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Design and Performance of Shallow Foundations over Diagenetic Limestone Along the Arab Gulf Coast: Realities and Challenges

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DESIGN AND PERFORMANCE OF SHALLOW FOUNDATIONS OVER DIAGENETIC LIMESTONE ALONG THE ARAB GULF COAST: REALITIES AND CHALLENGES

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ABSTRACT

The near surface, highly weathered limestones of **the southern shores of the Arab Gulf region** have complex lithologies attributable to post depositional changes that have altered hard rocks into soils and some carbonate soils into a rock matrix. The matrix, often clayey, sometimes cemented (with gypsum, anhydrite, and /or calcite grains) is not a rock nor could be considered as a soil per se. These deposits are: difficult to sample in the undisturbed state, extremely variable in composition and properties, and are susceptible to degradation, particularly when wet. The paper presents typical geotechnical information from selected sites where these deposits (diagenetic limestone) have been encountered. Plate load test data, carried out to predict settlements, are shown. Arrival at appropriate foundation geometries and allowable bearing capacity values, consistent with field conditions, are noted. For the present, design of shallow foundations along Region's coasts and in nearby areas, has remained empirical and dependent upon site-specific information aided by: judgment, local experience, and plate load test results. Moving forward, and thus reducing ambiguity and uncertainty in design of shallow foundations, would invariably require a long-term commitment to: i) proper analysis and scrutiny of appropriate field data, ii) modeling of soil/rock behavior under changes in stress, and iii) the arrival at "well thought out" design guidelines to help practitioners overcome the difficulties usually faced, when designing shallow foundations in these deposits.

INTRODUCTION

The southern shores of the Arab Gulf region, has recently experienced an unprecedented construction boom. Projects of all types, including buildings, industrial plants, roads, etc. have been on the increase. Much of the Region's landmass (see Fig.1) comprises relatively thin unconsolidated desert soil overlying calcareous limestone. Elsewhere, and particularly along coastal margins and in some inland areas, saline soils (known as sabkha) occur extensively (Akili and Torrance 1981; Akili 2004). Also, relatively large areas, within 5 to 10 kilometers inland, are covered by eolian sands. They include areas of Barchan dunes, undulating sand sheets, and sand mounts that may be up to 50 meters high (Al-Sayari and Zotl 1978). Conventional geotechnical investigations carried out over the last twenty years have allowed construction of most existing buildings on shallow foundations bottomed into the highly weathered limestone, often thought to be sufficiently competent to provide adequate foundation support. However, as more geotechnical field data have become available, the picture has changed. Softer, less competent limestone interbedded with matrix materials (rock pieces, silts and clays) have been encountered at relatively shallow depths (Akili 2007).

The wide occurrence of the limestone with the matrix materials- referred to here as "diagenetic limestone"- is of concern to geotechnical consultants and contractors; particularly when shallow foundations are a likely alternative. This is so, because these materials are difficult to delineate with conventional geotechnical investigations in use today; and also, because of their heterogeneity, anisotropy, and lack of guidelines to assist designers in arriving at safe and appropriate foundations recommendations when these limestones are encountered.

The paper sheds light on: the occurrence, composition, and engineering properties of the "diagenetic limestones" of the Region. Use is made of extensive geotechnical data from several sites in and around Doha, the capital of Qatar, and else where. Local practice has always called for the use of the ***plate load*** test to aid in checking presumptive settlements, and assists in arriving at allowable bearing pressures. Good correlation of a full-scale field load test with *plate load* results, attests to the usefulness of the *plate load* in making design-related decisions. While more sophisticated testing devices are in use, the *plate load* test is regarded by most as: inexpensive to run, and tends to yield reasonably good results.

Fig.1.Geographical map of the Southern Shores of the Arabian Gulf

BACKGROUND

The Qatar Peninsula, the islands of the state of Bahrain, and the bulk of the United Arab Emirates are- from a geologic point of view- an integral parts of the Arabian Peninsula, and their geology follows the well-defined stratigraphy of Eastern Saudi Arabia. The bedrock of the Region is of early to late Tertiary and younger rocks that are predominantly limestones, interbedded with dolomites, marls, shales and clays. Below, are limestones of Paleocene to Middle Eocene age which belong to the Simsima Member of the Upper Dammam sub-formation (Cavalier 1970). The upper zone of this sub-formation consists of yellowish-gray, microcrystalline, partly dolomitic or white chalky limestone with thin layers of gypsiferous shale in the upper part. Near the top, the limestone contains pebble to boulder-size nodules that remain on surfaces where the limestone has weathered (Tleel 1973).

