Axial load transfer behavior of rock-socketed shafts

Lianyang Zhang, M.ASCE, P.E.[*], and Jinming Xu[**]

[*] Assistant Professor, Dept. of Civil Engineering and Engineering Mechanics, University of Arizona, Tucson, AZ, USA

[**] Associate Professor, Dept. of Civil Engineering, Shanghai University, Shanghai, China

ABSTRACT

In the design of rock-socketed shafts for supporting axial loading, the end bearing resistance is often ignored, resulting in excessive rock-socket lengths and increased cost. This paper investigates the axial load transfer behavior of rock-socketed shafts based on a database of 99 field test rock-socketed shafts. The shafts are 1.4 to 96.3 m long and have a diameter between 0.5 and 1.5 m. The rock-socket lengths are from 0 to 18.8 meters. The database is developed by collecting information on field test rock-socketed shafts from published papers and reports. The results show that it is important to account for the end bearing resistance in the design of rock-socketed shafts because (1) up to 25% of the shaft head load on average can be transmitted to and supported by the shaft base even at relatively small shaft head displacement in the working range of 5–15 mm, and (2) the portion of the shaft head load transmitted to and supported by the shaft base increases with time due to the effect of creep.

INTRODUCTION

Rock-socketed shafts are widely used as foundations of different structures to support large axial loads, including highway bridges and high-rise buildings. For design engineers, a great challenge is the determination of rock-socket length for drilled shafts under axial loading (Zhang 2004; Turner 2006). In current design practice, engineers often neglect the base resistance in their design assuming that the base resistance will not develop without large downward displacement (Crapps and Schmertmann 2002; Turner 2006). The draft Interim 2006 AASHTO *LRFD Bridge Design Specifications* (AASHTO 2006) state that "Design based on side-wall shear alone should be considered for cases in which the drilled hole cannot be cleaned and inspected or where it is determined that large movements of the shaft would be required to mobilize resistance in end bearing." According to Crapps and Schmertmann (2002), the most common reasons cited by designers for neglecting base resistance include settled slurry suspension, reluctance to inspect bottom, concern for underlying cavities, and unknown or uncertain base resistance.

Obviously, neglecting the base resistance in design will result in larger rock-socket lengths. Due to the high cost of shaft construction in rock, an over-design will lead to a great waste of money. For example, according to a North Carolina Department of Transportation construction estimate, the cost of shaft construction in rock is on the order of $1,500 per meter length for a shaft of 1.5 m in diameter; $1.5

million would be wasted for every 1,000 shafts if the socket length were unnecessarily over-designed by 1 m (Cho et al. 2001). Crapps and Schmertmann (2002) suggest that accounting for base resistance in design and using appropriate construction and inspection techniques to ensure quality base conditions is a better approach than neglecting base resistance.

In this paper, the axial load transfer behavior of rock-socketed shafts is investigated based on a database of 99 field test rock-socketed shafts. The database is developed by collecting information on field test rock-socketed shafts from published papers and reports. Using the database, the effect of the shaft length in soil, the rock-socket length, the shaft head displacement and the loading time on the load transfer behavior is investigated. The results show that it is important to consider the end bearing resistance in the design because (1) a large percentage of the shaft head load can be transmitted to and supported by the shaft base even at shaft head displacement that is much smaller than the tolerable displacement of the super structure, and (2) the portion of the shaft head load transmitted to and supported by the shaft base increases with time.

DATABASE OF FIELD TEST ROCK-SOCKETED SHAFTS

The database consists of 99 field test rock-socketed shafts collected from published papers and reports. Information for each test rock-socketed shaft is collected as comprehensively as possible. The parameters considered are defined in Fig. 1. The total shaft lengths (L) range from 1.4 to 96.3 m, the shaft lengths in soil (L_s) from 0.0 to 94.8 m, the socket lengths (L_r) from 0.0 to 18.8 m, and the shaft diameters (B) from 0.5 to 1.5 m, resulting in ratios of L/B from 1.9 to 96.3, L_s/B from 0.0 to 94.8, and L_r/B from 0.0 to 17.7.

