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K. S. A. Rahim
King Saud University, Riyadh, Saudi Arabia

A. W. Dhowian
King Saud University, Riyadh, Saudi Arabia

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Foundations on Stone Columns Resting on Coralline Limestone

K.S.A. Rahim
Associate Professor, Civil Engineering Department, King Saud University, Riyadh, Saudi Arabia

A.W. Dhowian
Associate Professor, Civil Engineering Department, King Saud University, Riyadh, Saudi Arabia

SYNOPSIS: The subsoil conditions along the Red Sea coast in Saudi Arabia are complex due to existance of very thick beds of coralline limestone of recent geological origin. These coral beds are soft, porous and nonhomogeneous. They are often interspaced with large cavaties and soft sandwitched layers of finer particles. Analysis of the subsoil conditions to a fifty meter depth based on data from deep boreholes, Standard Penetration Tests (SPT), Quasi Static Cone Tests (DCT) and large size Plate Load Tests is presented. The strength and compressibility characteristics of the strata and the correlation factors for the SPT and DCT in coralline limestone are evaluated. The results from the plate load tests conducted on natural soil and on soil compacted with stone columns are included. An evaluation of the performance of the foundation for the heavy turbines resting on soil compacted with vibro-compaction replacement method with stone columns was made.

INTRODUCTION

Saudi Arabia is a vast country with several geologic environments. The western coastal area is a flat narrow plain bounded by the Red Sea in the west and by the Al Hiyaz mountain ranges in the east. It is underlain by the Arabian Shield. The Precambrian Basement Complex of the Arabian Shield are mainly igneous and metamorphic and form a dome shaped topography, Saad and Zolt (1978). The main geological features and climatic conditions in Saudi Arabia are discussed by Oweis and Bowman (1981). Due to favourable marine and climatic conditions coral cultures grew along the Red Sea coast forming terraces of coralline limestone. The reef conditions caused continuous changes in coralline limestone beds. The high porosity of the soft coral beds and the destruction caused by the boring organisms permitted flowing of water and sedimentation of sand and silt particles between coral layers. Sometimes the sediments and soft coral formations were washed away creating cavaties.

This case study involves a large project located on the Red Sea coast about 140 kilometers south of Jeddah. This multi-million dollar Power and Desalination Plant is spread over an area of approximately 10 hectors and it has five foundations pads of 100 square meters (SQM) for each of the five turbines. Only the heavy foundations with loads of 15 mega newtons (MN) each for the five turbines are discussed in this case study.

SUBSOUL INVESTIGATIONS

The shed housing the turbines and the boilers covers an area of 300 meters (M) by 150 M. To investigate the subsoil conditions, a 50 M deep borehole was drilled in the center of the area and six more boreholes up to 25 M depth were sunk within the area. Forty five Quasi Static Cone penetration tests (Dutch Cone Test (DCT)) up to 25 M depth were conducted within the area. The DCT results along with the borehole log data representing the average subsoil conditions in the area is given in Figure 1. The DCT was conducted in the immediate vicinity of the borehole and Standard Penetration Tests (SPT) were performed during drilling of boreholes. Two plate load tests at a depth of one meter below ground level were also conducted. The details for all the boreholes, the DCTs, the plate load tests and the laboratory tests are given by Keller (1984).

SUBSOIL CONDITIONS

The water table lies between 1.25 to 2.5 M below ground level (G.L). The overburden is 5 to 7 M thick. It is composed of a mixture of silt (up to 60 percent (%)), fine sand (up to 25%) and clay (up to 20%). A generalised grain distribution plot is given in Figure 2. The silts are soft to medium soft in consistency and are classified as Silts of Low Plasticity (ML). The SPTs indicate low penetration resistance with blow count (N) ranging between 5 to 15 N with an average of N=11 for the 12 tests. The N values show that the stratum is loose to medium loose with q_{ad} (allowable bearing pressure) is less than one bar, Terzaghi and Peck (1948). In conformity with SPTs, the DCTs gave the cone resistance (q_c) ranging between 10 to 20 bars with an average of 14 bars and a friction ratio ranging between 4 to 6% for the 45 DCTs conducted for the full depth of the overburden. Thus q_{ad} for the stratum is one bar for raft foundation, Terzaghi and Peck (1948). The correlation factor, $n = q_c/N$, relating the SPT blow count N to DCT cone resistance q_c ranges between 2 to 4 for all the tests in the overburden. The correlation factor is in conformity with the published results for loose silts, Schmertmann (1970), and Sanglerat (1972). The plate load test conducted on a 5 SQM concrete slab indicated a bearing pressure of 0.75 bars with a settlement of 2.58 millimeters (mm). The laboratory test results are given in Table 1.

