Journal of Architectural Design and Construction Technology
Volume 2 | Issue 2

HELICS GROUP Scientific Networks

Case Report Open Access

Prebored Pressure-meter Tests for an Offshore Project, Its Interpretation and Comparison of Deformation Modulus

[1]Neville Dsouza, [2]Emmanouil Spyropoulos, [1]Tarek Maakaroun, [1]Venkata Kolla,[1]RamanJeneyulu

[1]Osaimi Engineering Office (OEO), Al Khobar, Kingdom of Saudi Arabia
[2]Saudi Aramco, Dhahran, Kingdom of Saudi Arabia

***Corresponding author:** Neville Dsouza, Osaimi Engineering Office (OEO), Al Khobar, Kingdom of Saudi Arabia, E-mail: neville.dsouza@osaimiengineering.com*

Citation: Dsouza N, Spyropoulos E, Maakaroun T, Kolla V, RamanJeneyulu. Prebored Pressure-meter Tests for an Offshore Project, Its Interpretation and Comparison of Deformation Modulus. J Arch Des Cons Tech. 2021;2(2):8-17.

Received Date: November 01, 2020; **Accepted Date:** July 02, 2021; **Published Date:** July 08, 2021

Abstract

This paper is aimed to study the deformation modulus of rock from the PreboredPressuremeter Tests (PMTs) conducted for an offshore project, its interpretation and comparison between deformation modulus from the PMTs and those estimated from empirical relationship as per BS 8004 using laboratory UCS values. The PMTs were performed in prebored boreholes at depths varying from 14 m to 40 m below seabed level by using OYO Elast Logger 2 (Model-4022), Elastmeter HQ Sonde (Model- 4180). The PMTs were carried at each borehole location where a socket at the base of the borehole was formed using a suitable drill bit producing a hole of nominal diameter for the test. Laboratory Unconfined Compressive Strength (UCS) tests were also performed on rock cores retrieved at same depths where PMTs were conducted. The behavior of stress-strain curves of laboratory UCS were also studied with that of the PMT curves. It is observed that the deformation modulus values from PMTs and those estimated as per BS 8004 using laboratory UCS values of rock showed variation, except at few boreholes/depths which showed comparable values. As the pressuremeter is an in-situ test and the deformation modulus observed from the rock behavior is at an in-situ state in comparison to the empirical relationship as per BS 8004 which depends on laboratory UCS on samples retrieved in a disturbed state from the borehole, the pressuremeter test values are advised and recommended to be used in foundation design.

Keywords: Pressuremeter Tests (PMTs); Unconfined Compressive Strength (UCS); Rock; Unload-Reload Cycle; Borehole

Brief History and Literature Review

The original concept similar to pressuremeter test dates back to 1930/1931 (Baguelin et al, 1978). The pressuremeter test was first developed by Louis Ménard in 1954 and patented in 1955. After Menard, several others contributed to the development of pressuremeter test and especially in 1970 and 1980 there were major developments. Over the years there has been a lot of advancement in pressuremeter testing equipment and its interpretation. Several authors have also published papers on pressuremeter tests and its interpretation.

Arild Palmström and Rajbal Singh, 2001 in their paperhave made comparison of different in-situ tests and indirect methods for determining the deformation modulus of rock masses. Briaud J.-L, 2013 in his paper has described pressuremeter tests and its applicability for determining unload-reload modulus, correlations with other soil parameters and the use of the entire expansion curve to predict the load settlement behavior. S.M. Peaker & A. Sirati, 2013 in their paperhave presented rock modulus from in-situ pressuremeter and laboratory tests. Kedar C. Birid, 2015in his paper has presented interpretation of pressuremeter test in rock. L.F. Cao, Cassidy Mathews P.E., 2017 in his research thesis has estimated the rock mass modulus using pressuremeter tests.

Marian Kuvik et al., 2018in his paper has presented deformation modulus determination from pressuremeter and dilatometer tests for crystalline rock. All these research papers /thesis were studied in relation to the subject of this paper.

Pressuremeter Test

The pressure-meter test is an in-situ load test which involves setting the probe in place, expanding the probe and data acquisition. As this is an in-situ test, it can assess soil/ rock properties at an in-situ state as opposed to laboratory testing that is undertaken on samples retrieved from the borehole and often in a disturbed state. The pressure-meter tests can measure in-situ stress ~ strain, which helps in determining strength, stiffness and deformation characteristics of soil/ rock.

There are three types of pressuremeter tests i) pre-bored pressuremeter which is conducted in pre-drilled borehole, ii) self-boring pressuremeter, which drills by its own and iii) push-in-pressuremeter, which is pushed upon reaching the base of borehole.

This paper deals with pre-bored pressuremeter tests conducted for an offshore project. The pressuremeter tests were conducted on moderately weathered & fractured, extremely weak to weak rock (sandstone/cemented sand/ claystone) encountered at test depths.

A layout of the pre-bored pressuremeter tests is as shown in Figure 1.

