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GROUND IMPROVEMENT OF A BEACH STRUCTURE COMPLEX BY MEANS OF STONE COLUMNS – A SAUDI ARABIAN CASE HISTORY

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ABSTRACT

Saudi Arabian is a vast peninsula with varying surface and sub-surface geology. There are many regions, especially near the eastern and western coasts, where the sub-surface soil is very poor. In these regions ground improvement is inevitable. The case in point is a Beach Structure Complex built along the famous Half Moon Bay Beach of Al-Khobar in the eastern coast of the Kingdom. The geotechnical investigations revealed poor soil condition and suggested use of Stone Columns for improving the ground condition. A total of 3119 Stone Columns were installed under five important buildings by means of Vibro-Replacement Techniques. The performance evaluation of the improved ground was carried out by conducting a number of Pre and Post-Penetration Tests and full-scale Plate Load Tests. The facilities upon these improved grounds are now up since past two years and performing satisfactorily. The focus of this paper is the Case Study of the problem. The paper also highlights the phenomenal recent construction boom in the Kingdom that has now swelled to more than US$ 200 billion. There is a wide scope of consultancy and contracting in the field of ground improvement, which at present is limited to a few local companies only
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INTRODUCTION

At famous Half Moon Bay in the Eastern Province city of Al-Khobar (Saudi Arabia) a beach complex were planned to be constructed. This beach complex included some 30 facilities of very high importance. Since this beach complex was very close to the seaside known for its very weak surface and sub-surface strata, a rigorous and detailed geotechnical investigation was conducted to ascertain the safe bearing capacity and the types of foundations that could be built. The structures in the proximity of the seashore were mostly ground + 1 structures. The initial report of April 2004 by M/S Riyadh Geotechnique & Foundations (RGF) suggested use of deep foundations like bored cast in-situ or pre-cast Piles or else to go for ground improvement by means of Stone Columns, in case shallow foundations were to be adopted. This was especially for the building facilities in the proximity of seashore where Sabkha Soils were spotted. Both of these options were expensive and hence not acceptable to the Contractor. The Contractor therefore decided to go for a second expert opinion. This was warranted also because of the fact that the final grading was revised whereby the buildings finished floor levels were to be raised substantially; to the tune of 3 m at some places. M/S Gulf Consult was thus engaged in March 2005, to review the entire situation and come up with their own independent opinion on the foundation types and the value of safe bearing capacity. This was all in a hope that this new report might provide for some kind of shallow foundations for the facilities near the seashore without having to do any ground improvement. All hopes were dashed as the new report also suggested shallow foundations, like Pad Foundations, etc., after ground improvement by means of Stone Columns. The findings of these two reports are dealt with in detail in the following sections of this paper.

GEOTECHNICAL ISSUE AT THE SITE

The project site is located in the Half Moon Bay Area in Al-Khobar. It is situated on the beach and the western boundary runs along the beach. The eastern boundary is adjacent to the highway. An existing villa bound the northern boundary and there is an existing sand dune about 4-6 m high in the north. The project site is covered with loose dune sand. Some of the boreholes were located on the water line of the beach. M/S Riyadh Geotechnique & Foundations (RGF) carried out initial investigations in April 2004. As per this report, drilling for 17 Nos. of boreholes was carried out using Acker ADII drilling rig. The sub-surface strata were penetrated by rotary drilling method using wash boring technique. Standard Penetration Tests (SPTs) were performed at 1.0 m depth intervals in the soil layers. These tests were performed generally in accordance with ASTM D-1586 using a split- spoon sampler of 35 mm inner and 50 mm outer diameter. The samples recovered from split-spoon sampler were visually inspected and classified as per ASTM D-2488. A description of soil samples recovered and the number of blows of the Standard hammer used in the SPTs for successive 15 cm of penetration was recorded on field borehole logs. All the samples recovered from the split-spoon samplers were carefully preserved and sent to the laboratory for further testing and evaluation. Based on the above summary, the Site was divided into two zones, as defined in Table-1 below.

