula and, also, the removal of gypsum by dissolution in circulating groundwater derived from recent recharge. Cavities develop in Qatar due to 2 mechanisms i.e., dissolution of gypsum where the sulphate facies is present, thus collapse, and dissolution of the upper formations and ponding, north of Qatar. Subsequently, the surficial structure and geomorphology were affected by localized collapse as a result of the dissolution of gypsum and anhydrite at depth. The landscape has been further affected by centuries of erosional action, which has resulted in fine-grained material being scoured from surface material. Karstic features are relatively common throughout central and northern Qatar in the strata of the Dammam and Rus Formations, some of which are of significant size. The indications are that rock type and the presence of joints and fractures have played a major role in the development of karst features, most of which show a NE-SW, N-S and NW-SE trends, similar to the joint and fracture systems. As well as occasional caves, sinkholes and numerous shallow depressions are present throughout these areas, as the dissolution of sulphate facies and dissolution of the upper formations and ponding, north of Qatar.

2.4 Stratigraphy

Qatar’s geological map shows that the most widespread rock outcrop in the country is the Eocene Dammam Formation (Middle Eocene). Rocks of the Simsima Limestone Member of this Formation cover about 80% of the peninsula’s area. A significant amount of the stratigraphic column is no longer found in Qatar (from Eocene to Pliocene) and is most likely eroded but the overall thickness of these deposits cannot be fully estimated. From late Eocene to Oligocene time, global cooling led to a considerable drop of sea level. In tandem with this marine regression, intensifying tectonic uplift along the Qatar Arch exposed the Paleogene strata above sea level, forming the Qatar peninsula. Since then, erosion rates have been effectively exceeding sedimentation rates. Arid to semi-arid climate conditions prevailed throughout the quaternary, hindering the accumulation of considerable sediment and the development of soil.

2.5 Simsima Limestone

The Simsima Limestone member comprises of about 20.0m deep from 1.50m below the ground level, contains Upper Dammam Formation outcrops over 80% of the land surface of Qatar, and, due to its thickness and geotechnical properties, has been the main founding stratum for most developments in the area. It is subdivided into Simsima A, B, and C zones based on UCS and weathering characteristics. The Upper Dammam Formation is underlain by the Lower Dammam Formation, which is in turn underlain by the Rus Formation. This stratigraphic succession is consistent throughout Doha since it has not been disturbed by the gentle tectonic movements

(Fourniadis, 2010). Nevertheless, there is spatial variance in the thickness and geological characteristics of these formations owing to depositional, diagenetic, and erosion factors. The proposed classification system suggests the division of the Simsima Limestone Formation in three units of differing fracturing/weathering degrees based on borehole core assessment. In order to have a practical unit differentiation using site investigation records, unconfined compressive strength (UCS) classification was suggested.

3. MATERIALS AND METHODS

The methodology for the present geotechnical investigation consisted of surveying of exploratory locations, rotary drilling, and sampling, diagraphy drilling, pressure meter testing, double packer testing, groundwater level monitoring, etc. In this article, the tests relevant to the characterization of Simsima limestone are presented and discussed. The geotechnical investigations were carried out in general accordance with the "British Standard BS 5930 (2010): Code of Practice for Site Investigations", QCS (2010), and Eurocode 7 Standards (2009).

3.1 Diagraphy Profiling

Diagraphy profiling is a pioneering method of soil investigation to provide real-time continuous monitoring of the drilling parameters. This technique is used in the drilling process to help evaluate the sub-surface and locate possible stratum variation, fractures, loose pockets, or cavities. The diagraphy monitoring system comprises pressure sensors installed on a conventional drilling rig connected to a data acquisition system to collect real-time data automatically for the drilling parameters monitored. Diagraphy probing was performed with hydraulically powered rotary top drive drilling rigs. These rigs have independent control via a hydraulic regulator valve of the following parameters: tool pressure, injection pressure, rotation speed, and torque pressure. The drilling rigs used were capable of maintaining a constant net tool pressure throughout the entire drilling process. Recording of the probing parameters such as Thrust pressure, Rotation speed, Rate of penetration and Torque, was done using purpose built-designed logging unit.

