Construction and Behavior of Drilled Shafts

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Omar Alsamman, Ph.D., P.E.

Continuing Education and Development, Inc.
22 Stonewall Court
Woodcliff Lake, NJ 07677

P: (877) 322-5800
info@cedengineering.com

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INTRODUCTION

General practices used for the construction of drilled shafts are briefly reviewed in this course. The influence of construction method and concrete quality on the development of side and base resistance is presented, and load transfer characteristics of drilled shafts are described. Various details of the construction procedures such as equipment types, rebar cages, components and types of slurry, casing types, and other available construction methods can be referred to elsewhere (for example, Greer and Gardner, 1986; LCPC, 1986; and Reese and O'Neill, 1988).

DESCRIPTION OF DRILLED SHAFTS AND DRILLING EQUIPMENT

A drilled shaft is a type of deep foundation that is constructed by first drilling a cylindrical hole and then filling the hole with fresh concrete. Typically, steel reinforcement is placed in the excavation prior to pouring concrete. Drilled shafts have also been called bored piles, cast-in-situ piles, drilled piers, and caissons.

The soil is excavated either by use of rotary drilling equipment or by use of the percussion method. Both procedures typically use a surface casing or guide to initiate drilling. Excavation is carried out in the U.S. almost exclusively using rotary drilling that incorporates either an auger or a drilling bucket. Percussion drilling is used to a larger extent in Europe. Soil is excavated by a grab bucket or a hammer grab that is equipped with sharp teeth and that permits simultaneous penetration of the soil and extraction of the debris.

CONSTRUCTION METHODS

The use of drilled shafts to transfer surface loads to competent soils at depth goes back to the early twentieth century (Peck, 1948). Early shafts were hand-dug with sidewalls often supported by wood lagging. The use of drilled shafts has increased significantly due to their ability to carry very large loads economically.

The need for faster and more dependable excavation techniques grew as this type of foundation became more popular. Rapid developments in drilling equipment and machinery have made it possible to construct very deep, large-diameter shafts in almost all subsurface conditions including caving soils below water table, rock, karstic foundations, and offshore construction.

Three principal methods of excavation used for constructing drilled shafts are:

1. the dry method,
2. the wet (or slurry) method, and
3. the temporary casing method.

The excavation method (or a combination of methods) selected for a shaft is based on consideration of subsurface conditions, construction equipment, and economy. The dry method of excavation is generally applicable to cohesive soils above the water table. Typically, a short surface casing is inserted at the ground surface, and the hole is excavated to the required depth. A reinforcing cage is placed in the excavation and fresh concrete is used to fill the hole. The dry method can also be employed in cohesive soils below the water table if the hole exhibits enough stability.

The wet method is generally used when the dry method of construction would result in unstable sidewalls of the excavation. Soils below the water table such as clean sands, silts, and some stiff highly fissured clays may require excavation of the shaft with slurry. A mineral (mostly bentonitic) slurry or a polymer slurry may be used to stabilize the hole during drilling. Upon reaching the depth required, a pump or a tremie is lowered to the bottom of the hole and concrete is poured. The slurry (that has a lower density than concrete) is displaced into a sump above the ground surface as concrete fills up the hole. Descriptions of slurry types and their effects on construction are presented extensively by Majano and O’Neill (1993).

The temporary casing method is another method that can be used when the dry method of construction would result in unstable sidewalls for the excavation. It is particularly useful when a self-supporting soil layer of low permeability exists beneath a caving soil layer. The casing is inserted in the hole and is driven through the collapsible soil layer by applying pushing and twisting action. A drill is then introduced through the casing, and excavation is carried out to full depth of the shaft. Concrete is poured as the casing is removed from the hole. In high permeability soils below the water table, if the casing can not be driven and sealed in a low permeability stratum, the wet method is usually preferred.

