

Borehole Roughness: A Key Parameter in Predicting Rock Socket Side Resistance

B. Collingwood

B.E., Grad IEAust.

Postgraduate Student, Department of Civil Engineering, Monash University, Australia

SUMMARY Predicting the performance of rock socketed bored piles has traditionally been a difficult task. The results given by conventional methods of predicting shaft resistance, based on empirical correlations with intact rock strength, have proven to be poor when used outside the specific data set for which they were developed. Researchers have long recognised that socket roughness is an important parameter. However, attempts to incorporate roughness parameters as an integral part of design have been unsuccessful. Recent advances at Monash University have led to a wholly theoretical design method which incorporates roughness as a key parameter. The Monash method is broadly applicable, but its use requires a prediction of socket roughness to be made. At present, rock socket roughness is poorly understood. A better understanding of socket roughness production across a variety of drilling conditions is crucial for the full potential of this new approach to be realised. Using the Monash method, historical load test data has been re-analysed to evaluate the contribution of socket roughness to pile capacity. The results of the study suggest upper and lower bounds on socket roughness, and confirm that roughness variations are particularly significant in low to medium strength rock. A borehole profiler is being developed which will be used in an imminent field investigation of socket roughness. The aim of this investigation will be to develop socket roughness guidelines for use in design.

1.0 INTRODUCTION

Rock socketed bored piles are a common foundation solution for large concentrated loads. They derive their load bearing capacity from both shaft and base resistance components. Figure 1 shows a typical load settlement response for a rock socketed pile. The base resistance component can contribute significantly to the ultimate capacity of the pile. However, as shown in Figure 1, shaft resistance is typically mobilised at considerably smaller pile settlements than that of the base. Ensuring the reliability of base response requires a construction and inspection technique which leaves the socket free of debris. This may be difficult and costly to achieve, particularly in deep sockets which are often drilled under water or drilling mud. As a consequence of these factors, shaft resistance generally dominates pile performance at working loads. Efforts to improve prediction of rock socketed pile performance are therefore primarily concerned with the complex mechanisms of shaft resistance development. Shaft resistance only is considered in this paper.

The paper outlines the limitations of conventional methods of shaft resistance prediction, and introduces the Monash rational approach which incorporates socket roughness as a key parameter. The wide applicability of this new approach is currently restricted by insufficient information relating to socket roughness characteristics in the field. A method of estimating socket roughness by back-analysis of historical data from rock socket load tests is described. The application of this method to a database of 137 pile load tests has provided insight into typical levels of field socket roughness. Selected results from this study are presented and a future field investigation of socket roughness is outlined.

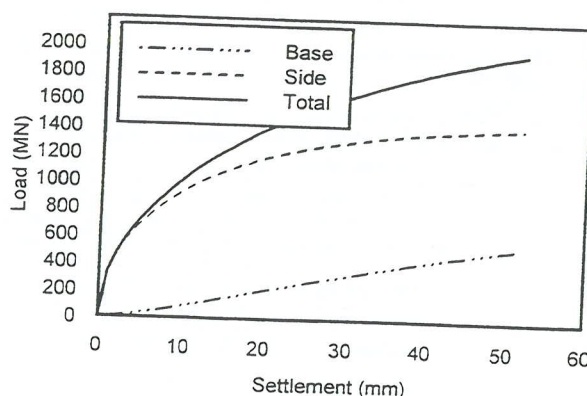


FIGURE 1. Typical load settlement response of a rock socketed pile (Rocket Prediction).

1.1 Conventional design of pile shafts in rock

Detailed discussions of the limitations of traditional methods for predicting rock socket side resistance have been previously published (Seidel and Haberfield, 1994; Seidel et al., 1996). The summary provided in this section draws heavily upon these accounts.

Traditional methods for design of piles socketed into rock have been based on the results of full scale load tests, from which empirical correlations and locally applicable guidelines have been derived (Seidel and Haberfield, 1994). Numerous correlations have been proposed which relate the unit side resistance of the socket to the uniaxial compressive

strength of the surrounding rock. These empirical models generally take the form:

$$f_{su} = \alpha q_u^\beta \quad (1)$$

where f_{su} is the ultimate socket shaft resistance, q_u is the uniaxial compressive strength of the weaker material (in most cases rock), and α and β are empirically determined from load test results.