3.2 Laboratory Tests

A range of laboratory tests was conducted to understand the physical and chemical behavior of Simsima limestone.

3.3 Bi-directional Static Load Test (BDSLT) of Piles

Bi-directional Static Load Test (BDSLT) is performed using a multiple expandable jack assembly embedded within the foundation element. Each jack assembly consists of two hydraulic jacks located between upper and lower bearing plates. As hydraulic pressure is applied, the jack assembly can expand in both directions, and loads are applied to the foundation in upward and downward directions (Fig. 1). 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. This requires not only the knowledge of geotechnical parameters but also the local experience gained from various projects. To further observe and analyze the behavior of Simsima limestone under loading conditions, the foundation is instrumented using four levels of strain gauges, telltales, and displacement transducers. For the purpose of pile testing, the Simsima limestone was characterized into three site-specific grades (zones) using UCS and weathering pattern, grades A through C, with grade A being the most intact/competent rock and grade C representing the lowest quality rock. Strain gauges were installed along these zones to measure strains associated with each applied load, and aid to further determine the foundation's internal load distribution and skin friction capacity (Cherian, 2018). 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 (Fig.2). 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 were installed 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 were installed. The data from strain gauge and displacement are analyzed and compared with the skin friction values of the geotechnical data (Cherian, 2020).

Figure 1 - BDSLT pile installation

Figure 2 - Pile load test setup

4. RESULTS AND DISCUSSION

The results of the recorded diagraphy drilling parameters, like tool pressure, rotation speed, penetration speed, torque, and injection pressure were used to calculate values of alteration index, ease to drill parameters and specific energy (Table 1).

Table 1 - Diagraphy drilling parameters of Simsima limestone

Rock type	Alteration Index	Specific energy (MJ/m^3)	Ease-to-drill & hard-to-drill
Simsima limestone	1.83 to 1.93	788 - 2238	-0.03 to 0.00 & 0.07 to 0.30

4.1 Alteration Index (AI)

Alteration indices were derived to assess the presence of weak/soft materials using Eq.1 proposed by Pfister (1985).

$$AI = 1 + (W' / W'_{max}) – (V_d / V_{d\ max}) \quad (1)$$

where

AI= Alteration Index,
W' = effective weight on bit or net down-thrust pressure (kPa),
W'_{max} = maximum effective weight on bit (kPa),
V_d = drilling speed, and
$V_{d\ max}$ = maximum drilling speed.

The Alteration Index (AI) shows the possible variation of the drilling data with respect to the soil formation for a given borehole at a given site. The value of AI varies from “0” (in open voids) to “2” (in hard materials). For AI = 1, the applied net down-thrust pressures are in equilibrium with the penetration speeds. For values of AI lesser than 1, high penetration speeds are achieved by high applied net down-thrust pressures while for values of AI greater than 1, low penetration speeds are achieved by high applied net down-thrust pressures. The Alteration Index is highly sensitive to encountered soft materials during drilling, and thus, may be used to identify soft pockets of clay or infill materials in potential cavities.

4.2 Ease-to-Drill

According to Gui et al. (2002**),** the relationship between the velocity-related parameter (Γv), and a force-related parameter (Γf), characterizes the ground failure mechanism at the drill-tooth interface, being sensitive to material strength. These were analyzed to derive the Ease-to-Drill values. The velocity-related parameter, Γv, includes the penetration speed and the rotation speed, and is determined using Equation 2.

$$\Gamma_v = V_d / (\omega_d \times D) \quad (2)$$

where

Γ_v = ratio of vertical speed over circumferential speed of a drilling tooth,

V_d = drilling speed (m/s),
ω_d = rotational speed (revolutions per second), and
D = bit diameter (m).

