Construction Practices and Defects in Drilled Shafts

MICHAEL W. O'NEILL

Certain construction practices can lead to defects in drilled shafts. Defects can occur in the form of voids; degraded or debonded concrete; entrapped cuttings, slurry, or groundwater; and geometric errors. They are considered generically according to the place in the construction cycle at which the defect occurs: general defects, defects due to drilling, defects arising from casing management, defects arising from slurry management, and defects related to design. Examples are presented, and suggestions are made for post-construction integrity evaluation techniques that might be effective in locating a given defect and defining its extent. Methods are also suggested for avoiding defects, which often involve subtle factors. Because of modern construction techniques, experienced contractors, and knowledgeable inspectors, relatively few defective drilled shafts are currently constructed.

The wide variety of subsurface soil, rock, and groundwater conditions encountered throughout the United States has given rise to a number of general drilled shaft construction techniques, which often must be modified because of the individuality of subsurface conditions. In effect, each drilled shaft is a unique construction project, complicated by the fact that the drilling and concreting occur mostly out of sight of the drilled-shaft contractor and the inspector. On occasion, structural defects result from incorrect construction or design details, or evidence may exist that such defects may have occurred in the completed shaft that require the services of integrity testing specialists to investigate the nature, location, and extent of the defects. The objective of this paper is to describe how and where common defects can occur and to suggest general methods for investigating their presence. It should be clear that all of these defects can be prevented by contractors and inspectors who are conscious of the actions in the subsurface that occur during construction.

Several methods are in use in the United States for the evaluation of the location, nature, and extent of defects or potential defects in drilled shafts, including the following:

1. Excavation of the soil and visual inspection of the shaft (EVI) (for suspected defects near the ground surface);
2. Reflection of sonic waves, usually from a surface source back to a surface receiver, with various types of signal analysis and, with some systems, wave equation simulation of the signal to identify the defect [termed low-strain testing (LST)];
3. Driving the completed drilled shaft with redundant measurements of force and velocity at the shaft head and interpreting the defect through the use of stress wave theory [termed high-strain testing (HST)];
4. Backscatter gamma logging (GL), which gives information on concrete density within about 0.1 m of the nuclear probe;
5. Crosshole ultrasonic testing (UST), in which velocities of shear and compression waves are measured between two instruments in a shaft and from which concrete quality can be inferred;
6. Drilling and coring through the shaft (CD); and
7. Slow or rapid quasi-static load testing of the drilled shaft (QSLT).

Methods 1–3 and 6 can be used if the decision is made to investigate integrity after construction has been completed, although Method 2 should be performed with redundant measurements or special acoustic source hammers if it is to be used to distinguish defects within about 10 ft (3 m) of the top of the drilled shaft. Methods 4 and 5, which involve searching for anomalies, require that access tubes be placed in the shaft to be tested and must be planned before construction. Method 7 is appropriate only if systematic defects are suspected on a large number of shafts, although new methods of conducting quasi-static loading tests using slow-burning explosives may make load testing of individual shafts with nonsystematic defects economically feasible. Procedures not included in this list, including vibration of the shaft head and probing the exterior of the shaft, are occasionally used. Baker and Khan (*1*) describe many of these methods in detail and discuss other integrity-evaluation methods that have been used in the Chicago area. They also suggest that a single method may not always provide definitive results and recommend that multiple procedures be used wherever feasible.

TYPES OF CONSTRUCTION

Reese and O'Neill (*2*) describe three general techniques for constructing drilled shafts: (a) the dry method, in which a borehole is excavated and backfilled directly with concrete; (b) the casing method, in which a temporary casing lines the borehole to prevent caving of soil or intrusion of groundwater until the concrete can be placed, after which the casing is usually removed; and (c) the direct slurry displacement, or "wet," method, in which a drilling fluid is used to stabilize the borehole during excavation and the fluid is displaced directly by placing concrete under the fluid using a tremie or pump. A number of variations on the casing method are common: (a) drilling the borehole to completion and dropping a casing into place to prevent long-term sloughing of soil or rock into the borehole (when conditions permit); (b) drilling

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Department of Civil and Environmental Engineering, University of Houston, Houston, Tex. 77204-4791.

the borehole under a fluid to bypass waterbearing or caving soil or rock layers, then sealing the casing into an impermeable material below the bypassed layer, followed by removal of the fluid from inside the casing; (c) driving the casing directly into a material of low permeability, usually through cohesionless soil with a vibratory driver, and excavating the material from within the casing; and (d) setting casings that are successively smaller in diameter in the borehole as required to develop seals in deeper and deeper strata (when excavating overburden over weathered rock or in boulder fields).

With each method of excavation and borehole retention, concrete must be placed in the borehole in such a way that it does not produce voids or seams of weakness. Furthermore, it must displace any extraneous cuttings, water, or drilling fluid in the excavation. These performance criteria require a fluid concrete with coarse aggregate as small as is feasible and slump generally in the range of 7 to 9 in. (175 to 225 mm). In addition, slump loss must be controlled such that if delays occur in placing the concrete, the concrete will retain at least marginally acceptable fluidity. The use of well-graded aggregate and high cement factors (6.5 to 7 sacks per yard) is advisable when water, even in small amounts, will be present in the borehole during concreting.