In addition to shaft dimensions, the information on the maximum test load Q_t, the shaft head and base displacements s_t and s_b at Q_t, and the total and base resistance of the rock-socket, Q_{rb} and Q_b, corresponding to Q_t is also collected. The total resistance of the rock-socket Q_{rb} is simply the sum of the side shear resistance Q_r and the base resistance Q_b (see Fig. 1). It need be noted that Q_t recorded is the maximum test load which may be much smaller than the ultimate load capacity for some of the test rock-socketed shafts. Four shafts (#96, 97, 98 and 99) were not conventional test shafts but were instrumented construction shafts to measure the time effect on load transfer.

AXIAL LOAD TRANSFER BEHAVIOR OF ROCK-SOCKETED SHAFTS

Based on the developed database, the axial load transfer behavior of rock-socketed shafts is analyzed in the following.

Q_{rb}/Q_t versus L_s/B

Fig. 2 shows the variation of Q_{rb}/Q_t with L_s/B based on the test data in Table 1. As expected, as the shaft length in soil (L_s) increases, the percentage of the total load supported by the rock-socket Q_{rb}/Q_t decreases. It is noted that even when the overburden soil is thick, say $L_s/B > 30$, it is still possible to have more than 40% of the total load transmitted to and supported by the rock-socket, meaning that rock-sockets are still useful even if the overburden soil is thick.

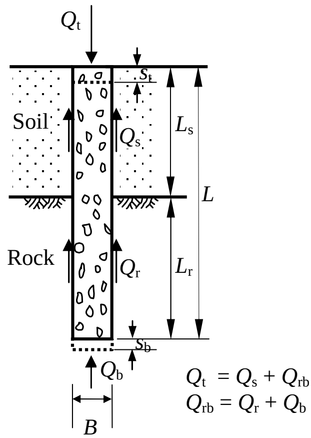

FIG. 1. Parameters considered for a test rock-socketed shaft.

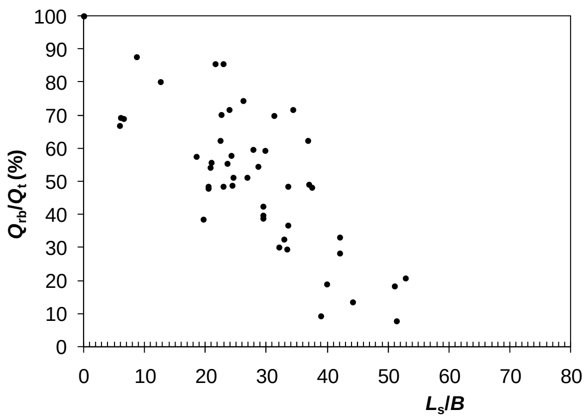

FIG. 2. Variation of Q_{rb}/Q_t with L_s/B.

Q_b/Q_{rb} versus L_r/B

Fig. 3 shows the variation of Q_b/Q_{rb} with L_r/B. As the rock-socket length (L_r) increases, the percentage of the total rock-socket load transmitted to and supported by the socket base Q_b/Q_{rb} decreases. Also shown in the figure are the Q_b/Q_{rb} versus L_r/B curves based on the finite-element elastic analysis by Rowe and Armitage (1987). It can be seen that the elastic results lie in the lower part of the zone defined by the test data and the Q_b/Q_{rb} versus L_r/B curve corresponding to $E_p/E_r = 1$, and $E_b/E_r = 0.5$ can be considered the lower bound of the test Q_b/Q_{rb} versus L_r/B data points, where E_p, E_r and E_b are the elastic modulus, respectively, of the socket, the rock surrounding the socket and the rock below the socket. $E_b/E_r = 0.5$ can be considered for the case that the soft debris is left at the shaft base. This is as expected because, as described in the previous section, the test data correspond to the maximum test load Q_t and at Q_t some yielding of the socket-rock interface should have taken place for most of the test shafts. As the yielding of the socket-rock interface occurs, a higher percentage of the socket head load will be transmitted to and supported by the socket base.

