LOAD TRANSFER AND CAPACITY OF DRILLED SHAFTS WITH FULL-DEPTH CASING

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Construction of drilled shaft foundations with the use of hydraulic oscillators and rotators to install temporary casing over the full depth of the shaft is described. The equipment and techniques were developed in the 1960's in Germany and full-depth casing is now the predominant method of construction in Europe. Its use in North America is increasing. This paper presents an overview of full-depth casing methods and a summary of available load test data evaluated by the authors to compare the load transfer and capacity performance of shafts installed by various construction methods. Results demonstrate that load transfer and capacity of full-depth casing shafts are equal to or exceed that of shafts constructed by dry or slurry methods and that measured capacities are consistent with generally accepted design equations.

The principal advantage of full-depth casing methods over other installation techniques is that the risk of defects in the shaft is minimized. Casing is able to penetrate into the ground under any geologic or groundwater condition when this technique is applied. Potential delays and cost overruns can thus be avoided and a safe, economical foundation element is created.

Background

Worldwide, the most common method for construction of drilled shafts (bored piles) involves the use of rotary drilling equipment to excavate a cylindrical hole. The hole may remain open in soils with cohesion or in rock (dry method), or may be kept open by the installation of temporary steel casing or by filling the hole with slurry. Historically, casing has been advanced by an impact or vibratory hammer. If necessary, sections of casing are joined by welding and separated when the temporary casing is removed during concrete placement. It is not uncommon for casing to be left in the ground when it becomes difficult to remove. Beginning in the 1960's, mineral slurries made from processed clay (bentonite) and water became the predominant method of slurry construction. Slurry made with synthetic polymers appeared in the 1980's and now constitutes a significant portion of slurry construction. Combined methods, involving use of casing and slurry (sometimes referred to as "mudded-in" casing), are also used.

In European practice, factors such as historic preservation, more strict regulatory requirements, higher concentration of structures, and others led to the development of low-vibration, impact-free casing installation methods that minimize noise and damage during installation. The first generation of pneumatically driven "casing-oscillators" was developed and used in the early 1960's in Germany. This led to the development of more powerful hydraulic casing oscillators, and later hydraulic rotators, for the installation of full-depth casing. Concurrently, the development of hydraulic drill rigs with vertically-movable rotary drives allows the installation of segment-wise joined casings of up to 6 m in length during drilling.

Today in Europe most drilled shafts are constructed using full-depth casing methods. In North America all methods are in use but for situations that require temporary borehole support, the two most widely-used methods are: (1) installation of temporary casing using a variety of methods, including vibratory or impact hammer and (2) slurry method. Use of full-depth casing installed with hydraulic oscillators and rotators is limited to a few contractors who have the equipment. However, full-depth casing methods are being used increasingly in some markets and it is likely this approach will be utilized in more applications in the future.

Engineers and contractors have long realized that construction method and quality have a significant influence on load transfer behavior and capacity of drilled shafts. These effects are often considered in terms of the three major construction methods: (1) dry, (2) casing, and (3) slurry methods. Very little work has been published pertaining to the effects of full-depth casing methods on load transfer. A comment in the current FHWA drilled shaft manual (O'Neill and Reese 1999) states that "full-depth casing rigs have the potential disadvantage that they can produce smooth boreholes in clay and rock, which can have an adverse effect on skin friction". However, no evidence is presented showing this adverse effect and no recommendations are given for quantifying side resistance when full-depth casing is used. With regard to slurry methods, several studies have shown that bentonite slurry can reduce side resistance of shafts in permeable soils compared to construction with polymer slurry or casing, because of filter cake formation. In low-permeability soils filter cake formation is suppressed and bentonite slurry appears to have no detrimental effect on side resistance.

This paper summarizes the results of a study conducted by the authors to document the performance of drilled shafts constructed with the full-depth casing method using oscillators and rotators. An overview is presented of both casing and slurry methods of construction, including a comparison of the principal features of each method. This is followed by a summary of a study of drilled shaft load tests published in the literature. The results are used to compare the load transfer and capacity performance of drilled shafts constructed by the dry, casing, and slurry methods, with a focus on full-depth casing methods with oscillator/rotator.

Overview of Current Practice

Construction methods used when the ground conditions require some form of temporary support can be placed into two categories: (1) methods involving temporary casing and (2) slurry methods.

