Optimization of Drilled Shaft Design using High Strain Dynamic Monitoring

E.A. Sellountou, PhD, PE[1], P. Hagerty Duffy, PE, D.GE[2], T.P. Holman, PhD, PE[3]

1. Pile Dynamics Inc., 30725 Aurora Rd., Cleveland, OH 44139, PH (216) 831-6131, FAX (216)-831-0916, e-mail: asellountou@pile.com
2. International Association of Foundation Drilling, 8445 Freeport Parkway, Suite 325, Irving, TX 75063, PH (502) 553-3211, FAX (469) 359-6007, e-mail: phagerty@adsc-iafd.com
3. Geosyntec Consultants Inc., 1420 Kensington Road, Oak Brook, IL 60523, PH (630) 203-3340, FAX (630)203-3341, e-mail: tholman@geosyntec.com

ABSTRACT

High capacity of rock-socketed or end bearing drilled shafts is often not fully exploited due to the highly conservative design that many local codes and local practices around United States dictate. This reduces the cost efficiency of drilled shafts versus other foundation solutions. ADSC is interested in developing a test program procedure that will be economically feasible for engineers and foundation contractors to perform in every project even when load tests are not specified. Static load tests (including conventional top-down and bi-directional load tests) are invaluable but often prohibitive due to high cost and time constraints. Alternatively, high strain dynamic testing of drilled shafts has increased significantly in recent years with well-established testing procedures and analyses. More specifically, ADSC is considering using dynamic load testing to prove the high capacities of drilled shafts in several rock formations around the country and establish limits of extrapolation to larger diameter shafts from tests on smaller diameter shafts.

The purpose of this paper is to present the theoretical basis of ADSC's technical endeavor. More specifically the paper will focus into 2 different topics; i) parameters affecting drilled shaft performance and ii) the theory and principals of dynamic testing as applied to rock socketed drilled shafts, as well as, case studies of dynamic tests in rock socketed drilled shafts.

INTRODUCTION

The use of drilled shafts as high capacity single deep foundation elements is well-established in both private and public sectors. Within the private sector, comprising commercial real estate, heavy industry, and utility projects among others, drilled shafts are frequently designed and constructed using very conservative, locally accepted practices that have developed over time and represent values attributed to safe performance, although the actual factor of safety may be rather high and the foundation, therefore, overdesigned. With the increased loading demands on structures, the conservative nature of local practices has impacted the cost-effectiveness of drilled shaft foundations. The elasto-plastic effects of diameter on settlement and load distribution of drilled shafts are well understood based on work by Pells and Turner (1979) and Carter and Kulhawy (1988), but these proven methods of static analysis are largely absent from local practices which may be one cause of overly conservative design.

Osterberg (2000), reports several cases where actual capacity of rock sockets were proven to be much greater than assumed in design. For example, a drilled shaft socketed into hard limestone in Kentucky had an actual capacity (as measured by an O-cell test) that was 18 times the design load in compression. In the same paper the author stresses the need for a more economical design, suggesting that load testing should be performed ahead of production shaft installation to guide design rather than merely confirming that the design is safe. Data from Crapps and Schmertmann (2002) from a relatively large number of static tests suggests that base resistance mobilization represents a significant contribution to the overall shaft resistance at downward displacements that correspond to typical serviceability requirements and that end-bearing is generally greater than predicted by numerical calculations using an elastic soil or rock model. Similar cases of overdesign of drilled shafts have been reported by other practitioners. However and although static load testing (conventional top-down i.e. ASTM D1143, or bi-directional loading tests), can be utilized to prove the potentially high end bearing, these tests are often prohibitively expensive for moderately sized projects and adversely impact construction schedules. On the other hand, application of high strain dynamic testing (i.e. ASTM D4945) has increased significantly in recent years and the testing procedures and analyses are well-established in the industry (Rausche et al, 2006; Hussein and Likins, 1995; Sellountou and Rausche, 2013). High-strain testing of drilled shafts is quick and inexpensive compared to other modes of testing, and allows evaluation of the maximum mobilized end-bearing in intermediate to hard rock masses or ultimate end-bearing in soft rock masses by the incorporation of the CAPWAP signal post-processing procedure. Moreover, CAPWAP provides an estimate of side resistance and end-bearing distributions and a simulated load-settlement curve without the requirement for instrumentation along the length of the test shaft.