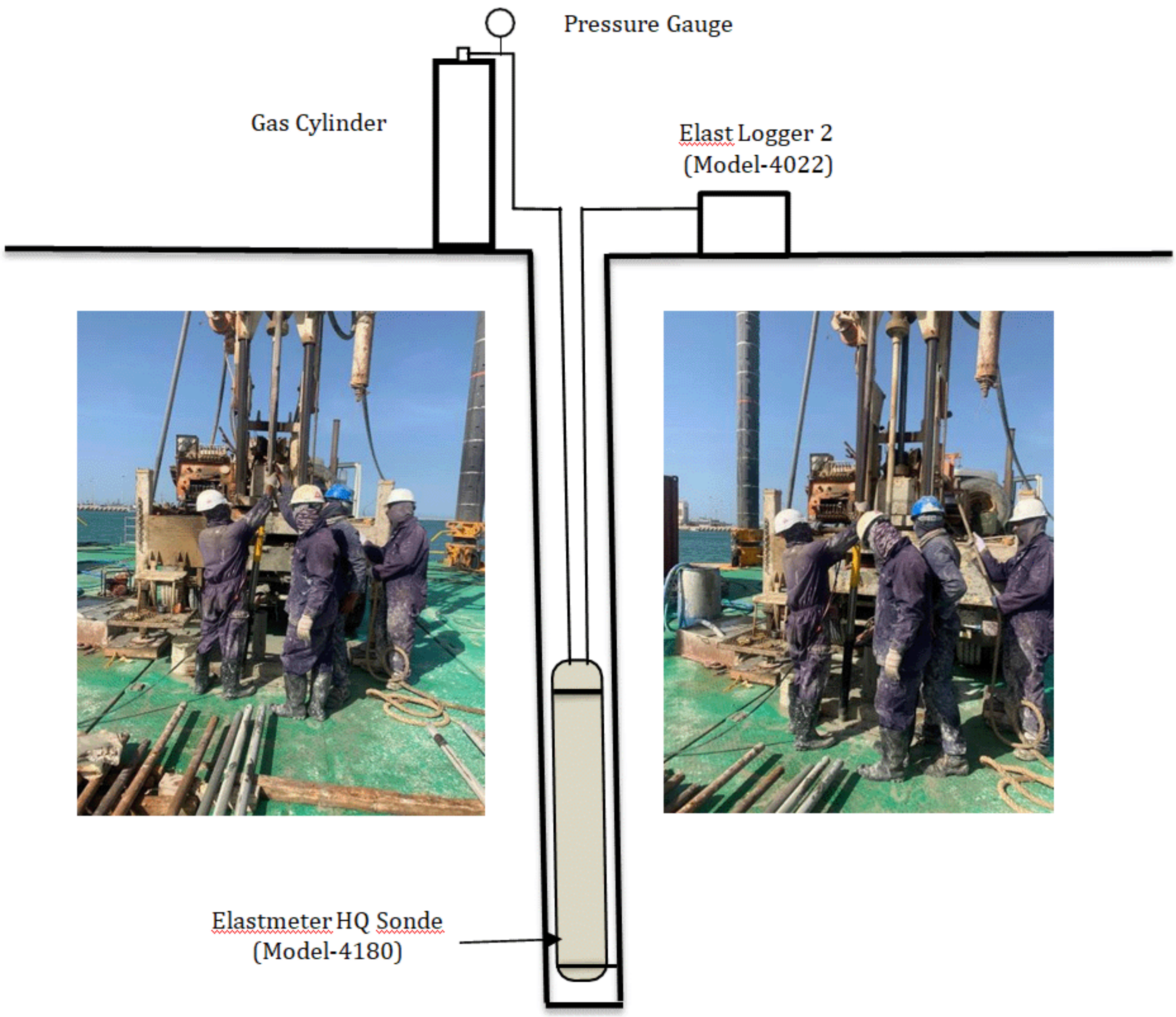


Figure 1: Layout of Pre-bored Pressuremeter Test

The pressuremeter tests were performed using OYO Elastmeter 2, HQ Sonde (Model-4180) and Elast Logger 2 (Model 4022) for data acquisition as shown below.

HQ Sonde
(Model-4180)

Elast Logger-2 ((Model-4022)

(Courtesy: OYO Corporation, Japan)

<u>Elastmeter HQ Sonde (Model 4180)</u>

Deformation detection method: Caliper arm method

Max. Pressurization: 20MPa

Outside diameter: 62mm

Measurement distance length: 520mm

Packers: BX, NX size

<u>Elast Logger-2(Model-4022)</u>

CPU :ARM940T

Display: QVGA(320x240),5.7 inch color LCD Pressure, displacement to be displayed in digital values and stress-strain curve

Measurement parameters: Pressure, displacement, elapsed time

Measurement interval: Pressure interval, displacement interval, time interval

Data storage: Flash ROM, USB port

Power requirement:10.8～13.2V DC

Outer dimensions:470(W)x180(H)x370(D) mm

Weight: 10kg

A total of twenty-three (23) pre-bored pressuremeter tests were carried out in five (5) offshore boreholes at depths varying from 14m to 40m below seabed, using OYO Elast Logger 2 (Model-4022), Elastmeter HQ Sonde (Model- 4180). The tests were conducted on moderately weathered & fractured, extremely weak to weak rock (sandstone/cemented sand/ claystone) encountered at test depths. The tests were carried out in accordance with ASTM D 4719.

The pressuremeter tests were carried out at each pre-bored borehole location, a socket at the base of the borehole was formed using a suitable drill bit producing a hole of nominal diameter (72 to 76mm) for the test. The test boreholes were taken care to ensure that the holes are least disturbed, as the preparation of a quality borehole is important in obtaining a satisfactory pressuremeter test. A borehole test zone with a diameter within the following tolerances was maintained: $1.03D_2 \le D_1 \le 1.20D_2$ (D_1 = Initial diameter of the Borehole Test Zone and D_2 = Diameter of the Deflated Probe). The borehole designation, probe diameters and the nominal / maximum diameters of borehole to be maintained as per below Table 1.

Table 1: Borehole designation, probe diameters and nominal / maximum diameters of borehole

Hole Diameter Designation	Probe Diameter (mm)	Borehole, Diameter	
		Nominal, mm	Max, mm
AX	44	45	53
BX	58	60	70
NX	74	76	89

The internal displacement calipers and the rubber membranes were calibrated before each test and during the field work as per relevant standards. Calibration of the calipers was performed using a calibration ring over the membrane displacement/expansion range. Rubber membranes were calibrated for thickness variation by pressurizing over the testing pressure range, within a rigid steel calibration sleeve. Calibrations of rubber was performed, once before starting the tests and a new calibration was made in case of bursting or change of the rubber.

