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ANALYSIS OF ROCK-SOCKETED PILES BEHAVIOR USING JOINTED ROCK MODEL

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الملخص
من تجربة حقلية , تم استخلاص المعلومات و البيانات من اختبار الحمل الاستاتيكى بكامل التجهيزات على خازوق قطره 0.9 متر راسخ في الحجر الجيري. تم استخدام برنامج العناصر المحددة لمحاكاة نتائج النموذج العددي مع نتائج الاختبار الحقلية (الميدانية). أظهرت نتائج التحليل توافقًا جيدًا بين نتائج الاختبار ونتائج نموذج الصخور المفصلية. قدم هذا البحث تأثير اختلاف بعض المتغيرات المختلفة على سلوك الخازوق مثل نسبة الطول المخترق إلى القطر (Ls / D). أيضا ، يتم إجراء مقارنة بين الأساليب التجريبية لحساب الهبوط لاختيار أفضل طريقة تعطي أقرب أداء للواقع
الكلمات الدالة :- الطول المخترق , نموذج الصخور المفصلية , النمذجة المحددة.

ABSTRACT
Field data was extracted from an instrumented full-scale load test on a pile of diameter 0.9 meters embedded in Siltstone. A finite element program is used to verify the results of the numerical model with the field results. The results of the performed analysis expressed a good agreement between the field data and the results of the Jointed rock model. This paper examined the effect of varying different parameters on the pile behavior as the socketed length to diameter ratio (L_s/D). Also, a comparison is executed between the empirical methods for calculating the settlements to choose the best method that gives the nearest performance to the field.
KEYWORDS: - socketed length, Jointed rock model, finite element

1- INTRODUCTION
The ratio of the socketed length to the pile diameter (L_{socket}/D) is a significant factor. This factor is used in the analysis of the stresses along the socketed part. It should be considered in the design of rock-socketed piles. [1] and [2] related the socketed length to the pile diameter for the sedimentary rocks as follows:-

$$L_{Socket} = (3 \rightarrow 4)D. \tag{1}$$

The target of this paper is giving a general image of the behavior of rock-socketed piles and discuss the effect of some factors on the overall performance.

2- CASE STUDY: JURONG FORMATION (PILE M1)
2.1 GEOLOGY OF SINGAPORE
Singapore is situated in Southeast Asia, which is located between east longitude of 103° and 104° (103°50′E), and north latitude of 1° and 2° (1°17′N). About 70 % of Singapore's land consists of Bukit Timah granite and Jurong formation, as shown in Figure8. Residual soils have lengths range to 40 meters over the weathered rocks as (Chang and Wang 1987) mentioned.

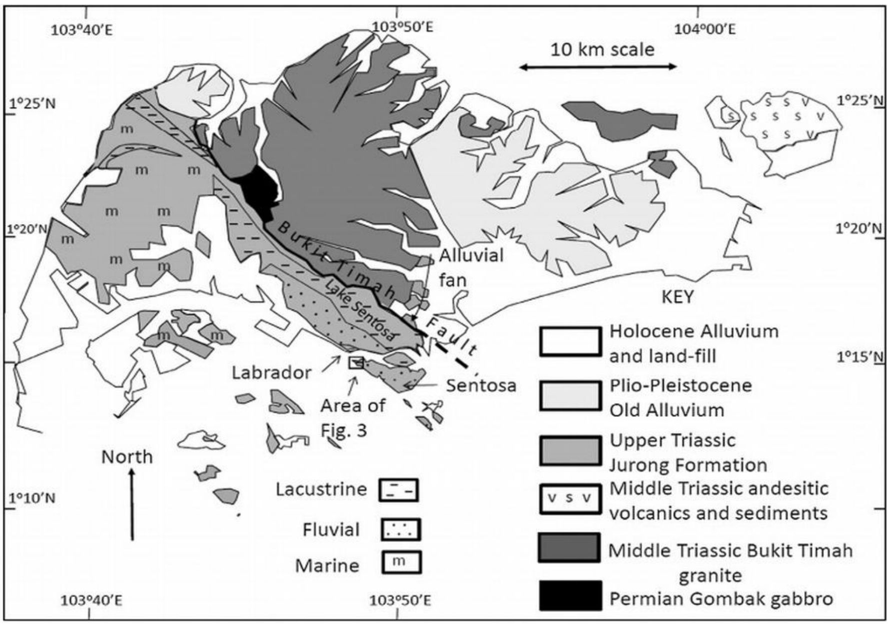

Figure8.Geology of Singapore (Lee, K.W., Zhou, 2009)