Many empirical relationships in the form of Equation 1 have been formulated which correlate well with the specific data sets from which they were derived. However, there is no single correlation which can be applied universally to the design of bored piles. O'Neill et al (1995) undertook a comparison of 9 previously proposed empirical correlations based on Equation 1 with an international database of pile load tests in intermediate strength rock. Their database was sufficiently large to include pile sockets of varying geometry, drilled by different methods, at many sites and in a range of rock types. They concluded that none of the methods could be considered an accurate predictor across the range of tests contained in the database. The limitations of the traditional empirical approach are similarly illustrated in the results of two other major database studies (Rowe and Armitage, 1984; Kulhawy and Phoon, 1993).

TABLE 1. Roughness classification (after Pells et al 1980)

Roughness Class	Description
R1	Straight, smooth-sided socket, grooves or indentations less than 1 mm deep.
R2	Grooves of depth 1-4 mm, width greater than 2 mm, at spacing 50 mm to 200 mm.
R3	Grooves of depth 4-10 mm, width greater than 5 mm, at spacing 50 mm to 200 mm.
R4	Grooves or undulations of depth > 10 mm, width > 10 mm at spacing 50 mm to 200 mm.

The empirical correlations proposed by Rowe and Armitage (1984) are shown in Figure 2. They recognised the significance of socket roughness and attempted to incorporate this variable in their study. Correlations were proposed for data obtained from sockets exhibiting roughness levels of R1 to R3 (as defined in Table 1), and for those with roughness R4. Considerable scatter around the proposed correlations is evident.

A similar study was undertaken by Kulhawy and Phoon (1993), who investigated the side resistance of a large number of full-scale load tests in material ranging from firm soil to hard rock. Trend lines were identified for piles in both soil and rock, however, considerable scatter remained. The extent of the scatter is reflected in the correlations they proposed. These were of the general form:

$$\alpha = \Psi (q_u / 2p_a)^{-0.5} \quad (2)$$

with a constant of proportionality to the outcome, Ψ , being 0.5 for piles in soil, but varying between 1.0 and 3.0 with average of 2.0 for piles in rock. Importantly, Kulhawy and Phoon noted that sockets in soil are generally very smooth whereas sockets in rock exhibit larger variations in roughness.

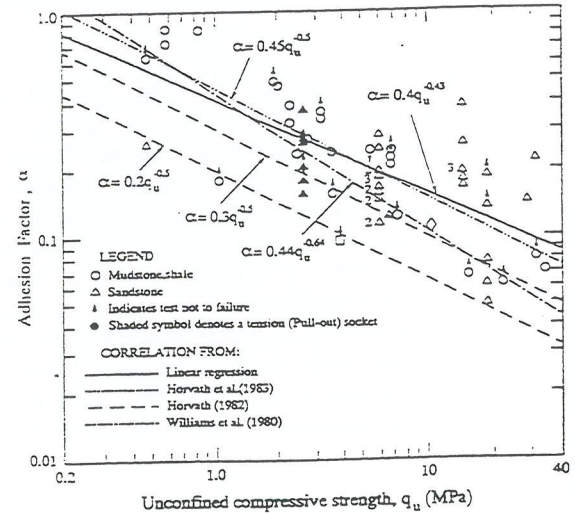


FIGURE 2. Socket resistance correlations for Roughness R1 to R3 (after Rowe & Armitage, 1984)

Seidel et al. (1996) concluded that all three major investigations have shown that the reliability of current available empirical design methods for predicting rock socket shaft resistance is questionable, because they do not address a sufficiently broad range of parameters to account for the many variables which come into play.

1.2 Socket Roughness

The importance of socket roughness on shaft resistance has been recognised by numerous researchers for a considerable time (Horvath et al., 1983; Johnston, 1977; Pells et al. 1980; Williams, 1980).

