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ABSTRACT

Presence of highly plastic clays in Hofuf in Al-Hassa (an oasis in the eastern part of Saudi Arabia) indicated existence of potential expansive soil problems in these regions. Hofuf is notoriously known as the area with expansive clay problem and finds mention in text books on the subject also.

The first ever "Stiffened Slab Waffle Foundation" in Saudi Arabia was poured on Sunday the 7th February1999 for the Barracks in Prince Abdullah Military City, in Hofuf.

In this Paper, a Case History is being presented encompassing: the experiences of this project vis-à-vis geotechnical complexities of the Site, decision to adopt Stiffened Slab Waffle Foundation to address the expansive clay problem, development of design procedures using Spread Sheet and finally construction & performance track record of the same.

INTRODUCTION

By pouring concrete in the foundations for Barracks (Facility, B010) on Sunday the 7th February 1999 (21 Shawwal 1419 H) a mark was made in the history as the first ever 'Stiffened Slab Waffle Foundation' was cast in the Kingdom of Saudi Arabia. This especial foundation system was built under 56 nos. (out of a total of 222 nos.) of facilities in Zones: 3 & 8 that is in only 2 out of 8 Zones.

This new type of foundation system is perhaps known to be the State-of-the-Art solution for countering swelling problems underneath foundations due to presence of deep layers of expansive clays. This system built for the project is first of its kind in the Kingdom as well as in the region. Thus, the Kingdom becomes, perhaps, only the third country in the world, after USA & Australia, to have built this type of foundation system, exclusively to address the expansive soils problem underneath foundations.

This project and the name of the kingdom may, therefore, find mention in the future text books of Soil Mechanics as one of few countries where Stiffened Slab Waffle Foundation system has been built to address expansive soils problem.

OVERVIEW OF EXPANSIVE SOILS PROBLEM

Expansive Soils have a tendency to undergo excessive volume change upon contact with water and exert upward pressure underneath foundations resulting in damages to the elements of structure.

Chen, an expert, relates expansive soil problems to the cancer research. According to him, it appears that expansive soil is the cancer in Soil Mechanics. Similar to cancer the seriousness of the problem has been discovered only in recent years.

He adds, this problem was not recognized by Soil Engineers until the later part of 1930. Prior to 1930, most of the lightly loaded buildings in the United States consisted of dwellings that could withstand considerable movement without exhibiting noticeable cracks. By 1930, brick veneer residences became widely used. It was then that the owners found cracks developing in the brick courses. These were then attributed to shoddy construction, without recognition of the role of the expansive soils [Chen, F. H. 1975].

The U. S. Bureau of Reclamation first recognized the expansive soil problem in 1938 for a steel siphon project in Oregon. Since that time, Engineers realized the cause of damage to be other than settlement or shoddy construction.

It is reported [James Krohn, 1980], within the United States alone, expansive soils are responsible for damages to man made structures worth billions of Dollars, annually. It is said, perhaps not as sudden or traumatic as an earthquake, tornado or landslide, expansive soil causes more damages (in the US) to buildings, highways, etc., than the combined effects of the other aforementioned natural calamities. In Saudi Arabia, it is reported [Dhowian, 1989] that structures placed on shales of Tayma, Tabuk, Madina and Al-Ghat regions are seriously affected due to expansive nature of the shales. Presence of highly plastic clays in Hofuf indicated existence of potential expansive soil problems in these regions. Hofuf is notoriously known as the area with expansive clay problem and finds mention in textbooks on the subject also. And globally besides the USA and Australia, expansive soil is found to be troublesome in large areas of India and in some parts of Pakistan. Also in parts of Africa and the Middle East including Saudi Arabia. This problem is also reported in the northern parts of Peru in South America, due to its proximity to the equatorial zones. In addition, in England, the London Clay, Gault Clay and Oxford Clay contain montmorillonite. In Montmorillon, a town in Central France, care has been taken with foundations ever since these expansive soils called montmorillonite were identified and interestingly enough, named after the town of Montmorillon [Millard, 1993].