The force-related parameter (Γ_f) includes the net down-thrust pressure and torque. It is determined from Equation 3.

$$\Gamma_f = W' / (T_q / D) \tag{3}$$

where
Γ_f = ratio of vertical forces over horizontal forces action on a drilling tooth,
W' = net down-thrust pressure (kPa),
Tq = torque pressure (kPa), and
D = bit diameter (m).

Using the above equations, "easy to drill" values and "hard to drill" values are derived as given in Eqs. 4 & 5.

$$\Gamma_{easy} = - \Gamma_v / \Gamma_f = -V_d T_q / (W'\omega_d D^2) \tag{4}$$

$$\Gamma_{hard} = - 1 / \Gamma_{easy} \tag{5}$$

The "easy to drill" and "hard to drill" values were normalized between -1 and 0 and 0 to 1, respectively. The determined values were used to identify probable zones of weak and strong rocks. For example, the easy-to-drill parameter approaches a value close to zero when the rate of penetration generated by a high tool pressure is low. Easy-to-drill values close to zero usually indicate rocks with high strength. The easy-to-drill parameter approaches to -1 value when the rate of penetration generated by a low tool pressure is high. Easy-to-drill values approaching to -1 value indicate rocks with low strength. It should be noted that the easy-to-drill equation is not useful in identifying open voids or open fractures as torque drops to zero, giving an easy-to-drill value close to zero.

4.3 Specific Energy

Teale (1965) derived the following formula to determine the work (specific energy) to advance drilling through a specific lithological unit.

$$e = e_t + e_\tau = (F/A) + [(2\pi/A) \times (NT/\mu)] \tag{6}$$

where
e_t = thrust component,
e_τ = rotary component,
A = cross-sectional area of the borehole (m^2),
N = rotational speed (revolutions per second),
T = Torque (kN), and
μ = ratio of vertical speed over circumferential speed of a drilling tooth.

Specific energy (e) values relate to the work required to drill through rock and gives an indication of the drillability of rock. For example, a high specific energy value is usually observed when drilling through hard rocks such as chert, thus, indicating low drillability. The high specific energy value is usually observed when drilling through heterogeneous materials such as Simsima limestone, thus, indicating low drillability.