The tests were performed with one unload-reload cycle in every test. The unload-reload cycle was performed near the end of the elastic range of the material response. It was anticipated that testing may reach the plastic range in softer materials, so care was exercised to perform the unload-reload test prior to reaching the plastic range of the material response or just past the elastic range. Adjustment was done for the magnitude and quantity of the load increments in any given test so as to obtain an appropriate quantity of data points to provide a well-defined curve. The tests were performed with sufficient data points in plastic deformation to provide a reasonable estimate of the limit pressure.

Test pressure was applied in equal increments and was held for a minimum period of 60 seconds, to allow for the deformation reading to stabilize. Loading was done using the high-pressure gas cylinder and the displacement for the corresponding pressure applied was recorded. The test was carried out in equal increments of loading till the required maximum pressure is reached and then unload-reloading was done near the end of the elastic range of material response. The pressure and the subsequent radial displacement of the probe membrane were continuously monitored. During the test, the pressure and displacement values were recorded. At the end of the test, loading curves (pressure vs. displacement) were plotted after applying corrections to the readings.

Pressuremeter Curve

As shown in Figure 2, there are three phases of a typical deformation curve of a pressuremeter test, the first phase is called the re-establishing phase (when the probe adjusts and the walls of the borehole are pushed back to its original position), the second phase is called the pseudo-elastic phase (which shows the elastic behavior of the material) and the third phase is the plastic deformation of the material (which helps in determining the limit pressure). The pressure vs. deformation graph as shown in Figure 3, as recorded for each test.

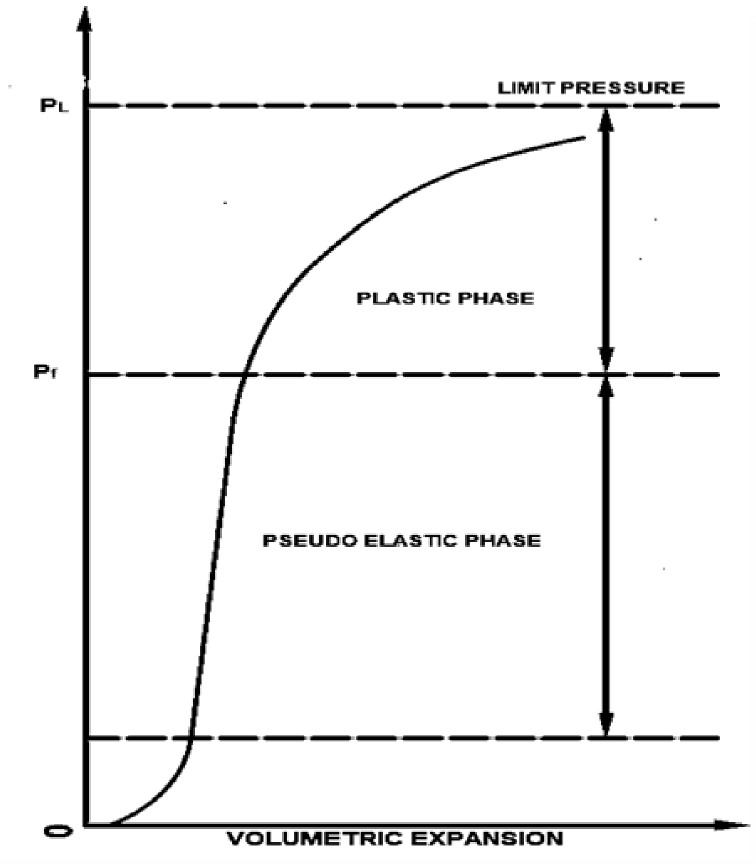
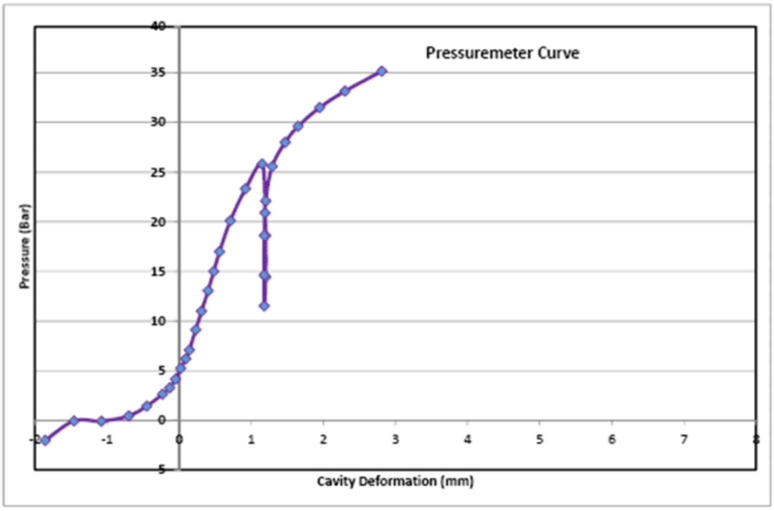


Figure2: Phases of Pressuremeter Test Curve

Data Readings	
Pressure	Deformation
(Bars)	mm
-2.03	-1.86
-0.07	-1.46
-0.09	-1.08
0.44	-0.70
1.43	-0.45
2.63	-0.23
3.28	-0.13
4.15	-0.05
5.22	0.02
6.19	0.09
7.07	0.14
9.13	0.23
10.99	0.31
13.05	0.40
15.01	0.48
16.98	0.56
20.11	0.71
23.32	0.92
25.83	1.15
20.91	1.19
18.61	1.20
14.42	1.20
11.53	1.18
14.63	1.18
18.62	1.18
22.11	1.20
25.57	1.29
28.00	1.47
29.63	1.65
31.51	1.95
33.17	2.30
35.18	2.81