Since their formation, these limestones have been subjected to an extensive and complex history of diagenesis, and the cumulative result is the present state of these materials - a mixture of: (i) hard, recrystalized (original) limestone, and (ii) diagenetically derived matrix materials-referred to as "secondary" material-that varies from massive gypsum, or carbonate siltstone, to clays. The clays encountered are mostly ***attapulgite***. The 'original' portion of the limestone has become very well cemented, occasionally dolomitised and exhibits a high unconfined compressive strength of between 10 to a 100 MPa. From engineering prospective, the strength and deformability of the "diagenetic limestone" is largely influenced by: (i) the relative percentage of 'original' limestone to "secondary" material; (ii) physical, chemical and mineralogical composition of "secondary" material; and (iii) the degree of cementation that these materials can impart. When *attapulgite* is present in relatively large proportions, the diagenetic rock mass becomes weak and susceptible to deformation under load.

The variation in the quality of the "diagenetic limestone" can be significant over relatively small lateral or vertical distance with vastly varying strength values, even over a distance of three to five meters. It is also important to note that wetting/ saturation can cause significant reduction in the strength of the limestone as "secondary"*attapulgite* becomes highly plastic upon wetting. To come to grip with the problems of the "diagenetic limestone" as a foundation material, answers to several questions must be found, including the following: (i) How extensive is this material underneath a proposed structure - preferably, in three dimensional space? (ii) What are their engineering properties as they lie in the ground? (iii) What are the stress changes they would be subjected to as a consequence of the proposed structure? To address the questions noted, there is an obvious need for thorough systematic and reliable studies of these materials, making use of: well-controlled field experiments along with: laboratory studies on 'undisturbed' samples, proper monitoring of foundations, and appropriate analysis of field data.

SITES SELECTED

Three sites, where these materials ("diagenetic limestone") have been encountered are described, including: their occurrence, their characteristics, and the problems that would confront the foundation engineer in making foundation recommendations. The three sites, referred to as sites: I, II, and III, are within Doha proper (see Fig. 1), the capital of the state of Qatar, and can be considered, to a large extent, as being representative of conditions encountered at other locations within Qatar, and, most likely, elsewhere within the Southern Shores of the Arabian Gulf region.

<u>Site I</u>:

A five storey commercial center, approximately 4000 m^2 of usable area, in Al Saad district, occupies Site I. Ground conditions at the site, thought to comprise mostly competent Simsima limestone, allowed for design and subsequent construction of isolated footings at relatively shallow depth (<1.5 m below ground). As work progressed, “diagenetic limestone”, of the type described earlier, was unfortunately encountered in the central area of the site. Preliminary sampling confirmed that a relatively high percentage of silty and clayey matrix material, in comparison to the ‘original’ competent limestone, appears wide spread. As a consequence, contractor’s work was temporarily stopped and a geotechnical investigation was launched to delineate the “diagenetic limestone”, and to recommend an appropriate alternative to the existing foundation scheme. Three boreholes were drilled in an attempt to define the lateral and vertical extents of the “diagenetic limestone”, and to carry out five *plate load* tests at proposed foundation level. Figure 2a shows material encountered and Figure 2b presents the *plate load* test results over the central portion of the site.

The modified foundation scheme has recommended removal of the isolated footings and their replacement by a solid reinforced concrete mat over the entire building area. The mat alternative, at 1.5 m below ground level, was arrived at because of the following factors: (i) relatively large deflections exhibited by the plate load tests; (ii) the large extent of the “digenetic limestone” underneath the building, estimated to cover approximately 35% of total building area;

Type		Depth (m.b.g.l)	Description	Legend	Tests
		GL 0.6	Sandy Limestone Gravel with Attapulgitic Clay		SPT'N' < 20
Simsima Limestone	Diagenetic Limestone	1.0 1.75	Moderately Weathered Limestone with Attapulgitic Clay Pockets. Limestone/Clay ratio: 85/15%		RQD = 31% RQD = 0% SPT'N' = 40 SPT'N' => 50
		2.0 3.0 3.5	Red and Green Silty Attapulgitic Clay with Gravel Size Rock Pieces in a Matrix. Limestone/Clay ratio: 30/70%		RQD = 0% SPT'N' => 50 RQD = 0% SPT'N' => 50 RQD = 0%
	Competent Limestone	4.0 5.0 6.0 7.0 7.4	Slightly to Moderately Weathered Limestone with Fractures and Inclusions. Limestone/Clay ratio: 85/15%		RQD = 37% RQD = 56% RQD = 82%

Fig. 2a. Summary of ground conditions at site I.

and (iii) the relative thickness of the “diagenetic limestone” in central portion of the site- estimated to vary from one to three meters below proposed bottom of mat. A total settlement of 20 mm was estimated underneath mat due to an average load of 170 kPa applied over entire mat area, as indicated in the analysis part of this paper. Since its construction, eight years ago, only negligible settlements have been recorded.