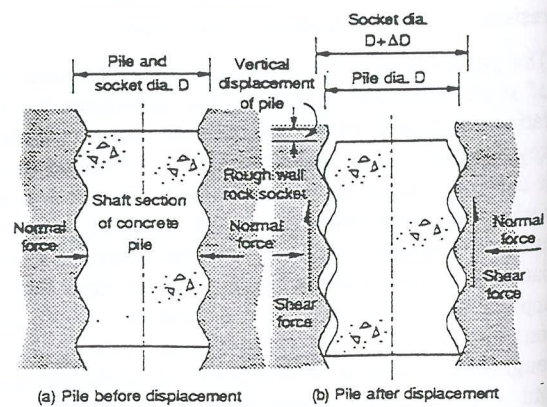


FIGURE 3. Pile rock socket idealisation.

The influence of socket roughness is a consequence of the dilative nature of a rough concrete-rock joint and the constant normal stiffness (CNS) boundary condition which governs interface normal stress. Figure 3 shows a schematic representation of a rock socket in cross-section. The concrete of the pile is initially in contact with the rock socket against which it has been cast (Figure 3(a)). When a load is first applied, elastic deformation of the pile-rock system will occur without any slippage of the pile relative to the rock.

Eventually, a critical load will be reached at which slip commences at the pile-rock interface. As interface is non-planar, this shear displacement must be accompanied by dilation as illustrated in Figure 3 (b). The corresponding radial enlargement of the borehole is resisted by the surrounding rock, resulting in an increase in normal stress at the pile-rock interface. The increase in normal stress will be governed by the radial stiffness of the borehole. This normal stiffness, K , is approximately constant and is given by:

$$K = \frac{E_m}{(1 + \nu_m) \cdot r_s} \quad (3)$$

where E_m is rock mass modulus, ν_m is the Poisson's ratio, and r_s is the pile radius. K is known as the constant normal stiffness (CNS).

The mechanisms of sliding and shearing at the pile rock interface are complex. In general, however, the rougher the interface the greater dilation and corresponding normal stress which will result for any given axial displacement of the pile-rock joint. This increased normal stress increases the frictional resistance between pile and rock.

From Equation 3, the change in normal stress, $\Delta\sigma_n$, for a given interface dilation, Δr_s , is:

$$\Delta\sigma_n = K\Delta r_s = \frac{E_m \Delta r_s}{(1 + \nu_m) r_s} \quad (4)$$

It is evident in Equation 4 that the increase in normal stress is proportional to the ratio of interface dilation to socket radius. Consequently, for a measure of roughness to be useful in comparing the behaviour of various piles, it must be normalised against socket radius or diameter.

Several researchers have proposed empirical correlations for predicting side resistance which incorporate socket roughness (Pells, 1980; Williams, 1980; Horvath, 1983; Rowe and Armitage, 1984). However, perhaps the greatest obstacle in this pursuit has been the absence of a reliable and sufficiently rigorous method of roughness quantification.

The roughness classification system devised by Pells and his co-workers (Table 1) is often used in Australia for specifying minimum roughness requirements for the purposes of visual rock socket inspections. Although useful in this context, the classification system is open to considerable subjective interpretation, which limits its applicability as a quantitative tool. Both Williams (1980)

and Horvath (1983) proposed quantitative methods of evaluating socket roughness, which involved recording and analysing the geometry of measured profiles. However, both roughness models proved to be sometimes ambiguous and open to theoretical criticism (Seidel, 1993, Seidel et al., 1996). Their widespread use has also been hindered by the difficulties associated with measuring roughness profiles in the field.

The lack of a reliable method of roughness quantification and the shortage of measured roughness data have long served as an impediment to the incorporation of socket roughness in routine design.

2.0 RECENT ADVANCES IN UNDERSTANDING ROCK SOCKET BEHAVIOUR

A large fundamental research program into the behaviour of rock-socketed piles has been carried out at Monash University since the early 1980's. This program has been based upon large scale direct shear testing of concrete-rock joints, under CNS conditions. Physically-based analytical models of the observed responses have been formulated, which allow the complex mechanisms of side resistance development to be numerically reproduced (Seidel, 1993). Rather than adopting an empirical approach, Monash researchers have aimed to produce a widely applicable rational design method, based on fundamental rock mechanics principles. Their work has culminated in a development of a computer program named *ROCKET*, which embodies the Monash design approach. The theory behind the *ROCKET* program has been widely published (Seidel, 1993; Seidel and Haberfield, 1994; Seidel and Haberfield, 1995).