In all the methods described above, an under-reaming tool (expansion element) can be introduced to enlarge shaft base. This tool, referred to as a belling bucket, is inserted into a bored hole with its arms closed. Upon reaching the depth required, the arms are opened and the bucket is rotated to excavate the soil and form a bell. The bell is most commonly designed to make the sidewalls of the bell angled either 45 or 60 degrees to the horizontal. The bell diameter may be constructed up to three times the shaft diameter.

Other deep foundations constructed by filling a hole with concrete include augered piles, grouted piles, and pressure-injected footings. The behavior of these types of foundations is affected significantly by construction details and is beyond the scope of this course.

FACTORS INFLUENCING DRILLED SHAFT BEHAVIOR

The methods used for constructing drilled shafts and the soil response during construction can significantly influence the axial load capacity. During excavation, soil is subjected to a reduction of lateral stresses along the excavation walls, and experiences some disturbance at the bottom of the excavation.

The three most influential factors on the behavior of drilled shafts are discussed in the following sections. These factors include soil type, construction technique, and concrete quality. The first two factors are inter-related since the construction method is usually determined by the soil type and soil characteristics.

Soil Type

When a drilled shaft is constructed in homogeneous clay, changes in the soil properties occur in the area surrounding the shaft. Clay immediately adjacent to the excavation sides is softened resulting in loss of strength. The remolding effect due to the auger is more pronounced in highly structured clays. Also, lateral-stress relaxation occurs, and can cause the clay to creep towards the hole if the clay is very soft. This creep effect is minimal for stiffer over-consolidated clays.

In stiff fissured clays, the excavation of a drilled shaft changes stress not only at the surface of excavation but also along the discontinuities near the hole. Fleming and Sliwinski (1977) reported that the stress relief, caused by excavating shafts with the dry method, caused inward movement of blocks of intact soil towards the hole. In such cases of highly fissured clays, it might be necessary to drill with slurry to stabilize the soil around the perimeter of the hole. The use of slurry in the excavation and its effects on load transfer is discussed in the following section.

The use of temporary casing in excavating through sand layers can alter soil density around the hole. In loose sands, vibrations (from driving a casing) cause the soil to move downward and outward resulting in some soil densification and minor ground surface settlement. In very dense sands and gravels, penetration of the casing is accomplished by crushing soil grains at the base.

The base of the excavation must be cleaned thoroughly when slurry is used to construct drilled shafts in sand. Otherwise, the end-bearing capacity can be reduced greatly and more settlement of the shaft can occur for the same applied load. Special care is also needed when constructing a bell in cohesionless soils under the water table. Kulhawy et al. (1983) reports of a complete collapse of bells in two shafts constructed with slurry in silty sands with the water table near the ground surface (Figure 1).

Construction Technique

As described earlier, drilled shafts are constructed dry, wet, with casing, or by using a combination of these techniques. Numerous studies on full-scale and model shafts have been made in the past to compare load transfer characteristics around drilled shafts for various construction techniques.

Aurora and Reese (1976) studied four instrumented shafts in clay-shales. The shafts were constructed dry, wet, cased with slurry, and cased without slurry. They found that the highest base resistance was developed in the shaft drilled dry. Shafts constructed using the wet method and those constructed with casing exhibited similar load transfer behavior along the shaft sides.

O'Neill and Reese (1970) conducted four load tests in the stiff Beaumont clay formation. Three shafts were constructed dry and one shaft was constructed using the slurry method. They concluded that the use of bentonite reduces the frictional capacity due to the entrapment of slurry between the shaft and the soil.

Fearenside and Cooke (1978) studied seven drilled shafts in London clay; three were constructed using bentonite and four under dry conditions. They found no evidence that the use of bentonite adversely affected skin friction. In fact, tests constructed with slurry had higher capacities than those constructed dry. However, they attributed that to the difference in sidewall roughness in shafts constructed with slurry using a drilling bucket versus shafts drilled dry using an auger.

Touma and Reese (1972) performed load tests on drilled shafts constructed in sands with the use of slurry. They inferred from the results that there was no clear reduction of the side resistance due to slurry construction.