HOW TO RECOGNIZE EXPANSIVE SOILS

Before setting out to undertake foundation design, it is imperative to first learn to recognize expansive soils. There are three different methods of classifying expansive soils. The first is Mineralogical Identification. The clay mineralogists claim that the swelling potential can be evaluated by identification of the constituent mineral of the same. The methods are both impractical & uneconomical hence are of not much significance to the practicing engineers. The second category includes the Indirect Methods. They are: the Index Property, PVC Method, and Activity Method. They are effective in evaluating the swelling property of soils. The Third one, called Direct Measurement, offers the most useful data. This entails Swell Potential tests by one-dimensional consolidometer on expansive soils. Consistency Limits are taken as a base for the swell classification. Soil Suction is also an important factor. The classification parameters, which are mostly used, are shown in Tables: 1 & 2.

Table: 1 Expansive Soil Classification, USAEWES method [Holtz, 1969]

Sno	Liquid limit	Plasticity Index (P. I)	Swell Potential %	Soil Suction (tsf)	Swell Potential Classification
1	< 50	< 25	< 0.50	< 1.5	Low
2	50 - 60	25 - 35	0.50 – 1.5	1.5 – 4	Marginal
3	> 60	> 35	> 1.5	> 4	High

USAEWES: United States Army Engineers Waterways Experimental Station

Table: 2 Expansive Soil Classification, USBR method [Slater, 1983]

Sno	Colloid Content % <2μ	Plasticity Index	Shrinkage Limit	Probable Expansion %	Expansion
1	< 15	< 18	> 15	< 10	Low
2	13 - 23	15 - 28	10 – 16	10 - 20	Medium
3	20 - 31	25 - 41	7 – 12	20 - 30	High
4	> 28	> 35	< 11	> 30	Very High

USBR: United States Bureau of Reclamation

EXPANSIVE SOILS IN SAUDI ARABIA

Slater [1983] first presented a map for potentially expansive soils of the Arabian Peninsula. The map per se, however, was of a very general nature and lacked many details. Researchers at King Saud University, Riyadh and King Fahad University of Petroleum & Minerals, Dammam later did a lot of work on the subject. The King Abdul Aziz City for Science and Technology (KACST) a research promoting organization, has been the fountainhead for all these works. Dhowian [1989] finds especial mention here for his in-depth study and excellent documentation of Saudi expansive soils. The expansive soils found in Saudi Arabia mainly consist of two distinct materials, namely: i) Sedimentary Rocks, and ii) Clayey Soils. Expansive Sedimentary Rocks include shales, claystone, and siltstones that exhibit some degree of lithification, and possess the properties that cause volume change. The shales with various degree of weathering prevail in a strip adjacent to the west boundary of the Arabian Shield. The strip starts around Al-Ghat and extends to the North-West enclosing the Tabuk and Tayma regions. Expansive Clayey Soils are usually found in small areas scattered in the Arabian Shield and Arabian Shelf, such as the Madina and Hofuf regions. Table: 3 show the formation, geological age & topography of the regions where expansive soil formations were found. Average properties of plasticity characteristics of both Shales and Clayey Soils are represented in Table: 4.

Table: 3 Description of Expansive soils in Saudi Arabia [Dhowian, 1989]

S no.	Regions	Formation	Geological Age	Topography
1	**HOFUF**	**Calcareous Clay (Marl)**	**Upper, Middle Miocene**	**Terraces**
2	MADINA	Alluvial Deposits, Colluvial Deposits	Tertiary and Quaternary	Terraces
3	AL-GHAT	Alluvial Deposits (Dhruma Formation)	Quaternary and Middle Jurassic	Terraces
4	TABUK	Alluvial Deposits (Tabuk Formation)	Quaternary	Terraces and Low Hills
5	TAYMA	Weathered Shale (Tabuk Formation)	Quaternary	Terraces and Low Hills

Table: 4 Geotechnical Properties of Typical Expansive Soils in Saudi Arabia [Dhowian, 1989]