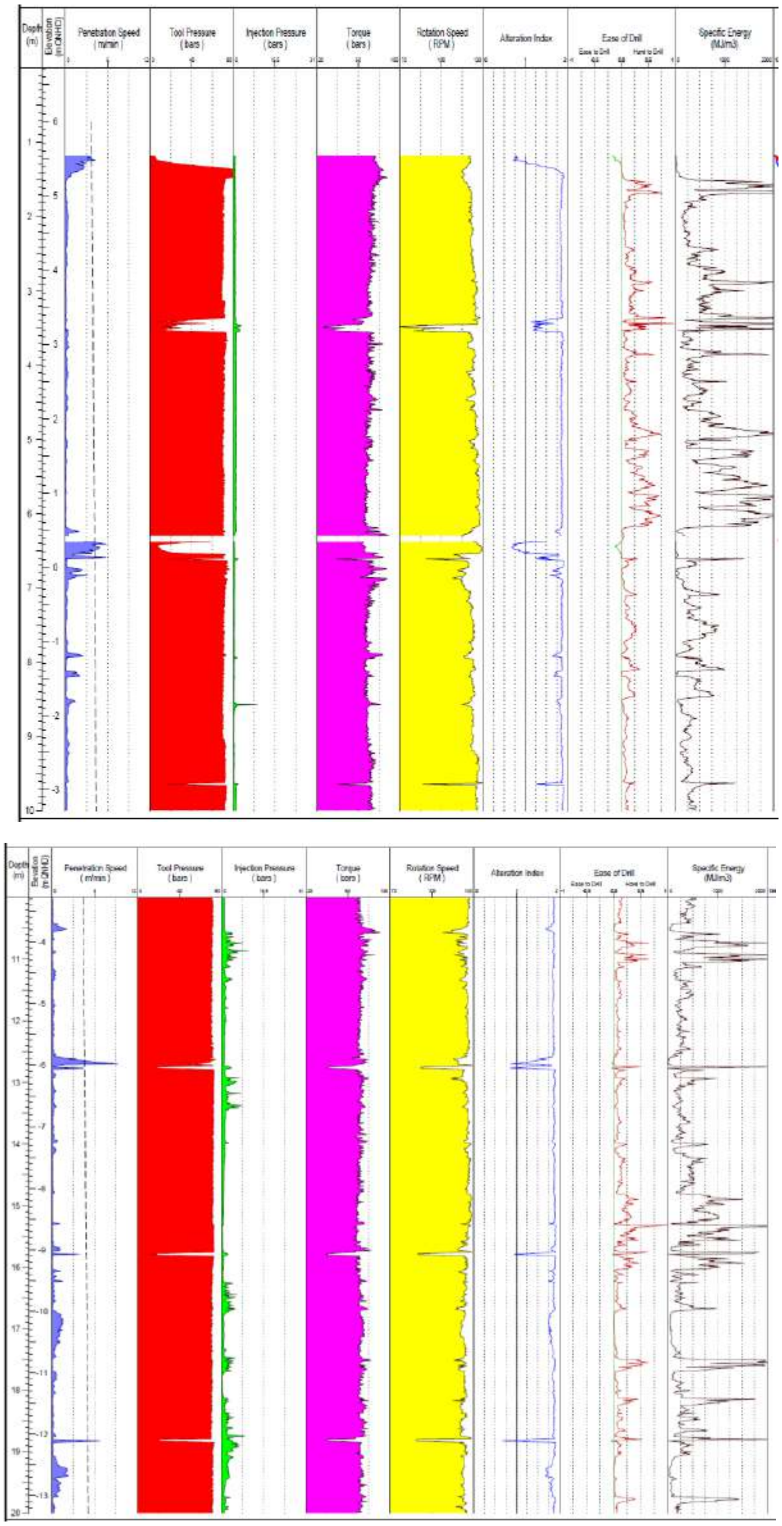

Figure 3 - Diagraphy drilling profile (up to Simsima layer)

The stratigraphic formations at the location of diagraphy drilling borehole (Fig.3) were assessed and shows that until 5.20m QNHD (Qatar National Height Data) made ground. The Simsima limestone with weak to medium strong, light to dark grey, slightly to moderately weathered, occasional lenses of chert inclusions until approximately 0.20 mQNHD. The Simsima limestone with weak, dark greyish brown, slightly to moderately weathered until -6.20m QNHD. Below this level, until -12.20m QNHD, Simsima limestone of highly weathered, very weak to weak with silt/clay intercalation was identified. Below this level, different types of Rus formation were found until the end of the borehole. The Simsima limestone generally has high and highly variable specific energy values. Highly variable specific energies are expected due to the heterogeneous composition of the Simsima limestone observed from the coring boreholes (pockets of clay, dolomitized fragments, etc.). Finally, a remarkable reduction in the specific energy can be observed at the transition point between the different zones of Simsima limestone.

The diagraphy results indicate a good correlation with soil/rock parameters obtained from the laboratory results. The lines designating the changes between weathering zones/ soil and/or rock layers represent clear boundaries. The other drilling parameters did not result to be anomalous during the crossing of the foundation ground. The specific drilling energy also constantly remains low for the entire section that involves the foundation ground. The increase of the specific energy at some depths is due to the presence of lenses of cemented layers.

4.4 Laboratory test results

The physical and chemical analyses of Simsima limestone were carried and results are presented in Table 2a and 2b.

