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Comparison of Instrumented Pile Load Test Results with Finite Element Simulation

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Abstract **-** Due to the proximity of the bedrock**,** rock socketed bored and cast in-situ piles are used to support the heavy super structure loads from the high-rise structures transferring to bedrock. In order to design single piles or group of piles, it is very important to know the carrying capacity of the bedrock in terms of skin friction distribution along the pile shaft and the load carried by the pile toe. Such information can be obtained by using the instrumented pile load tests but the instrumented pile load tests are expensive and not always carried out in most of the piling sites in Sri Lanka.

In this study, it was aimed to find out the carrying capacity of cast in-situ bored single piles using commonly used finite element software PLAXIS 2D and compare the results with the instrumented pile load test results obtained in the field. Prior to the use of software package based on finite element analysis to find out the carrying capacity of the pile, the accuracy of the model used was verified by the results instrumented pile load test and the nearby borehole test results. Further, the differences and the difficulties of the interpretation of results with their potential reasons were discussed within the study.

In the current study, the soil and rock properties were used from the nearby borehole results. It was shown that the best match results with the field instrumented pile load tests for weathered rocks were obtained when the elastic modulus for rock layers were twice the value suggested by Hong Kong geo guidelines (Geo,2006) whereas the best match results with instrumented pile load test results were given when half the value of the Young's modulus of rock suggested by the Hong Kong geo guidelines (Geo,2006).

Keywords**:** Bored and Cast in-situ Bored piles, Instrumented Pile Load Test, PLAXIS 2D, Young's Modulus, Socketed, Bed Rock, Finite Element Simulation

Introduction

With the ending of three decades long civil war in 2009, the economy of Sri Lanka is on the rise to a rapid development in its infrastructure facilities. Colombo, as the major financial center, the commercial capital, and the largest city of Sri Lanka by population is in the center of this development. In addition, its central position is a major reason for attraction of foreign investors for development projects, mainly construction projects. With the growth of the construction industry there is a vast development in the construction of high-rise structures.

The underlying foundation material is of extreme importance for the construction of high-rise buildings. Majority of the island of Sri Lanka is underlain by Proterozoic Gneisses, which consists of Precambrian Basement, and Panerozoic sediments being which is mainly restricted to the coastal areas. The capital city of Colombo and the suburbs, where most of the development are taking place, is situated in the western part of the country in the coastal terrain. This Panerozoic sediments is underlain by the rocks of Wanni complex which is one of the major subdivisions of the three major units of the Precambrian basement in Sri Lanka (Cooray, 1984). Considering the ground profile across the major cities in Sri Lanka, solid bedrock is present at relatively shallow depths, on average at about 20m depth. Therefore, most large structures such as high-rise buildings are very often supported on end bearing bored and cast in-situ piles socketed into this hard basement rock. However, the top portion of the bedrock is in highly weathered and fractured state, and the thickness of the weathered zone and the degree of weathering vary spatially. Moreover, under these circumstances, pile base cleaning or pile base stiffening treatment with the verification is very important (Sharudin, E.S. et al, 2016).

Bored piles are a type of replacement piles, where the soil and rocks are bored out and then this bored hole is filled with reinforced concrete. One of the main challenges of bored pile construction is the estimation and confirmation of the ultimate bearing capacity of the pile from the skin friction and the end bearing. As the weathered zone and the thickness of the alluvial crust on it varies spatially, it is very important to determine the required pile length and socket length of the end bearing piles for economical design. Therefore in this research study, with the other commonly used soil and rock properties, the stiffness of the bedrock was investigated to accurately predict the measured pile response from the numerical techniques. In this regard, the applicability of obtaining the compressibility properties of the rocks based on the rock classification using RMR, the applicability of obtaining the shear strength parameters of rock based on Hoek Brown failure criterion and the applicability of obtaining the Dilatancy angle of rock based on Hoek Brown dilatancy estimation model, were checked.