This paper offers some theoretical background on parameters affecting rock socket response and presents the background of high strain dynamic testing as applied in drilled shafts along with some examples demonstrating applicability of dynamic testing in rock sockets.

ADSC'S SMALL DIAMETER LOAD TEST PROGRAM

The Drilled Shaft Committee of the International Association of Foundation Drilling (ADSC) is evaluating use of dynamic load testing to demonstrate the high capacities of drilled shafts in several rock formations around the country and to attempt to establish limits of extrapolation to larger diameter shafts from tests on smaller diameter shafts. More specifically, the ADSC is considering using dynamic testing in order to

i) prove the high capacities of drilled shafts to be expected in several rock formations around the country,

ii) develop a routine and inexpensive testing procedure that can be successfully implemented at contractors' discretion on every project, and

iii) attempt to develop relationships between unit end bearing resistances of smaller and larger-diameter shafts in certain rock formation that will set a basis of extrapolation when test loading of larger-diameter shafts appears cost prohibitive. Additional static top-loaded and/or bi-directional loading tests may be utilized for enhancing the extrapolation task. Existing data from prior full scale load tests will be compiled and utilized where available.

In a first phase ADSC's load test program will focus on the construction of end-bearing drilled shafts that will be installed in a well-characterized rock formation and will be dynamically tested in order to predict the unit base resistance. Shaft diameters under consideration are 0.61 m to 1.52 m. The authors believe that a 0.61-m diameter shaft may be too small for extrapolations, but this will be evaluated during the research program. Mobilization of ultimate resistances will depend on rock formations, length of rock socket and ram weight. A 712 kN (80 ton) ram will be used for the dynamic load tests. CAPWAP analysis will be utilized to estimate mobilized capacities as well as unit resistances. Additional shafts will be statically tested to facilitate the extrapolation task.

PARAMETERS AFFECTING ROCK SOCKET RESPONSE - TECHNICAL CHALLENGES OF EXTRAPOLATION

Drilled shaft geotechnical performance, particularly where shafts are predominantly end bearing on rock, is significantly dependent on diameter. Performance metrics for deep foundations are related to the margin of safety on bearing failure and foundation settlement due to elastic-plastic interaction with the underlying geomaterials. Diameter plays a role in calculation or load testing to evaluate end bearing resistance, and it has a geometric impact on the zone of soil or rock significantly stressed by the application of foundation loads. One of the major objectives of the ADSC research program described herein is to evaluate geometric effects of the shaft diameter and to develop a theoretical basis for safely extrapolating field testing data on small diameters to larger shaft diameters.

Fundamental behavior of deep foundations including drilled shafts indicates that diameter of the shaft has a direct, linear impact on the predicted ultimate bearing resistance at the base of the shaft. This is especially the case for a socket with very limited length to diameter (L_s/D) ratio. For the study development referenced in this paper, we are considering sockets with L_s/D of ½ or less. For rock masses comprising closely spaced, closed joints, a general wedge shear failure may develop and is described by the Bell solution for plane strain conditions, with appropriate modifier factors C_{f1} and C_{f2} for the circular shape of the drilled shaft (Wyllie, 1999):

$$q_{ult} = C_{f1} c N_c + C_{f2} \frac{\gamma B}{2} N_\gamma + \gamma D N_q$$

$$q_{ult} = (1.2) c N_c + (0.7) \frac{\gamma B}{2} N_\gamma + \gamma D N_q$$

From this commonly-used equation, one can see that the only term directly influenced by the diameter is the second term, dominated by N_γ. For a rock mass angle of internal friction ϕ' ranging from 15 to 45 degrees, the value of N_γ in the Bell solution will range from 1.2 to 40, making the total N_γ term range from approximately 6B kPa to 191B kPa, where B is the shaft diameter in meters. Otherwise, the influence of diameter is the possible variation in rock mass shear strength parameters due to greater depth of influence. This concept will also be true for consideration of deformations related to maximizing end bearing values on rock, the mechanism which dominates the shaft performance.