It has been shown that pile shaft resistance is a function of the following parameters (Seidel et al., 1996):

- rock strength (drained intact and residual strength parameters are used);
- rock mass modulus (and Poisson's ratio);
- socket roughness;
- socket diameter;
- hydrostatic pressure of concrete at the socket wall; and
- construction practices.

ROCKET accounts for all of the above parameters, with the exception of the last which is currently being investigated. The program predicts the complete shear-displacement ($t-z$) response of a rock socket.

2.1 The Monash Roughness Model

A major obstacle in the pursuit of a more rational method of side resistance prediction was overcome when Seidel (1993) developed the Monash roughness model. Seidel proposed that a two dimensional roughness profile can be characterised by a series of interconnected line segments or chords of a constant length as shown in Figure 4. The slope of each chord can be determined and a frequency distribution of chord angles produced.

As is the case with natural rock joints, rock socket roughness has been found to produce a normal distribution

of chord angles. Using the Monash model, the mean height of the asperities which comprise the profile can be evaluated at any particular chord length. This is known as the *mean roughness height*, $\overline{\Delta r}$.

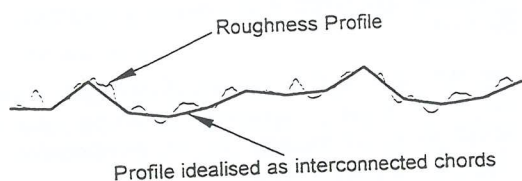


FIGURE 4. Roughness profile idealised as a series of interconnected chords (after Seidel, 1993).

The roughness of a socket profile can be approximated using a range of chord lengths. The shorter the chord length used, the greater the level of detail captured. Small scale roughness will influence socket side resistance at small displacements, while side resistance at large pile settlements is affected by roughness at a larger scale. Mean roughness height can be calculated for any chord length from the standard deviation of chord angles. Ultimate shaft resistance has been shown to be dependent on the maximum mean roughness height which is present in a socket (Seidel et al., 1996)

3.0 THE SOCKET RESISTANCE COEFFICIENT

On the basis of a parametric study using the *ROCKET* program, Seidel et al. (1996) developed a simple method of predicting the peak unit side resistance for a rock socket. They proposed a non-dimensional parameter known as the Shaft Resistance Coefficient, *SRC*.

The *SRC* is computed as follows:

$$SRC = \frac{E_m}{q_u} \cdot \frac{\tan \alpha \cdot l_a}{D_s} = n \cdot \frac{\overline{\Delta r}}{D_s} \quad (5)$$

where n is the modular ratio (E_m/q_u);
 $\overline{\Delta r}$ is the mean roughness height; and
 D_s is the socket diameter.

The *SRC* factor incorporates all parameters that significantly influence socket resistance. Only the Poisson's ratio and the initial hydrostatic concrete stress are not incorporated, however, these parameters have been found to have a secondary influence on shaft resistance (Seidel et al., 1996).

Seidel and his co-workers conducted a parametric study using *ROCKET* to develop a shaft resistance design chart which allows preliminary estimation of shaft resistance over a wide range of rock strengths. Figure 5 shows the *SRC* design chart. They demonstrated that the adhesion factors predicted using the *SRC* design chart, are in good general agreement with international databases of rock socket load tests.

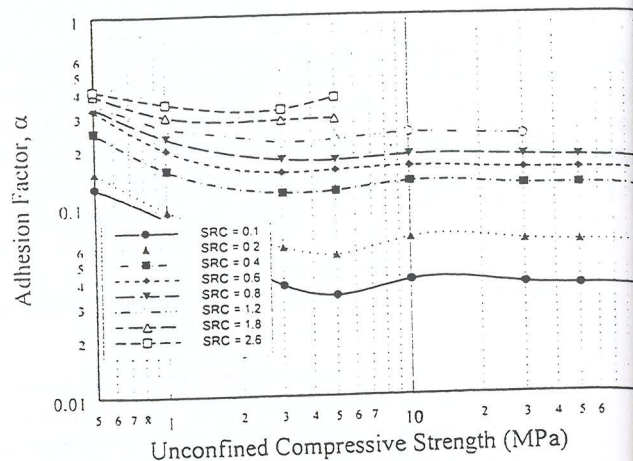


FIGURE 5. Effect of *SRC* on socket adhesion factor (Seidel et al., 1996)

