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Geotechnical and geophysical site characterization of a nuclear power plant site in United Arab Emirates

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ABSTRACT: This paper presents the various geotechnical and geophysical site characterization techniques utilized and typical results obtained during the site characterization of the selected site for the civil nuclear energy power generating project in Barakah, Western Region, Emirate of Abu Dhabi, UAE. The techniques adopted included conventional rotary drilling and testing in overburden soils followed by rock coring and conventional and advanced laboratory testing. In-situ testing of subsurface rocks included pressuremeter testing, and hydraulic conductivity testing. Geophysical testing included on-shore and offshore surface seismic reflection surveys, and down-hole shear wave velocity measurements using P-S suspension logging cross-hole logging techniques as well as acoustic televiewer surveys. Non-seismic geophysical testing surveys consisted of induction logging, natural gamma measurements, fluid conductivity and temperature measurements. The paper also presents typical estimated engineering properties using various techniques and the resulting estimated foundation performance as compared to actual observed behavior at site.

1 INTRODUCTION

In support of its long term sustainable growth vision, the government of the United Arab Emirates has embarked on the development of very large multi-billion dollar infrastructure projects relating to water, wastewater and energy sectors. These projects generally involve extensive site characterization programs tailored to the specific requirements of each project's unique characteristics. One major project being developed by Emirates Nuclear Energy Corporation (ENEC) in the Western Region of the Emirate of Abu Dhabi is the Barakah Nuclear Power Plant (BNPP) project, a large civil nuclear energy power generating project with a total planned capacity of 5600 MWe.

This paper presents an overview of the various geotechnical and geophysical site characterization techniques utilized through the initial stages of the project. A summary of the typical results from in-situ and laboratory tests and geophysical investigations is presented for the BNPP project.

A suite of site characterization techniques, ranging from conventional geotechnical rotary drilling and rock coring, to advanced geotechnical in-situ and laboratory testing was conducted. Surface and down-hole geophysical surveys, both seismic and non-seismic, were carried out to obtain geologic information on lithology and pore fluid characteristics. These are described in more detail in the following sections of this paper.

2 SITE CHARACTERIZATION PROGRAM

2.1 Geotechnical Investigation

The extensive geotechnical site investigation program carried out at BNPP was specifically designed to investigate the subsurface conditions by gathering ground characteristics relevant to the project's design and construction requirements. The site investigation comprised of drilling of exploratory boreholes with disturbed sampling of soils, rock coring, and suites of in-situ and laboratory testing.

A total of 223 exploratory geotechnical borings were completed over three phases drilled to a maximum depth of 184 meters below ground surface (m bgs). A representative typical subsurface profile at BNPP site is shown in Figure 1. Ground surface elevation at the site was an average of ~ 2m according to the Abu Dhabi Datum.

Boreholes were advanced through soil and rock using mud rotary drilling techniques, with the use of a temporary steel casing and water or drilling mud circulation for removal of cuttings. Standard penetration tests (SPT) were performed in the majority of boreholes through the unconsolidated overburden soils at typical intervals of 1m.

Additionally, Cone Penetration Tests (CPT) were conducted in selected boreholes advancing through the soil to the top of rock.

Rock coring was performed using mostly PQ size core barrels and bits, with a typical run of 1.5m long, starting from the top of rock, continuously to the final designated borehole depths. In order to enhance recovery and the quality of the core samples, double tube core barrels and wireline equipment was used when appropriate.

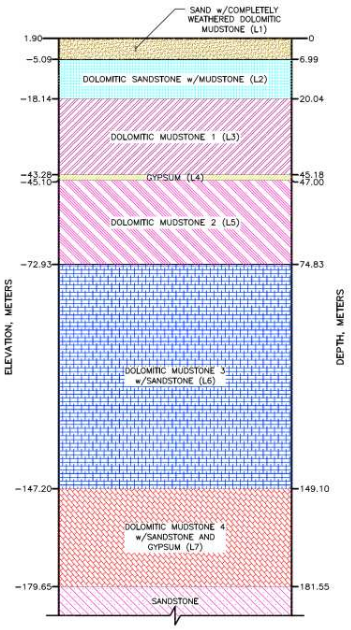

Figure 1. Typical Subsurface Profile (Parashar 2013).

In-situ testing included borehole pressuremeter tests, and hydraulic conductivity tests (packer) at selected intervals. Pressuremeter tests were used to measure the in situ rock mass modulus which was used for evaluation of the anticipated settlement of structures and the behavior of foundations. The test intervals focused on the primary foundation influence zone extending to depths approximately 1.5 times the foundation width. Other areas were also selected if weaker layers or layers of interest were encountered.