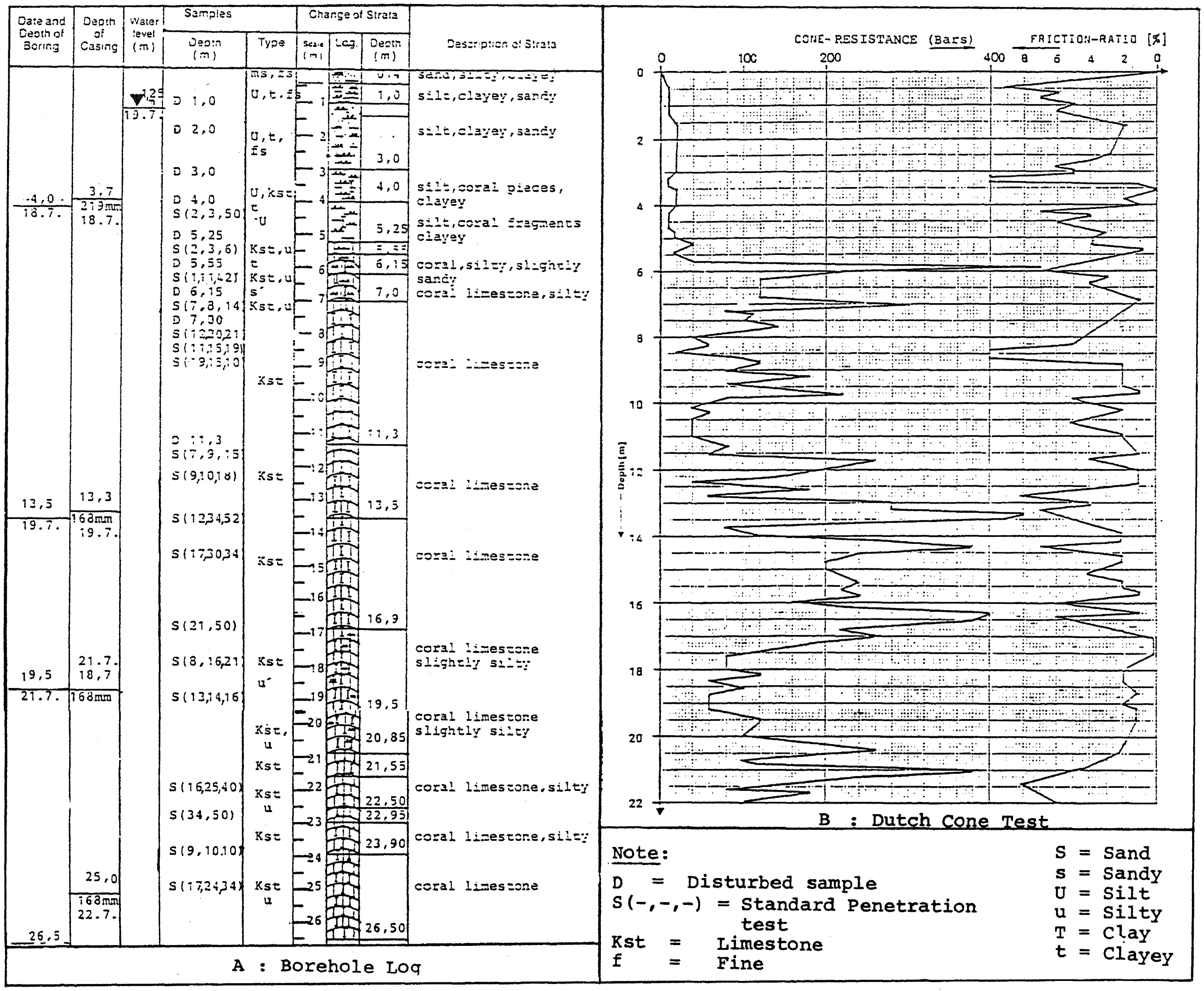


Fig. 1 Subsoil Conditions

Below the overburden lies the coral limestone extending to deeper depths (more than 50 M below ground level). Due to its natural growth the coralline limestone is soft, nonhomogeneous and porous. The density, porosity, and strength characteristics of the coral formation vary erractically. The core recovery ranged between 10 to 70 % with an average of 40 % that confirms the erractic and weak characteristics of the coral formations.

Data from 50 to 60 M deep boreholes (Borehole log for a 50 M deep borehole was not included due to space limitation) show that thin sandy silty layers are sandwitched between thick coralline limestone layers at deeper depths. It also shows that there are cavaties (up to 5 M thick) at depths of 35 to 45 M below ground level followed by a 1.5 to 2.0 M thick gravel beds. It was possible to penetrate the coral

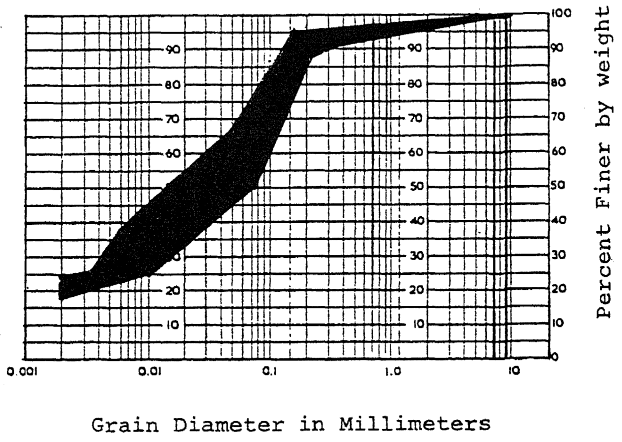


Fig. 2 Grain Distribution Curves

formation and a few SPT and DCT tests were conducted. SPT tests indicate medium resistance of 15 to 35 N and the q_c in DCT tests ranged between 20 to 70 bars in the porous and weaker grey coralline limestone containing sandwitched layers of silt and fine sand. Compact coralline limestone is white to brown in color with a tight but porous structure. The SPT ranged between 25 to 60 N and q_c in DCT tests ranged between 80 to 