Casing Methods

Soil may be excavated and followed by casing installation, or casing can be installed and soil or rock excavated from within the protection of the casing (case-ahead method). The latter is desirable and applies to oscillated or rotated full-depth casing methods. When final depth is achieved, the borehole support is transferred from the temporary drill casing to fresh concrete as the casing is withdrawn.

As illustrated in Figure 1, installation and extraction of temporary casing can be carried out by:

- vibratory
- impact hammer
- rotating and pushing with the Kelly bar of the rotary drilling rig
- oscillator
- rotator

Vibratory. The top of the casing, generally with a wall thickness of 10 mm to 25 mm, is connected to a vibrator by a set of hydraulic clamps. High frequency vibrations produced by a vibrator cause the soils in the immediate vicinity of the casing to liquefy and thus enable the casing to penetrate under its own weight. As liquefaction only occurs in loose to medium dense sands, gravels and soft silts and clays, the use of vibrations is limited to these soil types.

Practical limits for the use of vibratory are casing diameters of 2 m and casing depths of 20 m. Greater depths and diameters have been reported using extremely powerful vibratory units. However, excessive casing wall thickness is required and the casing removal becomes very difficult in most cases.

Impact Hammer. The casing is advanced by the force of an impact hammer. Similar to vibratory, use of impact hammers is limited to loose and medium dense sands and gravels and soft silts and clays. Boulders, dense sands and gravels, and weathered rock may act as obstructions and prevent further casing advancement. Local buckling (crippling) is often a problem at the tip of the casing.

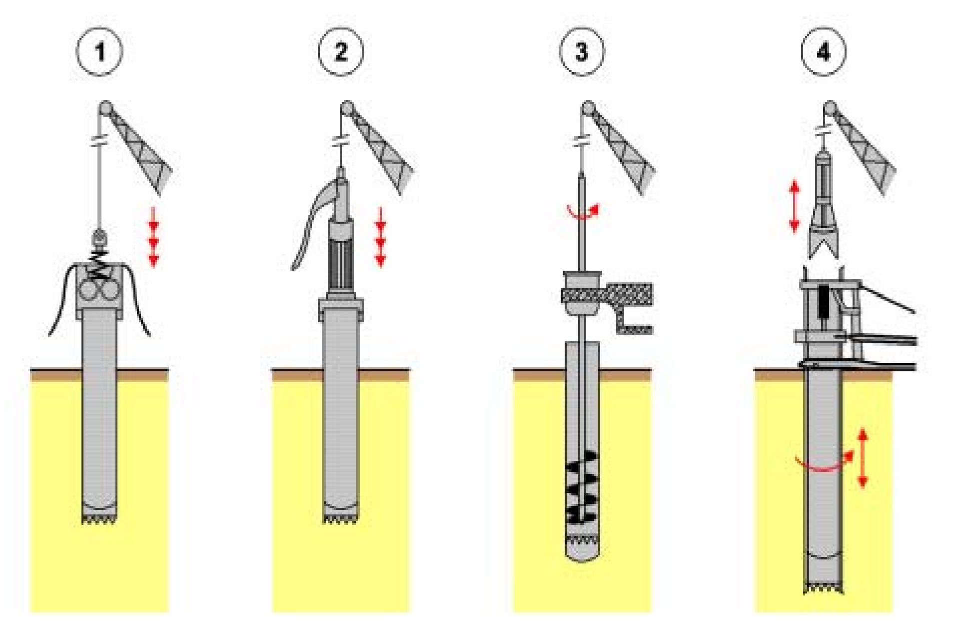

Figure 1. Installation and extraction of temporary casing.

In U.S. practice, installation of temporary casing by vibratory and impact methods historically have been the preferred method when casing is installed ahead of excavation. However, as more equipment manufacturers and contractors have made the transition from drill rigs with stationary rotary tables to hydraulic rigs with movable rotary drives, methods to install casing are changing.