4.0 DEVELOPMENT OF A SOCKET ROUGHNESS DATABASE

Application of the *SRC* method or *ROCKET* in design requires estimation of likely socket roughness height. Despite widespread recognition of its significance, few studies have addressed the production of socket roughness during construction. Although a great many rock socket load test results have been published, few accounts include sufficient information relating to borehole roughness to allow meaningful interpretation of their results.

The *SRC* provides a simple means of re-analysing load test results in consideration of all major parameters. When parameters E , q_u , D , and α are reported or can be reasonably estimated, the mean roughness height, $\overline{\Delta r}$, can be evaluated.

Using the *SRC* Design Chart shown in Figure 5, from the value observed in a load test and a representative value of uniaxial compressive strength, q_u , the *SRC* which is apparent for the socket can be evaluated. From Equation (5) the effective roughness height can then be calculated as:

$$\overline{\Delta r}_e = \frac{SRC \times D_s}{n} \quad (6)$$

This allows a quantitative assessment of the contribution of socket wall conditions to be made from existing load test results, for which socket roughness observations were recorded.

It is necessary to make the distinction between measured socket roughness, and back-calculated values that reflect other factors, such as socket cleanliness, which influence pile response. Consequently, the term *effective roughness height*, $\overline{\Delta r}_e$, is introduced for back-calculated values of $\overline{\Delta r}$.

As part of research into the effect of construction practices on the capacity of rock socketed piles at Monash University a load test database has been compiled. Unlike other databases previously published such as Rowe and Armstrong (1984) and Kulhawy and Phoon (1993) which are primarily

concerned with side resistance as a function of rock strength, the Monash study aims to consider the full range of parameters which influence shaft resistance. Consequently, the database contains all available details of rock properties, construction techniques, socket roughness and cleanliness, and load test results.

The database currently contains 137 records of load tests carried out worldwide, many of which were addressed in previous empirically based studies. Piles constructed in a variety of rock types are represented, including shale, mudstone, sandstone, chalk, limestone, and schist. The database includes sockets constructed under bentonite, as well as artificially roughened sockets. However, only the results from 93 load tests on unroughened sockets drilled without the aid of a slurry are presented herein. These will be referred to as *conventional* sockets.

The development of the SRC design method has allowed the re-analysis of these load tests, in consideration of all relevant parameters. Using the method detailed in this section, the effective roughness height apparent in each load test was able to be back-calculated, and a database of effective socket roughness has been compiled.

4.1 Back-calculated Effective Socket Roughness

Figure 6 shows normalised effective roughness heights back-calculated from the 93 load tests on conventional rock socketed piles. Data points shown as triangles represent load tests in which failure was not achieved. The effective roughness height active in these sockets is therefore greater than or equal to the value plotted.

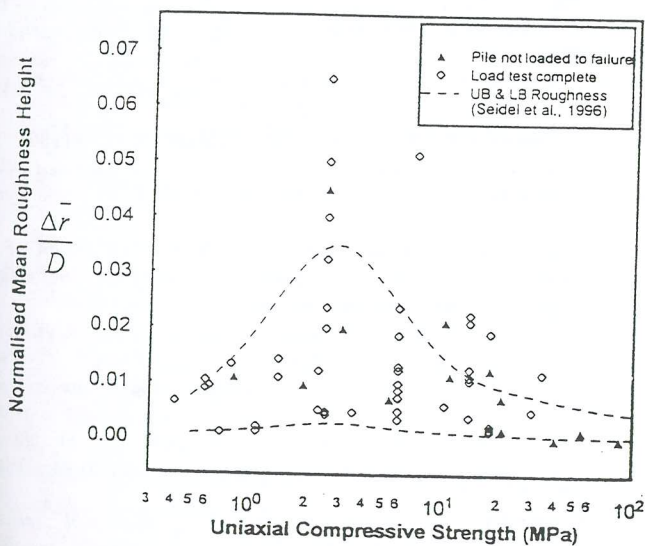


FIGURE 6. Back-calculated effective roughness height versus rock strength

The data shown in Figure 6, supports the observations of Kulhawy and Phoon (1993), and roughness recommendations made by Pells et al. (1980) and Kodikara et al. (1992), that sockets in low strength and high strength materials generally exhibit low roughness, while in intermediate strength rock roughness varies widely. Based