CATEGORIES OF DEFECTS

Common defects arising from incorrect application of the details of the construction procedures just described were first described by Reese and Wright (*3*). These and other defects described here can be placed in several categories for purposes of discussion. In this context, defects are defined as structural flaws that may or may not affect the serviceability of the foundation. Only a careful evaluation of the location and extent of defects relative to zones of high load transfer and high internal stresses can determine whether the defect requires repair. Repair methods are beyond the scope of this paper but are discussed by Baker and Khan (*1*), Reese and O'Neill (*2*), and others.

Categories of defects are as follows:

- Defects arising from general construction problems,
- Defects arising from drilling problems,
- Defects arising from casing management problems,
- Defects arising from slurry management problems, and
- Defects resulting from design deficiencies.

Although concreting is an important step in the construction cycle and is critical in the production of a competent drilled shaft, it is not categorized separately because concreting is involved directly or indirectly in all of the categories. The last class of defects is not, of course, caused by incorrect construction but by ignorance on the part of the designer of the limitations of construction procedures or by errors in the geotechnical characterization of subsurface materials. Examples of specific defects in each of these categories are given next.

Defects Arising from General Construction Problems

Defects or construction errors leading to defects are depicted here schematically. To assist in the understanding of the intent of the various schematics, a legend of symbols is provided in Figure 1. In Figure 2 are shown four common general defects: (a) placing concrete by free fall without directing the stream away from reinforcing steel or the sides of the excavation, (b) excavating a borehole for a drilled shaft near a shaft that has just been concreted, (c) placing concrete through water that has accumulated in the borehole, (d) drilling the shaft out of position, and (e) developing mudwaves in surface soil without protecting the newly concreted shaft, placing lateral loads on

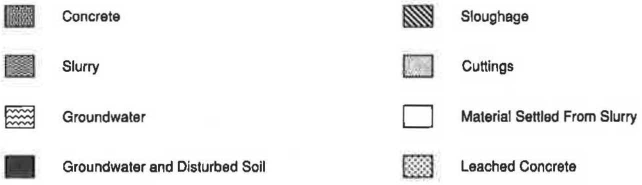

FIGURE 1 **Key to symbols.**

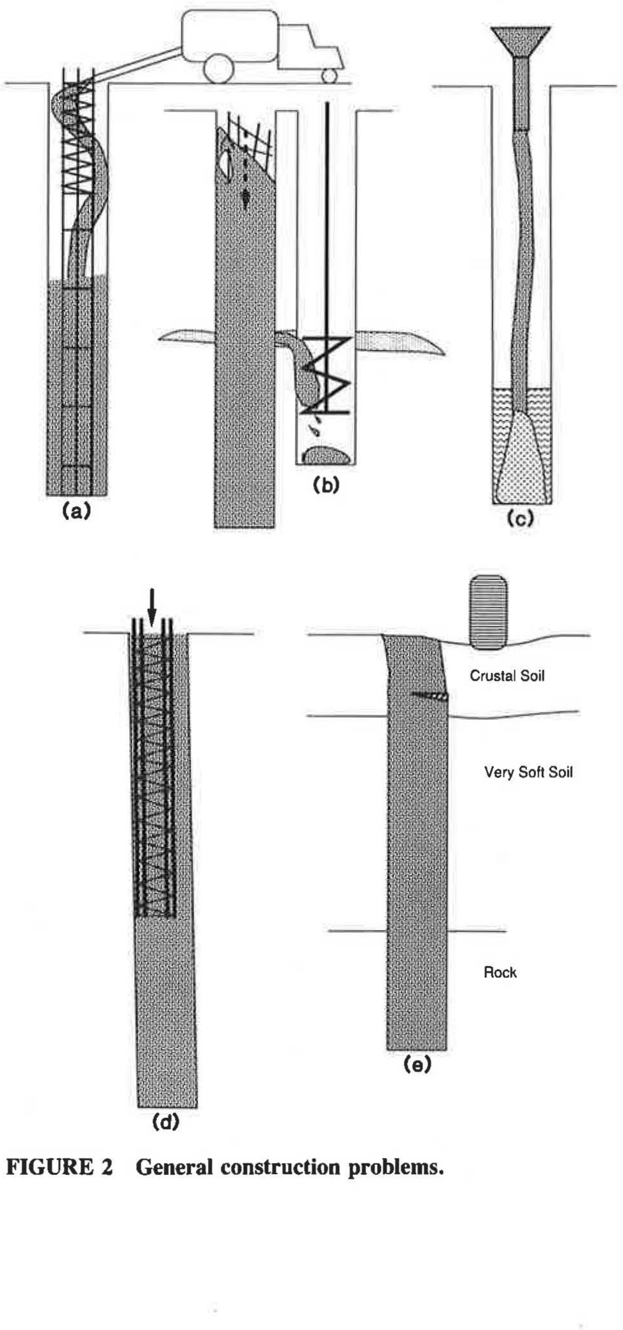

FIGURE 2 **General construction problems.**

the setting or green concrete at the shaft head, which causes cracks.