ITEMS	Shales				Clayey Soils		
	AL-GHAT		TABUK	TAYMA	**HOFUF**	MADINA	
	Clay Shale	Silty Shale	Clay Shale	Silty Shale	**Calca-reous Clay**	White Clay	Green Clay
Dry Unit wt γd, KN/m³	18.50	18.50	19.50	19.40	**14.20**	12.60	12.20
Water Content, Wn, %	19	12	4.50	2.30	**14**	33.10	59.10
Liquid Limit, LL %	65	46	61	38	**60**	82	105
Plastic limit PL, %	30	21	27	25	**24**	37	39
Plasticity Index, PI	35	25	34	13	**36**	45	66
Shrinkage Limit, SL %	21	16	23	20	**18**	28	16
Percent Sand, %	--	3	7	9	**23**	2	7
Percent Silt, %	28	52	48	68	**40**	30	29
Percent Clay, %	72	45	45	23	**37**	68	64
Specific Gravity, Gs	2.78	2.70	2.78	2.75	**2.69**	2.74	2.76
Group Symbol	CH	CL	MH	CL-ML	**CH-MH**	CH	CH
Activity, Ac	0.50	0.55	0.75	0.55	**0.97**	0.70	1.00

And, the other properties like Index Values and the Suction Parameters of samples from various regions are represented in Table: 5. According to [Dhowian, 1989] the log suction versus water content behavior can be approximated by a straight line.

Then the suction-water content relationship can be expressed in the following manner:

Log Ψ = A - B W, where:
Ψ = soil suction, bws.
A, B = intercept and slope of log suction-water content.
W = water content, **%**

Thus, from known initial and final water contents, the range of change in the Soil Suction as a result of Swell, can be determined by means of the above equation, and correspondingly the values of **A** and **B,** as given in Table: 5.

Table: 5 Suction Parameters of Expansive Soils of Saudi Arabia [Dhowian, 1989]

Regions	Soil Types	Consistency			Suction Parameters	
		LL	PL	PI	A	B
TAYMA	SHALE	38	27	11	1.85	- 0.057
TABUK	SHALE	61	27	34	1.61	-0.025
AL-GHAT	SILTY SHALE	37	22	15	1.67	-0.017
AL-GHAT	CLAY SHALE	67	32	35	2.10	-0.025
MADINA	GREEN CLAY	105	39	66	2.28	-0.030
MADINA	WHITE CLAY	82	37	45	2.34	-0.045
HOFUF	**CALCAREOUS CLAY**	**60**	**24**	**36**	**2.16**	**-0.033**

EXPANSIVE SOILS OF THE PROJECT SITE

The Project Site is located about 12 Km west of Hofuf in the Eastern Province. Hofuf, an oasis is situated between the rock desert of Al-Summan Plateau in the west and the sand dunes covering the adjoining plain in the east. The upper strata, known as Hofuf Formation of the upper Miocene consist of terrestrial sediments. These marine strata, known as Dam Formation, consist of limestone, marls, and clays of the middle Miocene. It is overlain by continental deposits of conglomerate, sandstone, sandy limestone, sandy marl, and sandy shale of the Hofuf Formation. The upper beds consist of sandy, fresh water limestone. It is heterogeneous and both the thickness and lithology vary considerably [Syed, 1998].

As per the investigations, the subsurface strata predominantly consist of either Fat Clay or highly to moderately weathered & fractured Limestone. This is under a cover of Silty Sand, with Limestone fragments and calcareous Clay. The thickness of this cover, in general, was observed to be 1.0 meter.

The N-Values, observed through Standard Penetration Tests were recorded in the range of 28 blows to in excess of 50 blows for 30cm penetration of the sampler. This indicated medium dense to very dense condition of the strata. The N-Values obtained in Fat Clay layers mostly indicated 'Refusal' conditions. The Clay is obviously pre-consolidated; however, upon ingress of water, the Clay layer change in its volume and swelling is likely to occur. Tests performed on representative samples also showed that upon saturation the Free Swell of Clay varied between 1.60 % and 3.0 % and such swelling developed an upward Pressure between 125 Kpa (2608 Psf) to 300 Kpa (6258 Psf) as against Allowable Bearing Pressure of 175 Kpa (3651 Psf) only. A Plate Load test, performed on the clay layer at test elevation of – 1.30 meters, showed that upon soaking, the swelling was 18.90 mm, with moisture penetration depth of 35 cm resulting in about 5.40 % swell. The clay layer underlies a cover of light brown, medium dense to dense silty/clayey sand. The thickness of the sandy cover is mostly restricted to 1.0 meter [RGME, 1998].