Table-1: Zone Wise Description of the Site [RGF, 2004]

Zone	**Borehole**	**Facilities Nos.**
A	BH-1 to 8	B001, B002, B005 & B009
B	BH-9 to 17	B003, B004, B010, B011, B012 & B015

Table-2: Typical Sub-Surface Profile for Zone-A [RGF, 2004]

0.0	**Depth**	**Description**
0.50 m **2.0 m**	**Water Table**	Brown loose to medium dense SAND with Silt γ_{sub} = 8 KN/m^3; N = 6 – 25; Ø = 29°
5.0 m		Gray, very loose to loose Sand with Silt γ_{sub} = 7 KN/m^3; N = 2 – 10; Ø = 26°
9.0 m		Gray, very loose to loose silty Sand γ_{sub} = 7 KN/m^3; N = 2 – 10; Ø = 25°
15.0 m		Gray, medium dense to very dense Sand with silt γ_{sub} = 9 KN/m^3; N = 20 – Refusal; Ø = 31°

A typical borehole log depicting the state of the affairs vis-à-vis sub-surface soils condition near the seashore can be seen at Table-2 for Zone-A, while the same for the rest of the regions, that is for Zone-B, are represented in Table-3. Based on the results of settlement analysis for various widths of square/isolated, strip footings and mat foundations, the allowable Bearing Capacities suggested for Mat Foundations are represented in Table-4 below.

Table-3: Typical Sub-Surface Profile for Zone-B [RGF, 2004]

0.00 m	**Depth**	**Description**
1.00 m **9.0 m**	**Water Table**	Brown to gray, medium dense to dense SAND with Silt γ_{sub} = 8 KN/m^3; N = 10 – 35; Ø = 29°
12.0 m		Gray, loose to dense Silty Sand γ_{sub} = 8 KN/m^3; N = 6 – 34; Ø = 29°
18.0 m		Gray, soft to very stiff Sandy Silt γ_{sub} = 8 KN/m^3; N = 2 – 23; Ø = 30°
20.0 m		Gray, very dense Sand with silt γ_{sub} = 9 KN/m^3; N = Refusal; Ø = 30°

Table-4: Zone Wise Bearing Capacity [RGF, 2004]

Zone	**Width of Footing**	**Depth of Footing**	**Bearing Capacity For Mat**
A	8 to 12 m	1.00 m	50 KPa
B	8 to 14 m	1.00 m	65 KPa

The Soils near the proximity of the seashore were identified as Sabkha Soils. Sabkha means trouble and is often dreaded by both structural and geotechnical engineers. The nature & properties of Sabkha Soils are taken up in details in the later sections of this paper. Just to make it short, in many situations, it is required to improve the load carrying capacity of Sabkha Soils and the use of geotextiles are found appropriate as far as roads and highways are concerned. For the building foundations, however, use of Stone Columns is seen to be very common in Saudi Arabia for the purpose of ground improvement of such types of problematic soils, like Sabkha Soils and other similar soils. Now, since the recommended Bearing Capacity value was not adequate enough to support loads from two-storeyed buildings in Zone-A (near shoreline), it was suggested in the report per se to adopt either deep foundations (like piling) or opt for ground improvement by means of Stone Columns. As per the report, deep ground improvements should be able to improve the allowable Bearing Capacity to 100 KPa and upon which a design for shallow Pad Foundations could be based. Both of these options were expensive and hence not acceptable to the Contractor. So a second investigation was planned for reconfirmation purposes [RGF, 2004], [Ingold, T.S., 1982].