Design of drilled shafts bearing in or on rock is, for most conventional circumstances, dependent less on ultimate bearing resistance and more on serviceability. Ultimate bearing capacities are typically very high by virtue of the high shear strength of the rock mass, but division of the ultimate bearing resistance by a factor of safety does not guarantee satisfactory performance. In many locales, working stress design is directly calibrated to adequacy of performance given the known nature of the rock mass. Settlement at working or service loads is the driving criterion for selection of maximum permissible bearing stresses. Moreover, concrete strength may govern the limit state design for very high strength rock masses. Project or local practice requirements for settlement at working load or test load need to be incorporated (i.e. maximum 6 mm, 13 mm, or 25 mm settlement, etc. at working load or at some multiplier of working load). Moreover, the future development of a methodology to allow correlation of small diameter testing results to larger diameter designs will be rooted in settlements compatibility and scaling.

Pseudo-elastic analysis of drilled shaft foundations for the purpose of estimating settlement under loads is well-established in practice. Methods for analysis include those published by Mattes and Poulos (1969), Poulos and Davis (1980), Pells and Turner (1979), and Carter and Kulhawy (1988). Operative factors having a significant influence on settlement are the ratio of overburden soil stiffness E_s to "rigid" base material stiffness E_b, diameter, and pile stiffness factor $K = E_{pile}/E_s$. Using the closed-form solutions of Randolph and Wroth (1978), a simple analysis has been developed to demonstrate the dependence of many of these factors on the relationship between drilled shaft diameter, load, and settlement. For a basic shaft geometry with 10 m of loose overburden soil and a hard shale bedrock with RQD of 50%, unconfined compressive strength σ_{ci} of 55 MPa, and shear modulus of 1.61 GPa, a range of diameters and shaft top loads were evaluated to develop plots of load versus diameter for given values of settlement. Refer to Figure 1a and 1b below. For the weak overburden soil mass in this example, the great majority of the shaft-top load will be transferred directly to end bearing on the rock mass.

These simple analyses indicate that for a given acceptable magnitude of settlement, the mobilized end bearing stress will decrease as a function of drilled shaft diameter. This trend will be useful in establishing the means to extrapolate from small diameter test results to larger diameter shaft performance. For example, if the desired maximum settlement under working load is 25 mm, and the production shaft diameter is going to be 1.52 m, then any static or dynamic testing of a prototype 0.61-m diameter test shaft will need to mobilize a working end bearing resistance

140% larger. This is independent of the required factor of safety to be demonstrated relative to ultimate bearing resistance.

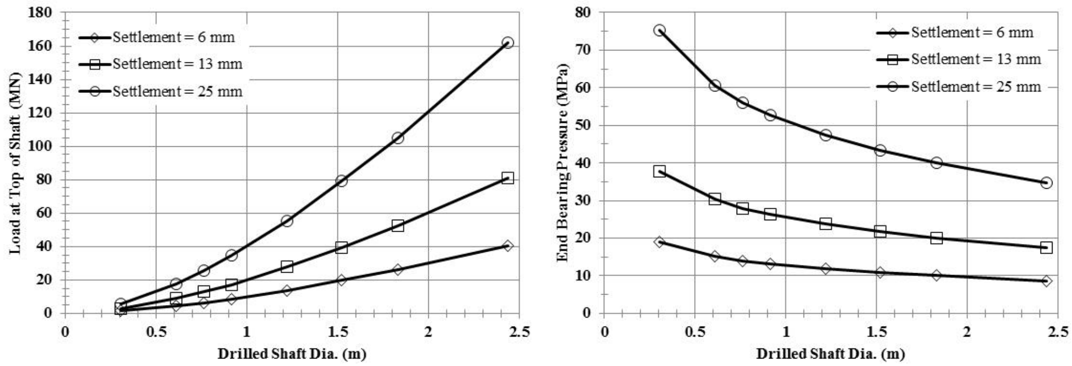

Figure 1. Drilled shaft (a) load and (b) end bearing pressure as a function of diameter and elastic settlement

Construction uncertainties must be incorporated in the development of the extrapolation relationship. For example a 30-inch diameter rock socket may have a more conical shape base, whereas a 5-foot diameter shaft may present a more flat base. That could skew the unit end-bearing extrapolation from smaller to bigger diameter shafts. Deviations in construction would also affect the results as it is not easy to guarantee identical construction even within the same project. Drilled shaft base cleaning, roughness of the rock socket walls etc. would affect the overall response and therefore the end-bearing mobilization. For these reasons site-specific load testing is an integral part of a safely designed project. Valuable information is expected to be obtained that will perhaps define ranges of expected unit resistances, set minimums and reduce unnecessary conservatism. Conventional top-down static tests and bi-directional tests will also be conducted to assist with development of the extrapolation relationships.