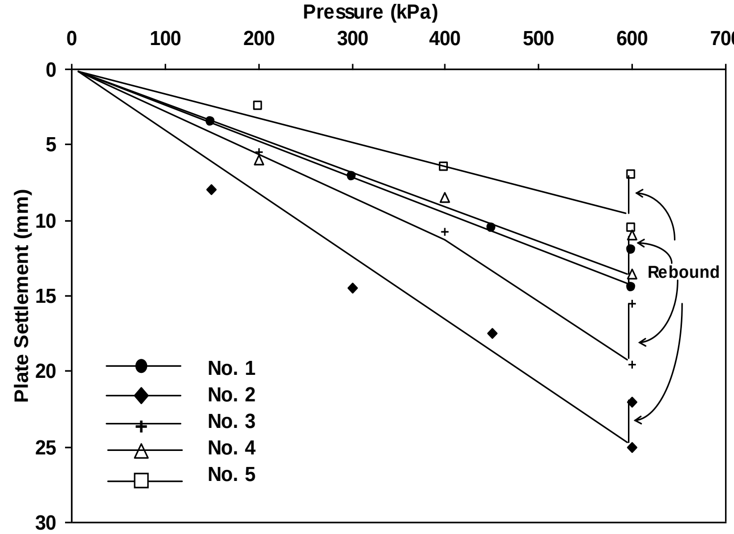

Fig. 2b. Plate load test results at site I (five tests).

Site II:

This site was to house a ground plus one level car park. Total usable building space is 12500 m^2. The project specified isolated footings on the “presumed” original limestone at 1.0 to 1.7 m below ground level. To the surprise of the contractor, and as construction proceeded, the bedrock encountered was shown to be soft and of ‘very poor’ quality in approximately 20% of the building area. Bulk samples and “on-site” observations, made during the excavation, have confirmed that the material is “diagenetic limestone” with approximately 50% matrix material (sand, silt, clay) and 50% hard original limestone. Ground water was encountered at 1.5 to 2.0 m below ground level. The “diagenetic limestone”, judged as being excessively deformable under proposed loads, triggered an investigation. As a consequence, six *plate load* tests were performed at different locations. Results are shown in Fig.3.

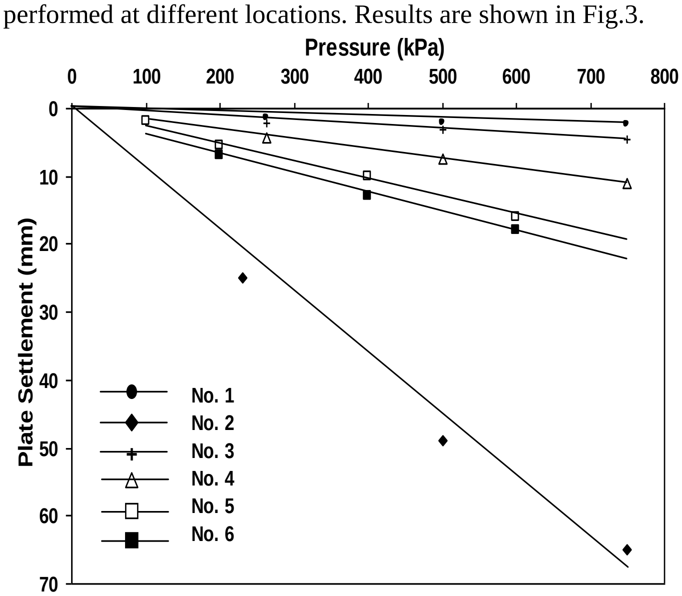

Fig.3. Plate load test results at site II (six tests).

One *plate load* test (test no.2), in particular, exhibited large deflections compared to the other five (Fig. 3). To safeguard against excessive settlement, the design was modified in favor of strapped footings. Additionally, a recommendation was made to reduce working loads from an assigned average value of 275 kpa to 150 kpa. Settlements, closely monitored for three years after construction, were well within tolerable limits.

