NUMERICAL MODELLING OF ROCK-SOCKETED PILES

S.S.I. Kodagoda [1] and U.G.A. Puswewala [2]

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ABSTRACT

Axisymmetric finite element meshes are developed to model the pile tip in the rock-socket, for four different ratios of socket length to pile diameter, the values being 1 to 4. The pile material (concrete) and the surrounding rock material are both considered as isotropic linear elastic materials. Analyses are conducted to determine the shear stress distribution profile at the interface and the axial load variation within the pile along the socket length, for various socket length/pile diameter ratios and a range of Young's Moduli representing the rock material. The results indicate the variation of the percentages of load resisted by interface shear along the socket wall and end-bearing at pile tip as the pertinent parameters are varied. An interface element to model the interface shear behaviour is introduced, and its performance in the finite element analysis is discussed.

INTRODUCTION

Rock-socketed piles are a type of deep foundation frequently encountered in geotechnical engineering. These are cast-in-place concrete piles or piers socketed into rock, where the applied load is predominantly resisted by stresses developed at the rock socket, by both the end-bearing pressure and the interface shear along the socket shaft. Allowable loads for these piles are often determined from the results of field tests. Elastic solutions for load distribution and displacement are frequently used to analyse such field tests, and have been suggested for use in design of rock-sockets (Pells and Turner, 1979).

Literature considers the design of rock-socketed piles over a range of socket length(L)/pile diameter(D) ratio varying from 1 to 10 (Pells and Turner 1979, Williams and Pells 1981, Row and Armitage 1986), but in Sri Lanka, this ratio rarely exceeds 4 (Tennekoon, 2001).

Elastic solutions for rock socketed piles are available in the literature (Poulos and Mattes 1969, Osterberg and Gill 1973, Pells and Turner 1979). The latter authors used some finite element analysis, and results of tests designed for shear only sockets and end-bearing only sockets. Williams and Pells (1981) considered interface roughness, and showed that even a small degree of interface roughness is sufficient to ensure that side shear displacement is not brittle.

Horvath et al (1983) reported that the load transferred to the base of the socket at the linear elastic limit of pier-socket load was in the range of 15%

to 20% of the total load. Rowe and Armitage (1986) used finite element analysis with plastic failure within rock and slip at a cohesive-frictional socket interface. Their work indicated that the problem requires a parametric study over a range of possible values of pertinent parameters of the problem, which included Young's Modulii of pile and rock, socket geometry, initial stress in rock, pile-socket interface strength properties, etc. Wyllie (1992) presented a fairly comprehensive treatment of design and analysis aspects of rock-socketed piles. Leung (1996) presented results of several case studies where instrumented, rock-socketed bored-piles were load tested to find the socket shear strength and end-bearing.

This paper presents a parametric elastic analysis of a rock-socketed pier of selected diameter where the shear stress transfer at the pile-socket wall interface and axial load carried by the pile are investigated in detail for different rock stiffnesses and socket lengths. This part of the study where interface elements are not involved can be considered as an extension of the work of Osterberg and Gill (1973), and Pells and Turner (1979), in the range of socket length/pile diameter ratio of 1 to 4. The present study does not concern pile settlements.

An elastic slip element is suggested to represent the adhesive behaviour at the pile-socket wall interface. The performance of this interface element is introduced. Numerical results obtained in this work are compared with some test results reported in the literature (Leung 1996).

DEFINITION AND IDEALISATION OF PROBLEM

Figure 1 depicts the problem considered in this work. An axially loaded cylindrical pile is socketed into rock at its tip. The diameter of pile is D and length of socket L. The work concerns the rock socket only; thus the behaviour above the rock formation is not considered. The analysis is carried out assuming that an axial load P is introduced to the pile at the crown of the rock socket.

The axial load P will be resisted by socket wall interface shear and end bearing at the tip of the pile. The problem is one of axisymmetry, and axisymmetric finite element analysis is used to analyse the problem.

The current elastic analysis is carried out assuming that all materials behave as isotropic linear elastic material. Thus the rock material is represented by Young's Modulas E_r and Poisson's ratio v_r; similarly the pile material (concrete) is represented by E_c (Young's Modulas) and v_c (Poisson's ratio).