200 bars. The N values indicate that q_{ad} ranges between 1 to 3 bars for the weaker grey coralline limestone and it varies between 2 to 5 bars for the compact white coralline limestone. Similarly the q_c from DCTS show that q_{ad} varies between 0.5 to 2 bars for the grey layers and it ranges between 2 to 5 bars for the compact white stratum. Hence, a value for q_c of 2 to 3 bars can be assigned for the entire coralline limestone strata. The correlation factor (n) for the weaker grey layers ranges between 2 and 3 and it varies between 3 and 4 for the compact white layers. The unconfined compressive strength of intact cores from the white layers ranged between 6.2 to 22.6 bars with unit weight ranging between 10.4 to 18.8 kilo-newtons per cubic meter.

TABLE 1. Laboratory Test Results

A: Undisturbed Samples From Overburden

Borehole No.	Sample	Dept (meters)	Water content (percent)	Dry unit weight (KN/M^3)	Liquid limit (percent)	Plasticity Index	Direct shear Test	
							Cohesion (bar)	Angle of internal friction (Degrees)
1	(a)	3.6	28.5	15.0	40	15	0.08	14
12	(a)	2.3	26.4	14.2	-	N.P	0.25	11
	(b)	3.8	33.2	13.9	45	16	0.20	11
14	(a)	2.3	36.5	13.4	41	14	0.07	12
	(b)	3.5	-	-	40	12	0.06	16
	(c)	4.5	21.6	16.5	39	12	0.04	12
18	(a)	3.7	29.9	14.8	47	17	0.30	6
29	(a)	3.0	30.3	-	35	8	0.46*	0
58	(a)	2.0	29.3	14.7	30	6	0.44*	0
	(b)	3.3	33.7	-	36	10	0.38*	0

Note: * = Triaxial Test - Unconsolidated Undrained (U.U.)