Packer testing was conducted in selected borehole locations, in order to obtain direct measurements of in-situ hydraulic conductivity of distinct geologic layers. Tests conducted within the same layer in adjacent boreholes aimed to evaluate lateral variability of hydraulic conductivity within the same layer.

Piezometers or monitoring wells were installed in certain boreholes for continuous monitoring of the groundwater levels. Upon completion of drilling, in-situ testing, and piezometer installation where applicable, the boreholes were grouted with a cement bentonite grout.

Soil and rock core samples were visually characterized in the field following conventional field classification methods. Rock core samples were placed in wooden boxes, depths recorded, and photographs of the core boxes taken. The samples were stored in a temperature controlled area for the duration of the site characterization program.

2.2 *Geophysical Investigation*

A suite of surface and borehole geophysical surveys were conducted during the site characterization stage in three Phases. Overall, these included:

- On-shore P-wave and S-wave surface seismic reflection surveys, and offshore geophysical profiles,
- P-S suspension logging, downhole seismic velocity surveys, AT surveys, and induction/natural gamma logging,
- Combined P-S suspension logging, borehole deviation, dual induction, caliper, natural gamma, and acoustic televiewer surveys in depths varying from 30 m to 175 m in boreholes across the site.
- Crosshole seismic logging conducted in the two pairs of boreholes near the reactor center points, to a total depth of approximately 100 m while maintaining test intervals of 1.5 m.
- Downhole seismic surveys were conducted within two boreholes near the reactor center points, to depths of approximately 150 m and at 1.5 m vertical test intervals.

Considering that the upper sections of the boreholes through the surficial sand deposits and upper weak or sloughing rock layers, the surveys were only conducted in the stable rock, therefore excluding the overburden soil layers.

The purpose of the geophysical surveys was to determine rock dynamic and geophysical properties that were in turn used to evaluate the site's seismic response, subsurface layer continuity, and identify any potential weak zones in the subsurface profile. An example geophysical profile from a randomly selected borehole is shown in Figure 2.

2.3 *Laboratory Testing*

The field site investigation techniques were supplemented by an array of soil and rock sample laboratory testing program.

The laboratory tests on soil samples consisted mostly of soil index property tests conducted on specimens recovered from SPT samples. These included particle-size analysis of soils, Atterberg limits, and Unified Soil Classification System (USCS).

Rock core samples were tested for index and static properties, dynamic properties, chemical and mineral properties. Index and static properties included unit weight, natural moisture content, specific gravity, permeability, unconfined compressive strength (UCS), UU triaxial compression, one-dimensional swell test on a limited number of samples, and classification based on Unified Rock Classification System (URCS). Dynamic property testing included Resonant Column Torsional Shear (RCTS), and Free-Free Resonant Column test. Laboratory tests for chemical properties included sulfate ion and chloride ion content, pH, and resistivity tests. Finally, petrographic and X-ray Diffraction (XRD) and Fluorescence (XRF) tests were carried out for determination of the mineral properties of selected rock core samples.

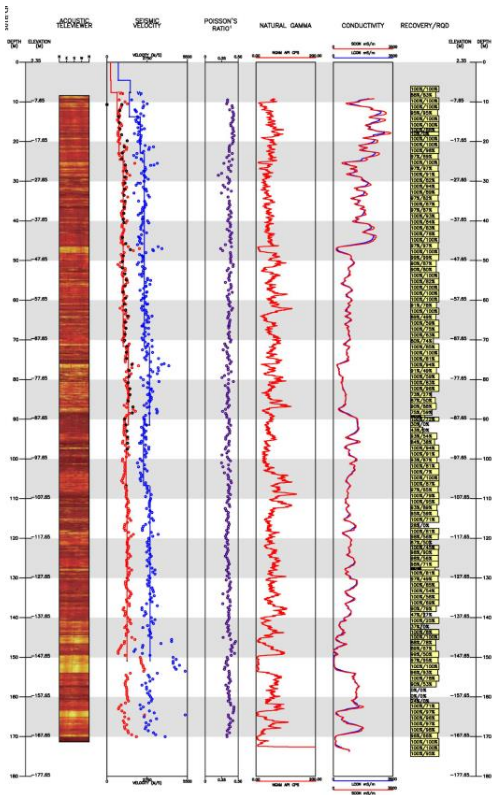

Figure 2. Example Geophysical Profile (Parashar 2013).

3 TYPICAL PROFILE AND ENGINEERING PROPERTIES

3.1 *General Site Stratigraphy*

The results of the geotechnical and geophysical surveys carried out during all phases of the site investigation indicated a generally homogeneous site profile. The site is a coastal site in the Western Region of Abu Dhabi, and the ground surface elevations range from El. 0 m to El. +3.0 m.