The current parametric finite element (FE) analysis is carried out for L/D ratios of 1.0, 2.0, 3.0 and 4.0. A typical finite element mesh used for this analysis is shown in Figure 2(a), where the L/D ratio is 4.0 (with no interface elements). The diameter of pile considered was 300mm. The mesh in Figure 2(a) consists of 4-noded rectangular elements.

The far boundaries of the FE mesh are selected at distances sufficiently far from the pile socket so that their effect is not felt at the socket. The boundary conditions are as indicated in Figure 2(a).

FE ANALYSIS WITH CONTINUUM ELASTIC ELEMENTS ONLY

Meshes similar to that in Figure 2(a), with no interface elements introduced at the pile-rock interface, were used for this analysis. The pile and rock are assumed to be perfectly bonded together.

Finite element analysis was carried out by the Finite Element Analysis Programme (FEAP) initially developed by Prof. R.L. Taylor (Zienkiewicz, 1977), which was expanded, modified and installed in a PC environment by the second author. The reliability of elastic axisymmetric analysis performed by this program was established by simulating a simple axisymmetric problem for which the analytical solution was known.

FE analysis was carried out for the four different L/D ratios considered (1 to 4), and for each L/D ratio, five E_r/E_c ratios were considered. Elastic parameters for concrete were taken as $E_c = 2.1 \times 10^7$ kN/m² and $v_c = 0.2$. A general Poisson's ratio of 0.3 was taken for rock material, and the E_r was varied to get the E_r/E_c ratios of 0.1, 0.5, 2.0, 3.5 and 5.0. These E_r/E_c ratios cover the range of realistic values of rock moduli reported in literature (Krynine and Judd, 1957). An axial load of 100 kN was applied on the pile length in the socket.

Figure 3(a) shows the shear stress distribution along the socket-wall for different E_r/E_c ratios for the case of $L/D = 1$. Figure 3(b) shows the axial load, as a percentage of the load applied (at the crown of socket), carried by the pile length in the socket for different E_r/E_c ratios, for the case of $L/D = 1$.

Figures 4(a), 4(b) show the shear stress distribution and axial load percentage over the socket length respectively, when $L/D = 2$, and as the E_r/E_c ratio varied from 0.1 to 5.0. Figures 5(a), (b) give similar results for $L/D = 3$ and Figures 6(a), 6(b) show the results when $L/D = 4$.

INTRODUCTION OF THE INTERFACE ELEMENT

An axisymmetric interface/joint element of zero thickness had been developed independently by the second author, which was used to simulate the interface shear behaviour in this problem. The interface element was developed following the approaches of Goodman et al. (1968) and Soo (1983).

An interface element has 4 nodes, and is as shown schematically in the Figure 2(b). Nodes 1 and 2 connect with the material on one side of the

interface, and nodes 3 and 4 with that on the other side of the interface. Initially, the node pairs (1,3) and (2,4) will have identical coordinates.

The constitutive model for the zero thickness interface element was based on a stress-relative displacement relationship (rather than a stress-strain relationship employed in the continuum elements). The relative displacement at a given location on the interface is defined as the difference in displacement undergone by two corresponding points on the two surfaces of the interface which initially had identical coordinates.

The elastic interface behaviour is defined as,

$$\sigma_s = C_s \, d_s$$

where σ_s is the shear stress on the bond interface (stress parallel to the interface), d_s is the relative displacement parallel to the bond interface, and C_s a bond modulus for the bond strength in units of Force/Length^2/Length.

Stress-displacement relationship normal to interface can similarly be defined, but in the present elastic analysis, it will have no bearing on the results. The interface element was able to yield exact force balance in a simple test FEA problem where a steel rod was pulled out of some embedding material surrounding it. Thus its performance was verified.

The above interface elements were introduced along the pile-rock interface in the FE mesh in Figure 2(a). The different roughness/bond conditions at the interface can be simulated by using various C_s values; this exercise was actually carried out as a parametric study by using the FEAP program with the interface element, and the results are shown in Figure 7(a) and Figure 7(b). Figure 7(a) shows the shear stress distribution along the socket wall for the case of $L/D = 4.0$ and $E_r/E_c = 2.0$ as the C_s value is varied from 10^5 to 10^8 (kN/m^2/m). Figure 7(b) shows the axial load carried by the pile length in the socket when C_s is varied as above.