Table 2a - Laboratory test results of Simsima limestone

Description	Min.	Max.	Total no. of tests
Specific Gravity		2.65	1
Particle Size Distribution			
Gravel (%)		49	1
Sand (%)		18	1
Silt/Clay (%)		33	1
Atterberg Limits			
Plasticity Index (%)		42	1
Liquid Limit (%)		72	1
Chemical Analysis			
Poisson's Ratio		0.34	1

Table 2b - Laboratory test results of Simsima Limestone

Description	Min.	Max.	Average	Median	Total no. of tests
Chemical Analysis					
Chloride (%)	0.04	0.02	0.11	0.08	3
Sulphate (%)	0.01	0.14	0.06	0.02	3
pH @ 25°C	8.2	9.0	8.6	8.7	3
Organic Matter (%)	89	95	92	92	2
Calcium Carbonate (%)	93	95	94	94	3
Carbon Dioxide (%)	41	42	42	42	3
Brazilian – Tensile strength (MPa)	2.30	13.08	5.70	3.82	8
Point Load Index, Is_{50} (MPa)	0.45	5.28	2.67	2.55	36
Elastic Modulus (GPa)	9.36	46.5	20.11	12.40	7
Bulk Density (kg/m³ x10^3)	2.18	2.65	2.51	2.53	34
Dry Density (kg/m³ x10^3)	2.02	2.64	2.46	2.50	34
Unconfined Compressive Strength (MPa)	2.00	50.30	18.08	15.40	30
Moisture Content (%)	0.2	7.8	2.2	1.6	79
Los Angeles Abrasion	30	39	34	33	7

4.5 Pile load test results

The skin friction of pile is identified as a parameter of pile shaft displacement. It will differ for each type of soil and weathered rocks. Due to this, the key dynamic skin friction zone is always shifted down with the increase of load. Pile load test with strain gauge instrumentation can provide the skin friction values at different segments of the pile and can be compared with the skin friction values derived from uniaxial compressive strength (UCS) to evaluate the pile design. The unit shaft friction calculated from UCS using the equation given by Horvath and Kenney (1979) as follows.

$$r_s = b\sqrt{q_u} \tag{7}$$

where

r_s	=	unit shaft resistance,
b	=	empirical coefficient (0.25), and
q_u	=	uniaxial compressive strength of rock.

The parameters considered for the assessment of Simsima limestone are derived from vertical boreholes and considered representative of the fracturing state of the rock mass (Table 3). In order to understand the weathering zones of Simsima limestone, diagraphy profile, rock quality designation (RQD), core recovery (CR) and UCS plots are compared. It is identified from the results that RQD and UCS values are varying in the different weathering zones of the limestone formation.

Table 3 - Simsima limestone grades with UCS and Skin friction values

Simsima weathering zone	Average depth range (m QNHD)	Grades of Simsima limestone	RQD (%)	CR (%)	Average q_u (MPa)	Skin Friction (r_s) (kPa)
A	5.20 to 0.20	Weak to medium strong, light to dark grey, dolomitic, slightly to moderately weathered and occasional lenses of chert.	< 50	100	19.0	1090
B	0.20 to -6.20	Weak, dark greyish brown, dolomitic, slightly to moderately weathered.	30 - 45	100	14.0	935
C	-6.20 to -12.20	Highly weathered to completely weathered with inclusions and patches of stiff to firm, yellowish brown silt/clay.	13 - 27	100	5.0	560

Table 4 - Test pile details

Pile type	Diameter (mm)	Cut-off level (mQNHD)	Toe level (mQNHD)	Ultimate test load (kN)	Strain levels (mQNHD)	UCS (MPa) with depth (mQNHD)
Type 1	900	+2.50	-5.50	26000	2.00, 0.38, -3.38, -5.00	19.0 (5.2 to 0.2) 14.0 (0.2 to -6.2) 5.0 (-6.2 to -12.2)
Type 2	900	-5.50	-10.00	11500	-6.00, -6.75, -8.75, -9.50	
Type 3	900	-10.00	-17.00	20000	-10.50, -11.88, -15.13, -16.50	