The site generally consists of a layer of an unconsolidated carbonate sand – silty sand layer, up to 8 m thick, underlain by sedimentary rock deposits consisting of dolomitic mudstone, siltstone, and sandstone locally interlayered with crystalline gypsum lenses or nodules. A simplified generic subsurface profile is shown in Figure 1. The subsurface profile and geotechnical properties have also been reported by Parashar et al (UAE, 2013) and Parashar et al (Singapore, 2013).

3.2 *Overburden Soils*

The overburden soils generally consist of fine to medium grained native silty sand deposits and low to non-plastic silt. A thin layer of completely weathered mudstone encountered at the top of the rock layer was also considered as part of the overburden soil layer.

The SPT N-values of the overburden sand layer ranged from 1 to 100 with an average of ~ 30. The peak friction angle was approximately 33 degrees.

3.3 *Underlying Rock*

3.3.1 *General*

The underlying sedimentary rock deposits encountered generally comprised very weak to weak rocks, with the exception of the crystalline gypsum. The rock deposits predominantly consist of dolomite, mostly encountered as dolomitic mudstone, dolomitic sandstone. The mudstone encountered on site is typically very weak to weak, light yellowish gray, slightly to moderately weathered, and is often encountered with inclusions of crystalline gypsum (Fig. 3).

Dolomitic sandstone is generally very weak to weak, yellowish gray, slightly to moderately weathered with bands of weakly cemented sand.

The crystalline gypsum, characterized by a fine to coarse grained crystalline structure, is mostly encountered as inclusions or distinct nodules within the dolomitic mudstone or sandstone, and also in layers of up to 4 m thick.

The average unconfined compressive strength (UCS) values of the rock column ranged between 2.4 MPa and 7.3 MPa, with the exception of the crystalline gypsum layer with an average UCS value of 9.8 MPa. Average UCS, Core Recovery and Rock Quality Designation (RQD) values for the typical rock profile are shown in Table 1.

Table 1. Rock Profile and Average Unconfined Compressive Strength Properties

Layer	Rock Type	Rock Strength Classification	UCS	Recovery	RQD
			MPa	%	%
1	Sand	Soil	-	-	-
2	Dolomitic Sandstone with Mudstone	Very Weak Rock	2.38	93	84
3	Dolomitic Mudstone 1	Very Weak Rock	3.72	91	77
4	Gypsum	Weak Rock	9.78	96	91
5	Dolomitic Mudstone 2	Very Weak Rock	3.68	91	77
6	Dolomitic Mudstone 3 with Sandstone	Very Weak Rock	4.19	80	57
7	Dolomitic Mudstone 4 with Sandstone and Gypsum	Weak Rock	7.25	91	78
8	Sandstone	N/A	N/A	100	92

Rock mass strength parameters, including Rock Mass Rating (RMR) and Geological Strength Index (GSI) were used to estimate shear strength properties of the foundation materials. Table 2 presents the average Rock Mass and Shear Strength properties of the rock column.

Table 2. Average Rock Mass Properties.

Rock Layer	RMR	GSI	m_i	D	φ'	c'
	Ave	Ave			deg	MPa
1	-	-	-	-	-	-
2	47	50	7	0.5	32	0.042
3	46	49	4	0.3	26	0.079
4	52	55	8	0.1	40	0.231
5	45	48	4	0.1	23	0.118
6	41	43	7	0	23	0.202
7	48	51	7	0	26	0.372
8	N/A	N/A	N/A	N/A	32	0.042

Figure 3. Example core box – Dolomitic Mudstone

3.3.2 *Elastic Properties*

The elastic modulus (E) and the rock mass modulus (E_{rm}) of the encountered rock layers were estimated based on data from pressuremeter tests, UCS tests, consolidation tests, and geophysical surveys (borehole geophysical tests and Resonant Column Torsional Shear and Free-Free Resonant Column Test).

The results of the in-situ pressuremeter tests were used to estimate G_p and E_p, as well as unload/reload modulus ($E_{u/r}$). UCS test results were used to obtain an estimate of E_{rm} based on the GSI, Disturbance factor, and RMR. The modulus of volumetric compressibility (m_v) obtained from consolidation tests conducted in the laboratory, was used to calculate the constraint modulus (E_c). Shear wave velocities and poisson's ratios from borehole geophysical tests were used to estimate the shear modulus (G_{max}) and the maximum elastic modulus (E_{max}). Shear wave velocities from Resonant Column tests were also used to calculate E_{max}.