Figure 8(a) and 8(b) show the results of FE analysis with interface elements having $C_s = 10^8$ kN/m^2/m, $L/D = 4$, and the E_r/E_c varying from 0.1 to 5.0.

DISCUSSION OF NUMERICAL RESULTS

Comparison of shear stress profiles in Figures 3(a), 4(a), 5(a) and 6(a) show that as the E_r/E_c ratio increases from 0.1 to 5.0 the shear stress in the upper part of socket increases, and that in the lower part of socket decreases. For soft rocks $(E_r/E_c = 0.1)$ the shear stress profiles remain approximately uniform throughout the socket length, for all L/D ratios. For hard rocks $(E_r/E_c = 5.0)$ the shear stress profiles show a large variation in magnitude over the socket length, for all L/D ratios. For larger L/D ratios, the shear stress towards the lower part of the socket length approaches negligible values for hard rock $(E_r/E_c = 5.0$; Figures 3(a) and 4(a)).

Comparison of axial load percentage profiles in Figures 3(b), 4(b), 5(b) and 6(b) show that as E_r/E_c ratio increases from 0.1 to 5.0, the end bearing resistance decreases for all L/D ratios. For soft rocks ($E_r/E_c = 0.1$) end bearing is about 35% of applied load for $L/D = 1$, and it decreases to 15% for $L/D = 4$. For hard rocks ($E_r/E_c = 5$) end bearing resistance decreases from 15% of applied load for $L/D = 1$ to almost 0% of applied load for $L/D = 4$.

Figures 3–6 show that larger the L/D ratio, lesser will be the end bearing resistance when all other parameters are held constant. This indicates that more of the applied load is resisted by socket wall shear as the socket becomes longer. This is in accordance with observations in the literature (e.g. Wyllie, 1992).

Figures 7(a) and 7(b) show that use of $C_s = 10^5$ kN/m^2/m for the interface element implies a comparatively smooth socket wall condition whereby very little shear is developed on the wall and more than 90% of the applied load is carried by end bearing. When C_s is increased to 10^8 kN/m^2/m, the wall condition tends to be very rough, with less than 5% of applied load resisted by end bearing.

There is similarity between Figures 6(a) and 8(a), and Figures 6(b) and 8(b), respectively. Figures 6(a) and 6(b) are for the case of $L/D = 4$, without the use of interface elements (assuming perfect bond between pile and rock), while Figures 8(a) and 8(b) are for the same L/D ratio (of 4), but with the interface elements incorporated. Thus $C_s = 10^8$ kN/m^2/m appears to represent the perfect bond condition along the socket wall interface.

Figure 9 represents results reported by Leung (1996) for instrumented piles with $L/D = 4.0$ (approx.) and socketed into siltstone (a weaker rock). The condition under which these results are obtained can be compared with the FE simulation indicated in Figure 7(b) for a moderately weak rock (E_r/E_c =2.0). The end bearing in Figure 9 (after Leung 1996) is ranging between 25% to 50% of the load applied at the crown of socket. By adjusting the value of C_s in Figure 7(b), a close comparison can be obtained.

Figure 10 represents results of Leung (1996) for piles with $L/D = 1.0$ and socketed into granite (a harder rock). Figure 11 carries the results of a FE analysis with the $C_s = 10^8$ for the same L/D ratio, from which a comparison can be made with Figure 10.

CONCLUSION

Elastic finite element analysis of rock socket piles is able to simulate experimentally observed behaviour of such piles within an acceptable margin of deviation (only the proportions of socket wall shear and end-bearing resistance were considered here). Exact parameters applicable for a particular field condition would be difficult to obtain, and a main use of the FE analysis lies in the parametric studies that can be conducted using it.

According to the numerical results, as the socket length/pile diameter increases, a larger proportion of the applied load is resisted by socket wall shear and end-bearing resistance becomes lesser. As the moduli ratio E_r/E_c increases, a larger proportion of the applied load is resisted by the socket wall shear. Both the above trends agree with the observations reported in the literature.

The interface element introduced enables the simulation of different socket wall roughness conditions, and will be very useful in parametric analyses of rock-socketed piles.