2.2 Subsurface Condition at The Area Under Study

Jurong formation is located at the southwestern of Singapore. A major structure of Jurong island consists of metamorphic and sedimentary rocks sediments. Soil and rock properties are summarized in Table 6. The case study was taken from [3]

Table 6 Properties of materials and layers used in Case study pile M1

Pile (M1)	Soil and Rock Properties							
	profile	**Depth (m)**	****σ_{ci} (MPa)**	**E_s (MPa)**	***v***	**φ^o**	****i* °**	**γ (KN/m^3)**
Shaft	**Silty Clay**	0-11		8.4	0.3	30		18
Shaft	**Siltstone**	11-24	1.6	1000	0.2	30	8	23
Toe	**Siltstone**	24	1.6	1000	0.2	40	8	23
Pile Material	**Concrete**	0-24	31	31000	0.17			24

3- FIELD PILE LOAD TEST

The pile load test was performed on a 0.9m diameter pile. Pile M1 was socketed by about 13m in Siltstone while penetrating 11m of silty clay, as detailed in Figure9. The properties of the material of the pile are found in Table 6.it was designed to carry 2500 KN , but it was tested to a load of more than 10000 KN.

***σ_{ci}** : The uniaxial compressive strength of the intact core

**** *i* ° :** The roughness angle between the rock asperities

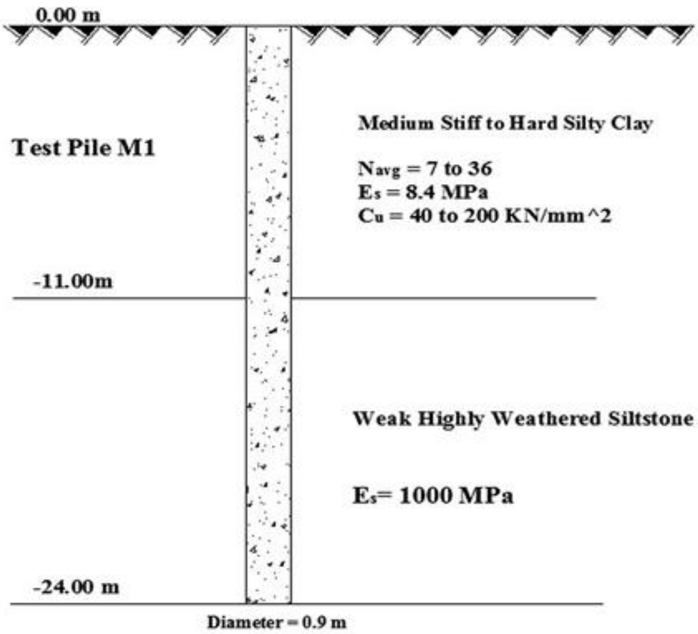

Figure9.Subsurface profile for pile M1

3.1 FIELD RESULTS

Strain gauges were fixed at five levels: - 7.5, -11, -15.5, -20.5, and -24 meters to observe the change in the load transfer and measure the pile end bearing and the settlement. Figure 3 shows the load-settlement relations during the whole test and the load-distribution along the pile's length. The maximum settlement was 8.5 mm, and the end bearing at the end of the test was measured to be 450KN.