When the socket-rock interface completely yields, the increased socket head load will be fully supported by the socket base and the corresponding Q_b/Q_{rb} will increase with Q_{rb} until the end bearing capacity is reached. The maximum Q_b/Q_{rb} will be reached when both the ultimate side shear resistance τ_{max} and the end bearing resistance q_{max} are reached. Using the expressions of Kulhawy and Phoon (1993) for τ_{max}:

Lower bound (LB): $$\tau_{max} = 0.225\sigma_c^{0.5} \quad \text{(MPa)} \tag{1a}$$

Upper bound (UB): $$\tau_{max} = 0.675\sigma_c^{0.5} \quad \text{(MPa)} \tag{1b}$$

and the expressions of Zhang and Einstein (1998) for q_{max}:

Lower bound (LB): $$q_{max} = 3.0\sigma_c^{0.5} \quad \text{(MPa)} \tag{2a}$$

Upper bound (UB): $$q_{max} = 6.6\sigma_c^{0.5} \quad \text{(MPa)} \tag{2b}$$

the upper bound Q_b/Q_{rb} curve can be obtained by

$$(Q_b / Q_{rb})_{UB} = \frac{(q_{max})_{UB}(0.25\pi B^2)}{(q_{max})_{UB}(0.25\pi B^2) + (\tau_{max})_{LB}(\pi L_r B)} = \frac{1.65}{1.65 + 0.225(L_r / B)} \tag{3}$$

where σ_c is the unconfined compressive strength of the intact rock, in MPa.

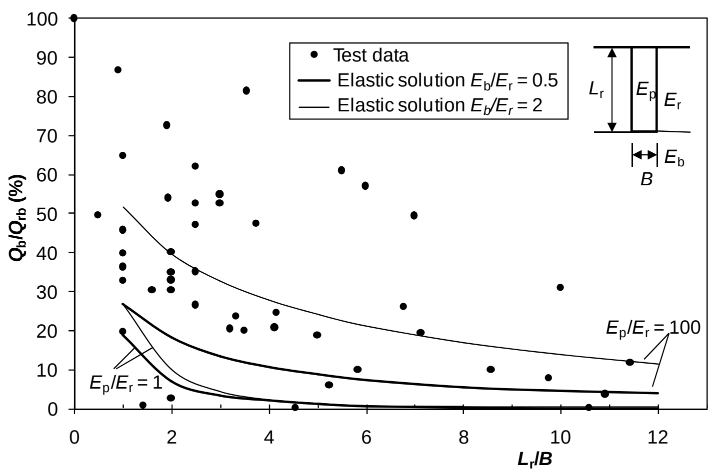

FIG. 3. Variation of Q_b/Q_{rb} with L_r/B – test data and elastic solutions of Rowe and Armitage (1987).

Fig. 4 shows the upper bound Q_b/Q_{rb} curve based on equation (3) and the lower bound Q_b/Q_{rb} curve based on the elastic solution of Rowe and Armitage (1987) at $E_p/E_r = 1$ and $E_b/E_r = 0.5$. It can be seen that most of the test data points are within the band formed by these two bounding curves.

Q_b/Q_{rb} versus s_t

Fig. 5 shows the variation of Q_b/Q_{rb} with the shaft head displacement s_t. Although the test data are widely scattered, the general trend clearly shows that Q_b/Q_{rb} increases with larger s_t. Even at relatively small shaft head displacement, say, in the typical working range of 5–15 mm (Crapps and Schmertmann 2002), a large portion of the total rock-socket load (about 30% on average) is transmitted to and supported by the socket base.

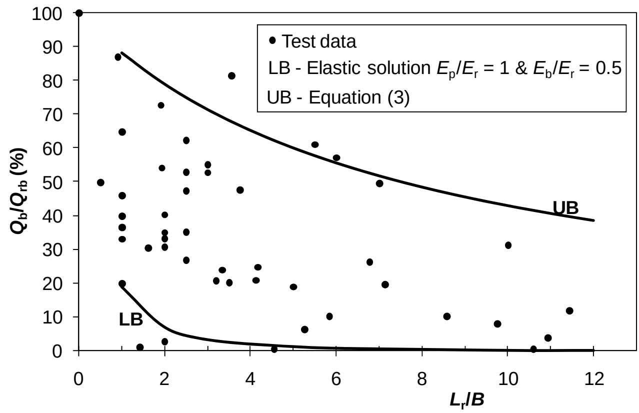

FIG. 4. Variation of Q_b/Q_{rb} with L_r/B – test data and lower and upper bounding curves.