The pile details and strain gauge levels are provided in Table 4. The sample load-displacement data from the test is provided in Fig.4 (Pile Type 1). The data is then analyzed (Cherian, 2020) to get the equivalent top load settlement plot (Fig. 5). Further, the data from the laboratory tests were checked with calculated skin friction data obtained from strain gauges of the instrumented bidirectional pile load test. From the installed strain gauges at different zones of Simsima limestone, skin friction was calculated and presented in Table 5. The skin friction parameters were influenced heavily by the results of the pile load tests. It was noted that the strata generally became weaker with increase in depth and soft-toe performed adequately. The average skin friction values obtained for Simsima limestone were 1335kPa, 1269kPa and 1197kPa in Zone A, Zone B and Zone C respectively based on the load test. The theoretical/design skin friction values calculated from UCS (Fig. 6) are1090kPa, 935kPa, and 560kPa 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. The measured values exceeded the design values and yet still do not represent ultimate values at any of the piles reached the ultimate state during testing. Moreover, the results on drilled shafts socketed in limestone demonstrate that shaft bearing capacity is a significant part of the total bearing capacity. The ultimate shaft bearing capacity of a rock-socketed in this foundation is obtained from the maximum shear stresses mobilized along the shaft skin. This designates that the Simsima limestone in this area of Qatar was capable of supporting high skin friction loads required for the foundations.

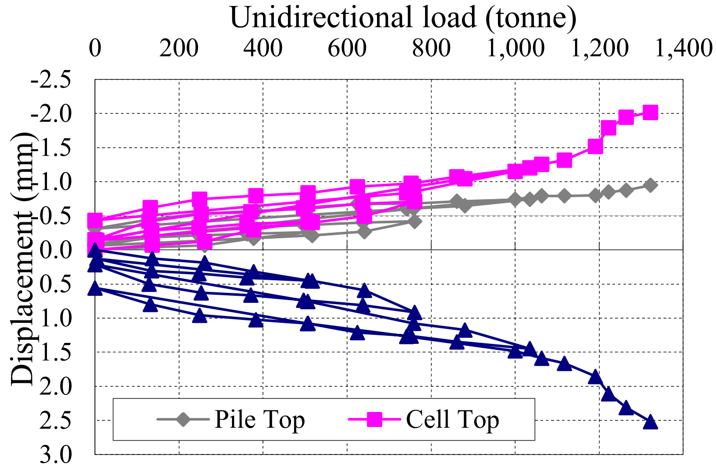

Figure 4 - Load versus displacement plot of BDSLT (Type 1 pile)

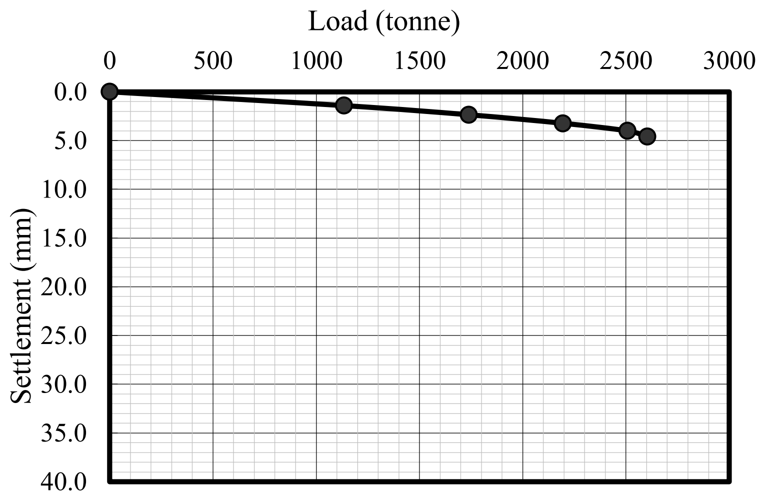

Figure 5 - Equivalent top load - settlement plot (Type 1 pile)