Summary of Data & Assumptions		
Poisson Ratio:	0.333	
Intial Radius (mm):	37.52	
First Loading Cycle		
	Loading	Reloading
Cavity Radius	37.55 mm	38.70 mm
Pressure	5.22 Bar	11.53 Bar
Second Loading Cycle		
	Loading	Reloading
Cavity Radius	38.23 mm	38.82 mm
Pressure P1	20.11 Bar	25.57 Bar



Summary of Test Results		
Creep Pressure	Initial Pressure	Limit Pressure
MPa	MPa	MPa
2	0.5	4.6
Radial Strain		
$\varepsilon_i = r_1 - r_o \ / r_o$		
ε1 =	0.001	0.031
ε2 =	0.019	0.035
Pressuremeter Modulus (Ep)		
$Ep = (1 + \nu) * (R_p + \Delta R_m) * \Delta P / d\Delta R$		
PMT Modulus Ep:	100.77	MPa
Unload-Reload Ep:	130.06	MPa
Shear Modulus (G)		
$G = 0.5 * \Delta P / \Delta \varepsilon_i$		
Shear Modulus G:	40.95	MPa
Unload-Reload G:	236.59	MPa

Figure 3: Pressuremeter Curve (BH-PMT-1 @ Depth =14.0m)

The deformation modulus is an important characteristic of the behavior of rock mass. The deformation modulus of rock mass can be determined by conducting PMTs. The PMTs were specifically performed to obtain representative deformation modulus values of rock encountered. Initial pressuremeter modulus (E_p), which is defined as a secant slope of the pressuremeter curve following achieving the in-situ geostatic stress at the test depth. The pressure meter modulus (E_p) is given as follows:

$$E_p \text{ (MPa)} = (1+ \mu)(R_p + \Delta R_m)(\Delta P / d\Delta R) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

R_p = radius of probe in uninflated condition, mm

ΔR_m = increase in radius of probe up to the point corresponding to the pressure where E_p is measured, mm,

$d\Delta R$ = increase of probe radius corresponding to ΔP pressure increase, mm,

ΔR = increase in probe radius, mm

ΔP = corrected pressure in crease in the center part of the straightline portion of the Pressure deformation curve

$R_p + \Delta R_m$ = current radius of inflated probe, mm and

μ = Poisson's Ratio. (0.33 was used in our calculation, as Menard proposed a Poisson's ratio of 1/3).

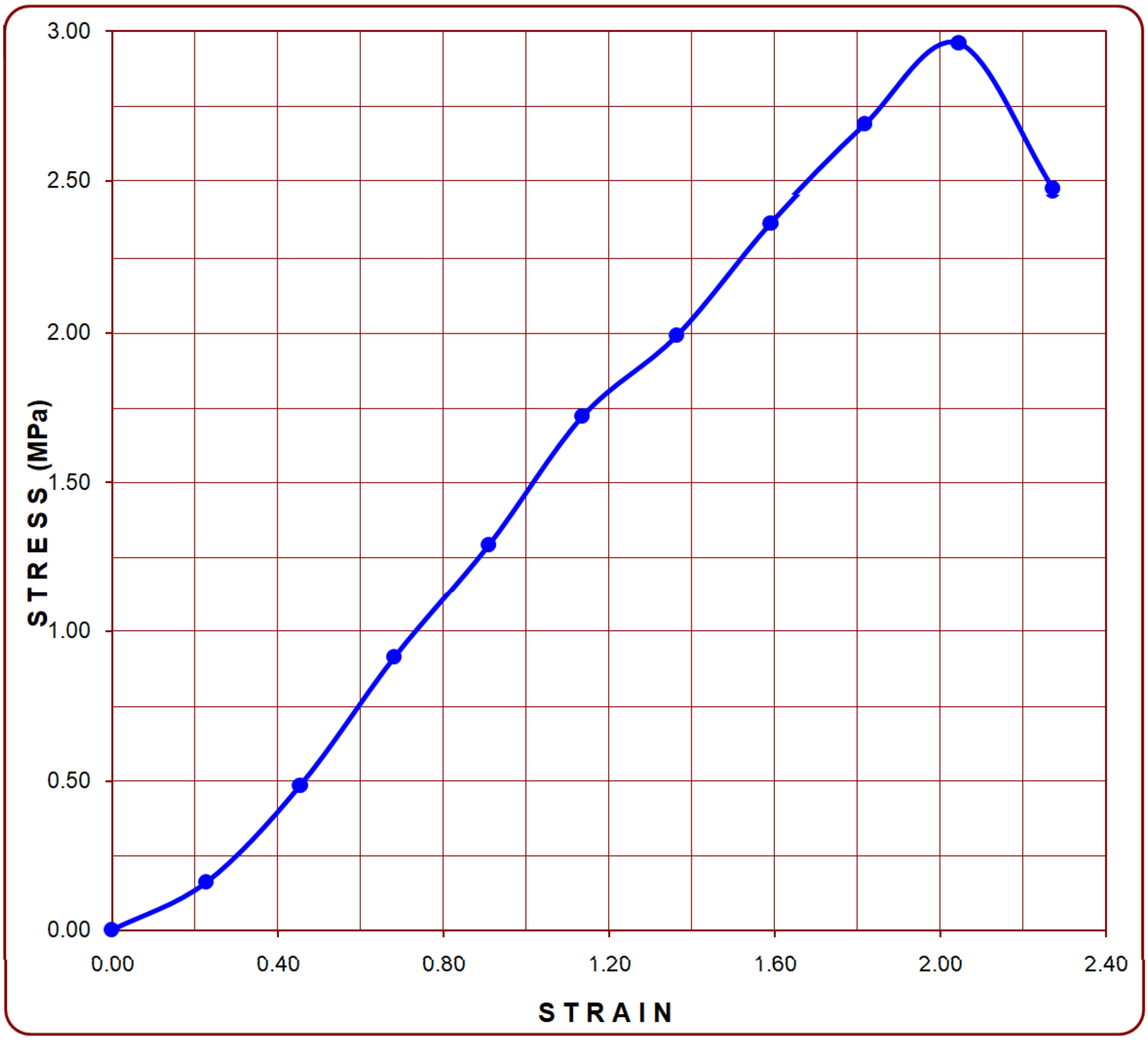
BS 8004 proposes empirical relationship to obtain deformation modulus (E_s) of jointed rock mass from laboratory Unconfined Compressive Strength (UCS) tests of intact rocks as follows