The Report concluded that the Site had Expansive Soils problem and suggested to use Stiffened Slab Waffle Foundation System; or else, connoted to change the location of the project Site, altogether, as an alternative [RGME, 1998]

FOUNDATION CONSIDERATIONS AT THE SITE

If a soil is classified as having a Low Swell potential, standard or regular construction practices vis-à-vis foundations may be followed. However, if the Soil has a Marginal or High Swell potential, one of the following recourses may be followed:

- ***Changing the nature*** of the expansive soil by Compaction Control, Pre-wetting, installation of Moisture Barriers and Chemical Stabilization.
- ***Replacing the expansive soil*** from under the foundations with suitable fill and construct the standard foundations like spread footings, strip footings, etc.
- ***By-pass*** the active zone of the expansive soil and construct deep foundations on non-swelling strata, and
- ***Design and construct a 'rigid foundation system'*** over the expansive soils, which has an inherent ability to withstand differential movement due to heaving.

Measures best suited to the Site conditions are suggested.

STIFFENED SLAB WAFFLE FOUNDATION

Three decades ago the prevailing philosophy was to attack these 'natural nuisances' of Expansive Soils with bulldozers, chemicals, and concrete. Now, the researchers suggest that with a better identification and preventive design techniques, it is possible to co-exist with these 'natural nuisances'. Design of ***Stiffened Slab Waffle Foundation*** developed by B. R. A. B in the US in 1968, is one such Design technique. This ensures safety and safe performance of structures built over expansive soils and in a way allows to co-exist with these nuisances of expansive soils [B. R. A. B., 1968].

FUNDAMENTALS OF B. R. A. B DESIGN PROCEDURES

The design procedures, outlined in the B. R. A. B Design Manual, consist of three basic operations

- Selection of appropriate Slab Type.
- Dimensioning the Slab, that is its layout.
- Reinforcing the Slab.

To perform the above outlined operations, the designer has to consider many factors that directly or indirectly influence the design. The important of them are:

- Soil properties of the ground.
- Type of super-structure.
- Quality Control in materials used for construction.

Selection of Slab (foundation) Type

B. R. A. B manual deals with design of foundation over both expansive & compressible soils. Therefore, selection of a Slab Type (for foundation design) appropriate to the soil types at the Site is to be done. The various Slab types considered are:

- Type – I : Un-reinforced
- Type – II : Lightly Reinforced against shrinkage & temperature cracking.
- Type – III : Reinforced and Stiffened, and
- Type – IV : Structural, not directly supported on Soil.

As per Table: 1 in the B. R. A. B manual, if:

- PI > 15, and
- $qu/w \geq 7.5$, then a Type III slab can be used, which will address the expansive, soils problem.

Design of Type III Slabs

Slab Type – III is focussed to addressing foundation design over expansive soils. Spread footings or other conventional footings are not advisable on such soils. In such types of Slabs *(Stiffened Slab Waffle Foundation)* loads are distributed by the Slab over its entire ground-support area. This reduces the bearing stresses on the soil and forces the foundation, the Slab, & the super-structure to act as a monolithic structure. It behaves like a rigid boulder in a soft mass of ground. Type-III Slab type was used to design all foundations for the Project Site per se.

Effects of Super-Structure

In Type III Slabs the walls and other load carrying elements of the super-structures follow any impending deformations in the Slabs. The deformations that can be tolerated, before any undesirable cracks begin to surface, depend upon the materials & nature of super-structure used. Some materials can perform better, like wood as compared to concrete, in absorbing differential deflections induced. The B. R. A. B manual provides a table with allowable values in terms of **Δ/L**, to be measured between any two points on the Slab along one or another of its principal rectangular axes. This value is based on the weakest exposed finish materials in super-structure. For the Project Site, a value of 1/360 was used based on plaster, being the weakest finish material at the Site.