Rotary with Kelly bar. The first hydraulically driven rotary drill rigs appeared on the European market in the 1960's. The torques of these machines were between 14 and 130 kN-m. Today the trend is pointing towards increasingly strong and powerful rotary drilling rigs with torques up to 500 kN-m and maximum vertical down - or upward forces of 400 kN. It is thus possible to install casing during the drilling process. Depending on ground conditions, it is possible to install and remove casings of up to 1.2 m in diameter to a depth of 30 m and casings of 2 m in diameter to a depth of 20 m. Drilling depths to 50 m can be reached if a second hydraulic rotary equipped with an oscillator or rotator attachment is added to the rig and operated in conjunction with its drilling hydraulic rotary. Rotational movement of the casing during pushing down into the ground is comparable to casing installation by oscillator and rotator machines.

Oscillator. This equipment consists of a crawler crane with a hydraulic oscillator attached to its base. The drill casing is clamped by a circular collar which is operated hydraulically and rotated by about 20 degrees in alternating directions under torques of up to 8000 kN-m (Figure 2).

The oscillating forces are transmitted into the ground via the crane's undercarriage. Simultaneously the casing is pushed into the ground by a downforce applied by hydraulic jacks reacting against the weight of the oscillator (100 - 800 kN). As drill casing is available in maximum lengths of about 6 m, sections of casing have to be joined during the installation process by tightly fitted collars with inset conical casing screws (Figure 3). The wall thickness of heavy duty drill casing ranges between 40 and 60 mm. In order to reduce the overall weight, double wall casings with intermittent stiffeners are used. This kind of casing advancement is, depending on the ground conditions, limited to a diameter of 3 m and a drilling depth of around 50 m without telescoping the casing.

Figure 2. Hydraulic casing oscillator.

Rotator. In the 1980's, machines similar to casing oscillators were developed with one-directional rotation ("rotators") and a maximum torque of up to 8,000 kN-m. A significant advantage is that the shape of the teeth in the casing shoe can be optimized for cutting in one direction only. As a result this system enables the casing to penetrate difficult soils and boulders. With a height of 3 m and a maximum weight of 800 kN the new rotators are about 30 % faster than traditional casing oscillators.

Full-depth casing methods described above can be further categorized on the basis of the excavation method used in conjunction with casing advancement. Two common excavation techniques are rotary drilling and percussion methods.

Figure 3. Joining the casing tubes.

Casing may be installed with a drilling rig equipped with vertically-adjustable hydraulic rotary drives. In this case, excavation is carried out using tools attached to the rotating Kelly bar, including augers, buckets, core barrels, and other tools that are used to bring the excavated material to the surface.

Percussion methods of excavation typically are employed in conjunction with casing advancement by hydraulic oscillator or rotator machines. Percussion tools include hammer grabs, drop chisels, and air-activated down-the-hole-hammers. Drill cuttings are then removed from the bottom of the hole by the hammer grab or clamshells, but can also involve use of flushing mediums, augers, and buckets. A typical setup is shown in Figure 4 in which a cable-operated hammer grab suspended from a service crane is used to excavate while the casing is installed by oscillator. The largest shaft diameters to be produced with this equipment configuration are 3.5 m and the maximum drilling depths are approximately 100 - 120 m.

Slurry Methods

Slurries for drilled shaft construction can be prepared by mixing water with minerals, such as bentonite, or with synthetic polymers. During drilling the slurry level within the borehole is maintained above the piezometric surface in the ground, thus providing constant support of the bore (Littlechild and Plumbridge 1998). Bentonite suspensions penetrate the wall of the borehole and bentonite particles filter out to form an impermeable membrane along the borehole

Figure 4. Excavation with spherical hammergrab and 3 meter casing oscillator.

wall, the so-called filter cake. This effect is more pronounced in permeable formations because the slurry is able to penetrate the soil. This membrane also prevents soil particles from caving into the excavation and thus provides support for the borehole wall. Due to their thixotropic behavior bentonite suspensions are able to develop sufficient shear strengths to keep gravel particles of up to 10 mm in suspension. This characteristic behavior provides additional support to the wall of the borehole. Polymer slurries consist of a solution of long chain molecules of low molecular weight in water. Because their insufficient gel-strength does not hold sands in suspension, all of the cuttings down to the size of fine sand must be removed prior to concrete placement. The main advantage of polymer over bentonite slurries is their ease of handling and disposal. An advantage of bentonite slurries is their ability to act as a flushing agent to transport the cuttings out of the bore, whereas polymer slurries are not capable of transporting cuttings effectively.