In Figure 2a the problem is not free fall. With small [0.75-in. (19 mm)], coarse aggregate, free fall of concrete through air to a direct impact in excess of 20 m will not cause significant segregation unless the mix design is inappropriate. However, if the stream of concrete flows through rebar or bounces off the side of the hole, segregated material will result, and small voids can develop adjacent to the rebar. To the investigator of structural integrity, segregated concrete will appear in the LST, UST, or GL to have either lower *p*-wave velocity or to be less dense than competent concrete, although minor segregation problems and voids may not be detectable.

A layer of cohesionless soil traverses both shafts in Figure 2b, such that lateral support of the concrete is removed in the recently placed shaft while the second shaft is excavated. The fluid concrete from the first shaft breaks through as the soil caves into the second excavation, causing the setting concrete to slump, dragging and racking the cage and producing voids. If the voids are large enough (occupying about 25 percent of the cross-sectional area of the shaft or greater), they can be detected by LST. They can also be detected by UST or GL, but only if the access tubes are fortuitously placed in the correct position. Steel racking without production of voids in the concrete is difficult to assess remotely. One must generally rely on visual observations of the condition of the steel at the surface during construction or EVI (with chipping of concrete down to the rebar) to ascertain whether racking may have been produced.

In Figure 2c several inches to several feet of water may have accumulated in an otherwise dry borehole before concreting. The water has either not been pumped out or is flowing into the borehole so quickly that pumping is ineffective (in which case the contractor should, but may not, change to an alternate method of construction, possibly the wet method). The water mixes with or leaches the cement out of the concrete and forms potential defects that can be investigated as per Figure 2a plus CD (drilling down to just above the location of the suspected defective zone and coring through that zone). Unless copious amounts of water have mixed with the concrete, however, this defect will be difficult to detect. Similar problems can occur when concreting under a drilling fluid when either the tremie or pump line is inadvertently lifted above the surface of the fluid concrete. LST is not effective unless cement leaching is nearly complete or there is a significant length of degraded concrete over a large part of the cross section (>30 percent).

In Figure 2d the contractor has constructed the shaft out of position, inadvertently on a slight batter, and perhaps too short, yet the reinforcing cage was placed in the proper position (centered on the load). This leads both to inadequate concrete cover on the rebar and eccentric loading of the concrete. In general, drilled-shaft contractors can place shafts so that the center of the excavation is within 3 in. (75 mm) of the planned position and is vertical to within 2 percent. The effect of this tolerance should be analyzed by the designer (for example, by using computer solutions to assess the effects of combined axial and lateral loads resulting from the eccentric load) to determine whether shafts this far out of position (or farther) are satisfactory structurally. It is obvious that if the shaft is small in diameter, these tolerances can result in a load being applied outside the Kern point. Even though this problem is categorized as a construction problem, the designer can mitigate its effect by designing reinforcing cages with at least 6 in. (150 mm) of cover, to allow the cage to be translated 3 in. (75 mm) within the excavation while still leaving 3 in. (75 mm) of actual cover. If necessary, the designer can specify the shaft diameter slightly larger than is necessary from a structural column or geotechnical capacity perspective to accommodate the tolerance. The only aspect of this problem that can be assessed by current integrity testing methods is shaft length, which can be determined by LST, HST, or CD. Possible omission or undersizing of a bell is a related error. Short shafts or undersized bells, if thought to be systematic, can be evaluated by static or dynamic QSLT. It is often possible to locate a bell with LST, but it is difficult to ascertain whether the bell has been cut to the correct diameter.

The defect in Figure 2e occurred after the shaft was successfully installed but while the concrete was still wet, or green. Perhaps mudwaves in the crustal soil were produced when the contractor moved the drilling or concreting equipment. The incidence of this defect is usually indicated through optical survey techniques (lateral displacement of the shaft head) and confirmed by near-surface EVI. Such a defect is almost always avoidable by using short sections of permanent casing to protect the shaft head or by using long-bridge crane attachments in placing shafts.

Defects Arising from Drilling Problems

Common defects produced by drilling are shown in Figure 3. In Figure 3a the contractor is constructing the shaft using the dry method. Cuttings are smeared on the inside face of the borehole as the drilling tool (auger or bucket) is extracted. The problem, common when drilling in clay-shale and mudstone, will virtually destroy side resistance if not corrected. The resulting defect is detectable by EVI, HST, and QSLT. Prevention is achieved by using side cutters on the auger or spiral roughеners on buckets to scrape the loose material off the sides of the borehole before concreting.