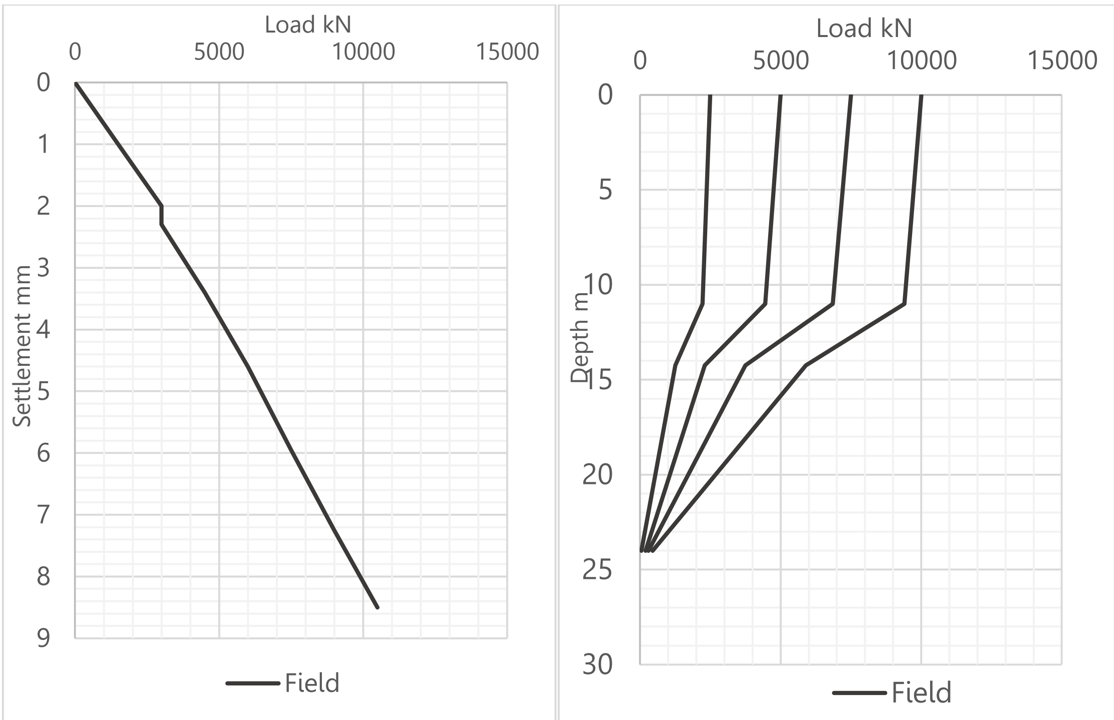

Figure 10.Load-settlement relationship and load-distribution along the pile's length (field results)

3.2 Shear Stress along The Pile Shaft

Figure 11 shows the shear stress distribution along the pile shaft. The average skin friction along the shaft is about 300KN, the results are from FE analysis using the J-R model. The shear stresses are concentrated at the rock shaft due to the difference in deformation modulus between the Siltstone layer and the silty clay layer. $E_{rockmass}$=1000Mpa, while $E_{Silty\ Clay}$=8.4Mpa. So, $E_{rockmass} \approx 119 * E_{Fill}$

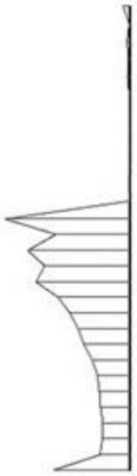

Figure 11.Distribution of shear stress along the pile M1 shaft

4- NUMERICAL ANALYSIS RESULTS

4.1 CONSTITUTIVE MODELS USED AND MATERIAL PARAMETERS

The concrete pile is modeled by a linear elastic model. The Mohr-Coulomb model models the residual soil and fill. cohesion(c) = 0.1Kpa, Poisson's ratio(v) = 0.3 and friction angle(φ) = 30º.Also, the siltstone layer is modeled by the jointed rock model. All parameters of the material are adopted in Table 7.

Table 7 Soil and pile properties for the case study (M1) using J-R model

Pile	**Type**	**Depth (m)**	**Model used**	**Soil and Rock Properties**					**Joints Properties**					
				E_s (MPa)	***V***	**ϕ º**	**c (kPa)**	**γ (kN/m^3)**	**E_2 (MPa)**	**G_2 (MPa)**	**α**	**φ**	**c**	**R_{int}**
Shaft	Silty Clay	0-11	M-C	8.4	0.3	18	600	18						0.7
	SiltStone	11-24	J-R	1000	0.2	30	0	23	750	289	0	30	0.1	1
		11-24	L-E	1000	0.2			23						
		11-24	H-S	1000	0.2	30	1000	23	1000					
		11-24	M-C	1000	0.2	30	1000	23						
Pile	Concrete	0-24	L-E	31,000	0.17			24						1

4.2 Rock Deformation Modulus from Sensitivity Analysis

4.2.1 J-R Model Parameters

A sensitivity analysis is proceeded to obtain the nearest parameters of the J-R model to be in a good agreement with the field behavior.