on such observations, Seidel et al. (1996) proposed upper and lower socket roughness bounds prior to this study. These are also shown in Figure 6. The proposed bounds have been normalised against the range of socket diameters used in the study, and are in reasonably good agreement with the back-calculated data.

A number of data points in Figure 6 indicate extremely high levels of normalised roughness (ie. normalised roughness greater than 0.04). Examination of the source of these points shows that they are attributable to sockets which were constructed using manual excavation techniques or in extremely jointed rock (Webb and Davies, 1980; Williams and Ervin, 1981). Both these factors would be expected to produce extremely rough sockets. These outliers therefore support the validity of the method of analysis used.

The size of the database is not currently sufficient to properly assess the influence of factors such excavation technique and rock fabric on roughness production. This may be possible once additional historical data is incorporated. However, the records of many load tests do not include enough information concerning construction methods and geology to allow meaningful interpretation.

4.2 Comparison with Measured Roughness Data

Figure 7 shows measured roughness from a number of sockets varying from 300 to 1500 mm in diameter, along with the proposed roughness bounds of Seidel et al. (1996).

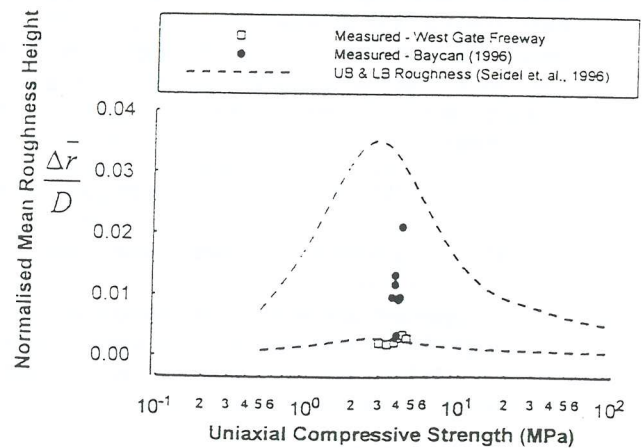


FIGURE 7. Measured socket roughness.

The measured data is limited to argillaceous rock of 3 to 5 MPa uniaxial compressive strength. However, this is within the range of rock strengths at which roughness has been observed to be most variable. The spread of the measured data is similar to that apparent in the back-calculated data of Figure 6, providing further support for the validity of back-analysis using the SRC method and Seidel's proposed roughness bounds.

4.3 Discussion

The level of roughness variation shown in Figures 6 & 7 is significant in terms of its influence on available side resistance across the entire rock strength range, but this particularly so between 2 MPa and 12 MPa uniaxial compressive strength. The implication of this finding is underlined when it is considered that the majority of sockets are installed in rock of low to medium strength, due to its drillability and generally good load bearing capacity (O'Neill et al. 1995). This may be particularly true in the U.S.A., where a strong market for bored piles exists (Ibid). Therefore, the benefits of understanding socket roughness production are significant, and justify considerable research effort.

The upper and lower bound roughness guidelines proposed by Seidel et al. (1996) are currently used with *ROCKET* in commercial practice, to evaluate the likely range of side resistance response. For piles in formations where sufficient roughness data has been collected, for example Melbourne mudstone, reliable *ROCKET* predictions can be made. However, there remains considerable scope for improved socket roughness guidelines covering a range of geological conditions and construction techniques.

5.0 FIELD INVESTIGATION OF SOCKET ROUGHNESS

Monash researchers have developed a socket profiler to remotely measure the roughness of rock socket sidewalls in the field. Known as the *Socket-Pro*, the device is capable of accurately profiling sockets in the dry or under water and drilling mud. It is operable in sockets of 600 to 1800 mm diameter, and to depths of up to 60 metres. The *Socket-Pro* incorporates a fully automated down-hole profiler, which is serviced from trailer mounted winching, control and data acquisition equipment at the surface. During measurement, roughness data is relayed in real time to logging equipment at the surface.