Figure 3b shows the general problem of sloughing of soil during concreting in the dry construction method. Sloughing may be an unavoidable natural phenomenon that must be dealt with through the use of casing or drilling fluid, or it may occur through contractor's actions such as developing suction pressures beneath drilling tools, destabilizing the borehole wall, creating stress waves in quasi-stable soil (e.g., clayey or silty sands) by placing concrete by free fall. Intrusion of surface material is a relatively common defect that is preventable with the use of temporary surface casing. Sloughing of the bell may occur where seams or layers of granular soil are present in otherwise stable clays or if the clay being excavated is heavily fissured or slickensided. The practice of making test excavations before finalizing the design will help to identify situations where sloughing may exist. Sloughed cohesive material encapsulated within the concrete is detectable by most integrity testing methods, although it must usually cover at least 25 percent of the cross-sectional area of the shaft to be detected by LST or HST techniques.

A simple drilling error has been made in Figure 3c. The excavation was drilled with a tapered auger, but the contractor did not use a flat-bottomed tool to remove the cuttings from the conical base. As a result, the cuttings are trapped on the

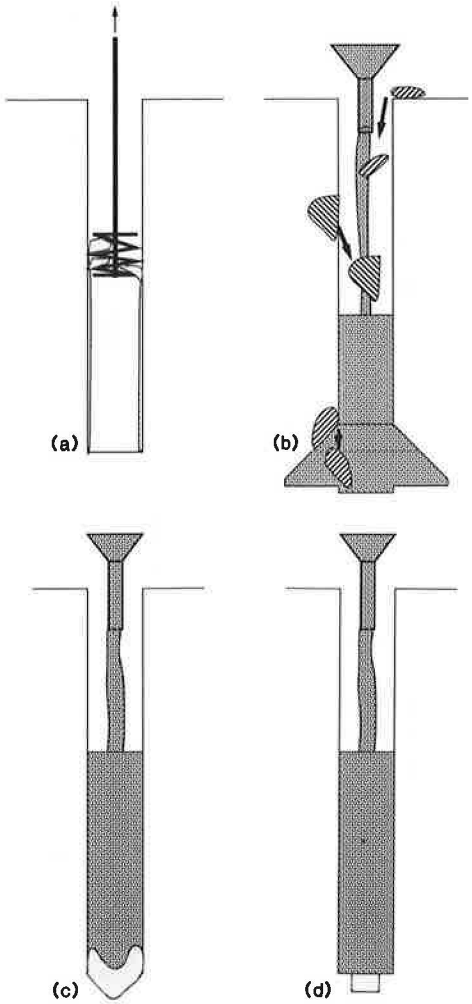

FIGURE 3 **Drilling problems and consequences.**

bottom as the concrete is placed, which could be a serious defect if the shaft carries a significant amount of its load through base resistance. CD and HST are the most effective means to infer such a defect, although EVI has been used where the shaft is shallow and has not been loaded (or where the load can be removed from the shaft). Other examples of ineffective cleanout can be envisioned; one is shown in Figure 3d. If the contractor does not have drilling equipment powerful enough to excavate a large-diameter borehole in soft rock, he or she may drill a pilot hole with a smaller tool and then "ream" the hole using an overreaming tool that is not capable of excavating down to the base of the pilot hole, which is not cleaned and remains full of cuttings. A similar problem can occur when the borehole is drilled properly but cleaned with a bucket or pan that is smaller in diameter than the borehole. As with the defect in Figure 3c, CD and HST are most effective in detecting this type of defect.

Defects Arising from Casing Management Problems

In the experience of the author, more defects have occurred from the use of temporary casing than from any other cause. A common defect produced by using casing that is excessively rough on the inside or by waiting until excessive concrete slump loss has occurred before extracting the casing is depicted in Figure 4a. Shearing stresses sufficient to lift the column of concrete have developed between the steel and concrete, which causes the concrete column inside the casing to rise and place tension on the concrete just below the original elevation of the bottom of the casing, causing a "neck," with the space previously occupied by the concrete becoming filled with soil or groundwater. Small voids may also form around the rebar if the slump loss is excessive as the concrete level rises. At times, instead of forming a neck, the concrete may completely separate, forming a total discontinuity across the shaft. Upward movement of the concrete or rebar cage is the best indication of a potential defect of this type, which can best be investigated after construction by LST, HST, UST, or GL. Large necks and complete separations are relatively easy to identify with all of these procedures; however, small necks confined to the area outside the rebar cage may not be detectable by any but the GL method.

In Figure 4b the concrete actually set within the casing before the contractor could extract it, and the casing has been left in the hole. Because the casing is normally placed in a slightly oversized borehole, it may not be possible to ensure intimate contact between the casing and soil, and much side