Fleming and Sliwinski (1977) studied 21 load tests in clays, 9 load tests in sands, and 3 load tests in chalk. The shafts were constructed using the dry and wet methods in clays, and using the wet and temporary casing methods in sands. The casing was driven in place without pre-excavation with slurry. They concluded that in granular soils, the slurry penetrates into the voids forming a filter cake or a thin membrane. Results indicated that skin friction at high displacements can be reduced about 10 to 30 percent from that developed using a temporary casing; however, they were uncertain if that was because of the bentonitic slurry or because of some other factors.

For fine-grained soils, Fleming and Sliwinski stated that slurry does not penetrate the small pores, but a thin film of several millimeters can get trapped between the concrete and soil. They noted that no major effect was detected on the shaft friction mobilized near ultimate load when slurry is employed in the excavation. Their findings in sands were consistent with results of model studies performed by Farmer and Golberger (1969) in sand.

Beech and Kulhawy (1987) performed uplift load tests on 4 large-scale and 21 small-scale model shafts in a soil made of silt and kaolinite mixture. Large-scale shafts were constructed using the casing method in a test pit 7 ft in diameter and 6.5 ft in depth. Small-scale shafts included 19 shafts constructed in deposits consolidated from slurry and two shafts constructed in block samples from the field. These were constructed using the dry, wet, and casing methods. The skin friction developed in their model shafts was highest for those constructed with the casing method, lowest for those constructed with the dry method, and intermediate for those constructed with the slurry method.

Long and Shimel (1989) collected and analyzed the results of 43 full-scale load tests performed in various soil types. Thirty shafts were constructed dry and thirteen were constructed with slurry. They found that greater uncertainties are associated with the development of end-bearing resistance for shafts constructed wet as compared to those constructed dry. They also noted a slightly higher variability in the magnitude of side resistance for shafts drilled under dry conditions.

Majano and O’Neill (1993) studied model shafts to evaluate the effects of mineral and polymer slurries on side capacity. Results showed that in the case of mineral slurries, the thickness of filter cake depends on the contact time with soil, soil permeability, viscosity of slurry and differential pressure. An excessively thick cake reduces the load carrying capacity at the shaft perimeter.

In summary, it appears that the results of the research conducted on full-scale and model drilled shafts to evaluate load transfer response for various construction techniques are inconsistent and sometimes contradictory. This is particularly true for drilled shafts constructed with slurry. Specific construction details such as drilling disturbance, time slurry is allowed into the excavation, concrete properties and imperfect bottom cleanup may significantly influence shaft behavior. The effects of these construction details might be responsible for the differences in shaft capacity exhibited for various construction techniques.

Among other factors influencing load transfer response in drilled shafts are the natural variability of soils and the quality of workmanship. Both factors vary from one site to another, and therefore are very difficult to quantify. Even if construction is carried out at the same site, by the same crew, and using the same construction technique, identical axial capacities are not warranted.

The variability of load testing results can be best illustrated using two of the load tests conducted by Fearenside and Cooke (1978). The two shafts were constructed dry with an auger and in close proximity to each other. Both shafts were 2.5 ft in diameter and 16.5 ft in length, and were built on soft toes over a void to isolate end-bearing resistance. The measured capacity in one shaft was about 1.5 times that measured in the other (Figure 2).

It should be concluded that it is not only important to know how a shaft was constructed to be able to predict its behavior, but rather how well the shaft was constructed. Shaft behavior should be evaluated for a drilled shaft by taking various construction details into consideration rather than only considering the general construction method (i.e. dry, wet, or with casing).

Concrete Quality

Freshly poured concrete exerts a horizontal stress on the soil along the sidewalls of the excavation. The amount of stress exerted by concrete depends on the workability slump and the degree of compactness of concrete. Lateral stresses in the soil are believed to be restored to a great extent if a high-slump concrete is used. Concrete with a low-slump will tend to bulk and not collapse under its own weight resulting in less lateral stresses against the sides (Bernal and Reese, 1983).