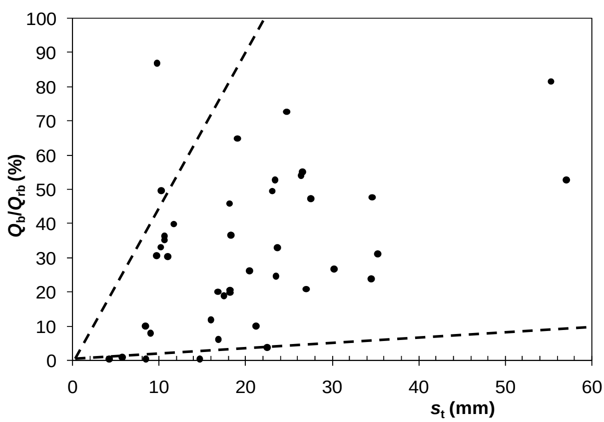

FIG. 5. Variation of Q_b/Q_{rb} with shaft head displacement s_t.

Q_b/Q_t versus s_t

Fig. 6 shows the variation of Q_b/Q_t with the shaft head displacement s_t. The general trend clearly shows that Q_b/Q_t increases with larger s_t. At shaft head displacement in the working range of 5–15 mm, about 25% on average of the total shaft load is transmitted to and supported by the rock-socket base.

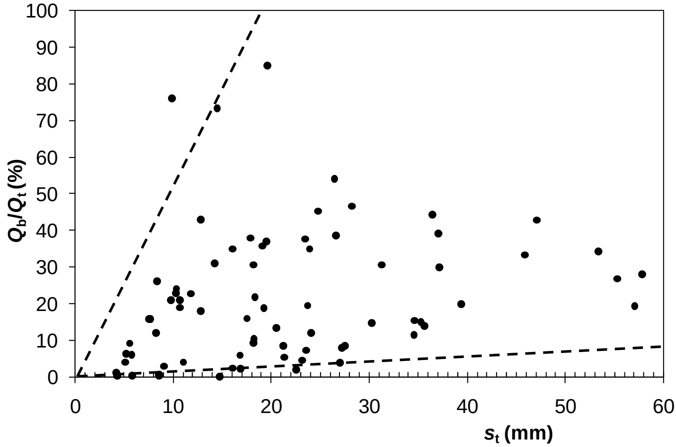

FIG. 6. Variation of Q_b/Q_t with shaft head displacement s_t.

TIME EFFECT ON AXIAL LOAD TRANSFER OF ROCK-SOCKETED SHAFTS

Time effect on axial load transfer of rock-socketed shafts has been studied by several investigators. Tang (1995) used four instrumented in-service rock-socketed shafts in karstic limestone to monitor the relative contribution of side shear resistance and end bearing resistance and their variation throughout the construction and service life of the structure. Fig. 7 shows the variation of Q_{rb}/Q_t with time after the completion of the concrete frame construction for three of them (the fourth shaft was not monitored because its instruments were seriously damaged). The percentage of the total load transmitted to and supported by the rock-socket increased significantly with time, from 92% to 100%, 45% to 80% and 52% to 80% in 300 days, respectively, for shafts 96, 97 and 98.

Not only is the load supported by the side shear resistance in the overlying soil transmitted to the rock-socket, the load supported by the side shear resistance of the rock-socket is also transmitted to the socket base. Ladanyi (1977) reported a case in which the end bearing pressure of an instrumented rock socket increased over a period of four years; although the total applied shaft head load remained essentially constant (see Fig. 8).

Horvath and Chae (1989) conducted long-term tests on model rock-socketed shafts and found that the average increase in base load with time (200 days) was about 10% of the applied loading.

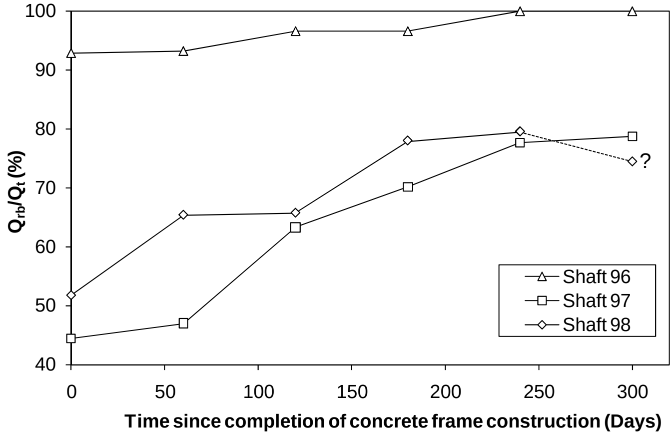

FIG. 7. Increase of rock-socket resistance with time (data from Tang 1995).