B : Intact Core Samples From Coralline Limestone

Borehole No.	Sample No.	Depth (meters)	Moist unit weight (KN/M^3)	Absorption (percent)	Compressive strength (bars)	Remarks
1	S-1	15.4	-	-	13.42	
3	S-1	10.8	13.8	15.9	8.12	Soft,white,highly porous
	S-2	12.0	10.4	12.8	6.23	Ligt,soft,highly porous
	S-3	15.6	17.6	12.3	16.07	Hard,white,compact
	S-4	30.5	18.8	8.5	12.78	Hard,white,compact
12	S-1	7.2	-	-	10.98	
	S-2	10.4	-	-	6.71	
	S-3	11.4	-	-	22.57	
14	S-1	8.7	16.1	-	13.00	
	S-2	10.9	14.8	-	10.00	
	S-3	15.9	15.6	-	12.00	

THE PROBLEM AND THE SOLUTION

The upper stratum of 5 to 7 M thick is mostly silts mixed with sand and clay size particles. It is nonhomogeneous, compressible and of low bearing cpacity of 0.75 to 1.0 bar. The coralline limestone formations underneath are of recent geological origin. The density and strength characteristics vary erracticaly. Thin layers of silts and sands are sandwitched between thick layers of coralline limestone. The coralline limestone possesus medium strength with q_{ad} = 2 to 3 bars and is unsuitable for bearing piles.

Any solution to the foundations must ensure the load distribution within the upper stratum of 5 to 7 M in order to avoid load concentration on coralline limestone underneath. It should also meet the settlement criteria. The other factors are the time element and the cost. Thus the improvement of the upper stratum by compaction techniques is one of the best economical solutions to be considered.

Dynamic Compaction

The subsoil condition are not ideally suited for application of dynamic compaction. The compaction of a 7 M thick stratum with high water table and a large content of fines would make dynamic compaction ineffective. Also, the shock waves generated during dynamic compaction could loosen the structural boundaries of the coralline limestone.

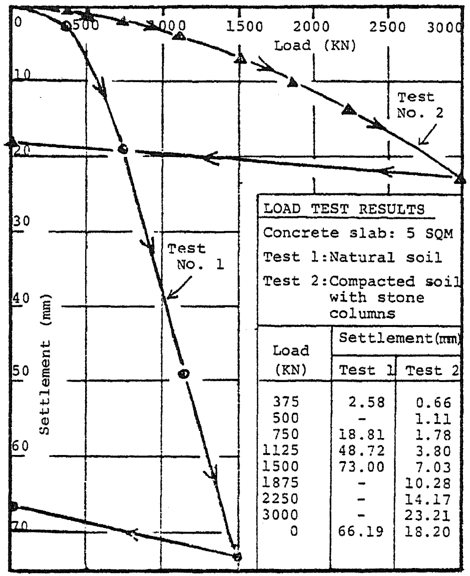
Preloading - Surcharge Method

The required massive surcharge loads and the drainage system necessary to compact the 7 M thick stratum below the water table would require a long duration and would be uneconomical.

Vibro-Compaction with Stone Columns

For the subsoil conditions the Vibro-compaction Replacement Method with stone columns for compacting the 7 M thick upper stratum was an effective and economical solution requiring a minimum of time. The method improves the subsoil with reduction in voids and compaction of weak material due to formulation of densely compacted stone column tightly interlocked with the surrounding soils.