The second geotechnical investigation was carried out by yet another Consultant in a bid to acquire a second professional opinion on the issue. In this second investigation, the project site was divided into three zones: A, B, C and D. Zone-A comprised of the area under the facilities close to the seashore. As per this second report, near the shoreline where boreholes BH-1, 2, 3, 4, 5, & 6 were drilled, the subsoil was similar in soil type (mainly consisting of non-cohesive Sand) and densification with depth. All these boreholes indicated very loose soil formation between 2-8 meters in depth. They were once again categorized as Sabkha Soils. Table-5 shows a general profile of the sub-surface strata in all these four zones mentioned above [Gulf Consult, 2005]. The average depth of ground water level in the area located near the shoreline where BH-1 to BH-6 were drilled was shallow. At the middle portion where BH-9 to BH-12 were drilled, the average depth to ground water level was 0.60 m, while in the other boreholes BH-13 to BH-17), it was 1 m deep. As per the second review report, the following recommendations were made vis-à-vis Bearing Capacity of the soil. In Zone-A, where facilities B001, B002, & B005 were proposed to be constructed, the safe Bearing Capacity of the existing soil was reported to be 32 KPa for raft type of footing placed at a depth of 1 m below the finished grade. Thus it was now clearly known that it might not be adequate enough to support the two-storeyed building loads on such a poor soil. Hence, in this region it was recommended to carry out necessary soil improvement for the purpose of enhancing the Bearing Capacity. Considering the shallow ground water table, Vibro-Replacement technique was suggested for the purpose. It was suggested, after the soil improvement, it was possible to adopt a Safe Bearing capacity of 120-150 KPa for shallow footings like, Pad/Strip

Table-5: Typical Sub-Surface Profile at the Project Site [Gulf Consult, 2005]

Assigned Zone & Drilled Borehole Nos.	**Layers Encountered & their Engineering Characteristics**
Zone-A BH-1, 2, 3, 4, 5, & 6 at Facilities Nos. B001, B002, and B005	Almost similar subsoil condition with depth in this area as follows: Layer-1: Depth 0.00-2.00 m; Light brown to medium dense, poorly graded, fine to medium Sand with Silt. SPT values: 6-25 Layer-11: Depth 2.00-9.00 m; Light gray to darkish gray, loose to very loose Sand with seashells. SPT values: 2-9 Layer-111: Depth 9.00-15.00 m; Light gray to darkish gray, fine to medium, dense to very dense Sand. SPT: 25 to refusal.
Zone-B BH-7 & 8 at Facilities Nos. B009	Layer-1: Depth 0.00- 3.00 m; Light brown to light gray, medium dense Sand with Silt and seashells. SPT values: 14-31 Layer-11: Depth 3.00- 9.00 m; Light gray, very loose to medium dense Sand with Silt. In BH-7, this layer was in loose to very loose condition with SPT values: 2-8. While, in BH-8, this layer was in loose to medium dense condition with SPT values: 8-14. Layer-111: Depth 9.00-15.00 m; Dark gray, medium to very dense Sand with Silt to Silty Sand. This layer was underlain with above formation with SPT values: 17 to refusal.
Zone-C BH-10, 11, 12, & 9 at Facilities Nos. B003 & B004.	Layer-1: Depth 0.00-10.50 m; Light brown to gray, medium dense Sand with Silt. Surface soil up to 1 m depth was in loose condition with SPT values: 8-10. Below 1 m it was in medium dense state and with SPT values: 14-30. Very loose pocket was observed in BH-12 between 3-4 m depth with SPT values: 4. In BH-9, it was encountered between 6-7.5 m depth. Layer-11: Depth 10.50-15.00 m; Light gray to darkish gray, very loose to loose, Silty Sand. SPT values: 2-6. In BH-9, very loose soil pocket of 1.5 m thick was encountered from 10.5 m. Layer-111: Depth 15.00-20.00 m; Light gray to darkish gray, dense to very dense Sand with Silt. STP values: 32 to refusal.
Zone-D BH-14, 15, 16, 13, & 17 at Facilities Nos. B011, B012, B010 & Security Gate.	Layer-1: Depth 0.00-13.50 m; Light brown to darkish gray Sand with Silt in varied proportion. Soil up to 1 m depth was in loose condition with STP values 1-9. Below 1 m depth, it was in medium dense to dense condition with STP values: 11-41. Layer-11: Depth 13.50-18.00 m; Gray medium stiff to very stiff Sandy Silt with STP values: 5-25. Layer-111: Depth 13.50-20.00 m; Light gray, dense to very dense Silty Sand with STP values: 49 to refusal.