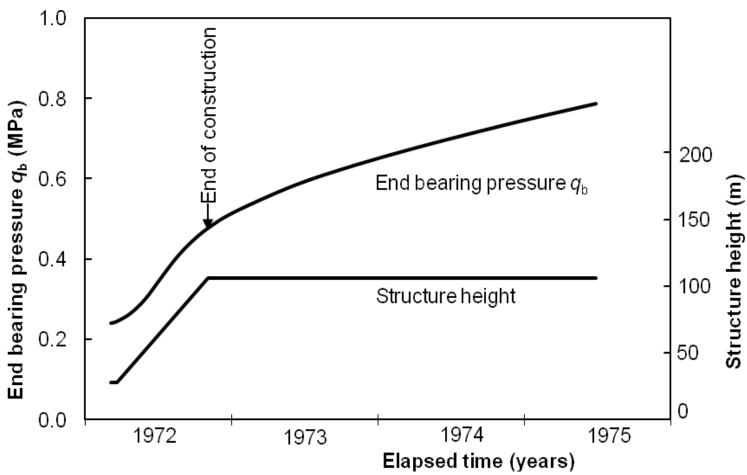

FIG. 8. End bearing resistance increase with time (data from Ladanyi 1977).

SUMMARY AND CONCLUSIONS

This paper has investigated the axial load transfer behavior of rock-socketed shafts using a newly developed database consisting of 99 field tests. The contents and conclusions can be summarized as follows:

1. The portion of the total shaft head load transmitted to and supported by the rock-socket decreases as the shaft length in the soil increases. Even when the overburden soil is thick (say $L_s/B > 30$), however, it is still possible to have more

than 40% of the shaft head load transmitted to and supported by the rock-socket, meaning that rock-sockets are still useful even if the overburden soil is thick.

2. The percentage of the rock-socket load transmitted to and supported by the rock-socket base decreases as the socket length increases. The possible percentage value is within the range between the upper bound Q_b/Q_{rb} curve based on equation (3) and the lower bound Q_b/Q_{rb} curve based on the elastic solution at $E_p/E_r = 1$ and $E_b/E_r = 0.5$.

3. It is important to consider the end bearing resistance when designing rock-socketed shafts because (1) even at shaft head displacement in the working range of 5–15 mm, a large portion of the total shaft head load is transmitted to and supported by the rock-socket base, and (2) the percentage of the total shaft head load transmitted to and supported by the rock-socket base increases with time.

REFERENCES

AASHTO (2006). *Interim Standard Specifications for Highway Bridges*. American Association of State Highway and Transportation Officials, Washington DC.

Cho, K.H., Clark, S.C., Keaney, B.D., Gabr, M.A., and Borden, R.H. (2001). "Laterally loaded drilled shafts embedded in soft rock." *Transportation Research Record* 1772: 3-11.

Crapps, D.K., and Schmertmann, J.H. (2002). "Compression top load reaching shaft bottom – Theory versus tests." *Proc. of International Deep Foundations Congress*, Vol. 2, Orlando, Fla.: 1533-1549.

Horvath, R.G., and Chae, K.-J. (1989). "Long-term settlement of model rock-socketed piers." *Can. Geotech. J.* 26: 348-358.

Kulhawy, F.H., and Phoon, K.K. (1993). "Drilled shaft side resistance in clay soil to rock." *Proc. of Conference on Design and Performance of Deep Found: Piles and Piers in Soil and Soft Rock*. Geotechnical Special Publication No. 38: 172-183.

Ladanyi, B. (1995). "Friction and end bearing tests on bedrock for high capacity socket design: Discussion." *Can. Geotech. J.* 14: 153-155.

Rowe, R.K., and Armitage, H.H. (1987). "Theoretical solutions for the axial deformation of drilled shafts in rock." *Can. Geotech. J.* 24: 114-125.

Tang, Q. (1995). Load transfer mechanisms of drilled shaft foundations in karstic limestone – Behavior under working load. PhD Dissertation, The University of Tennessee, Knoxville.

Turner, J. (2006). *Rock-socketed shafts for highway structure foundations*. A Synthesis of Highway Practice, NCHRP Synthesis 360.

Zhang, L. (2004). *Drilled shafts in rock – Analysis and design*. A. A. Balkema, London, UK.

Zhang, L., and Einstein, H.H. (1998). "End bearing capacity of drilled shafts in rock." *J. Geotech. and Geoenvir. Engrg*. 124(7): 574-584.