Another problem in using concrete of low workability arises as honeycombing might occur during concrete placement. This is particularly important in very long shafts with large rebar cages and where vibrating the concrete becomes more difficult. The separation of aggregates from concrete can greatly reduce the amount of contact between the shaft and soil, especially at the shaft base. To achieve higher workability, the water/cement ratio of concrete is increased. However, a high water/cement ratio can cause water to transfer from concrete to the soil adjacent to the shaft. This is referred to in the literature as water migration and is believed to influence shaft behavior by creating a thin softened region of lower shear strength around the shaft.

Meyerhof and Murdock (1953) found that water contents of the clay around a drilled shaft in London clay increased between 2 to 7 percent at the contact surface. The increase in water content diminished at a distance of about 2 inches for shafts constructed using water/cement ratios of 0.4. In other shafts constructed with a water/cement ratio of 0.2, the water content in the clay around the shaft was not altered.

Chuang and Reese (1969) performed laboratory experiments by placing a layer of concrete over remolded soil samples. They found that water transfer from the fresh concrete to the soil samples increased with increasing water/cement ratio. Testing of the resulting specimens in a direct shear device showed that failure did not occur at the concrete/soil interface but rather within the soil at about 3 to 6 mm from the interface. Similar depth of failure surface into the soil has been reported by Dubose (1957) and O'Neill and Reese (1970).

Kulhawy and Peterson (1979) observed that in granular materials, surface irregularities of the shaft control the location of failure, and not water migration into the soil. Beech and Kulhawy (1987) conducted load tests on model drilled shafts and observed that the failure surface was independent of the construction procedure and is rather linked to the soil type and roughness of the shaft surface. Typical failures occurred between 6 and 19 mm (0.25 to 0.75 in) away from the shaft. They argued that shafts with large irregularities such as pieces of aggregate, force the failure surface away from the shaft.

Reese and O'Neill (1988) reported that results of direct shear tests on partially saturated clays revealed that some kind of chemical bonding occurs between clay particles and cement in the concrete. Higher shear strengths were measured at the clay-cement interface than the shear strength of the clay itself.

In summary, observations in the field and model pile studies suggest that the failure surface occurs in the soil and not at the concrete-soil interface. The distance at which failure occurs is small and varies depending on soil properties and shaft roughness. This indicates that even though water does migrate from concrete to the soil around the shaft, there appear to be some benefits with regards to strength resulting from a small amount of chemical bonding between the soil and cement. The higher strength of the soil-cement interface forces the shear failure away from the shaft.

LOAD TRANSFER DURING LOADING

The development of side and tip resistances is dictated by the amount of movement a shaft experiences. Side resistance is mobilized much earlier than that mobilized at the bottom of the shaft. Figure 3 shows how both capacities develop as settlement increases. The amount of displacement needed for full mobilization of side resistance is about 0.2 to 0.4 inches (5 to 10 mm) regardless of the installation method, shaft dimensions, and soil type (Whitaker and Cooke, 1966; Coyle and Reese, 1966). On the other hand, the displacement required for mobilizing full tip resistance is found to be a function of base dimensions. It amounts to about 8% of diameter for driven piles and up to 30% of diameter for drilled shafts (Vesic, 1977).

Appreciable shaft resistance is typically developed before significant load can be transferred to the base, especially in long slender shafts. The settlement required for mobilizing the full base capacity of a drilled shaft is usually too large for a structure to undergo; therefore, only a fraction of the available tip capacity is relied upon in design.

SUMMARY

During the construction of a drilled shaft, soil parameters and properties can be altered dramatically from in-situ values. During the excavation stage, soil is subjected to lateral stress relief around the perimeter of the hole, and to some disturbance at the base. The ultimate capacity of the shaft is affected by the soil type, details of the construction procedure, and the water/cement ratio of concrete.

Possibly the greatest source of variability in the design of drilled shaft foundations is the construction technique. Changes that soil goes through during construction are very hard to quantify and are variable from one site to another. Efforts have been made to characterize shaft behavior base on the comparisons of axial load developed in shafts of same geometry, but with different construction procedures (e.g. dry or wet). The results of these studies sometime contradicted each other, and overall were rather inconclusive.