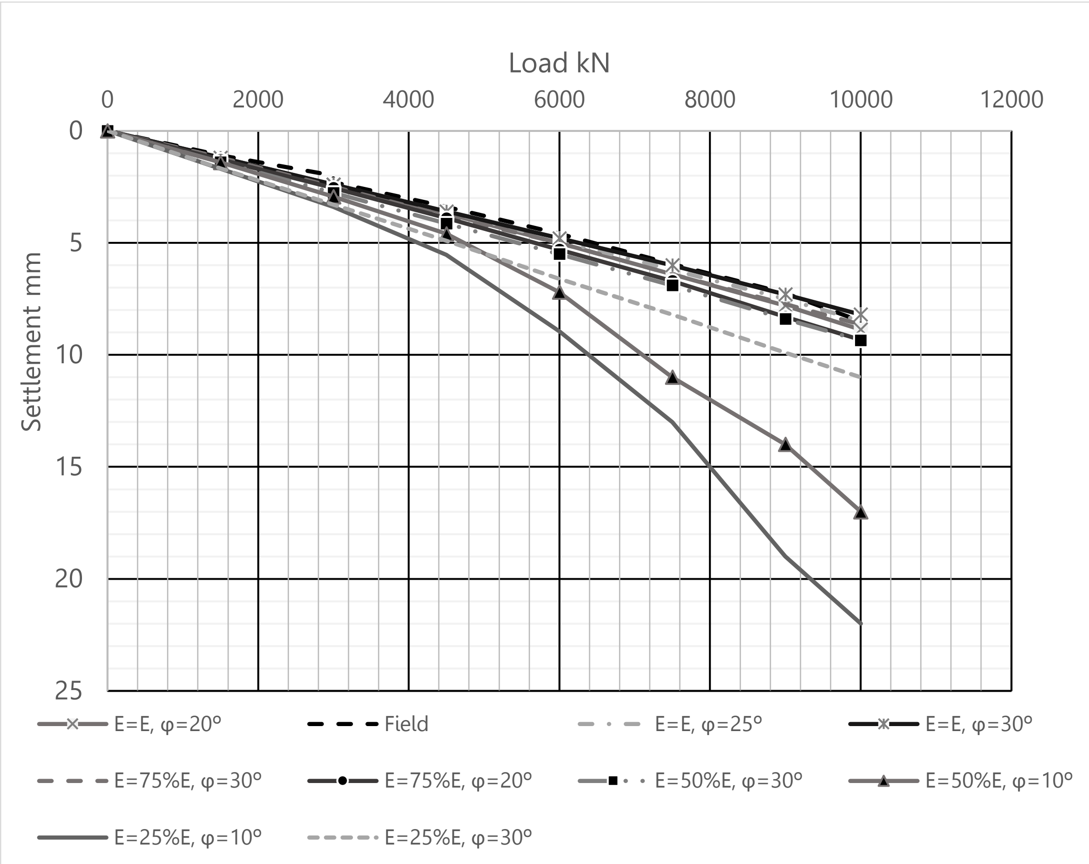

Figure 12. Load-displacement relationships for different jointed-rock model trials

The joint's deformation modulus ranges from 25% of $E_{rockmass}$ as to $E_{rockmass}$. From the analysis. It's found that, the most suitable deformation modulus for joints (E_{joints}) is75% of $E_{rockmass}$,i.e E_{joints} = 0.75*1000=750Mpa. This analysis extends to include the friction angle of the rock joints. The joint's friction angle ranges from 10º to $\varphi_{rockmass}$ º ($\varphi_{rockmass}$ =10º→30º). The most suitable friction angle (φ_{joints}) =100% $\varphi_{rockmass}$ =1*30= 30º. Figure **12** and

Figure **13** show the load-displacement relations and load-distribution of the jointed-rock models' trials.