Methodology

Properties of the soil used in this study were calculated according to the borehole investigation data from a typical construction site in Colombo, Sri Lanka, whose contour plan is shown in Figure 1. Twenty-two numbers of investigation boreholes were drilled within this site. Soil and rock layers and the corresponding findings of the boreholes close to the two instrumented test piles; borehole 19 close to Test pile 1 and borehole 7 close to Test Pile 2 as illustrated in Figure 1; were used in estimation of soil and rock properties. The core recovery (CR), rock quality designation (RQD) value and the uni-axial compressive strength (UCS) values for the two boreholes are given in Table 1 below as per the geotechnical investigation reports.

Table 1- Soil Investigation data for two boreholes

Bore hole	Depth (m)	Soil	CR	RQD	UCS (MN/m2)
7	25.1-26.1	Biotitic Granitic Gneiss	90	87	100.43
19	28.95-30.40	Biotitic Gneiss	90	13	33.18
	30.40-31.60	Biotitic Gneiss	33	0	
	3160-32.90	Biotitic Gneiss	77	28	

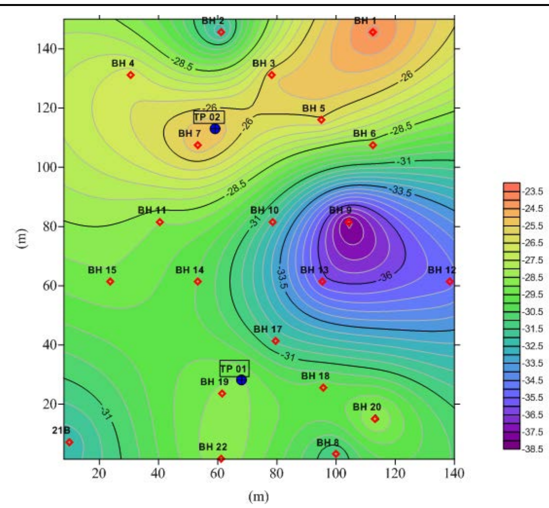

Figure 1 Contour plan of the site (Thilakasiri et. al. 2019)

PLAXIS 2D axi-symmetric simulation with Mohr Coulomb models with appropriate input parameters and optimum boundary dimensions were used to simulate the field conditions. The loads were assigned as uniform distributed load at the pile top. Then, the models were run by applying incremental loads until it reached the ultimate failure condition. According to the test piles considered in this research, Test pile 1 represents the weathered rock and the Test pile 2 represents the fresh rock as shown in Table 1.

Shear strength and compressibility properties of soil layers were extracted using energy correction method (Bowles, 1996). For the rock layers, shear strength properties were extracted using Hoek-Brown failure criterion (Hoek E. 1990) and the compressibility properties of rock mass were calculated using RMR and Hong Kong guidelines (Geo, 2006). Dilatancy angles for rocks were calculated using Hoek-Brown dilatancy estimation model (Hoek et al., 1997)

Using the borehole investigation data for the two boreholes mentioned above, simulation models were prepared. The subsurface soil stratigraphy of the site for two test piles is shown in Tables 2 and 3 respectively with permeability and compressibility properties of the rock layers. Tables 4 and 5 shows the input data used while modelling the pile using PLAXIS 2D the input data includes poisson's ratio, shear strength parameters of soil and rock layers, dilatancy angle of soil layers and the strength reduction factor (Rint).

Table 2- Sub surface Soil stratigraphy for Test Pile 1

Layer No	**Layer Thickness (m)**	**Soil Description**	**Density (kN/m^3)**	**k (m/day)**	**Elastic Modulus (kN/m^2)**
1	3.5	Medium dense clayey sand I	17	1	$2.75x10^4$
2	0.8	Dense Clayey Sand	17	1	$3.8x10^4$
3	1.2	Dense medium sand I	17	1	$3.9x10^4$
4	2.4	Dense medium sand II	17	1	$3.2x10^4$
5	3.6	Medium dense clayey sand II	17	1	$2.9x10^4$
6	2.6	Medium dense clayey sand III	17	1	$3.85x10^4$
7	3.4	Very dense sand	17	1	$4.5x10^4$
8	3.8	Very dense clayey sand	17	1	$5.7x10^4$
9	7.1	Completely weathered rock	17	1	$4.9x10^4$
10	1.5	Moderately weathered rock I	24	0.001	$2.69x10^5$
11	1.2	Highly weathered rock	24	0.001	$1.99x10^5$
12	∞	Moderately Weathered rock II	24	0.001	$3.45x10^5$
13	-	Pile	25		$35x10^6$