The *Socket-Pro* will be deployed on construction projects to take direct measurements of field socket roughness. Geological conditions and relevant construction practices such as drilling technique will be recorded, and correlated with the measured roughness. The results will be used to develop roughness guidelines for use in design. The *Socket-Pro* can also be used to verify design assumptions after construction commences.

6.0 CONCLUSIONS

In order to significantly reduce the need for conservatism in rock socket design, a design approach must be adopted which takes all influential parameters into account. *ROCKET* incorporates such an approach, but its ability to enhance predictions is limited by the quality of input parameters.

To maximise the potential of *ROCKET* as a design tool, a sound understanding of socket roughness is required. If design certainty is to be significantly improved, designers must be able to reasonably predict roughness from a

knowledge of site geology and construction method. present, insufficient roughness data is available to provide more than approximate guidance.

The *SRC* design method provides a simple means of calculating effective socket roughness from pile load results. This has allowed more meaningful interpretation of historical data. The back-calculated roughness presented in this paper has quantitatively confirmed previous observations of socket roughness, and highlighted the need for better understanding.

Socket roughness has been shown to be particularly variable in low to medium strength rock. As a large proportion of rock sockets are installed in formations falling into this category, the benefits of understanding socket roughness are expected to be significant and wide reaching.

Monash researchers will shortly commence a field investigation using the *Socket-Pro*, aimed at compiling a comprehensive socket roughness database. The results of the study are expected to make a significant contribution to enhancing rock socketed pile efficiency.

7.0 REFERENCES

- Horvath, R.G., Kenney, T.C. and Kozicki, P. (1983). *Method for Improving the Performance of Drilled Piers in Weak Rock*. Can. Geot. Jnl. Vol. 20, 1983 : 758-772.
- Johnston I.W. (1977). *Rock-socketing down-under*. Cont. Journ. 279 : 50-53.
- Kodikara J.K., Johnston I.W. and Haberfield C.M. (1992). Analytical predictions for side resistance of piles in rock. Proceeding 6th ANZ Conf. on Geomechanics, 1992.
- Kulhawy F.H. and Phoon K.K. (1993). *Drilled shaft side resistance in clay soil to rock*. Proc. Conf. on design and performance of deep foundations: piles and piers in soil and rock. Geotechnical special publication No. 38, ASCE: 172 - 183.
- O'Neill M.W., Townsend F.C., Hassan K.M., Buller A. and Collins P.S. (1995). *Load transfer for drilled shafts in Intermediate Strength Rocks*. U.S. Department of Transportation, FHWA-RD-95-XXX Draft report, January, 1995.
- Pells P.J.N., Rowe R.K. and Turner R.M. (1980). *Experimental investigation into side shear for socketed piles in sandstone*. Proc. Int. Conf. on Struct. Foundations on Rock, Sydney, 1980.
- Rowe R.K. and Armitage H.H. (1984). *The design of piles socketed into weak rock*. Report GEOT-11-84, University of Western Ontario, London, Canada.
- Seidel J.P. (1993). *The analysis and design of pile shafts in weak rock*. PhD Dissertation. Dept. of Civil Engg., Monash University.
- Seidel J.P. and Haberfield C.M. (1994). *A new approach to prediction of drilled pier performance in rock*. Proceedings of U.S. FHWA "International Conference on Design and Construction of Deep Foundations", December 1994, Orlando, Florida.
- Seidel J.P. and Haberfield C.M. (1995). *The axial capacity of pile sockets in rocks and hard soils*. Ground Engineering, Melbourne, 1995.
- Seidel J.P., Gu, X.F.; Haberfield C.M. (1996). *A new factor for the improved prediction of the resistance of pile shafts in rock*. ANZ Conference on Geomechanics. Adelaide, July, 1996.
- Williams A.F. (1980). *The design and performance of piles socketed into weak rock*. PhD Dissertation. Dept. of Civil Engg., Monash University.