Foundations and Rigid Raft Foundations at a depth of 1 m below the finished grade level [Gulf Consult, 2005].

SABKHA SOILS IN SAUDI ARABIA [Bell, F. G, 1978].

Sabkha soil is abundant along the Arabian Gulf and Red Sea coasts and is a problematic soil due to its acute water sensitivity and chemical aggressiveness. Sabkha resembles playas in that they are depressions in desert floors, and contain fine-grained deposits (silt, sand, clay) and evaporites. Sabkha, however, differs enough from playas to warrant a separate description. The term Sabkha denotes the presence of salt, and always refers to the saline, puffy, crust-surfaced flat basins that intersect the water table. In the Eastern Province of Saudi Arabia, such features are most common in low-lying coastal plains, but older ones can be found in places as far inland as the edges of the Summan Plateau, some 125 km from the coast. Non-saline playas composed entirely of silt, fine sand, and clay, and which lie well above the water table, also occurs in depressions and lows of wadi (valley) beds. Some maps have labeled these features incorrectly as "Sabkha." The processes that form such playas, or "silt flats," differ from those that form Sabkha.

In Saudi Arabia, such non-saline playas are called Faydah. If vegetation is present, they might be referred to as Rawdah. These features, when dry, have a characteristic pale color, do not have crusted salts, and provide an excellent driving surface. When wet, they become soft, slippery, and sticky. Such playas frequently hold pools of rainwater, which can remain sweet for weeks. Even some Sabkha with an obviously saline surface crust have shallow, hand-dug wells with drinkable, if brackish, water 2 to 3 m below the surface. When wet, a Sabkha surface shows dark tones in images; when dry, it shows a light-toned salt crust. This crust can be a thick armor plate of salt that will support a load or a thin layer over quick sand. These surfaces are hygroscopic, and can absorb moisture from fogs and be sticky; in coastal Saudi Arabia fogs are quite common in late August to October.

Many Sabkha areas are covered with sand sheet or with dunes. Areas that appear to be inter-dunal flats are commonly Sabkha concealed by windblown sand. These areas should be considered non-trafficable until checked out. Sand around Sabkha edges is usually vegetated and hummocky. The distribution of Sabkha is topographically controlled, and borders are defined by beach ridges, marine terraces, discontinuous mesas and shoreline cliffs, old drainage-ways, or rock out crops. Sabkha forms where wind erosion removes surface materials down to the water table. Water is always associated with Sabkha in the form of flooding, runoff accumulation, capillary rise, and tidal fluctuation. The sediments that fill Sabkha consist of sand, silt, clay, and salts in varying combinations. Their flat surfaces mark the elevation to which soil moisture rises above the static water level. Below this surface, the materials are damp, wet, or saturated; above, they dry out and blow away [Bell, F. G., 1993].

USE OF STONE COLUMNS AT SITE

The results of the two geotechnical investigations had recommended that ground improvement was inevitable, if shallow foundations were to be designed & constructed at the site for the following five facilities located near the shorelines: B001, B002, B003, B004 and B005.