Table 3- Sub surface Soil stratigraphy for Test Pile 2

Layer No	Layer Thickness (m)	Soil Description	Density (kN/m^3)	k (m/day)	Elastic Modulus (kN/m^2)
1	3.2	Very fine to medium clayey sand I	17	1	1.4x10^4
2	2.6	Very fine to medium clayey sand II	17	1	5.3x10^4
3	1.5	Very fine to medium sand	17	1	5.32x10^4
4	3	Fine Clayey sand	17	1	4.15x10^4
5	1.5	Very fine sandy organic clay (What is the relationship used in getting the E? You may have to show how you obtained E in your presentation)	17	1	9.2x10^3
6	7.2	very fine clayey sand	17	1	5.2x10^4
7	6.1	Very fine to medium clayey sand III	17	1	6.4x10^4
8	∞	Fresh rock	24	0.001	1.205x10^6
9		Pile	25	-	35x10^6

Table 4- Input data for PLAXIS 2D for Test Pile 1

Layer No	Soil Description	Poison's ratio	Cohesion	Friction angle	Dilatancy angle	R_{inter}
1	Medium dense clayey sand I	0.35	5	32	2	0.67
2	Dense Clayey Sand	0.25	5	37	7	0.67
3	Dense medium sand I	0.25	5	37	7	0.67
4	Dense medium sand II	0.25	10	34	4	0.67
5	Medium dense clayey sand II	0.35	10	33	3	0.67
6	Medium dense clayey sand III	0.35	10	38	8	0.67
7	Very dense sand	0.25	10	38	8	0.67
8	Very dense clayey sand	0.25	10	35	5	0.67
9	Completely weathered rock	0.25	10	38	8	0.67
10	Moderately weathered rock I	0.25	19	59	0	0.67
11	Highly weathered rock	0.25	16	55	0	0.67
12	Moderately Weathered rock II	0.25	23	60	0	0.67
13	Pile	0.2	-	-		0.67

Table 5- Input data for PLAXIS 2D for Test Pile 2

Layer No	**Soil Description**	**Poison's ratio**	**Cohesion**	**Friction angle**	**Dilatancy angle**	R_{inter}
1	Very fine to medium clayey sand I	0.25	5	26	0	0.67
2	Very fine to medium clayey sand II	0.25	10	40	10	0.67
3	Very fine to medium sand	0.25	10	40	10	0.67
4	Fine Clayey sand	0.25	5	38	8	0.67
5	Very fine sandy organic clay	0.25	15	0	0	0.67
6	very fine clayey sand	0.25	10	40	10	0.67
7	Very fine to medium clayey sand III	0.25	10	40	10	0.67
8	Fresh rock	0.25	346	70	0	0.67
9	Pile	0.2	-	-	-	-