$$E_s = M_r \times j \times UCS \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

j = rock mass joint ("j-factor" after Hobbs depends on RQD values)

M_r = modulus ratio of rock is taken as 200-300 based on the rock type encountered.

Sample No.	:	**BH - PMT-01**	*Date*	:	June 2020
Location	:		*Sampled By*	:	
Depth	:	14.00 - 15.00 m.	*Tested By*	:	
Description	:	Grey, CLAYSTONE			



Maximum Stress	**P =**	**2.961**	**MPa**
Bulk Density	**=**	**13.51**	**kN/m^3**
Dry Density	**=**	**1.363**	**g/cm^3**
Natural Moisture Content	**=**	**1.0**	**%**

Figure 4: Stress ~ Strain Curves for UCS Test of Rock (BH-PMT-1 @ Depth =14.0m)

UCS = Unconfined Compressive Strength of rock core samples (MPa)

Laboratory Unconfined Compressive Strength (UCS) tests with stress-strain curves were performed on rock cores retrieved at same depths where PMTs were conducted. Deformation modulus obtained from pressuremeter tests and estimated from empirical relationship as per BS 8004 is presented in below Table 2.

Table 2: Deformation Modulus from PMTs and from empirical relationship as per BS 8004

Borehole Number	Test Depth (m)	Type of Soil/ Rock	RQD (%)	Lab UCS (MPa)	Limit Pressure (MPa)	PMT Modulus Ep (MPa)	BS 8004 Es (MPa)
PMT-1	14.0	CLAYSTONE	31	2.96	4.60	100.77	118.44
	19.0	SANDSTONE	67	4.41	9.50	213.55	264.84
	24.0	CEMENTED SAND	30	0.98	6.20	107.51	39.32
	29.0	SANDSTONE	26	1.35	20.70	159.84	53.84
PMT-2	15.0	CEMENTED SAND	51	0.83	10.00	156.93	33.12
	17.0	SANDSTONE	22	0.79	7.30	206.79	31.52
	22.0	MUDROCK	90	2.85	12.20	241.66	456.48
	27.0	CLAYSTONE	85	1.83	4.30	75.86	256.20
	32.0	CEMENTED SAND	47	1.39	4.10	80.55	55.88
	37.0	SANDSTONE	93	1.24	9.40	157.08	198.08
PMT-3	15.0	CEMENTED SAND	50	4.80	2.80	90.99	192.12
	20.0	SANDSTONE	35	6.30	4.40	119.99	252.12
	24.0	CLAYSTONE	83	8.19	7.20	151.35	819.90
	39.5	SANDSTONE	100	0.01	14.00	441.94	2.40
PMT-4	16.0	SANDSTONE	60	0.72	4.40	79.46	43.50
	18.0	CLAYSTONE	68	2.73	23.70	338.13	164.16
	24.0	CLAYSTONE	87	1.02	1.50	43.47	143.22
	31.0	CEMENTED SAND	10	0.13	5.50	330.35	5.16
	38.0	CEMENTED SAND	20	1.98	3.30	73.92	79.36
PMT-5	14.0	CLAYSTONE	60	10.79	3.70	81.35	647.28
	19.0	CEMENTED SAND	85	1.81	16.60	183.36	253.68
	28.0	CEMENTED SAND	73	0.35	13.30	155.07	48.86
	34.0	CEMENTED SAND	50	2.79	10.60	119.03	111.96

Comparison of PMTs and Laboratory UCS Test Results

The in-situ deformation modulus obtained from PMTs test and those estimated from empirical relationship as per BS 8004 using laboratory UCS values is presented in below graphs.

The deformation modulus obtained from pressuremeter tests and those estimated from empirical relationship as per BS 8004 using laboratory UCS values showed variations, except at boreholes, BH-PMT-01 @14.0m, 19.0m, BH-PMT-2 @32m, 37m, BH-PMT-4 @38m, BH-PMT-5 @ 19m, 34m which indicated comparable values.