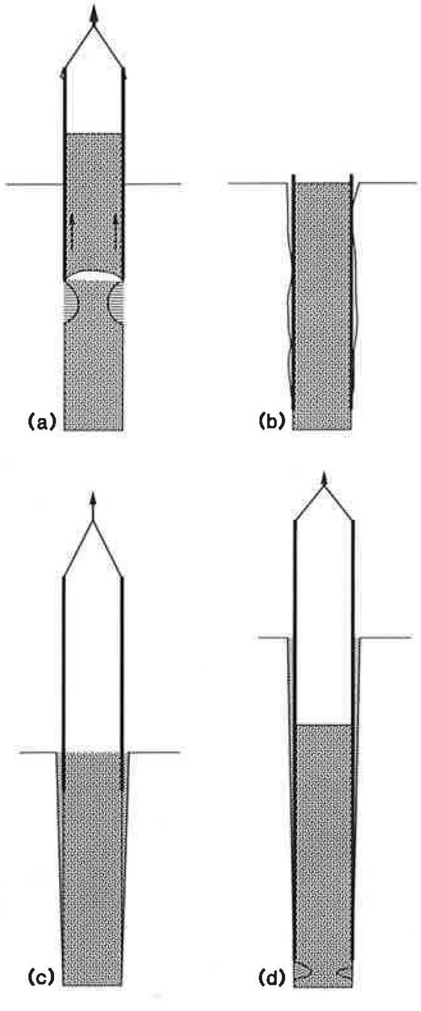

FIGURE 4 **Common casing problems.**

resistance may be lost within the cased zone (*4*). Even if the casing has been vibrated into position and intimate contact exists between casing and soil, the side resistance may still be less than that used in design because shearing resistance between steel and soil may be less than that assumed in design between concrete and soil. HST and QSLT are currently the only effective means to evaluate the effects of a defect of this nature. A related defect is shown in Figure 4c. The concrete has not bonded to the casing, but either the slump loss is so severe or the initial slump so low that concrete does not flow into the annular space between the casing and the borehole wall to displace groundwater or loosened soil. The consequences of this defect and means of evaluation are identical to those for the defect in Figure 4b. It should be obvious that the defect would be exacerbated by vibrating the concrete, which would fold trapped groundwater into the column of concrete, thereby spreading the defect into the interior of the shaft.

Failure to maintain fluid head within the column of concrete in the casing can also produce defects similar to that shown in Figure 4d. Here, the slurry used to drill the borehole initially has its head at the ground surface, but the concrete head is considerably below the ground surface when the contractor breaks the casing seal and begins removing the casing. Because there can be significant head losses as the concrete begins to flow downward, outward, and into the annular space, the pressure in the slurry can actually exceed that of the fluid concrete at the base of the casing, producing a neck of slurry or promoting mixing of the slurry with the concrete. This type of defect can sometimes be found by LST, HST, UST, or GL, and, if serious mixing with the concrete occurs, by CD (drilling down to the level of the suspected defect, at the elevation of the base of the temporary casing, then coring through the potential defect zone). This defect can also be caused by failure to balance fluid concrete pressure within the casing with external groundwater pressure, which can be a particularly severe problem (but easily solvable by using casing extensions) if the groundwater pressure is artesian. In any event, use of dense concrete and maintenance of concrete head above the groundwater or drilling fluid head should be sufficient to prevent this defect.

Some less common defects associated with casing management are shown in Figure 5. In some geologic settings, telescoping casing is used. In Figure 5a, the outer casing is placed through overburden soil, and the inner casing is placed into decomposed rock. The designer has called for high end bearing stresses and has required the inner casing so the base of the shaft can be dried out, cleaned, and inspected down-hole. Groundwater accumulates in the overlap zone between the two casings. The contractor places concrete to near the top of the inner casing (slightly above the level of the standing groundwater) and slowly extracts the casing, allowing the fluid concrete to flush the standing groundwater up between the two casings. If the inner casing is too short or the contractor overpours the inner casing, the free groundwater will become trapped outside the rebar cage or may become mixed with the fluid concrete. This defect can be difficult to detect, but UST, GL, or CD may reveal the defect if voids are large or if enough water has mixed with the concrete. HST is not a viable option because the shaft needs to be driven with a permanent set for proper evaluation, and it is presumed that the rock at the base is too strong to permit driving the shaft with a permanent set.

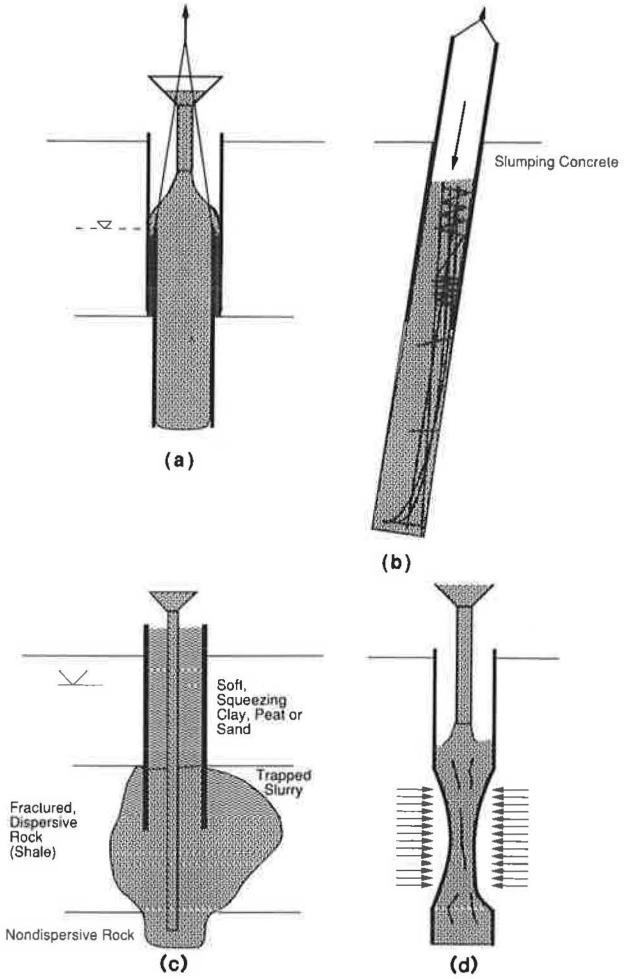

FIGURE 5 Less common casing problems.