Site III:

This site is in the old Salata district of Doha, the state of Qatar. The site is intended to accommodate an eight storey building that has an area of 3500 m^2. The site investigation comprised one borehole down to 20 m below ground level and two boreholes 15 m below ground. All three boreholes encountered the Simsima Limestone Formation at a depth of less than 1.5 m below ground level.

The first two boreholes have shown hard limestone all the way down, as reflected by good core recovery factors. However, the third borehole, depicted in Fig.4a, encountered a relatively high percentage of the “digenetic limestone” down to 9.3 m below ground.

Recovered samples, unfortunately, indicated that the matrix portion (sand down to clay size) comprises between 25% and 75% of total sample by volume; and *attapulgite* clay constitutes nearly 50% of the volume of the matrix. Therefore, precautionary measures need to be taken to safeguard against excessive settlement that could result, should the site get flooded due to excessive rainfall, or due to unpredictable rise in water table, that does take place, now and then (Akili 2007).

A full-size concrete footing block 2.0 m x 1.5 m, located on an even surface 3.0 m below ground, was tested using a piling load test reaction frame. The loaded footing block (the prototype) overlaid an estimated 6.3 m thick partially saturated “diagenetic limestone” which in turn, overlaid harder and more competent limestone. This arrangement, thought to depict actual conditions of the proposed structure, was loaded up to 500 kPa. Also, in the same excavation, four *plate load* tests were carried out. Results of the four *plate load* tests, along with the load-settlement results of the prototype footing (test footing) are shown in Fig.4b.

Based on the information derived from the field (general observations, test footing + *plate load* tests), the recommendation to use a mat at 2.0 m below surface was arrived at. A mat load of 225 kPa was recommended. This pressure on mat (225 kPa) induces a calculated elastic settlement of 20.0 mm, as described in the Section that follows.