<u>Design of Stone Columns</u>

The design of Stone Columns was made on the basis of results of geotechnical investigation of the project site. The design included the length, diameter, and the center-to-center spacing of the Stone Columns. Settlement analysis was performed for the foundations of the proposed facilities. Settlements were evaluated for the expected loadings using SPT values obtained during the soil investigation stage. Design method proposed by Priebe was used to evaluate the improvement in soil parameters after installation of Stone Columns using DC-Vibro software. A basic number “No” was assigned to each configuration of the Stone Columns. “No” is indicative of the reduction in settlements for each configuration of the Stone Columns. For a given configuration, “No” is based on the angle of internal friction of the material used for the construction of Stone Columns. For the types of aggregates used in the job, the angle of internal friction was 40°. The modified strength parameters (angle of internal friction and cohesion) of the improved soil were evaluated using the method proposed by Priebe and hence the improved Moduli of Elasticity (Es) were obtained. Expected settlements and bearing capacity were used to optimize the number of Stone Columns under the required area of improvement. The design was carried out giving due consideration to the envisaged loads, ensuring minimum differential settlements to take place. Since the foundation designs of the facilities were already based on a Bearing Pressure of 100 KPa, therefore soil improvement was focused in achieving this desired value of Bearing Pressure. The allowable settlements were taken as 25 mm for Isolated Footings / Strip Footings while for Mat the same was assumed as 50 mm [Leonards, G.A., 1962]

The depth of Stone Columns varied from 10.0 m to 11.0 m and the nominal design diameter of the same was 0.90 m. Various grid spacing were evaluated and the optimum design for each footing under consideration was adopted, and hence as such the number of Stone Columns required under each footing was calculated. Rectangular and triangular grids varying from 1.45 m to 1.90 m center-to-center were thus used to achieve the Allowable Bearing Pressures of 100 Kpa required for the project site.

<u>Number and Layout of Stone Columns used</u>

A total of 3119 Stone Columns were required under the footings for the five important facilities located along the shorelines. Table-6 presents building-wise details on the same.

Fig-1 shows layout of Stone Columns for B004. This was the smallest building in size in terms of footprint area. And, the figures in Table-6 are just for giving an idea as to the layout & spacing and number of Stone Columns actually used at the Project site. The asterisk mark (in column # 5 of Table-6) indicates some additional Stone Columns were used due to design changes made in the building plan at later stages.

Installation of Stone Columns at the Site

A typical design calculation's result summary for another facility B002 is presented in Table-8. Vibro-replacement method to install the Stone Columns was employed at the site. In this method per se, a powerful torpedo-shaped horizontally vibrating poker (Vibroflot) was used to create a hollow-shaft in the ground in which compacted Stone Column was formed. The water flush circulated under pressure through the Vibroflot was used to keep the hole open & stabilized and for washing out soft soils replacing it with a compacted Stone Column. The stone aggregates used for construction of Stone Columns conformed to the requirements of ASTM D422/136 and had the grading sizes from 25 mm to 100 mm. Plate-1 shows a typical procedure for installing Stone Columns by means of Vibro-replacement method while Plate-2 thru Plate-6 show the process of installing the Stone Columns at the project site.

Pre and Post Penetration Tests of Stone Columns

The pre and post-penetration tests were used to evaluate the soil improvement in between the Stone Columns. For the purpose, Dutch Cone Penetration Tests (CPT) were performed as per ASTM D3441; both prior to installation of Stone Columns and after. Increase in penetration resistance, in simple words, indicates the degree of improvement of the soil parameters at the site. Two CPTs were conducted in each building site both prior and after installation of Stone Columns. One full scale Load Test was also carried out in each of the five facilities, after installation of Stone Columns to ascertain the achievement of the required Bearing Capacity. The test was performed on one group of Stone Columns as per ASTM D1194 using 2 m x 2 m foundation block over a Marl Cap properly compacted to 95 % for the purpose. The design was based on the Allowable Bearing Pressure of 100 KPa for corresponding settlement of 25 mm for Isolated/Strip footings which were in fact used in the design of these subject facilities. The test plate was loaded at 25 % increment of required Bearing Pressure after ground improvement. The maximum test load was 1.5 times of the required Bearing Pressure. The details of the Load Test report are represented in Table-7. The Load Test had shown satisfactory results and adequacy of the stone columns installed in all five facilities as the settlements recorded were well within the acceptable design limits [Merlin G. Spangler et al, 1982].