In Figure 5b the shaft has been constructed on a batter, but the cage becomes caught on some object inside the casing (joint, caked concrete, etc.), which, along with the downward-moving concrete, causes torsional buckling of the cage. The only viable integrity test for this condition is observation of the movement of the steel during construction. It should be immediately obvious to an experienced construction inspector that cage buckling has occurred. An unusual, but possible, condition is shown in Figure 5c. A contractor has pushed or driven casing through a soft surficial deposit into a fractured shale formation. In order to excavate through the water-bearing shale to an underlying rock formation, the contractor uses either water or slurry to balance the water pressures in the shale. However, many shales and related geologic materials are dispersive, and if appropriate additives are not used in the drilling fluid, the condition shown in the figure may develop. When the concrete is placed (underwater, through a tremie), it cannot flow up behind the casing to the ground surface because the soft surficial soil is impinging tightly against the casing. The trapped slurry is under pressure and may fold back into the concrete within the planned volume of the shaft as the casing is removed further. LST methods can determine whether an enlarged zone has developed, inferring a defect. UST, GL, and CD methods are effective in detecting whether the fluid has folded back into the concrete in the area of the shaft.

Not to be overlooked is the problem of collapse of casing due to high lateral ground or unbalanced water pressures, particularly when the casing is evacuated (see Figure 5d). Such problems most frequently occur in drilled shafts of 48-in. (1.2-m) diameter or less if casings with wall thicknesses of less than 0.50 in. (12.7 mm) are used. For casings of larger diameter, higher wall thicknesses are frequently necessary. If the casing is long and designed to be left in the hole, it is possible that a collapse near the bottom of the casing will go undetected during the construction process. If the casing is to be withdrawn during concreting, it may not be possible to do so. The resulting structural defect is obviously potentially serious, even if no side resistance is employed in the design. The proper approach to uncovering a defect of this type is to caliper or otherwise determine the diameter of the inside of the casing before placing concrete, although a severe collapse will normally be detectable after concreting by LST and HST, because the resulting neck will result in reflection of energy in the form of tension waves to surface receivers.

Defects Arising from Slurry Management Problems

Underwater construction of drilled shafts has become relatively common during the past 20 years. Often, drilling slurries consisting of bentonite, attapulgite, or polymers are used in lieu of casing to maintain borehole stability during drilling and concreting. Figures 6 and 7 show several defects that can be produced by inattention to construction details. In Figure 6 are shown three situations in which soil (usually sand or silt) in the drilling slurry is not handled properly. In Figure 6a either the base of the shaft excavation has not been cleaned properly (with a cleanout bucket or pan the same diameter as the borehole, a submersible pump, or an air lift), or there is a delay in placing the cage and tremie that has allowed granular material in temporary suspension to settle to the bottom of the slurry column. When the concrete is placed through the tremie (or pump line), the material that has settled from the slurry is pushed to the side, forming a bullet-shaped shaft base, reducing base capacity. In Figure 6b the initial surge of concrete from the tremie has fortuitously caused the concrete to flow under the settled material and float it out. Unfortunately, as the settled material rises it may become loosely attached to the rebar or the side of the borehole and not be fully displaced by the fluid concrete.

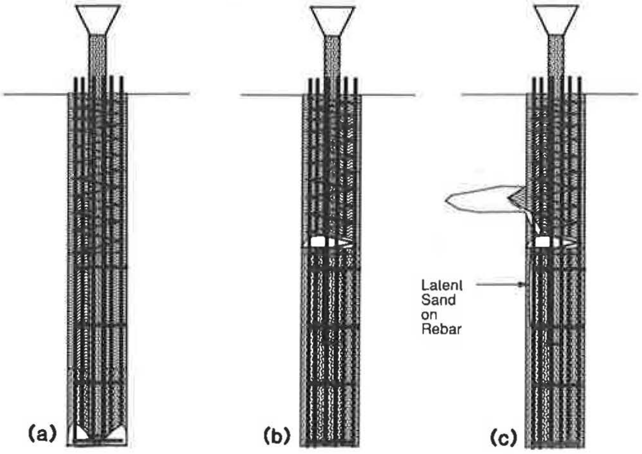

FIGURE 6 Common slurry problems.