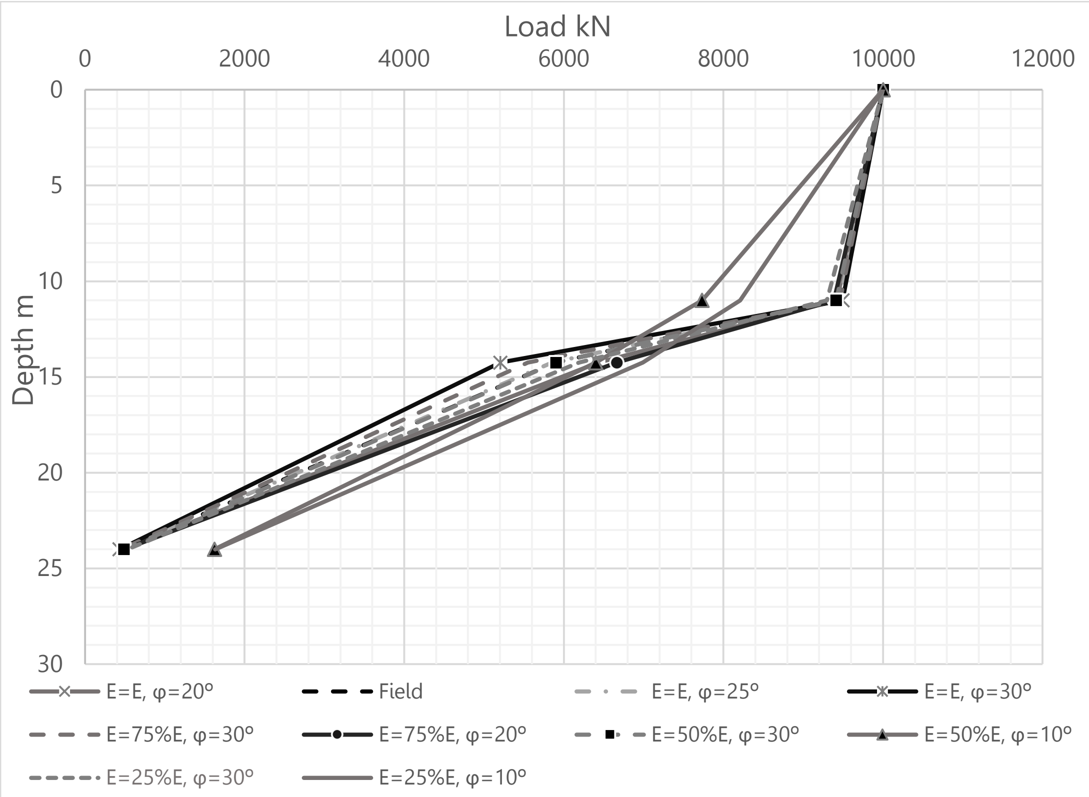

Figure 13. Load-distribution among jointed-rock models trials

4.2.2 Comparison with Field Results

The Siltstone layer is simulated using different constitutive models. The model results are verified with the field results.

Figure14 shows the results of the performed numerical analyses. Four different constitutive models that are the Linear elastic model, Mohr coulomb model, Hardening soil model, and Jointed rock model were adopted in the analyses. The maximum –field settlement at the end of loading was measured to be about 8.5mm. The estimated settlement values utilizing the different constitutive models are 7.7mm,7.6mm,8.3mm, and 8.49mm for the linear elastic model, mohr coulomb, hardening soil model, and jointed rock, respectively.