Results

Several finite element models were developed for different compressibility properties of rock to study the pile head settlement and the carrying capacity of the pile for respective loads applied on the rock socketed bored and cast in-situ piles. The elastic compressibility of the socketed rock mass, E, of the two test piles were simulated by changing E as given in Tables 1 and 2 to calibrate the PAXIS 2D software to predict the carrying capacity of the Test Pile 1 and Test Pile 2 respectively. For Test pile 1, considering BH 19 of the investigation data, rock modulus (E), C and φ values of rock were changed according to following four methods given in Table 1in order to simulate the pile in PLAXIS 2D. (i) E value obtained from RMR using Hong Kong guidelines (Geo, 2006) with disturbed C and φ parameters as explained by Hoek and Brown, (Hoek, E. 1990); (ii) Twice the E value obtained from RMR using Hong Kong guidelines (Geo, 2006) with disturbed C and $\emptyset$ parameters as explained Hoek and Brown, (Hoek, E. 1990); (iii) E value obtained from RMR using Hong Kong guidelines (Geo, 2006) with undisturbed C and $\emptyset$ parameters as explained Hoek and Brown, (Hoek, E. 1990); and (iv) Twice the E value obtained from RMR using Hong Kong guidelines (Geo, 2006) with undisturbed C and $\emptyset$ parameters as explained Hoek and Brown, (Hoek, E. 1990). The summary of the explained models for Test pile 1 were given in Table 1.

Table 6- Compressibility and shear strength properties used in PLAXIS 2D for Test Pile 01

Compressibility property	Shear strength property	
	C	Φ
E	Disturbed	Disturbed
E	Undisturbed	Undisturbed
E x 2	Disturbed	Disturbed
E x 2	Undisturbed	Undisturbed

Similarly for Test pile 2, bedrock properties, as shown in Table 2, were determined considering BH 7 investigation data Finally, the results obtained for different compressibility properties, shear strength properties and for dilatancy angle of rock were interpret and compared with instrumented pile load test results.

Table 7 - Compressibility and shear strength properties used in PLAXIS 2D Test Pile 02

Compressibility property	Shear strength property	
	C	ϕ
E	Disturbed	Disturbed
E	Undisturbed	Undisturbed
E x 2	Disturbed	Disturbed
E x 2	Undisturbed	Undisturbed
E x 0.5	Disturbed	Disturbed
E x 0.5	Undisturbed	Undisturbed

Changing the shear modulus of the rock and shear strength parameters of the rock as described in Table 1 and 2, finite element simulation method PLAXIS 2D was run, in order to get a similar result with the Instrumented pile load test. Figure 2 and 3 represents the settlement analysis for the two test piles. Here the PLAXIS 2D results for several rock properties as explained above Table 1 and 2 were compared with the Instrumented pile load test results.

Figure 2 summarizes that when use twice the RMR E with undisturbed shear strength parameters of the rock in PLAXIS 2D the result for settlement of the pile head matches with the instrumented pile load test results. When used the RMR E value for rock with the distrubed parameters it deviates from the actual test results by 116%. When the undisturbed parameters are used, of shear strength properties with same compressibility properties it is about 34% deviation. That means a reduction of 82 percent from the earlier case. When twice the E has used with same disturbed shear strength parameters, it gives a deviation of 39% . when twice the E has used with undisturbed shear strength parameters it reduces to less than 2 percents. That means there has a considerable effect from the disturbed or undisturbed behaviour of the rock on the shear strength parameters and on to the settlement of the pile head if the bedrock is weathered. The reason for this is according to the method used in this research to find the shear strength properties of rocks, the disturbed and undisturbed parameters had a considerable difference for weathered rocks. The method used is the Hoek Brown Failure criterian (Hoek E, 1990)