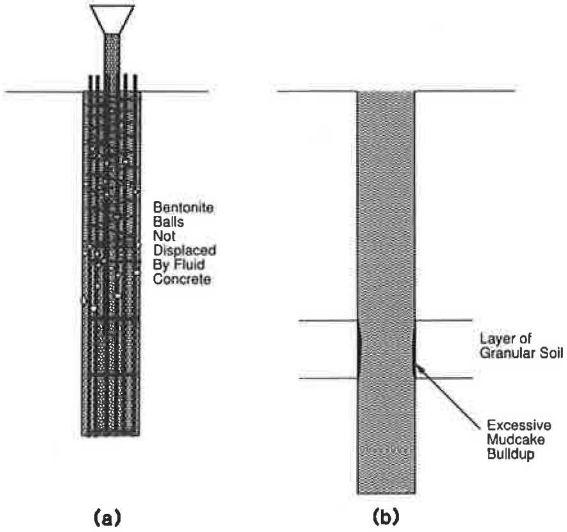

FIGURE 7 Slurry problems associated with improper slurry handling.

The same effect can also occur even if the base is clean at the time of setting the tremie when the slurry is carrying a sand or silt content that is too high to be held in permanent suspension and allows the suspended material to settle on the top of the rising column of concrete. Recent occurrences of this effect have been observed with polymer slurry, which normally does not suspend sand. Either the contractor did not allow sufficient time for the sand in suspension to settle to the base of the shaft, where it could be removed, or the polymer itself had been precipitated by free calcium, which encapsulates sand and silt particles, forming a fluffy, viscous conglomerate often described as "oatmeal." (If such material forms, it can be removed by standard cleanout techniques if it is identified before concreting.)

A related defect is depicted in Figure 6c. In this case the cleanout procedure is correct, and the slurry has been desanded and desilted. However, the drilling operation produced an undercut zone in a granular soil stratum (for example, by sucking the soil into the hole as a result of excavating the hole too quickly or not using pressure relief devices on the drilling tools), allowing sloughing of soil down onto the rising concrete column. When layers of granular soil become undercut, slurry, even with well-developed filter cake, may not be able to ensure hole stability. A similar situation may arise even if the granular stratum is not undercut but is loose and contains no bonding agent, such as clay. (Sloughing can be prevented by weighting the slurry with agents such as barium sulfate.) HST and CD are usually the most effective methods to evaluate a "mushy base" defect (Figure 6a). LST methods normally do not distinguish between the natural materials below the base and loose materials that have settled from the slurry. QSLT can be used if the defect is thought to be systematic. The defects produced by the practices shown in Figures 6b and 6c can be difficult to detect with any of the methods discussed here, although EVI, with chipping of the concrete to expose the rebar, may be useful where appropriate. In the past, some problems of this type have been uncovered by merely wiggling the longitudinal rebar manually because the coating of granular soil prevents it from bonding to the concrete.

The defects implied in Figures 7a and 7b can occur when a contractor is inexperienced in slurry construction. In Figure 7a the contractor has attempted to mix mineral slurry (bentonite or attapulgite) with water in the borehole. Not all of the solids hydrate, resulting in small balls of unhydrated material that float in the slurry and can become entrapped in the rebar or against the side of the borehole during concreting. This defect is virtually impossible to detect except by EVI. A more subtle problem occurs in Figure 7b. Mineral slurries tend to form a filter cake on the side of the borehole in granular strata (*5*). These cakes tend to become thicker with time, as a result of both filtration (loss of drilling fluid into the stratum) and thixotropy. Leaving mineral slurry in the borehole for more than a few hours without agitation can result in cakes so thick that they cannot be displaced by the upward flow of concrete, resulting in a loss of side resistance. This problem can also occur when casing is used because the cakes can also form from the slurry standing in the annular zone between the casing and the borehole wall. Whereas prevention is straightforward (continual agitation of the slurry or "overreaming" of the borehole before concreting), detection of the defect can be difficult. EVI can be used if the granular material is near the surface, and HST can be effective if the granular layer is deep and the shaft can be driven with a set. LST can possibly provide an indication of the defect if it has significant length and the cake is present around the circumference of the shaft. For example, the measured waveform on a pulse-echo test may be almost perfectly flat in the time interval representing the length of shaft coated thoroughly with a mudcake. Were it not coated, some small wave activity would normally exist as a result of the impedance afforded by the development of shearing resistance between the concrete and the undisturbed soil or rock. Such an interpretation should not be attempted at present, however, without concurrent low-strain wave equation modelling of the phenomenon.

Other miscellaneous defects associated with slurry construction are shown in Figure 8. A slurry-filled (or possibly water-filled) borehole has been excavated into a karstic limestone in Figure 8a. A large, submerged cavity is bridged by debris, such that during concreting the column of fluid concrete rises past the cavity; however, as the column of concrete rises farther, pressure from the column causes it to break though the debris, and the concrete, being heavier than water, is thrust into the cavity. This action allows the concrete level in the shaft to fall, possibly producing small voids around the rebar, and forces the water in the cavity back into the area of the shaft, potentially mixing with the concrete or leaching the cement out of the concrete. Any method that is capable of identifying low-modulus concrete, such as UST, GL, or possibly LST, will be helpful in evaluating the defect. LST can also be used to identify the vertical extent of the affected zone if the bulge is sharp.