Elastic moduli based on geophysical tests generally gave higher values than the rock mass modulus based on the pressuremeter test and the UCS. The unload/reload modulus ranged from 1.1 to 3.1 times the initial elastic modulus from pressuremeter tests, and between 3 and 13 times the E_{rm} from UCS results and RMR. Due to the significant difference between the different moduli, the estimated in situ strain in the rock is important in order to use the most appropriately representative values of elastic modulus. Table 3a and Table 3b present the average Elastic Moduli values based on the different methods described above.

Table 3a. Average Elastic Modulus Values Based on Geophysical Tests and qu (Units: MPa)

Layer	E (from Vs profiles and dynamic lab test results)				E_{rm}
	Geophysical	RCTS	UFRCT	Avg.	(from qu)
2	500	291	248	346	350
3	1046	690	376	704	380
4	1852	-	-	1403	1001
5	1075	1135	473	894	388
6	1633	537	581	917	332
7	1580	2962	-	2271	638
8	-	-	-	-	-

Table 3b. Average Elastic Modulus Values Based on Pressuremeter and Consolidation Tests (Units MPa)

Layer	E (from Pressuremeter Tests) Initial, Ei	E (from Pressuremeter Tests) Unload/ Reload E_{ur}	E (from Pressuremeter Tests) E_{ur} / E_i	Ec (from Consolidation Test)	Erm, (recommended)
2	398	1235	3.1	58	500
3	646	1600	2.5	65	1046
4	2876	3089	1.1	-	1852
5	794	1989	2.5	54	1075
6	1892	4211	2.2	-	1633
7	1599	2567	1.6	107	1580

Considering that the elastic moduli obtained from in situ shear wave velocity measurements are less likely to be affected by drilling disturbances, these values are considered more appropriate for use in settlement analysis.

4 ESTIMATED ENGINEERING PERFORMANCE

One of the representative engineering performance assessment comes from analysis of the static stability of structures, involving the estimation of both the bearing capacity and settlement, calculated using established soil mechanics theories.

4.1 Bearing Capacity

The bearing capacity of major safety-related structures at BNPP required that foundation materials shall have the capacity to support the bearing pressure with a Factor of Safety (FOS) of 3.0 for static conditions, and FOS of 2.0 for dynamic and seismic loads.

The geometry and loading on the structures foundations were considered, along with the geotechnical profile and material strength properties presented in Table 1, and global and local shear failure modes were considered in the analysis. The resultant FOS against bearing capacity failure consistently exceeded the minimum required FOS of 3.0 for static and 2.0 for dynamic conditions, for all structures.

4.2 Settlement

Settlement analysis for the major safety related structures at BNPP was performed using a widely used finite element software (PLAXIS), considering the elastic material properties and subsurface profile presented above.

Two different soil models were used in the finite element software to represent the subsurface profile, both of which utilized the recommended elastic modulus values presented in Table 3a and Table 3b above. The first approach utilized the Mohr-Coulomb soil model, which assumes a linear-elastic, perfectly plastic behavior of the subsurface profile. The second approach utilized the Hardening Soil approach, which accounts for stress-dependency of the stiffness moduli, which represents the stiffening soil behavior as a function of depth and thus increased pressure. In the Hardening Soil model, the stiffness is described using the initial stiffness E_{50}, the unloading stiffness E_{ur}, and the oedometer loading stiffness E_{oed} which serves to represent the stress dependency of the elastic moduli.

The maximum estimated settlement under each NPP unit ranged from 54 mm when the Hardening Soil model was used, to a maximum of 78 mm when the Mohr-Coulomb model was used.

The foundation settlement monitoring program that commenced from the time of placement of base raft of major safety-related structure, and is continuing throughout the construction of the structures and installation of equipment, indicated a maximum of 4.9 mm settlement in September 2015 when construction of Unit 1 is nearly completed. The measured settlements is approximately 10 times less than the estimated settlement, indicating that the estimated elastic modulus properties are significantly lower than the actual properties of the in-situ rock. A potential justification for the substantial underestimation of the predicted settlements would be the intrinsic conservatism within all parameters, most importantly the elastic modulus parameters. Further studies and back-analyses would be required to examine the degree of the underestimation of the engineering properties that result in significantly larger estimated settlement as compared to observed behavior at site.

5 CONCLUSIONS

Geotechnical site characterization adopting conventional drilling, in-situ tests, lab tests and geophysical testing were conducted at the civil nuclear power plant site in Barakah, Western Region, Emirates of Abu Dhabi, UAE. Using the input data obtained in the geotechnical site characterization, engineering performance was estimated. The estimated engineering parameters show that the site has sufficient capacity to support the bearing pressures under static and dynamic conditions, and that the anticipated settlement was well within the acceptable limits. Settlement monitoring results are in the order of 10 times less than the estimated settlements, indicating that the site was conservatively characterized, and the site characterization meets the safety goal for nuclear power plant.

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