Specific construction details such as drilling disturbance, time slurry is allowed in the excavation, concrete properties, and imperfect bottom cleanup may have a significant influence on axial load behavior. Consequently, comparing the behavior of shafts constructed dry and wet may fail to provide a meaningful relationship between axial load behavior and excavation method. Analysis of shaft-soil load transfer should take into account how well a drilled shaft is constructed in terms of various construction details.

In the past, water migration from concrete to the soil has been blamed for softening the soil around shafts in clay and thus lowering its shearing strength. It is now believed, however, that some chemical bonding occurs between clay particles and cement that actually strengthen the soil adjacent to the shaft and forces the failure surface away from the soil-concrete interface (Reese and O’Neill, 1988).

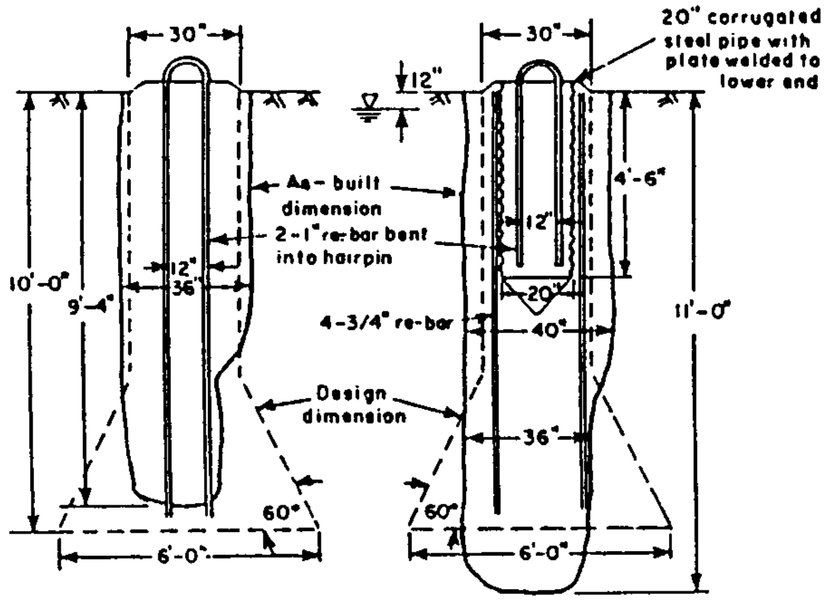

FIGURE 1

Examples of collapse of a drilled shaft bell in cohesionless soils below water table (Kulhawy, et. al, 1983)

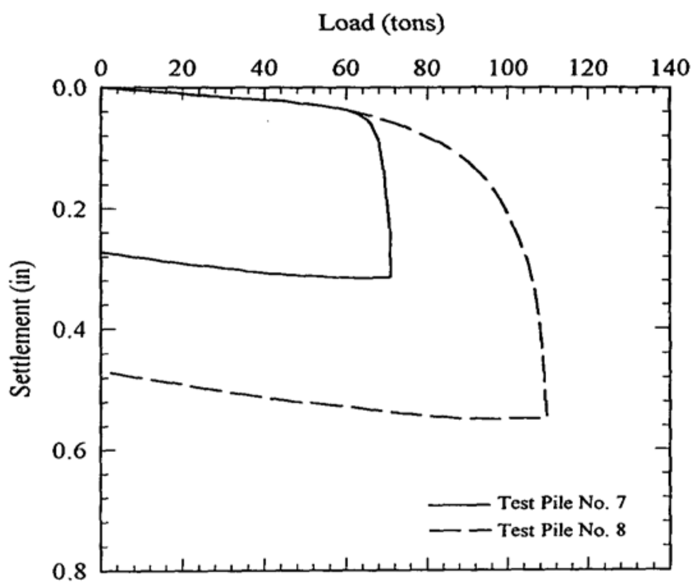

FIGURE 2

Variability in load test results at same site with same construction procedures (Fearenside and Cooke, 1978)