Gaps and Further Research

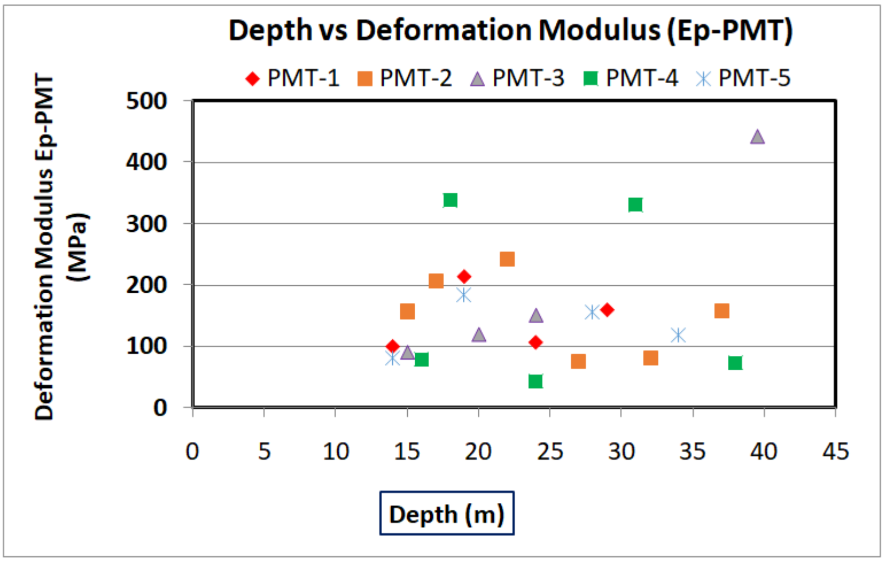
An attempt is made to analyze and interpret the deformation modulus of rock mass based on the limited number of prebored pressuremeter tests results and by estimating using empirical relationship as per BS 8004 based on laboratory UCS tests values on rock.

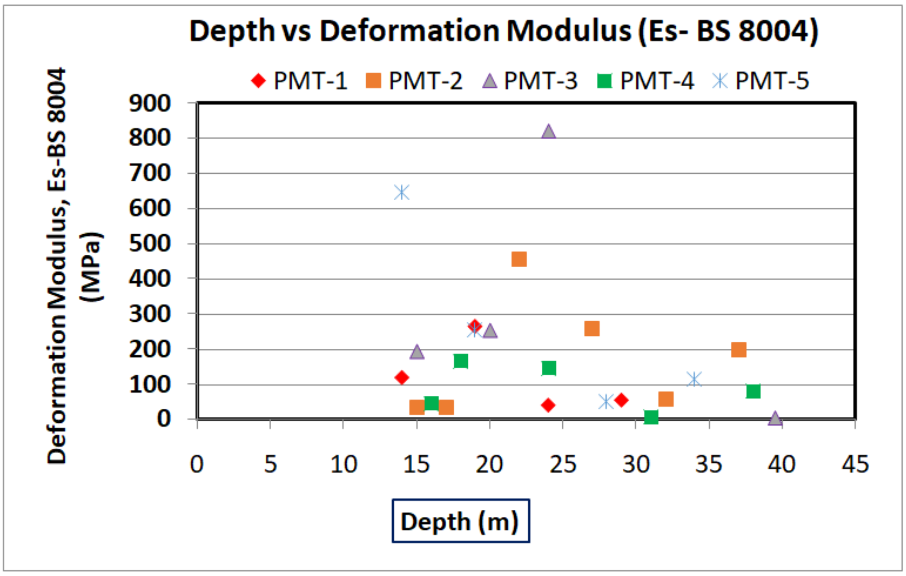
The pressuremeter tests were conducted at five (5) boreholes and at varying depths from 14.0m to 40.0m at study area and on varied rock formations encountered at test depths. Study may be carried out at different locations having same test depths and similar rock formations encountered, which could have been a better comparison.

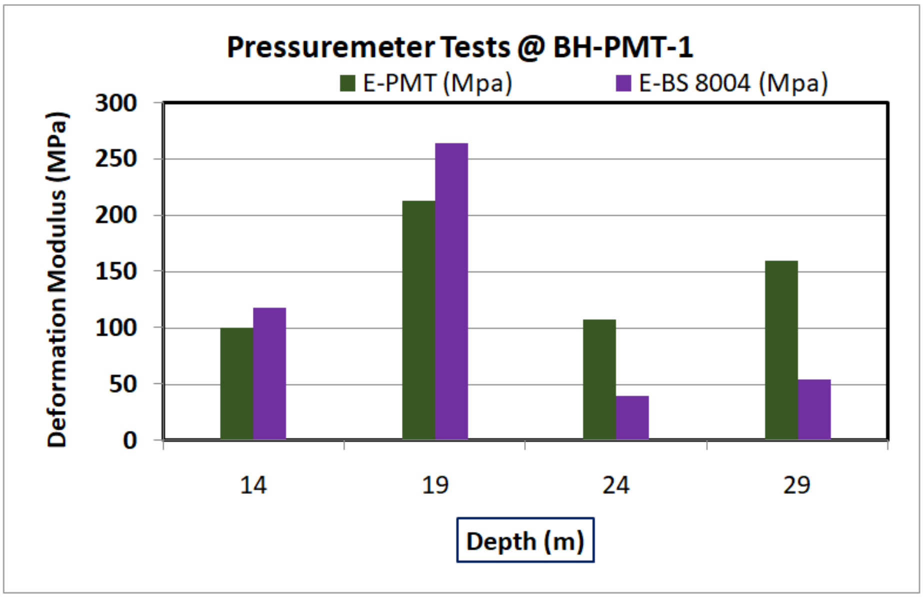
In present paper only one rock parameter i.e, deformation modulus is studied; however study can also be carried out for checking other rock parameters.