Plate load tests were conducted to accertain the effectiveness of the vibro-compaction method. The load-settlement curves for two plate load tests are given in Figure 3. Test No. 1 was performed on natural soil deposit (without any treatment) and Test No. 2 was conducted on soil compacted with stone columns. The stone columns were one meter in diameter and were placed at 1.2 M center to center embeded 7 M in the compacted overburden and penetrating one meter into the coralline limestone. Both tests were conducted with a concrete test slab; 600 mm thick with a base area of 5 SQM. Loads were applied in increments through a hydraulic jack located below the loading platform. The settlements were monitored at four points with dial gauges reading to 0.01 mm and the average settlement was recorded for each load increment which was held constant for six hours. Test No. 1 in Figure 3 shows that settlements increased excessively for loads exceeding 375 kilonewtons (KN) indicating general shear failure, Terzaghi and Peck (1948). Test No. 2 does not indicate any shear



LOAD TEST RESULTS

Concrete slab: 5 SQM

Test 1:Natural soil

Test 2:Compacted soil with stone columns

Load (KN)	Settlement(mm)	
	Test 1	Test 2
375	2.58	0.66
500	-	1.11
750	18.81	1.78
1125	48.72	3.80
1500	73.00	7.03
1875	-	10.28
2250	-	14.17
3000	-	23.21
0	66.19	18.20

Fig. 3 Plate Load Tests

failure for loads up to 3000 KN with a total settlement of 23.21 mm. At the design foundation pressure of 1.5 bars (load of 1500 KN on a 5 SQM slab), the total settlements was 7.03 mm. An analysis of these curves gave the Elastic Modulus for natural soil (Test No. 1), E = 6700 kilonewtons per meter square (KN/M^2) and the Elastic Modulus for compacted soil with stone columns (Test No. 2), E = 64000 KN/M^2. Using the deep borehole log data and DCT results the Elastic Modulus for different layers of coralline limestone varied between 40,000 KN/M^2 to 120,000 KN/M^2 for the 44 M thick strata in a 50 M deep borehole. The allowable bearing pressure on weaker layers of coralline limestone with q_c less than 70 bar is 2 to 3 bars, Sanglerat (1972). Thus the improvement of overburden with vibro-compaction with stone columns has in effect improved the characteristics of the overburden to be in conformity with the characteristics of the coralline limestone with respect to bearing pressure, settlements and other mechanical properties.

THE SOLUTION

The solution to the foundation problem was to grout the cavaties with a rich mixture of cement and sand under pressure and to compact the overburden with vibro-compaction with stone columns. The stone columns were 6 M to 8 M in length (penetrating one meter into coralline limestone) and 0.9 M to 1.0 M in diameter constructed on a triangular grid of 1.2 M center to center. All stone columns were constructed with clean gravel of size 10 mm to 75 mm using at least 0.75 cubic meters (M^3) of gravel per meter length of the column. The stone columns were vibrated and compacted with heavy machine hammers and the resistance offered to the hammer was electronically recorded on strip charts. Also, precautions were taken to limit washing out of fines during construction and compaction of the stone columns and the quality and quantity of gravel used was closely monitored. On completion of all the columns for each turbine foundation, the top one half meter was scraped as the soil was disturbed and the stone columns contained excessive fines in the upper most one half meter layer. A structural fill of 0.5 M with selected aggregate was constructed over the entire area and the turbine foundation pads were placed on the structural fill. An analysis with a uniform pressure of 1.5 bars on 100 SQM foundation pad for the turbine indicated a total settlement of 47.30 mm and a differential settlement of 5.8 mm for the elastic compression of the 50 M thick strata.

CONCLUSIONS

The data from each of the three different types of field tests, the STPs, the DCTs and the Plate Load Tests seem to correlate the results well as almost similar values were obtained for the allowable bearing capacity for the silty overburden and the coralline limestone. The correlation factor (n) for the SPTs and DCT appears to be 2 for the soft, grey and porous coralline limestone and n seem to range between 3 to 4 for the white, compact and hard coralline limestone.

The vibro-compaction replacement method with stone columns is an effective and speedier method to compact and improve thick layers of silty soils below the water table. The compaction of the overburden with stone columns has improved the bearing capacity and compressibility characteristics significantly (ultimate bearing capacity from 75 KN/M^2 to 600 KN/M^2 and elastic modulus from 6700 KN/M^2 to 64000 KN/M^2. The project is on a completion stage and presently it is on a trial run. The turbine foundations are performing satisfactorily.

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