Table 5 - Geotechnical and pile load test results

Test Pile Type	Type 1	Type 2	Type 3
Diameter (mm)	900	900	900
Ultimate Test load (kN) (260%)	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
Skin friction based on UCS values (kPa)	1090	935	560
Mobilized skin friction from load test (KPa) (Skin friction = (Lower load – Upper load)/ Surface area between two strain gauge levels)	1335	1269	1197

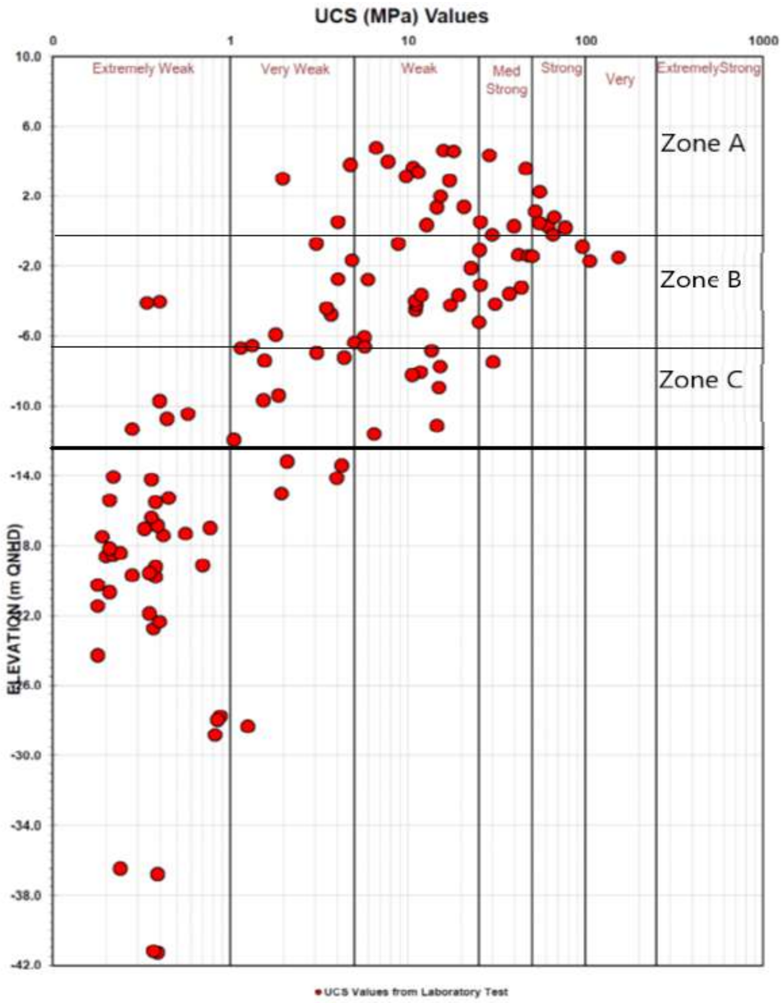

Figure 6 - UCS values with depth from laboratory test

5. CONCLUSIONS

The rapidly developing State of Qatar is situated on the southern shores of the Arabian Gulf. It has experienced unique construction and infrastructure boom, including the design and construction of new cities, towers, and mega projects, which requires good knowledge and judgment of all the related aspects that may affect the success of these projects. A comprehensive geotechnical analysis was conducted to confirm the geotechnical parameters of Simsima limestone to provide confidence in the foundation design. The application of this approach to geotechnical design and construction has proven effective in assessing geotechnical behavior. A range of characteristic geotechnical parameters is provided to understand the behavior of multilayered Simsima limestone. Pile load test results reconfirmed the different zones of Simsima limestone in the study area to provide a suitable value engineering design. Classical classification systems are not applicable to the soluble rocks due to presence of big solution cavities. However, a classification system based on weathering degree and UCS/skin friction value proposed for the Simsima limestone formation to classify the rock units of differing qualities. Hence the present study intended to understand the particular characteristics of multi-layered Simisima limestone will aid the construction applications to contribute to the country’s future development vision.

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