Slurry methods are used with rotary drilling rigs and with reverse or direct circulation rigs. When used with rotary drilling rigs, it is common for temporary casing to be required in the upper section. In the case of movable rotary drives these starter casings can be placed and removed by the rig itself. Otherwise, for fixed rotary drives, casings are installed and extracted with the use of a vibrator.

Construction Methods Compared

The support of boreholes with slurries is common practice in the U.S., whereas in most of Europe, especially in Germany, temporary casing methods dominate. Without considering the load capacity of the drilled shafts the above-mentioned construction methods are marked by the following characteristics:

Construction under slurry (mineral or polymer)

- For support of the borehole in the upper section a casing (short collar casing) is required. This also acts as a guide for the drilling tool used and is necessary in most cases.

- Slurry methods are less suitable in highly permeable strata due to the potential loss of bentonite or polymer and potential for caving.

- Production rates for drilling under slurry - compared to a typical 25 m deep borehole with a diameter of 1 m - are generally higher (faster) than drilling under the protection of a casing.

- The sides of the borehole, especially under the ground water table, are often irregular. The excavation tools cause ‘overbreak’ in less compact strata. The amount and geometry of the overbreak is uncontrollable. This leads to an excess of concrete being placed. Excess rates of more than 20% and up to 60% have been observed.

- The pressure of the slurry may reduce disturbances of the shaft base.

- Cleaning of the borehole base and the borehole wall before concreting is more complicated compared with a cased boring.

- In soft and coarse-grained soils without cohesion (like gravels and cobbles under water level) a casing is necessary in any case to guarantee a satisfactory and uniformly drilled shaft section (combined method).

- Higher risk of soil inclusions in the concrete due to local caving of borehole walls during concreting; this is most critical for shafts designed for lateral loads.

- Handling of the slurry and mineral slurry disposal (environmental problem) is often difficult.

Construction with casing

- Stability of the borehole can be assured for any geologic or hydrogeologic conditions.

- The risk of defects within the drilled shaft is minimized; the production ensures a sound and predictable drilled shaft. This is very important especially in cases where horizontal loads have to be transferred.

- The sides of the boreholes are even, the drilled shaft has a defined diameter, and excess concrete (overbreak) is negligibly small.

- Production rates are slower compared to a slurry supported borehole.

- The use of a casing oscillator and especially a rotator with heavy walled casing equipped with cutting shoes helps make a nearly vertical excavation. Boulders can be cut.

- The base of the casing is always kept below or at the base of the excavation, minimizing disturbance of the strata around and beneath the drilled shaft. This cannot always be ensured with normal casing with a wall thickness of 10 - 25 mm being driven into the ground by an impact hammer or vibrator.

- Casing installed by impact or vibratory methods causes vibrations that increase the risk of ground settlement and damage to adjacent structures, utilities, or recently constructed shafts.

- Impact or vibratory methods are prone to construction delays and casing damage in response to obstructions like boulders, weathered rock, and dense gravel. Oscillated and rotated casing eliminates these obstruction problems.

<u>Observations from Axial Static Load Tests</u>

Over 300 axial static load tests on drilled shafts installed with different installation techniques, different geometries, and in various ground conditions were examined and evaluated. The results of these tests were taken both from national and international literature and from the authors' own projects.

Results of 47 load tests were selected for more detailed evaluation on the basis of the following criteria establishing the type of information available either from the literature or the authors' case files:

- Subsurface profiles and groundwater conditions of the test site with information on the investigation method and results of field and lab tests

- Information on soil properties and boring logs

- Detailed information on shaft geometry, installation method, measuring devices (instrumentation) and methods.

- Presentation of load test results in tables and/or graphs, especially: load-settlement behavior, load-distribution behavior, and base and side resistances.

Load tests meeting the above requirements were conducted in the USA, Italy, Portugal, Great Britain, Germany, Thailand, and Taiwan. In Table 1 these 47 axial static load tests are divided according to:

- geotechnical conditions
- installation method

The term "combined method" refers to construction using both casing and slurry. A full description of the study, including detailed descriptions of each of the 47 load tests (and additional tests) and their analyses, is given by Katzenbach and O'Neill (1999). The following is a summary of the principal observations.