ACKNOWLEDGMENT

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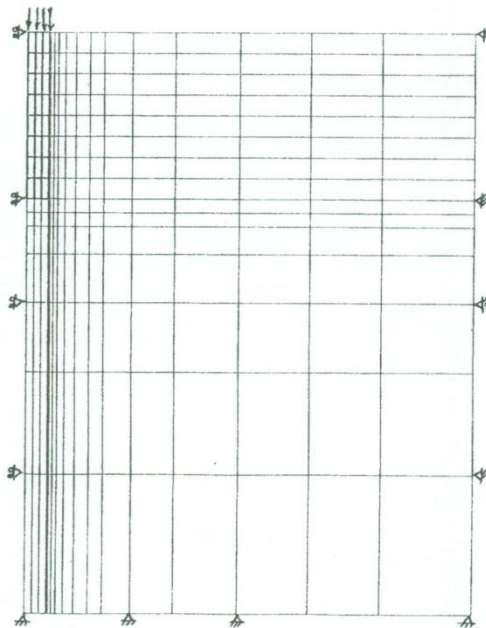
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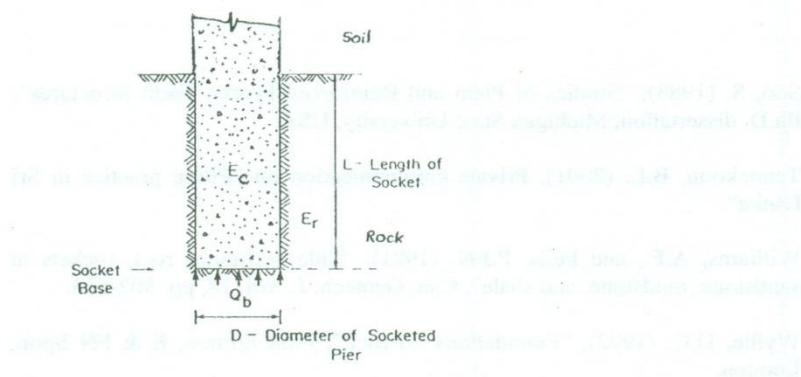
Figure 1 : Problem configuration

Figure 2(b) : Schematic representation of the interface element

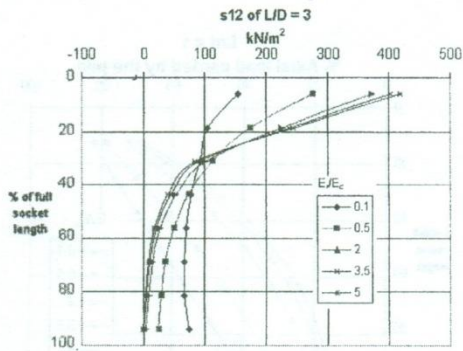**Figure 2(a) :** The finite element mesh with L/D ratio = 4

s12 of L/d = 1
kN/m²
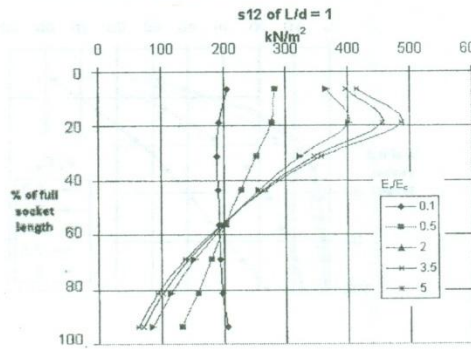
Figure 3(a) - Shear stress distribution along the socket wall for different Er/Ec ratios for the case of L/D =1

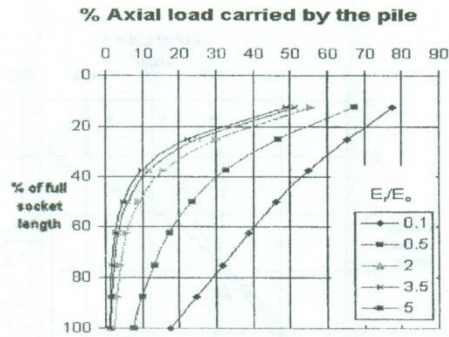**L/d = 1**
% Axial load carried by the pile
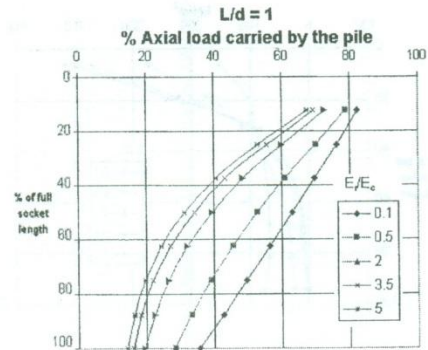
Figure 3(b)-Axial load carried by the pile length as a % of the load applied for different L/D ratios for the case of L/D = 1