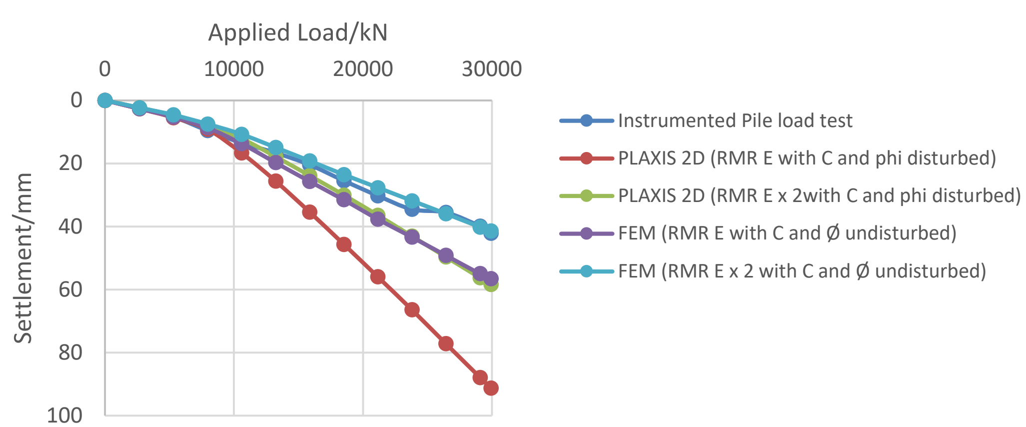

Figure 2 Settlement Vs Applied Load for Test Pile 1

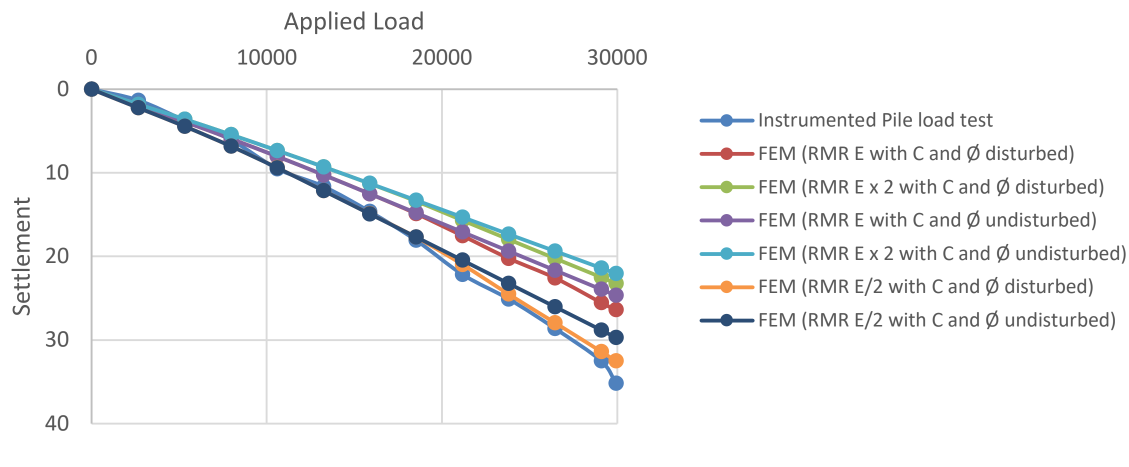

Figure 3 Settlement Vs Applied Load for Test Pile 2

But when it comes to the fresh rock, according to the Hoek Brown failure criterion when calculated the rock shear strength parameters, it does not had a considerable difference whether it is disturbed or undisturbed. So the settlement does not have a much effect from the disturbed or undisturbed behaviour of the bed rock. It has depend on the compressibility properties of the rock. Figure 3 represents the settlement of the pile head for the test pile 2 where the bottom of the pile socketed into the fresh rock.

Skin friction distribution along the pile shaft from PLAXIS 2D were compared with instrumented pile load test results for the same models as explained in Table 1 and 2. Following Figure 4 shows the skin friction distribution along the pile shaft for the applied incremental load of 29920 kN for Test pile 1.