Table-6: Building Wise Details of Stone Columns

Sno.	Facility No.	Footprint Area	Stone Column Spacing	Number of Stone Columns
1	B001	1754.52 m²	1.516 m to 2.400 m	737
2	B002	1189.12 m²	1.545 m to 1.770 m	590
3	B003	3537.32 m²	1.500 m to 1.819 m	881*
4	B004	961.30 m²	1.500 m to 2.800 m	370*
5	B005	1604.85 m²	1.500 m to 2.100 m	541

Table-7: Load Test Details

Load Test No.	Bldg No.	% of Design Pressure	Applied Pressure	Settlement
1	B003	100	100 KPa	4.09 mm
		150	150 KPa	6.12 mm
		0	0 KPa	5.12 mm

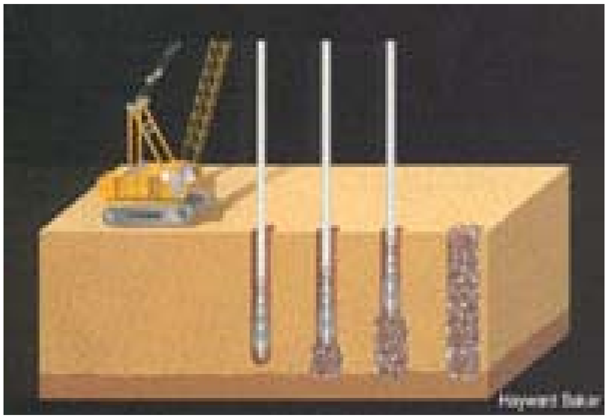

Plate-1: Stone Column Procedures

Plate-2: Aerial View

Plate-3: Stone Column by Vibro-replacement Method

Plate-4: Stones being poured into the Drilled Shaft

Plate-5: Finished Stone Column

Plate-6: B002 where Stone Columns were installed

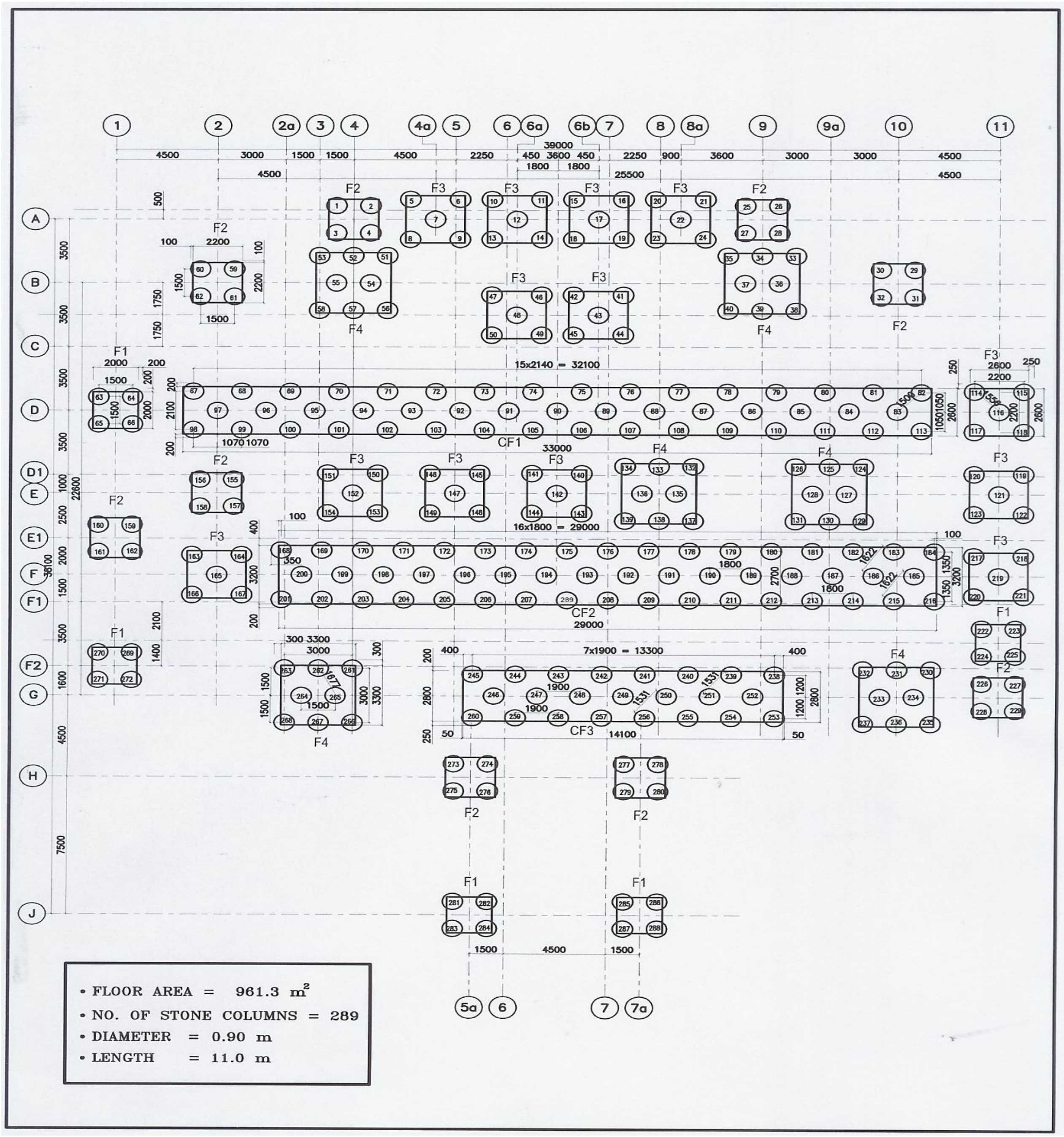

FIG-1: LAYOUT OF STONE COLUMN IN B004

Table-8: Design Calculation's Result Summary

S. No.	Footing No.	Width of Footing	Length of Footing	No. of Reqd. Stone Columns	Settlement Before Improvement	Settlement After Improvement
1	S9	3.4 m	12.9 m	24	29.67 mm	13.87 mm
2	S6	4.0 m	6.6 m	15	26.31 mm	10.60 mm
3	S3	4.8 m	17.2 m	44	38.78 mm	16.43 mm

CONCLUSIONS & RECOMMENDATIONS

- Sabkha Soils found mostly along the Eastern and the Western shorelines of the Kingdom of Saudi Arabia are a big nuisance and inevitably and invariably require ground improvement in order to sustain loads from the structures.
- Ground improvement by means of Stone Columns remains by and large the most common, convenient, economical and hence a popular option through out the Kingdom.
- In the project site under consideration in this paper, Stone Columns were installed by using the Vibro-Replacement method under the foundations of five principal and important facilities located mostly along the shorelines.
- The post CPT Tests and the full scale Load Tests conducted on the project site have indicated marked improvements in the soil bearing capacity after installation of Stone Columns thereon.
- The facilities built on the improved grounds are doing well since past two years. No problem of excessive settlements or any other sign of structural or architectural distress & cracks have been seen or reported so far.
- There is a phenomenal construction boom in the Kingdom of Saudi Arabia that has now swelled to more than US$ 200 billion. As such, there is a wide scope of consultancy and contracting in the field of ground improvement here, which at present is limited to a few local companies only.
- Techniques & technologies of ground improvement other than stone columns have not found inroads into the huge construction market of Saudi Arabia so far. Hence, owing to huge anticipated construction activities here, the international Consulting and Contracting companies of repute, specialized in the fields of ground improvement, stand a favorable chance to explore their role and hence land businesses for their companies by opening up a subsidiary outlet of their companies here.

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