s12 of L/d = 2
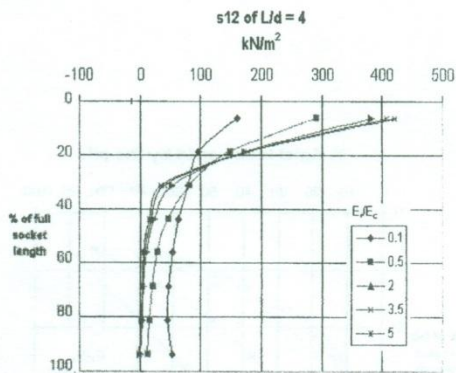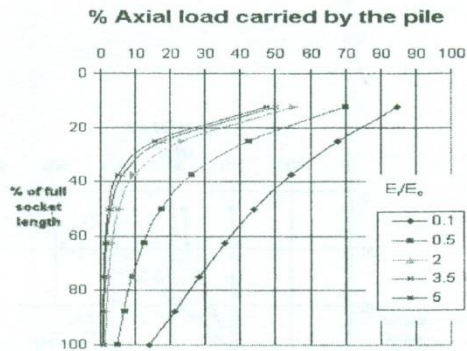kN/m²
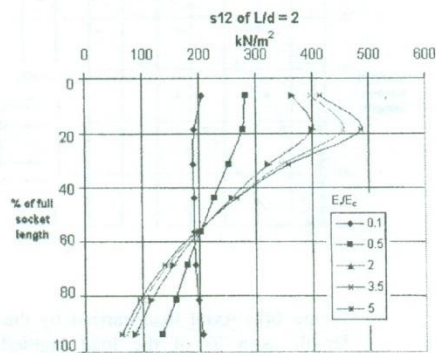
Figure 4(a) - Shear stress distribution along the socket wall for different Er/Ec ratios for the case of L/D =2.

% Axial load carrid by the pile
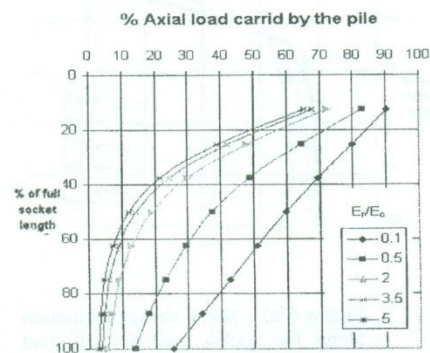
Figure 4(b)-Axial load carried by the pile length as a % of the load applied for different L/D ratios for the case of L/D = 2

s12 of L/D = 3
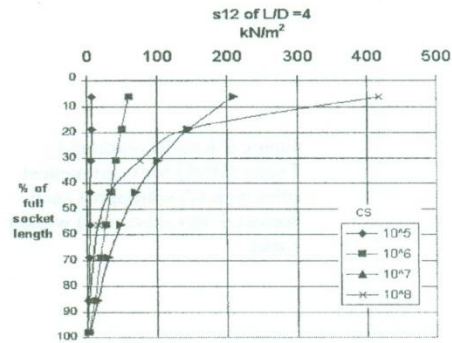**kN/m²**

Figure 5(a) - Shear stress distribution along the socket wall for different Er/Ec ratios for the case of L/D =3.

% Axial load carried by the pile

Figure 5(b)-Axial load carried by the pile length as a % of the load applied for different L/D ratios for the case of L/D =3

s12 of L/d = 4
kN/m²

Figure 6(a) - Shear stress distribution along the socket wall for different Er/Ec ratios for the case of L/D =4.