HIGH STRAIN DYNAMIC TESTING ON DRILLED SHAFTS

High Strain Dynamic Testing or Dynamic Testing was initially developed for driven piles but very soon started to be applied to drilled shafts and other cast-in-situ elements. The first dynamic test on a drilled shaft was performed in Mexico, in 1974. In the early 1980s the Road Construction Authority of Victoria authorized the dynamic testing of roughly 100 drilled shafts in Melbourne, Australia after a Class A series of static and dynamic tests produced satisfactory agreement. Since then dynamic testing is routinely used for the capacity determination of drilled shafts and other cast-in-situ elements. A significant amount of data has been published that suggests good correlations have been achieved in many parts of the world (Likins et al., 2004). Generating high loads is most economically accomplished by dynamic testing compared to any other field test and the method is particularly well suited for drilled shaft founded in rock because of the low energy dissipation of the rocks. Dynamic testing requires a small foot print, does not interfere with the progress on the construction site, generates loads that are adequate for their intended purpose and is relatively quick and inexpensive compared to other loading methods.

In the United States, dynamic load tests are performed in general accordance with ASTM D4945. To perform the test, strain transducers and accelerometers are attached near the top of the pile (Figure 2) to measure strain and acceleration that are induced in the pile top under the impact of a hammer. Wireless and smart sensors which transmit their calibration values to the recording Pile Driving Analyzer® (PDA) system, shown in Figure 3, are often remotely monitored, allowing the engineer to analyze the data in real time from the office.

A main difference between driven pile testing and drilled shaft testing is that the former is usually tested by using a pile driving hammer (diesel, hydraulic, air-steam etc.), whereas the latter is tested by means of large drop hammers with only a few, well controlled impacts for better stress and energy control. Typically, three to five hammer impacts are performed for a successful dynamic load test on a drilled shaft. The impact load should be sufficient to generate an adequate permanent pile penetration i.e. pile penetration that mobilizes the full capacity, if determination of full capacity is required. The drop height and therefore the applied energy is increased from blow to blow until an adequate set (permanent displacement) for the mobilization of the capacity is reached, without the stresses exceeding the allowable limits.

Figure 2: Stain gauges and accelerometers attached at the shaft top

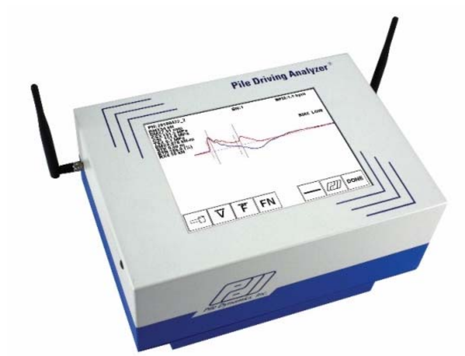

Figure 3: PDA with Antenna

For testing of drilled shafts typically requirements for ram weight is about 2% of the required capacity for shafts founded in soils and about 1% to 1.5% of the required capacity for shafts founded in rock. More specific recommendations on ram weight, drop height (stroke) and cushions are given by Hussein et al. (1996). Many different types and weights of drop hammers have been specifically developed for dynamic pile testing of cast-in-situ elements. They are dropped either by mechanical or hydraulic free release devices or simply by brake release of the crane winch. Guiding of the drop weight may be done by external frames (preferable for larger weights) or by center guiding rods which are fixed to a plate on top of the pile. Figure 4 shows a picture of the APPLE drop hammer by GRL Engineers, Inc., used in United States, whose drop weights can range from 1 to 80 tons and which feature an external guiding frame with hydraulic ram release.