Noncohesive Soils

The results of 15 axial static load tests at six different sites were analyzed. Details of each test are given by Katzenbach and O'Neill (1999). To illustrate the overall results, Figure 5 shows the measured side resistance values of the 15 cases as related to measured values of the static cone resistance tests. Additionally the design values according to German regulations can be taken from the dashed lines. From Figure 5 it can be concluded that the measured values of side resistance of drilled shafts installed with the oscillator and rotator method meet or exceed the predicted values arising from a widely accepted codified design method. The capacity of shafts installed under slurry support is in a similar range.

Table 1. Summary of Ground Conditions and Installation Methods

	Installation method				
Geomaterial type	Casing method	Slurry method	Dry method	Combined method	**Total**
Noncohesive (granular)	10	4	0	1	**15**
Cohesive	10	2	9	0	**21**
Residual soils and sound rock	6	2	1	2	**11**
Total	**28**	**12**	**10**	**8**	**47**

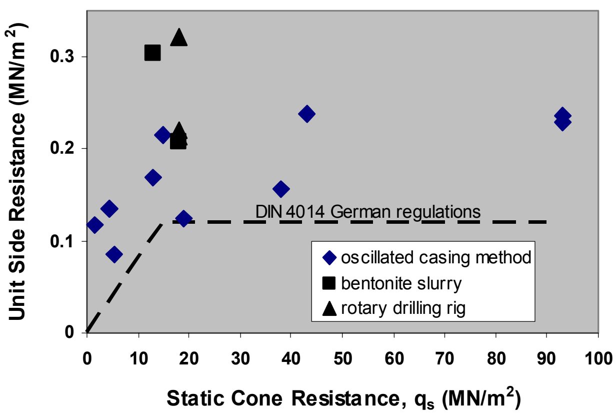

Figure 5. Measured side resistance versus cone resistance.

In addition to the results in Figure 5, Degebo (1983) published a study (in German) on the influence of installation technique on the load transfer and bearing capacity of drilled shafts in Berlin Sand. It was found that the bearing behavior of drilled shafts using the oscillated casing method is comparable to those installed by the use of slurry. With slurry, however, concrete overbreak rates up to 60% were observed.

Cohesive Soils

The results of 21 axial static load tests from the USA, Great Britain, Thailand, and Germany at different sites are given by Katzenbach and O'Neill (1999). For evaluation, consider the following widely used method for evaluating unit side resistance of shafts in cohesive soils, the α-method, in which unit side resistance is related to soil undrained shear strength by:

$$f_s = \alpha\, c_u \qquad (1)$$

where f_s = unit side resistance, c_u = undrained shear strength, and α = empirical "adhesion" factor. For comparison with the test results, consider the following expression given by Kulhawy (1991) relating the factor α to soil undrained shear strength:

$$\alpha \approx .21 + .26\left(\frac{p_a}{c_u}\right) \qquad (2)$$

where p_a = atmospheric pressure (.101 MPa). In Figure 6 normalized measured side resistances from laboratory or field tests are shown versus measured values of adhesion (α) as determined from the 21 case histories. The relationship given by Eq. 2 is shown by the dashed line. Results from full-depth casing shafts and slurry shafts plot near or above the relationship given by Eq. 2, while shafts constructed by the dry method show variable performance. It is concluded that side resistances are within the range predicted by this calculation method. The available data do not suggest any adverse effect on side resistance attributable to the full-depth casing methods.

Use of casing in soils with significant clay content can result in a smooth borehole wall, regardless of how the casing is installed. A widely-used method for roughening the soil/concrete interface with oscillated/rotated casing is to equip the casing shoe with cutting teeth oriented a few millimetres to the outside of the casing. The interface roughening effect is achieved by rotating or oscillating the casing as it is extracted.

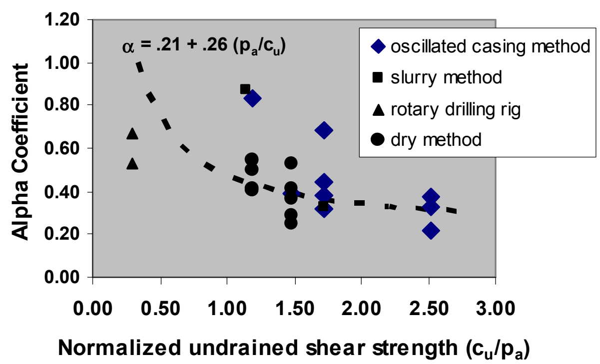

Figure 6. Side resistance versus adhesion factor.