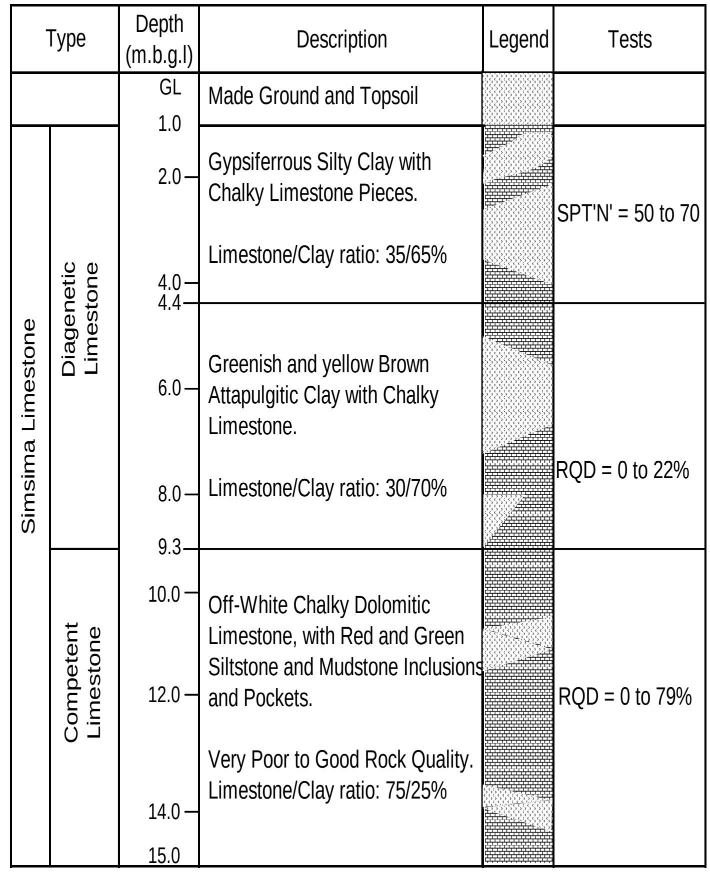

Fig. 4a. Summary of ground conditions at site III

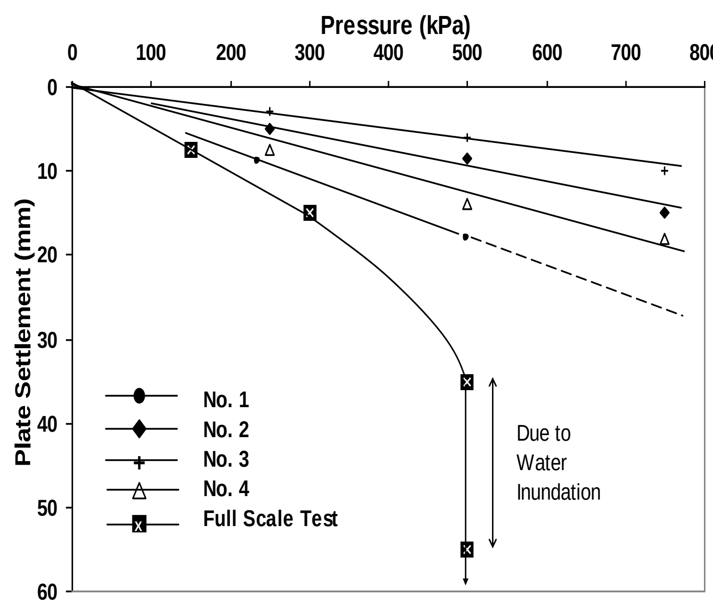

Fig. 4b. Plate load test results at site III (four plate load + one full scale).

ANALYSIS

It has become apparent that determining the extent of the "diagenetic limestone" below a proposed structure is a first priority. From the writer's experience, boring into these materials often gives low recoveries, especially when using small-size boring equipment by inexperienced operators. When "diagenetic limestone" is at shallow depth, trial pitting can be very useful as it allows: (i) visual examination of layering and materials encountered, (ii) the performance of some insitu testing, and (iii) the recovery of undisturbed samples and bulk samples for laboratory testing.

Despite its limitations, the ***plate load*** test has proven to be useful in calculating elastic modulii: and in turn, allows calculations of elastic settlement underneath a proposed footing. The 555 mm diameter plate (20 mm thick), loaded at nearly constant rate, produced settlement-pressure curves that appear linear over the pressure range applied (Figs. 2b, 3, and 4b). Since plate tests were not intended to measure the ultimate strength of the materials below, applied pressures on the plate were kept relatively small and well within the elastic range. The elastic moduli (Young's modulus) were calculated using Prandtl's method where the modulus **E** is determined using the equation shown:

$$\mathbf{E} = \frac{\mathbf{Ip\ q\ B}}{\boldsymbol{\delta}\ \mathbf{(1\text{-}\mu^2)}}$$

In the equation above, **Ip** is a shape factor equal to 0.88 for circular shapes as reported by Das (1995), **q** is the maximum pressure on plate, **B** is plate diameter, **δ** is measured plate settlement, and **μ** is Poisson's Ratio assumed equal to 0.3. A summary of calculated modulii at the three sites is presented in Table 1.

From the elastic modulii data shown in Table 1, the elastic settlements for the assumed foundation geometry, and under a specific applied pressure, can be calculated. Or conversely, the pressure to induce a selected settlement could be arrived at. Consistent with the latter, a rectangular footing, 1.5m x 2.0 m in plan is selected here as the prototype. Then, pressures on this footing, at depths indicated in Table 1, to cause a settlement of 20 mm is shown in Table 2 for each of the three sites noted earlier, namely: sites I, II, and III. As presented in Table 2, an upper pressure and a lower pressure are indicated for each of the three sites. The difference between these two values is a reflection of the difference between the high and low modulii calculated earlier (Table 1). The larger this difference, the greater the susceptibility of the site to differential settlement. The implication here is that site II appears far more prone to differential settlement than sites I and III.

COMMENTS ON THE FULL LOAD TEST

The full-scale load test carried out at site III, and reported in Fig. 4b – comprising a 1.5 m x 2.0 m footing placed 3.0 m below ground — was loaded only to 500 kPa, due to non-availability of reaction support beyond this limiting pressure value at the time of the test. Good correlation appears to exist between measured settlement of the load test (see Fig.4b) and calculated settlement at the same site, deploying elastic modulii from *plate load* tests. This is to say that applied pressure to induce 20.0 mm settlement of the test footing, estimated from Fig.4b as 350 kPa, falls within the calculated range of 363.4 to 224.8 kPa (see Table 2). This observation supports the notion that *plate load* tests do provide settlements, and thus modulii values, appear consistent with full-scale load tests.