The principles behind dynamic pile testing are based on one-dimensional wave propagation theory (Rausche et al., 1985, Rausche et al, 2006; Hussein and Likins, 1995; Sellountou and Rausche, 2013). The dynamic measurements of strain and acceleration are subjected to a rigorous analysis to calculate static pile capacity the so-called CAPWAP method. CAPWAP method is a signal matching process (or reverse analysis procedure), in which the measured input and an assumed soil model is used to obtain a calculated response that matches the measured input. Soil model parameters are adjusted until a good agreement between measured and calculated signals is obtained. More specifically, CAPWAP assumes that the soil reaction consists of elasto-plastic and viscous components which means assigning three unknowns at each discrete point of the soil model i.e. the ultimate static resistance, the quake of the soil (elastic soil deformation) and the damping constant. The CAPWAP analysis is completed when these three unknowns are determined for each point along the shaft and the toe of the pile. CAPWAP signal matching can be used for both uniform and non-uniform piles.

Figure 4: Apple Drop Hammer

HIGH STRAIN DYNAMIC TESTING ON DRILLED SHAFTS - CASE STUDIES

An interesting application, out of many applications of dynamic testing of rock sockets, is one conducted at the Tampa Port Authority's Container Terminal in Tampa, Florida (Conroy et al., 2010). Phase 2B extension of existing Berth 211/210 included the construction of 32-inch diameter rock socketed drilled shafts with a 20 to 7.6-m long rock socket into weathered limestone formation. Load testing was required to verify the foundation design parameters and installation method. The contractor proposed, and the engineer agreed, to perform Dynamic Load Testing on four (4) of the drilled shafts to verify a load bearing capacity of 8.1 MN per shaft. For hammer selection for the purposes of testing the drilled shafts the GRLWEAP wave equation analysis program was used to confirm suitability of Delmag D62* hammer system (i.e. ensure that the proposed hammer would be able to cause sufficient movement to mobilize the required load bearing capacity without overstressing the pile). Based on the wave equation analysis results the contractor's hammer was approved and dynamic testing was performed by utilizing the PDA field instrumentation system. Selected dynamic records obtained by the PDA were analyzed by CAPWAP data analysis. The analysis results include mobilized bearing capacity, shaft resistance distribution, end bearing, soil rock damping and stiffness parameters and a simulated static load-displacement curve. Mobilized bearing capacities greater than 1900 kips were verified by dynamic load testing in all 4 shafts, satisfying this way the requirements of the project. Figure 5 shows the CAPWAP calculated load-displacement curve for one of the four test shafts. This particular shaft's dynamic load test result shows a mobilized capacity of 10.2 MN (6.87 MN in skin friction and 3.45 MN in end-bearing).

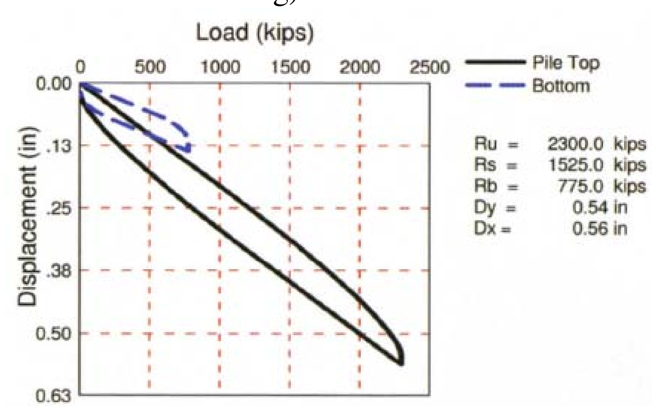

Figure 5: CAPWAP Data Analysis Results

Dynamic load testing provided a quick and inexpensive way to confirm capacity requirements for the rock sockets on this project. The cost of testing was less than $2,000 per shaft. The four shafts were tested in two days