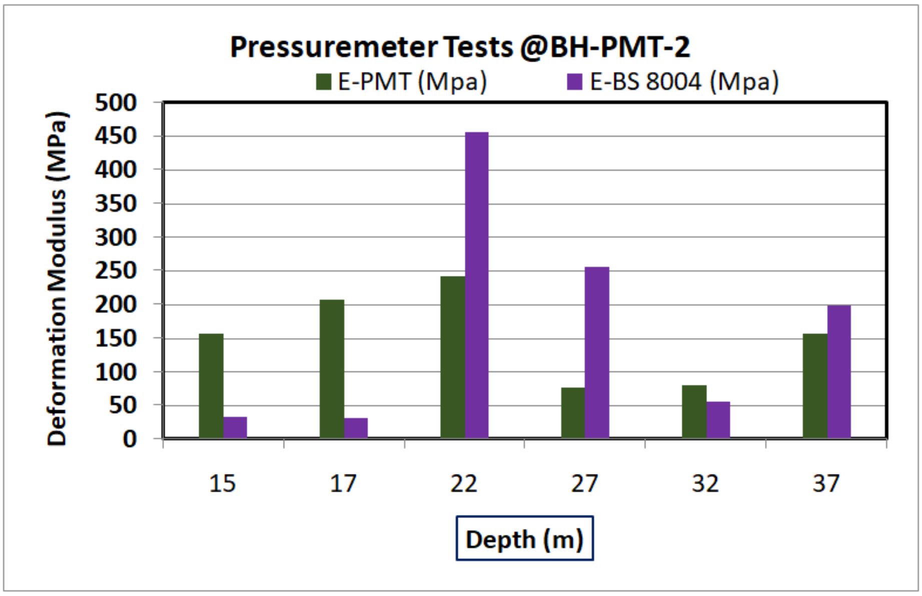
There are several other in-situ methods by which deformation modulus of rock can be obtained, however in this study only prebored pressuremeter test data is used. Therefore, study could be done by using different in-situ methods for determining deformation modulus of rock and an extensive research may be carried out using different in-situ tests methods for determining deformation modulus of rock mass and the results can be compared.

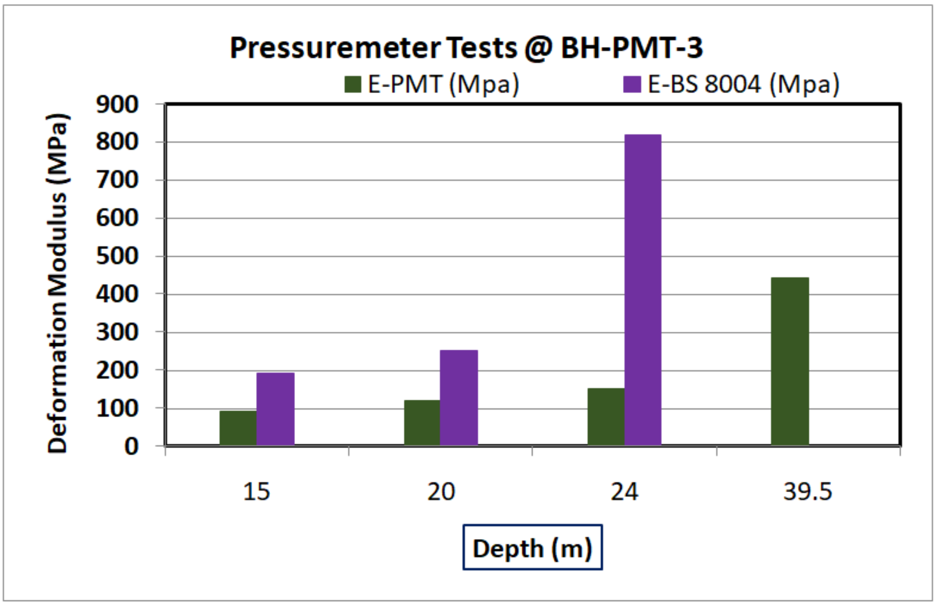
As per site observations performing preboredpressuremeter tests below seawater had difficulties and limitations, therefore other feasible tests methods may be carried out mostly preferred for an off shore project.

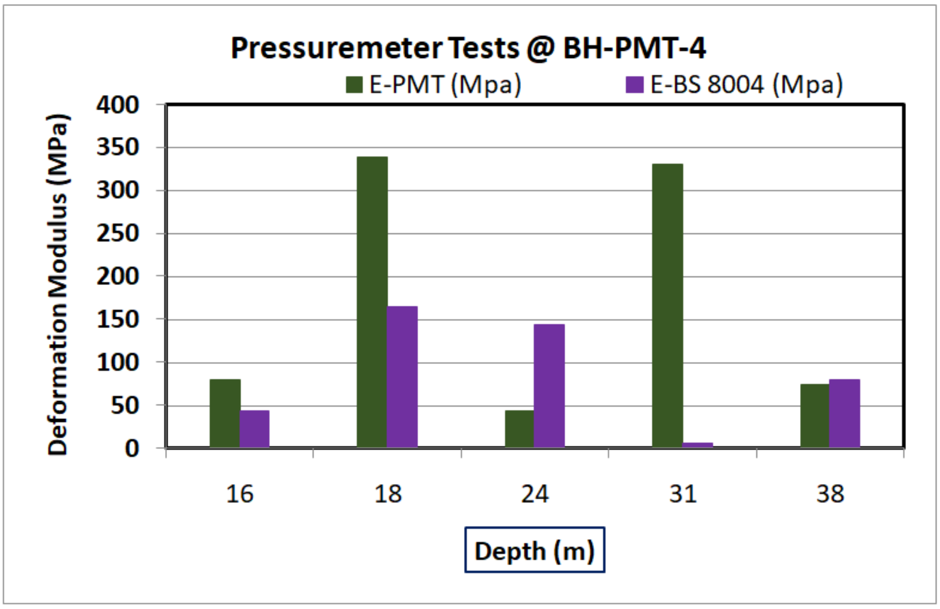

Depth vs Deformation Modulus (Ep-PMT)
PMT-1 PMT-2 PMT-3 PMT-4 PMT-5
Deformation Modulus Ep-PMT (MPa)
500
400
300
200
100
0
0 5 10 15 20 25 30 35 40 45
Depth (m)