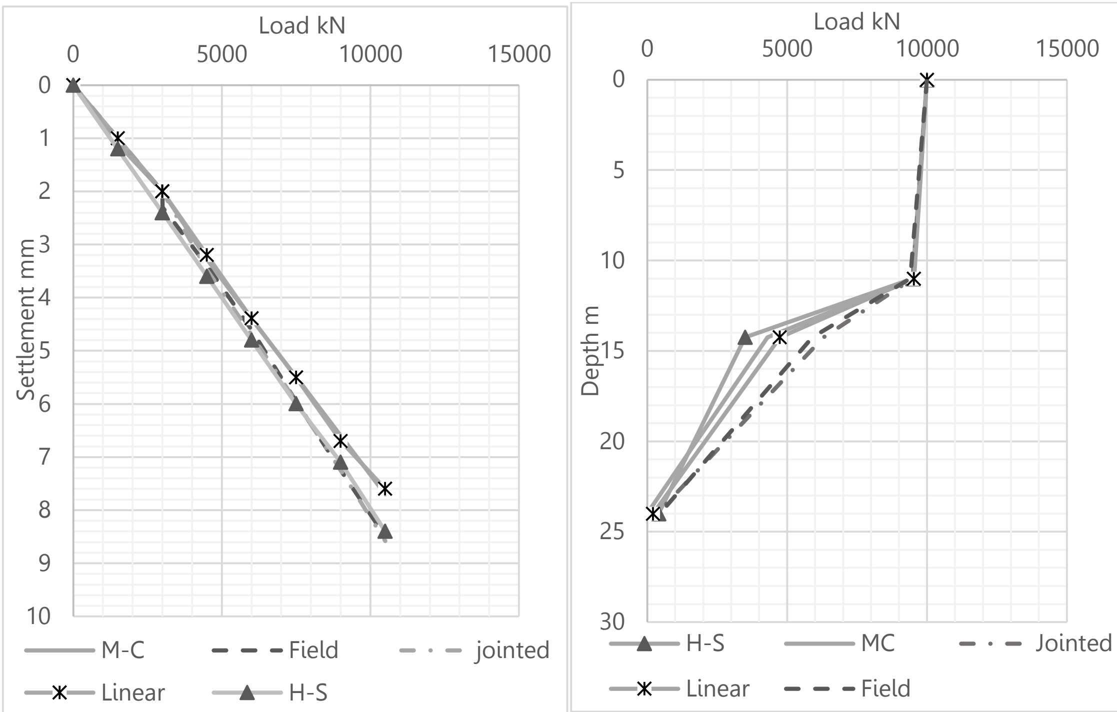

Figure14. A comparison between the results of different constitutive models for pile M1

The predicted settlement using the linear elastic model is about 11% less than the measured value. For the mohr coulomb model, the estimated settlement values are about 12% less than the measured value. For the Hardening soil model, they are about 3% less than the field values. For the jointed rock model, the predicated settlement values agree with the field test results.

The estimated end bearing values utilizing the different constitutive models are 212 KN,0KN, 413 KN, and 452 KN for the linear elastic model, mohr coulomb, hardening soil model, and jointed rock respectively. While the end bearing at the end of the test was measured to be 450KN. The predicted end bearing using the linear elastic model is about 42% less than the measured value. For the Hardening soil model, it's about 10% less than the field results. The predictions by the J-R model are in good agreement with the field observations, while the other models gave underestimate outputs.

5- PARAMETRIC STUDY

5.1 EFFECT OF VARYING SOCKET LENGTH ON PILE BEHAVIOR: -

The ratio of the socketed length to diameter (L_{socket}/D) is a significant factor to know the stresses along the socketed part. [1] stated that the most suitable ratio for the socketed length to diameter for the sedimentary rocks ranges from three to four times as follows:-

$$L_{Socket} = (3 \rightarrow 4)D \qquad (2)$$

Figure15 shows the effect of varying the socket length from 1 to 14 times the pile's diameter on the final settlement of the pile and stress distribution along the shaft.