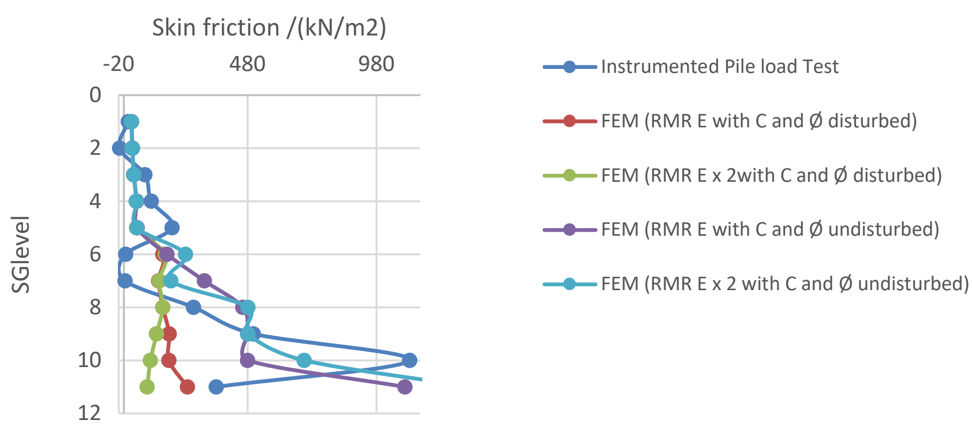

Figure 4 Skin friction distribution at different strain gauge locations for pile top load 29920kN for Test pile 01

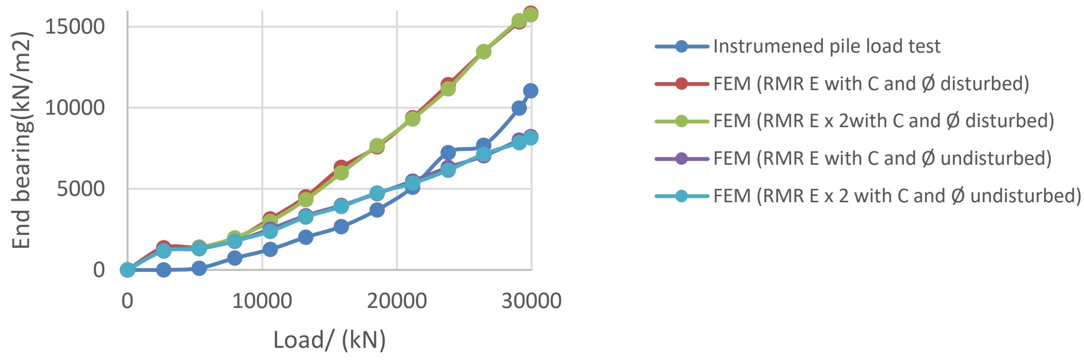

Figure 5 End bearing Vs Applied load for Test Pile 01

According to Figure 5 using twice the E with undisturbed shear strength parameters of rock gives an end bearing value with similar to the instrumented pile load test results with the settlement and skin friction resistance.

Skin friction distribution along the pile shaft from PLAXIS 2D were compared with the instrumented pile load test results for Test pile 2. The finite element simulation model was run according to the description given in Table 2. Figure 6 represents the comparison of skin friction for the applied pile top load 29920 kN for Test pile 2

Figure 7 shows the variation of end bearing capacity of the test pile 2 when modelled using PLAXIS 2D according to the Table 2 descriptions. Then the results were compared with instrumented pile load test results.