Effect of Soil Behavior

Soil properties & Climate play a vital role in estimating swelling which affect the pressure distribution under the Slab. If either a flexible or a rigid Slab rests on level ground, and the soil beneath the Slab shrinks or swells unevenly because of change in soil moisture due to climate variation, one of the two extremes will result.

- The flexible Slab deforms as per the ground contour, resulting in differential settlement in Slab but no stress.
- The infinitely rigid Slab will be supported on the high points of the soil surface without differential settlement.

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Type III slab is stiffened (via deep beams) and strengthened (via reinforcement) and is very rigid. Differential settlements that occur will be smaller than those of the supporting ground.

Support Index

The most severe foundation deflections will result from one or the other of two principal forms of bearing support, namely:

- when the maximum bearing stresses develop under the center of a rectangular Slab of dimensions L by L', that is the " Center Support". and/or,
- when the maximum bearing stresses develop on two diagonally opposite corners of the rectangular slab, that is, the "Diagonal Support".

Since climate & sensitivity of soil affect the extent of stresses under the Slab the Coefficient **C,** which defines the boundaries of the supported fractions of Slab, is termed as the Support Index of the Slab. This varies with the Climatic Rating (Cw) of the Site and the Plasticity Index (PI) of the soil upon which the Slab rests. Climatic Rating (Cw) is a constant related to the climatic characteristics of the region while Plasticity Index (PI) can be determined from tests on the soil samples from the site. Since the Climatic Rating values for Saudi Arabian regions were not available, for design purposes, the model of San Antonio in Texas, USA was adopted which is very close to the arid conditions of Saudi Arabia.

DESIGN PARAMETERS USED FOR THE PROJECT SITE

For design of foundations for the facilities in the Project per se, the following parameters were used:

- Allowable Bearing Capacity = 175 KN/m²
- Cw (Climatic Rating) = 17
- PI (Plasticity Index) = 33
- Free Swell = 3.0 %
- Qu(Unconfined Compressive Strength) = 300 KN/m²

Based on the above parameters, the value of Support Index C was interpolated (using B. R. A. B manual) to be 0.80. It was later modified to 0.85 using provisions allowed for the same in the B. R. A. B manual, to effect some economy in the design. Spread Sheet were prepared using sequential logic of the B. R. A. B Design Manual and design calculations were performed for each facility.

The upward heaving pressure is exerted on the contact surfaces of the foundations; the Stiffened Ribs in case of Stiffened Slab Waffle Foundations. It is therefore imperative to limit this pressure within the Allowable Bearing Capacity of the Soils per se. This is the reason B. R. A. B limits the width of the ribs to be within 200 mm (8-in) to 350 mm (14-in) only; the larger the width the greater is the Contact Area and hence proportionally greater shall be the Contact Pressure.

In all such designs of the facilities, for the Project, these limits for the width were respected. And, manual calculations were made to ensure the Contact Pressures (due to heave) didn't exceed the Allowable Bearing Pressure. This was also verified using the finite element based program of PCA-MATS.

In short, while the design principles of B. R. A. B were followed, by and large, to address the expansive soils problems all necessary computational techniques were utilized to ensure the safety & integrity of the structures.

DESIGN DETAILS ADOPTED FOR THE PROJECT SITE

A typical detail of Stiffened Slab Waffle Foundation System is represented in the attached figure, Fig: 1.

Since movements of the foundation system are to be expected B. R. A. B Design Manual strictly prohibits embedment of any sort of utility pipes in the foundation Slabs, to avoid damages to the same. The following measures were, therefore, adopted for ensuring safe performance of the utility pipe vis-à-vis the foundation system.

- Especial trenches were formed in Stiffened Slabs. All utility pipes, including sewer, water supply etc, were laid in them without any connection with the Slab. These trenches were back-filled with sand instead of concrete.
- Especial care was also taken to prevent breakage of such pipes by isolating them from the Slab whenever passage, of the same, through Slab was necessary.
- All such pipes passed through the Slab vertically with provisions of some kinds of isolation joints between them.
- It was made sure all pipes exiting the building didn't have any rigid connection with the same.

To prevent seepage of water under the foundation, the following additional measures were also adopted.