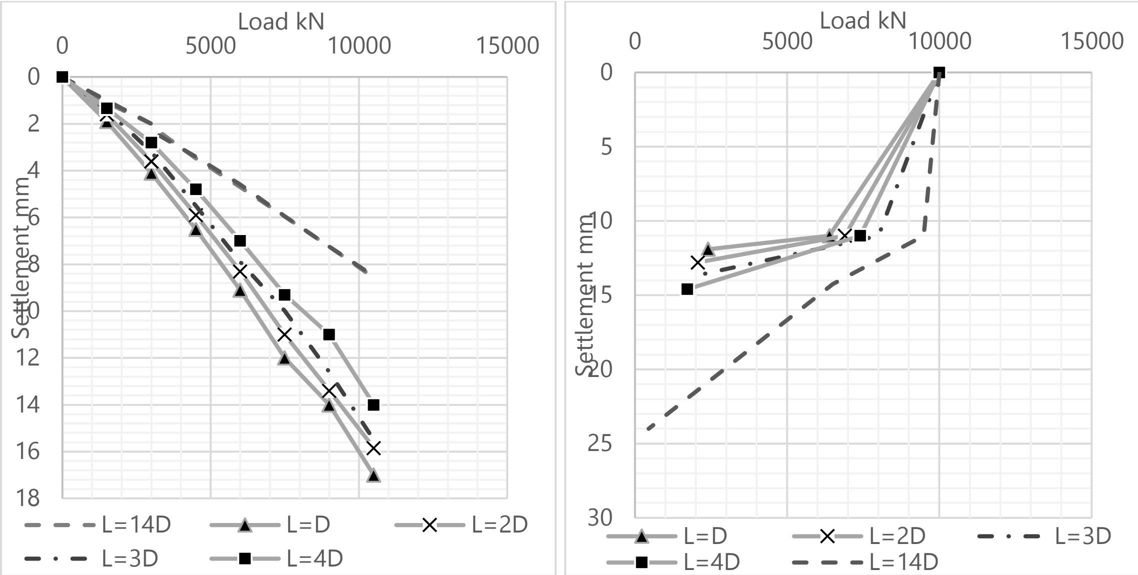

Figure15.Effect of varying L_{socket} on pile settlement and force distribution along pile length

When L=D, settlement = 17 mm(settlement increases by 100%) and End bearing = 2400 KN. It increases by 5.3 times the field case. when L=4D, settlement = 14mm (settlement increases by 64%) , End bearing = 1718KN (increased by 4 times the field case)
When L=14D (the current case), settlement = 8.5mm and end Bearing = 450 KN. End bearing, in this case, resists only 4% from the total load, as shown in
Figure **16**a.

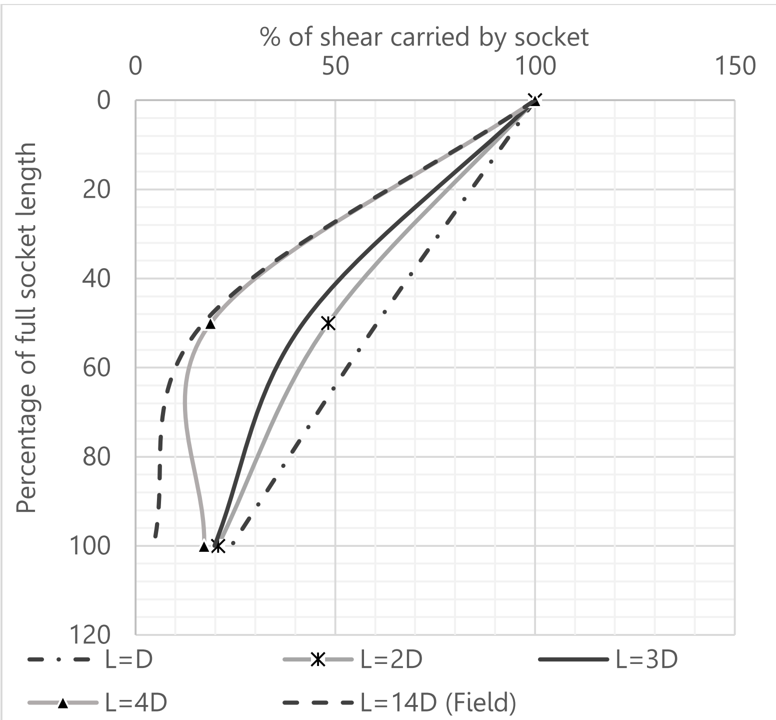

Figure 16.Effect of varying L_{socket} on a.shear distribution along with the socket

Figure 16 shows a drop in the rate of transmitting the shear stress when the socket length increases over 2D. when L_s=D, the percentage of transmitted shear along the socket length =76%. When L_s=2D, the percentage becomes 79.32%. So, the change in the ratio of transmitted shear =3.32%. When L_s=3D, the rate becomes 81%. When L=4D, the percentage becomes 82.8%. So, the change in the ratio of transmitted shear=1.8%. Thus, the optimum ratio for the socketed length to diameter in this case:-

$$(L_{Socket})_{Optimum} = 3D \tag{3}$$

The slope of the curve is changed (almost linear) over L=3D. The change in the rate becomes nearly 1% at a socketed ratio from 4 to 14. Any length over L=4D is of no use.