Rausche et al. (2006) presented 11 case studies of dynamic testing of rock socketed drilled shafts from 5 different sites. Diameters of rock sockets ranged from 0.91 m to 1.98 m and rock socket lengths from 1.1 m to 11.3 m. These cases were chosen because of their similar rock socket properties leading to a very stiff response during the tests with very little permanent penetration. Rock materials included limestone, claystone, Florida limestone and soft claystone. On average the ram weight chosen was about 1.3% of the activated capacity. Activated total capacities ranged from 9.52 MN to 37.7 MN but ultimate end bearing was probably not reached in any of the 11 cases, due to rather small pile movements. In fact no attempt was made in any of the 11 cases to activate the ultimate pile capacity and moderate fall heights were chosen as all 11 shafts (with the exception of one) were production shafts. However, bottom resistance of as high as 16.8 MPa was measured (Florida limestone, 0.91-m socket diameter, 8.23-m socket length, 23.9 MN total activated capacity). Limitations and recommendations for the design and execution of dynamic testing in rock socketed drilled shafts are discussed by Rausche et al. (2006).

Beim and Gracia, (2009) describe another application of dynamic load testing of 1.3 m diameter rock socketed shafts installed in Panama for the new bridge over the Changuinola River. Total (shaft plus toe) capacities between 12.4 MN and 19.9 MN were mobilized, with small permanent sets of only 0.1 mm to 1 mm by a 265 kN ram hammer, suggesting that the actual ultimate capacities were higher yet. However, the maximum mobilized capacities exceeded the required ones and were, therefore, satisfactory. The above references do not comprise an exhaustive list of dynamic testing of shafts with rock sockets but a rather a small example demonstrating applicability of dynamic testing in rock sockets.

PRACTICAL CONSIDERATIONS

Some of the practical considerations that should be included in the ADSC's load test program are described below.

- Definition of failure for the various diameter shafts have to be established in a consistent manner. That would probably most meaningfully be implemented by assigning a permanent final displacement applicable to all different diameter shafts. The selected final set should take into account typical service limit states and the fact that end-bearing mobilization typically occurs at higher displacements than shaft resistance mobilization.
- Presence of substantial shaft resistance will limit the amount of end bearing that can be mobilized during the dynamic test with reasonably economical test loads. In extreme cases the shaft resistance may be equal to the shaft's structural capacity which would only allow for a small end bearing activation. If the rock socket has substantial embedment into the rock, isolation of shaft resistance from end-bearing may be needed during construction. Alternatively, the test shafts could be constructed with relatively shallow rock sockets. It would be particularly valuable for the contractor if adequate capacity at acceptable displacement could be proven for a relatively shallow rock socket as this eliminates further drilling into rock. It is important however, to remember that load carrying distribution is affected by L/D and shaft resistance mobilization mechanism, and these have to be taken into account in the analysis.
- A sufficiently powerful loading apparatus has to be provided for best and most meaningful results.

- Cleanliness of the rock socket bottom is crucial. The presence of a soft bottom will affect the socket response under any type of testing (static or dynamic).
- Total capacity can be predicted with more confidence whereas a distinction between shaft resistance near the shaft bottom and end-bearing is a more challenging task in dynamic testing.
- All types of field testing (static or dynamic) present limitations. Although some limitations of dynamic tests have been addressed herein discussion of limitations of static load tests (conventional top-down and bi-directional) is beyond the scope of this paper and are not discussed herein.
- This is not an exhaustive list of practical considerations to be taken into account during the ADSC load test program.

CONCLUSIONS

The drilled shaft industry often has to face highly unrealistic, over-conservative designs, where actual compression capacities can be 10-20 times greater than the design capacities. The drilled shaft industry does not have a recognized published data table to reference when trying to demonstrate the conservatism of traditional designs. However, a cost-efficient test with minimal impact on the construction schedule is available which can prove that indeed much higher capacities than allowable are available. It would be beneficial to the drilled shaft contractor to be able to perform a quick and inexpensive field test with the dynamic loading test and be able to prove the available end-bearing, which often is much greater than assumed in the design. Furthermore, it would be beneficial to the drilled shafts contractor to be able to test a small-diameter rock socket (e.g. 0.76 m or 0.91 m) and be able to extrapolate unit end-bearings to his actual size rock sockets (up to about 1.52 m diameter) with some reasonable factor of safety. It is expected that the ADSC's small scale load test program as described above will set a basis for economical site specific testing that could be applied at the discretion of the contractor in any given project. Moreover, it will help prove the high capacities of drilled shafts to be expected in several rock formations around the country, and will attempt to set a basis of extrapolation when load test of larger-diameter shafts is cost prohibitive.