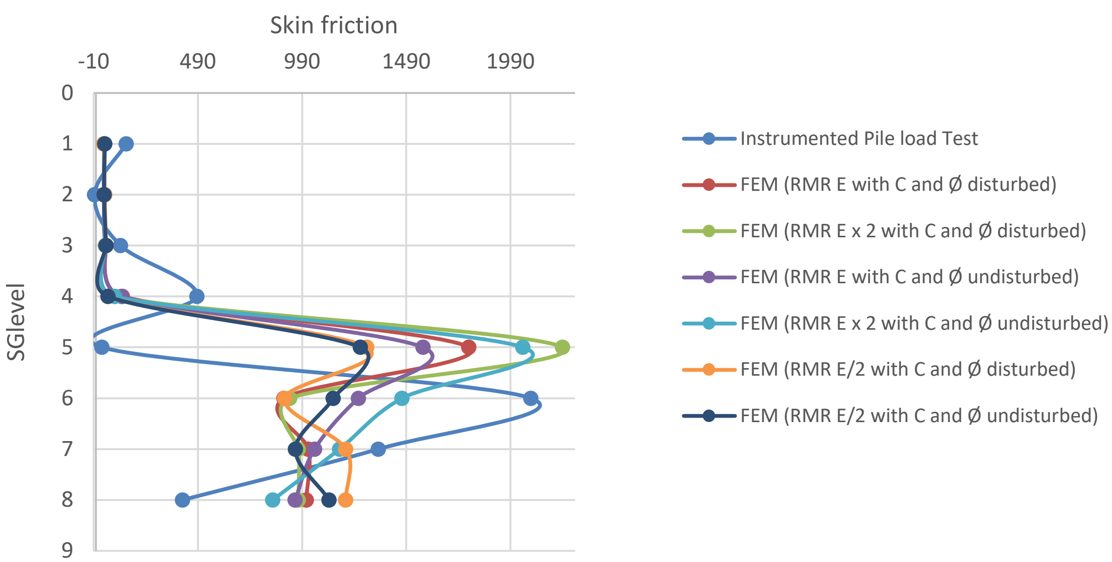

Figure 6 Skin friction distribution at different strain gauge locations for pile top load 29920kN for Test pile 2

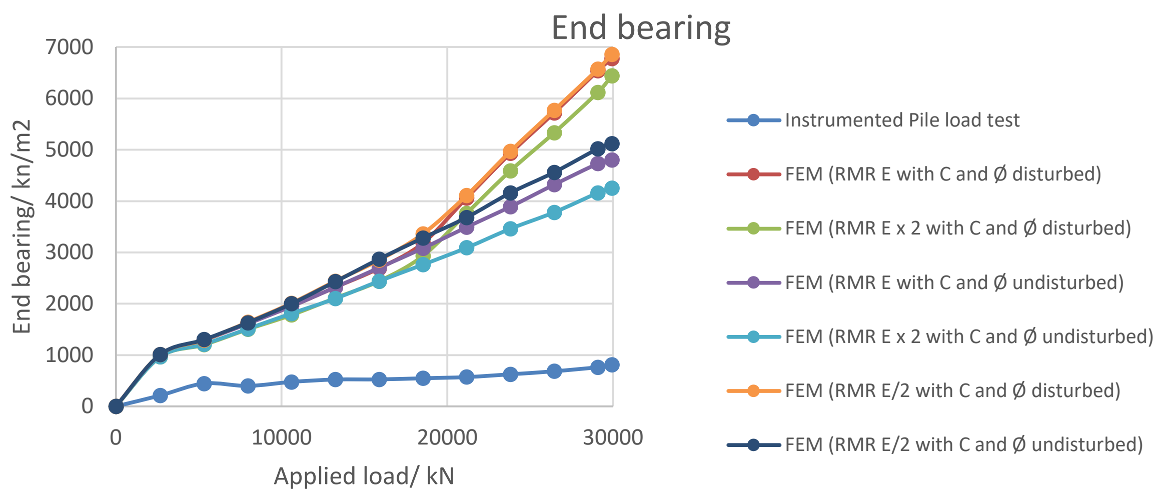

Figure 7 End Bearing Vs Applied Load for Test pile 02

Conclusion

A finite element study was conducted using PAXIS 2D computer package to predict the settlement behaviour and to predict the bearing capacity of bored and cast in-situ piles of Sri Lanka. Analyses were conducted changing the compressibility and shear strength properties of rock since, settlement and bearing capacity of the piles were directly relate with the compressibility and shear strength properties of rock. The conclusions obtained from this study can be summarized as the modulus of rock mass is under predicted by the Hong Kong geo guide for weathered rocks, by increasing the modulus of rock mass twice as the original value obtained from Hong Kong geo guide for weathered rocks gives a reasonable result for settlement, skin friction and end bearing of the pile, whereas the modulus of rock mass is over predicted by the Hong Kong geo guide for fresh rock, by taking the half of the modulus from the original value obtained from Hong Kong geo guide gives reasonable results for pile capacity and settlement of the pile. The selection of the disturbed and undisturbed parameters are important for weathered rock but the results are insensitive for fresh rock.

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