5.2 Settlement of Rock-Socketed Pile

There are a lot of empirical methods used to predict the settlements of piles socketed in rock as [3] and [4]. Most of these approaches overestimated the calculated final settlement.

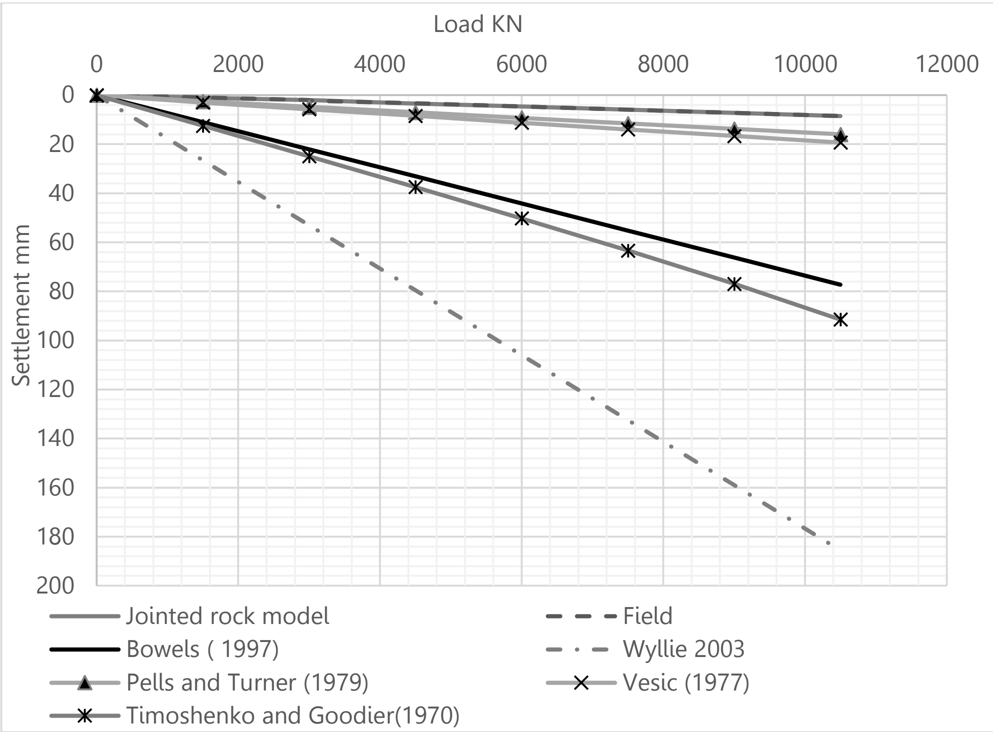

Figure 17. Comparison between the resulting settlements using different empirical methods

A comparison between these different methods is performed to clarify the most suitable one to compute rock socketed piles displacements. Figure 17 shows that Timoshenho and Goodier(1970) and Rowe and Armitage(1987) methods give too conservative predictions. While Vesic(1977) and Pells and Turner(1979) provide closer results to the field outputs. So, it’s preferable to use Vesic(1977) and Pells and Turner(1979) in calculating the settlement of the piles socketed in rocks.

Conclusion and Discussion

FE analyses are carried out using different constitutive models to evaluate the best one that can simulate the pile performance in rock. The conclusion are drawn from this study are expressed as follows: -

- The jointed rock model is the most suitable model used in simulating the rock layers as it accounts for the joints properties.
- The deformation modulus of the joints is expected to be 75% of the rock mass: - E_{joints} =75% $E_{rockmass}$ and φ_{joints} = 100% $\varphi_{rockmass}$
- The most suitable ratio for the socketed length to diameter in the sedimentary rocks ranges from three to four times the pile diameter. $L_{Socket} = (3 \rightarrow 4)D$. Any length over four diameters is not economical. However, this conclusion is for rocks with certain characteristics.
- The optimum ratio for the socketed length to diameter in this case:- $(L_{Socket})_{Optimum} = 3D$
- Timoshenho and Goodier(1970) and Rowe and Armitage(1987) methods methods give too conservative predictions and suitable to use.
- It's preferable to use Vesic(1977) and Pells and Turner(1979) in calculating the settlement of the piles socketed in rocks. Pells and Turner(1979) is closer.

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