Towards the end of the test, and at 500 kPa pressure, footing perimeter and the area below, were subjected to wetting. A 30 cm head of water above footing base was maintained for a duration of 48 hrs. During the time of wetting, settlements were monitored. As anticipated, a dramatic increase in settlement (additional due to wetting) began to occur simultaneously as water percolated down below. The final estimate of this increase was 63 % of value reached before wetting under the maximum pressure of 500 kPa (see Fig. 4b). This sudden increase in settlement, as water percolated down, is a form of 'collapse upon wetting' known to occur in cemented soils, and has been reported on (Alonso and Gens 1994; Wheeler 1994). The implications here is that matrix materials are 'water susceptible', and the extent of "the susceptibility" is a function of matrix composition; i.e., *attapulgite.*

Table 1. Summary of calculated elastic modulii (E) from plate load tests at sites I, II, and III.

Site	Test No.	Depth Range (m)	Applied Pressure (kPa)	Measured Settlement (mm)	Calculated (E) (MPa)
I	1	1.2 to 1.7	600	14.3	22.32
	2		600	25.1	12.71
	3		600	18.8	16.97
	4		600	13.8	23.12
	5		600	10.4	30.68
II	1	1.0 to 1.7	750	3.5	91.18
	2		750	63.5	5.03
	3		750	4.8	66.48
	4		750	12.6	25.33
	5		600	17.0	18.77
	6		600	19.0	16.80
III	1	3.0 to 3.2	600	18.1	17.63
	2		750	15.7	20.33
	3		750	11.7	27.28
	4		750	18.9	16.88

below ground — was loaded only to 500 kPa, due to non-availability of reaction support beyond this limiting pressure value at the time of the test. Good correlation appears to exist between measured settlement of the load test (see Fig.4b) and calculated settlement at the same site, deploying elastic modulii from *plate load* tests. This is to say that applied pressure to induce 20.0 mm settlement of the test footing, estimated from Fig.4b as 350 kPa, falls within the calculated range of 363.4 to 224.8 kPa (see Table 2). This observation supports the notion that *plate load* tests do provide settlements, and thus modulii values, appear consistent with full-scale load tests.

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The high percent settlement observed in this test during wetting is mainly attributable to three simultaneous processes: (i) collapse or destructuring upon inundation, (ii) softening of the clay within the matrix portion of the "diagenetic limestone", and (iii) rearrangement of particles, as a consequence of the collapse.

Table 2. Upper and lower pressures to induce 20 mm settlement underneath the prototype footing (1.5 m x 2.0 m) at sites: I, II and III.

Site	Modulus (E) (MPa)	Calculated Pressure (kPa)
I	**30.69 (Max)** **12.71 (Min)**	**408.8** **169.3**
II	**91.18 (Max)** **5.03 (Min)**	**1214.5** **70.0**
III	**27.28 (Max)** **16.88 (Min)**	**363.4** **224.8**

CONCLUDING REMARKS

Recently, "diagenetic limestone", comprising rock mass with matrix materials, has been encountered at several building sites in Doha, Qatar, and else where in the Arabian Gulf shores. The matrix is composed largely of rock fragments and solid grains immersed in fines. The fines can be clays (often ***attapulgite***) or other minerals such as gypsum, anhydrite, calcite, or a mixture of said minerals. A dominant feature of the matrix is its cemented structure that can be adversely affected by applied load and/or wetting. Because of their variety (type, composition, fabric, structure) and heterogeneity - these materials (the matrix) do pose problems and challenges, in terms of: their susceptibility to differential settlement, their reduced strength upon wetting, and the potential collapse of their cemented structure when subjected to loading and/or water.

In the absence of an appropriate framework and properly conceived guidelines to: sample, test, classify, analyze, and predict the behavior of the matrix material under load, extreme caution should be exercised in making shallow foundation recommendations onto these systems. In fact, spread footings should be avoided as a viable alternative, in favor of mats and strapped footings unless the material - the "diagenetic limestone"- is sufficiently scrutinized to justify the use of spread footings. As a rule, thorough insitu investigation should precede design recommendations at all times! An attempt to map out the volume and extent of the matrix material in a three dimensional space, below a proposed structure, would help a great deal "in narrowing the gap" and in arriving at a safer and more economic foundation geometries. It has also been shown that the *plate load* test is a useful tool in calculating settlements of proposed footings. In fact, the *plate load* test, despite its limitations, appears useful in assigning design loads.

It is imperative that credible research and high quality field work on the weathered limestones of the Arabian Gulf shore region be carried out and made available for the benefit of consultants, designers, and contractors involved in foundation construction over these formations. Further, a comprehensive framework may need to be devised to formulate a general model of mechanical behavior of these complex systems.

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