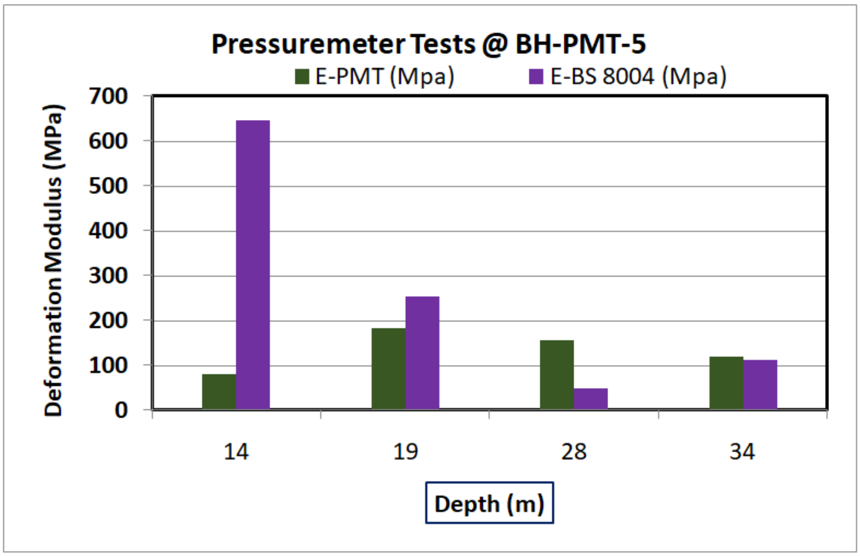

Depth vs Deformation Modulus (Es- BS 8004)
PMT-1 PMT-2 PMT-3 PMT-4 PMT-5
Deformation Modulus, Es-BS 8004 (MPa)
900
800
700
600
500
400
300
200
100
0
0 5 10 15 20 25 30 35 40 45
Depth (m)


Pressuremeter Tests @ BH-PMT-1
E-PMT (Mpa) E-BS 8004 (Mpa)
Deformation Modulus (MPa)
300
250
200
150
100
50
0
14 19 24 29
Depth (m)


Pressuremeter Tests @BH-PMT-2
E-PMT (Mpa)
E-BS 8004 (Mpa)
Deformation Modulus (MPa)
500
450
400
350
300
250
200
150
100
50
0
15
17
22
27
32
37
Depth (m)


Pressuremeter Tests @ BH-PMT-3
E-PMT (Mpa)
E-BS 8004 (Mpa)
Deformation Modulus (MPa)
900
800
700
600
500
400
300
200
100
0
15
20
24
39.5
Depth (m)


Pressuremeter Tests @ BH-PMT-4
E-PMT (Mpa)
E-BS 8004 (Mpa)
Deformation Modulus (MPa)
400
350
300
250
200
150
100
50
0
16
18
24
31
38
Depth (m)



Conclusion

The deformation modulus obtained from pressuremeter tests and those estimated from empirical relationship as per BS 8004 using laboratory UCS values showed variations, except at few boreholes / depths which indicated comparable values. As the pressuremeter is an in-situ test and the deformation modulus observed from the rock behavior is at an in-situ state in comparison to the empirical relationship as per BS 8004 which depends on laboratory UCS on samples retrieved in a disturbed state from the borehole, the pressuremeter test values are advised and recommended for use in foundation design.

References

ASTM D 4719-07. Standard Test Methods for Prebored Pressuremeter Testing in Soils. ASTM International. West Conshohocken, PA. 2007.

ASTM D7012 -14. Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures. ASTM International. West Conshohocken, PA. 2014.

BS 8004:1986. Code of Practice for Foundations. British Standards Institution. Milton Keynes.

Briaud JL. The Pressuremeter. AA Balkema, Rotterdam, Netherlands. 1992;210.

Baguelin F, Jezequel JF, Shield DH. The Pressuremeter and Foundation Engineering. Transtech Publications. Clausthal, Germany. 1978;2(4).

Naeem O Abdulhadi, Amjad F Barghouthi. Measurement of stiffness of rock from laboratory and field tests. JEA. 2013.

Arild Palmström, Rajbal Singh. The Deformation Modulus of Rock Masses - comparisons between in situ tests and indirect estimates. Tunnelling and Underground Space Technology. 2001;16(3):115-131.

Roger A Failmezgeri, Aaron L Zdinak, Jesse N Darden, Randall FAHS. Use of Rock Pressuremeter for Deep Foundation Design. 50 ans de pressiomètres. 2005;1. Gambin, Magnan et Mestat (ed.), Presses de l'ENPC/LCPC, Paris.

Kedar C Birid. Interpretation of Pressuremeter Tests in Rock. ISP7-PRESSIO 2015. Frikha, Varaksin & Gambin (Eds.). 2015.

LF Cao, SM Peaker, A Sirati. Rock Modulus from In-situ Pressuremeter and Laboratory Tests. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013. Parallel session ISP 6. 2013.

Cassidy Mathews PE. Estimating the Rock Mass Modulus of Missouri Shale Using Pressuremeter Tests. A Thesis presented to the Faculty of the Graduate School at the University of Missouri-Columbia. 2017.

Marian Kuvik, Miloslav Kopecký, Jana Frankovská. Deformation modulus determination from pressuremeter and dilatometer tests for crystalline rock. IOP Conf. Series: Materials Science and Engineering. 2019;471:042010IOP. doi:10.1088/1757-899X/471/4/042010

Abbas Taheri, Study on Shear Strength and Deformability Properties of Rock Masses by In-situ and Laboratory Testing Methods.