REFERENCES

Beim, J.W., de Gracia, C. A., (2009). "Dynamic Pile Testing of Three Drilled Shafts on the Bridge over the Changuinola River in Panama." *Contemporary Topics in Deep Foundations; Selected Papers from the 2009 International Foundation Congress and Equipment Expo, Geotechnical Special Publication No. 185*. Iskander, M.I., Laefer, D. F., Hussein, M. H. Eds. American Society of Civil Engineers: Orlando, Fl; 607-614.

Conroy, R., Mondello, B., Hussein, M.H., Gissal, R., (2010). "Drilled Shaft Load Testing: Made Easy and Inexpensive." *Foundation Drilling Magazine,* June/July 2010; 53-57.

Carter, J.P. and Kulhawy, F.H. (1988). Analysis and Design of Drilled Shaft Foundations Socketed into Rock, Electric Power Research Institute Report EL-5918, Palo Alto, 190 pp.

Crapps, D.K. and J.H. Schmertmann (2002). "Compression Top Load Reaching Shaft Bottom- Theory versus tests." *Proceedings International Deep Foundation Congress*, Orlando FL

Hussein, M.H., Likins, G. E., (1995). "High-Strain Dynamic Testing of Drilled and Cast-In-Place Piles." *Deep Foundations Institute 20th Annual Members Conference and Meeting:* Charleston, SC; 127-142.

Hussein, M.H., Likins, G. E., and Rausche, F. (1996) -*Selection of a Hammer for High-Strain Dynamic Testing of Cast-in-Place Shafts*- Proceedings of the Fifth International Conference on the Application of Stress-wave Theory to Piles, Orlando, FL, pages 759-772.

Likins, G. E., Rausche, F., (2004). "Correlation of CAPWAP with Static Load Tests." *Proceedings of the Seventh International Conference on the Application of Stresswave Theory to Piles 2004*: Petaling Jaya, Selangor, Malaysia; 153-165. Keynote Lecture

Mattes, N.S. and Poulos, H.G. (1969). "Settlement of single compressible pile." *Journal of the Soil Mechanics and Foundations Division*, American Society of Civil Engineers, Vol. 95 (SM1), 189-207.

Osterberg J (2000). "Side Shear and End Bearing in Rock Sockets". *Geo-Strata*

Rausche, F., Goble, G. G., Likins, G. E., (1985). "Dynamic Determination of Pile Capacity". *ASCE Journal of Geotechnical Engineering*, Vol. 111, No. 3: Reston, VA; 367-383.

Pells, P.J.N. and Turner, R.M. (1979). "Elastic solutions for the design and analysis of rock-socketed piles." *Canadian Geotechnical Journal*, National Research Council, Vol. 16, 481-487.

Poulos, H.G. and Davis, E.H. (1980). Pile Foundation Analysis and Design, New York, Wiley, 379 pp.

Randolph, M.F. and Wroth, C.P. (1978). "Analysis of deformation of vertically loaded piles." *Journal of the Geotechnical Engineering Division*, American society of Civil Engineers, Vol. 104 (GT12), 1465-1488.

Rausche, F., Morgano, M., Hannigan, P., Bixler, M., Beim, J.W. (2006). "Experiences With Heavy Drop Hammer Testing of Rock-Socketed Shafts". *Deep Foundations Institute 31st Annual Conference on Deep Foundations*: Washington, DC; 133-140.

Sellountou, A., Rausche, F., May 2013. "Quality Management by Means of Load Testing and Integrity Testing of Deep Foundations." *Proceedings from Seminario sul Tema "Evoluzione nella Sperimentazione per le Costruzioni" (Seminar on the "Evolution of Experimentation in Construction"):* Crete; 329-346.

Timoshenko S.P., and Goodier J.N. -*Theory of Elasticity*- McGraw-Hill Book Company, 3rd edition, NY, 1970.

Wyllie, D. (1999). Foundations on Rock, 2nd Ed., E&FN Spon, London, 451 pp.