% Axial load carried by the pile

Figure 6(b)-Axial load carried by the pile length as a % of the load applied for different L/D ratios for the case of L/D =4

Figure 7(a) Using interface element-Shear stress distribution along the socket length for L/D =4, Er/Ec=2 and different Cs values
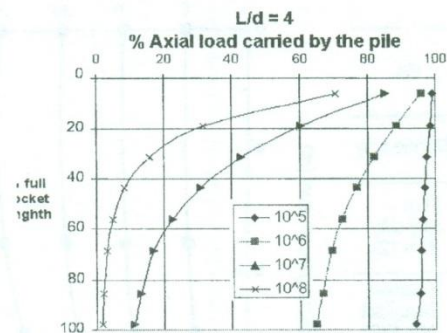
Figure 7(b) Using interface element-Axial load carried by the pile length as a % of the load applied for L/D =4, Er/Ec=2 and different Cs values
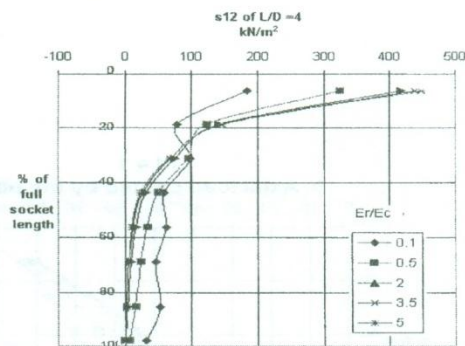

Figure 8(a) – Using interface element –Shear stress distribution along the socket length for Cs=10^8 Kn/m^2/m, L/D=4 and different Er/Ec ratios
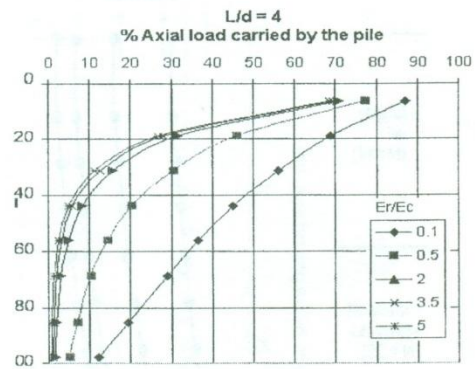
Figure 8(b) – Using interface element –Axial load carried by the pile length for Cs=10^8 Kn/m^2/m, L/D=4 and different Er/Ec ratios
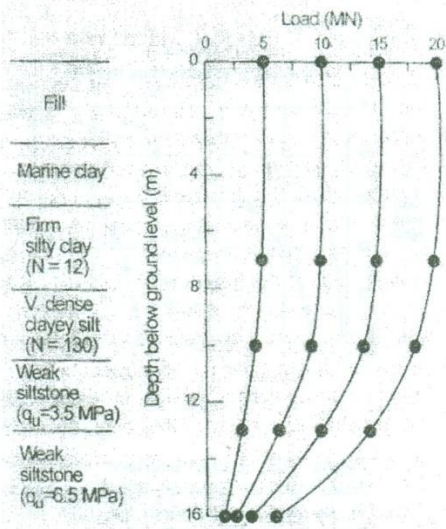
Figure 9-Results reported by Leung (1996) for instrumented piles with L/D=4(approx) and socketed into siltstone (a weaker rock)

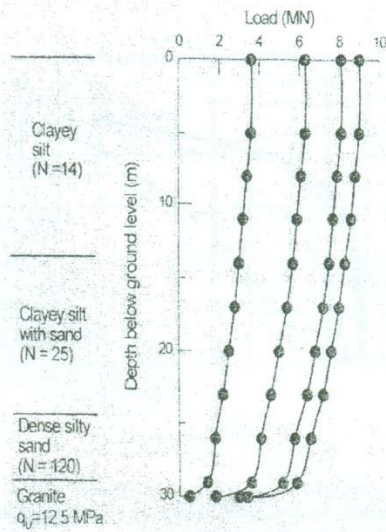
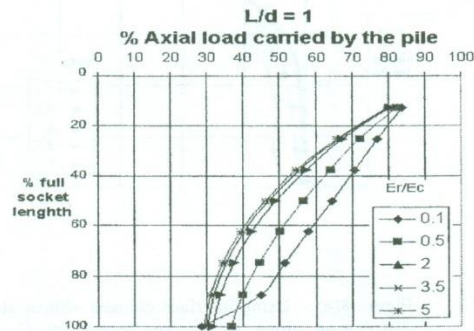Figure 10 – Results reported by Leung (1996) for piles with L/D =1.0 and socketed into granite (a harder rock)

Figure 11 – Results of a FE analysis using the interface element with Cs=10^8 for the same L/D ratio(1)

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