In connection with piled-raft foundations of high-rise buildings in Germany, especially in Frankfurt/Main (clay) and Berlin (sand), more than 100 drilled shafts have been instrumented for load transfer monitoring. All of these shafts were installed with temporary casing using oscillator or rotated casing method. In each case suitable values for the side resistance could be measured. In some cases, remarkably high side resistances were measured (Katzenbach et al. 2001; Katzenbach and Moorman 2001, 2003).

Residual Soils and Rock

Results of 11 axial static load tests from the USA, Italy, and Germany at seven different sites were analyzed. All measurement data obtained from oscillated cased drilled shafts are comparable to or better than measurement results from shafts installed by the slurry method. It is well known that the design of drilled shafts in decomposed and weathered rock involves generally much uncertainty. The design of drilled shafts in such ground conditions - whatever method of construction is chosen - should be based on a static axial load test.

Several load tests in recent years in the USA can be used to illustrate the performance of drilled shafts in residual soils and rock constructed with full-depth casing.

Brown (2002) reports load test on drilled shafts in residual Piedmont soils constructed by bentonite and polymer slurry and full-depth casing installed by a hydraulic rotary drilling rig. The soils are classified as ML-SM (silts), probably cohesionless, but exhibiting some plasticity (average LL = 46, PI = 10). The test shafts constructed using full-depth casing and polymer slurry exhibited the highest capacities and showed similar side resistances. Those constructed under bentonite slurry exhibited significantly lower side resistances. Selected shafts were excavated after the load tests to examine the nature of the soil/concrete interface. For the full-depth casing shaft, the concrete surface was observed to be smooth on a small scale but a rough macrotexture was created by the cutting teeth as the casing was rotated in a back and forth motion during extraction. Brown also demonstrates that the cased shafts exhibited side resistance values close to or exceeding design recommendations given in the current FHWA drilled shaft design manual (O'Neill and Reese 1999).

To illustrate the performance of rock sockets constructed with full-depth casing, consider the case of the New Benicia-Martinez Bridge in California. The initial plan for pier support consisted of 2.5-m diameter steel pipe piles driven into rock followed by drilling of 2.2 m diameter rock sockets using reverse circulation under slurry. Caving problems encountered with the first several attempts to drill into rock forced the owner and contractor to consider alternative approaches. The solution was full-depth casing using a hydraulic rotator for the remaining rock sockets. Casing diameter was 2.2 m. To prove the design axial resistance values, an Osterberg Load Cell test was conducted on a single test shaft. The O-cell test was multi-level, involving three 670-mm diameter O-cells installed at different elevations within the socket. The multi-level test enables the determination of side resistance over several isolated portions of the socket.

The O-cell test results at New Benicia-Martinez can be compared to the design method recommended in the current FHWA Drilled Shaft Manual (O'Neill and Reese 1999). The equation for predicting unit side resistance of shafts in rock without artificial roughening (by grooving) is given by:

$$\frac{f_s}{p_a} = \alpha \times .65\sqrt{\frac{q_u}{p_a}} \qquad (3)$$

in which f_s = unit side resistance, p_a = atmospheric pressure (101.3 kPa), α = reduction factor based on RQD, and q_u = uniaxial compressive strength of intact rock. Table 2 summarizes measured values of unit side resistance as reported by Loadtest Inc. (2003) and unit side resistances computed by Eq. 3.

Except for the third layer, Eq. 3 provides reasonably close agreement with side resistances obtained by O-cell testing. The loading sequence resulted in Layer 3 being subjected to multiple load cycles with reversal of shear direction and large displacement. This type of two-way cyclic loading reduces side resistance substantially and Eq. 3 is not applicable. For the New Benicia-Martinez bridge site, which is one of the few documented load tests on a shaft installed by rotator in rock in the U.S., measured side resistance values are within the range predicted by the design equation given in the FHWA design manual.

It is also common practice in rock to equip the casing shoe with teeth that are set outward to cut a hole with a slightly larger diameter than that of the casing. This is done to prevent the casing from binding but has the added benefit of roughening the socket during casing removal.