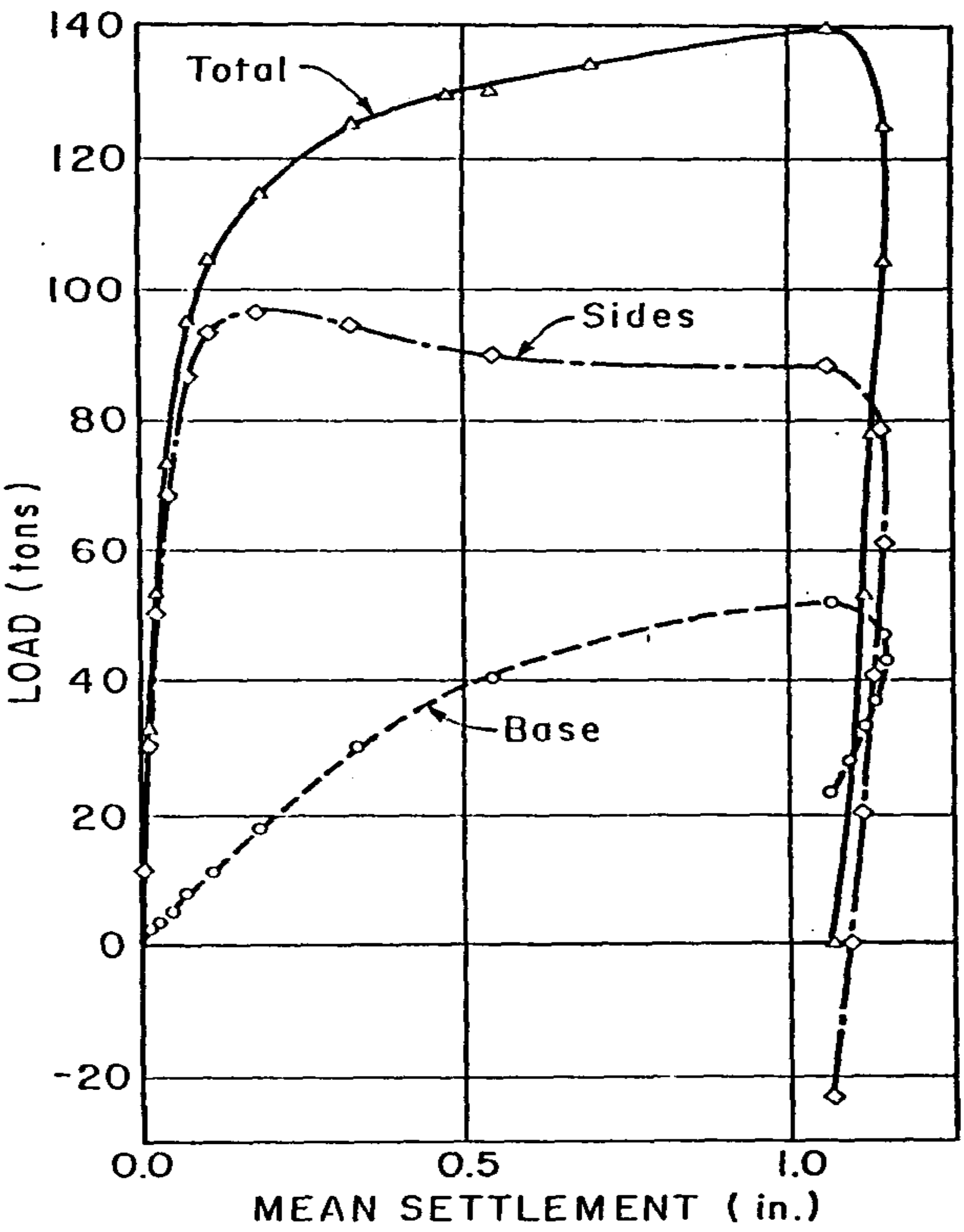

FIGURE 3

Development of shaft and base resistance (O'Neill and Reese, 1972)

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