- Site gradation was designed to ensure proper drainage away from the buildings.
- Sufficient pavings were made around the buildings, including a 600-mm (2-ft) wide plinth protection all around the buildings to keep water away.
- Tree plantation and the associated irrigation system were ensured to be away from the building to a distance of at least 3-m (10 ft) or so.
- No hidden or built-in downspouts were used. All roof drainage was done by means of scuppers and a splash block, ensuring proper drainage away from the building.

CONCLUSIONS

- Stiffened Slab Waffle Foundation System, developed by B. R. A. B (Building Research Advisory Board of USA) were used for design of foundations over expansive soils for 56 out of 222 facilities in 2 out of a total of 8 Zones of the project Site in Hofuf, Al-Hassa.
- This Project in Hofuf, thus becomes the first in the region and Saudi Arabia, perhaps, only the third such country in the world (after USA and Australia) to have adopted this type of foundation system solely to address the swelling & heaving problems of expansive soils underneath the foundations.
- Spread Sheets were prepared using sequential logic of the B. R. A. B Design Manual to perform design calculations for each facility.
- Wherever shallow depths of expansive soils (less than a meter) were encountered the same were over-excavated, removed and replaced with select engineering fill. The fill were then compacted to 95 % AASHTO before proceeding with any other activity related to foundation construction.
- The buildings with Stiffened Slab Waffle Foundations have been regularly monitored and are performing well since past four years or so. They have not exhibited any sign of distress whatsoever. These have also seen through several alternating wet-dry seasons without any problem.
- This Project has induced encouragement in others and it is expected more and more projects, in future, may adopt the same system both here & in the region.

Plate: 1 Excavation & Rebar placing for Stiffened Slab Waffle Foundation at the Site

Plate: 2 Concrete placing in Stiffened Slab Waffle Foundation at the Site

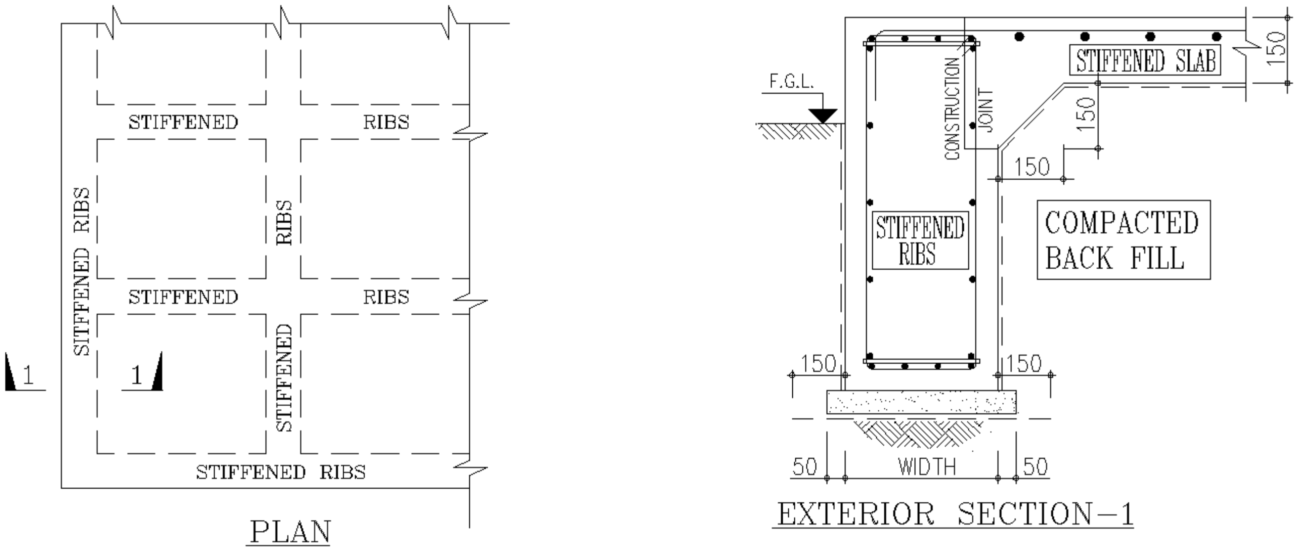

Fig: 1 A Typical Detail of Stiffened Slab Waffle Foundation

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