Construction Quality

To ensure the integrity of a drilled shaft, quality control measures are absolutely necessary during the installation. In addition, quality assurance measures are needed shortly afterwards on the finished drilled shafts by non-destructive integrity tests. Quality assurance is best performed both by the contractor and by an independent expert on site.

The European standard for the installation of drilled shafts (EN 1536), developed by a working group of the Technical Committee CEN/TC 288, was published in 1999. This standard is recommended highly as a guideline for the installation and quality control of drilled shafts.

Particular quality control and assurance measures to be undertaken by the contractor include:

- checking of bottom of casing and bottom of excavation
- if chisels are used to puncture hard stone layers, measurement of vibrations in the surrounding area to prevent damage to buildings or installations
- checking verticality of a drilled shaft after the drilling depth has been reached
- integrity tests such as ultrasonic logging or low strain integrity methods a few days after concreting the drilled shaft as a final quality certification.

Table 2. Summary of measured and computed side resistances, New Benicia-Martinez Bridge.

Layer	Thickness (m)	Description	Range of RQD (mean value)	Reduction Factor, α	Mean q_u (kPa)	Unit Side Resistance by Eq. 3 (kPa)	O-Cell Unit Side Resistance (kPa)
1	7.92	interbedded siltstone, sandstone, and shale; intensely weathered/decomposed to moderately weathered; intensely to moderately fractured; some layers decomposed to soft clay	0 - 40 (9)	0.45	4,864	205	280
2	4.94	siltstone, claystone, and sandstone; soft to moderately hard, most is slightly to moderately fractured; intensely fractured near the bottom of this zone	0 - 100 (44)	0.59	6,949	322	311
3	5.07	mostly siltstone, some sandstone; intensely to moderately fractured, numerous shear zones w/ gouge and slickensides	36 - 79 (58)	N/A	6,693	N/A	80
4	2.93	siltstone, moderately hard, unfractured to moderately fractured; interbedded laminated sandstone	42 - 70 (54)	0.67	7,507	380	368

Independent quality assurance on site by an expert or for large projects by a team of experts should ensure that the installation is carried out in accordance with the specifications defined for the design of foundation. An important aspect of the quality control system is the collection, interpretation, and summarizing of all data collected during drilled shaft construction. This information should be evaluated on an ongoing basis during construction so that any problematic conditions or procedures can be identified and addressed as necessary. The geology of each drilled shaft location should be recorded from the excavated material and an accurate boring log prepared to confirm the design assumptions pertaining to subsurface conditions. The construction work should be controlled continuously and documented in a detailed construction report in addition to records submitted by the drilled shaft contractor.

Summary and Conclusions

Results of axial load tests and measurements on drilled shafts supporting existing structures reported herein suggest strongly that load transfer and axial capacity of drilled shafts using the oscillator and rotated casing methods are comparable, and in some cases superior, to other installation techniques. Further research is recommended in which side by side load tests are conducted on shafts in similar materials but using different construction methods. This approach would permit a more direct comparison of the effects of installation method on side and base resistances, similar to the study by Brown (2002).

Positive practical experience has been gained in Germany with drilled shafts installed with casing that is oscillated or rotated to the final depth (Katzenbach and Moormann 2001, 2003). Also shafts designed to carry loads predominantly by side resistance with a small contribution by base resistance have performed successfully in cohesive soils encountered in Frankfurt/Main and in sandy soils encountered in Berlin, for shafts up to 1.8 m in diameter and 50 m in length. The bore has been advanced either by grab and chisel or by auger (Kelly-type) or by bucket depending on the soil properties. Over 100 drilled shafts have been instrumented with strain gages for measurement of load distribution under service loads. These measurements verify the long term (>15 years) carrying capacity in side resistance.

The advantage of the full-depth casing method using an oscillator or rotator is its predictable performance under all expected and unexpected subsoil conditions as well as its low risk of defects within the shaft. The other installation techniques are limited to special geologic, geotechnical, hydrogeologic, and environmental conditions.

As a basis for the design and performance of all drilled shafts, load tests are recommended.

The key to ensure the load carrying capacity of a drilled shaft, regardless of which construction is chosen, is a proper construction technique and a defined quality assurance concept. This includes all steps from the design up to the installation by the contractor.

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