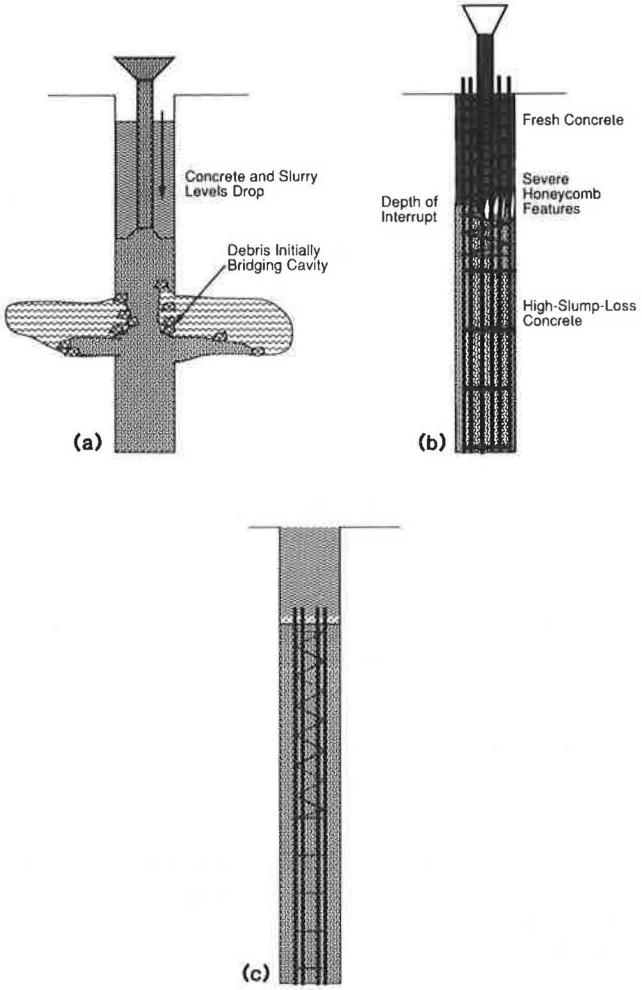

FIGURE 8 Other slurry problems.

A problem associated as much with concrete management as with slurry management is illustrated in Figure 8b. Concrete placement in the wet method of construction should be continuous. When the flow of concrete to the shaft head is interrupted for a significant period of time, it may be necessary for the contractor to remove the tremie or pump line from the column of concrete to avoid having it captured by the setting concrete. When fresh concrete arrives, the contractor may place the tremie or pump line back into the concrete column and try to reestablish flow per the procedure used to initiate flow from the base of the borehole. This process may thrust the upper portion of the old, stiffer concrete (and perhaps sand that has settled out of the slurry during the delay) outward and through the rebar. If slump loss in the old concrete is too great, it may not flow though the rebar properly, producing honeycombing. If the interrupt is near the surface, EVI is the most appropriate integrity test. GL can be useful if the voids are near the access tube. UST is only of use if the voids are large and extend into the interior of the cage.

In Figure 8c the shaft has been drilled and concreted properly, but plans call for cutoff below grade to accommodate future construction operations. This must either result in a cold joint below grade when the shaft is concreted, or the contractor must pour the concrete to grade and chip away the excess later. If there is to be a cold joint, the contractor must ensure that any debris or contaminated concrete on the surface of the rising column of concrete is removed and sound concrete exposed. (This might be done, for example, by pouring the concrete perhaps 0.5 m above the joint, placing a liner in the borehole well down into the unset concrete, evacuating the slurry from inside the liner, and cleaning the joint, by hand or remotely, before the concrete sets.) A defect will ensue if the joint is not properly constructed. Such a defect, if investigated after placement of concrete above the joint, can often be detected by CD, EVI, or LST.

Defects Resulting from Design Deficiencies

Not all defects are caused by workmanship errors on the part of the contractor. For example, the practice still exists in some organizations to use drilled shafts to replace driven piles on a one-for-one basis. This can lead to shafts that are long and slender yet have high percentages of reinforcing steel (required to resist lateral loading in a cross-section with a low moment of inertia). (See Figure 9a.) Shafts designed to be 18 in. (0.46 m) in diameter or less make it difficult to clean the base and for concrete to flow freely through and around the reinforcing steel cage. Voids in the zone outside the cage are possible even with high-slump concrete. Some agencies, in anticipation of such problems, place access tubes in the shafts for GL or UST tests, which leaves even less room for the flow of concrete and makes the problem even more acute. This sort of design defect is preventable if shafts are designed with diameters no less than about 0.75 m and the reinforcing steel arrangement allows for at least 5 in. (125 mm) of space between bars and 6 in. (150 mm) between the bars and the face of the borehole (by bundling bars, if necessary).

Situations arise in which drilled shafts are placed in alluvium or colluvium containing groundwater flowing horizontally at greater than about 1 ft/sec (0.3 m/sec) (Figure 9b). Even with proper construction the cement can be leached from the concrete by the flowing groundwater. In such a case it may be prudent to design the shaft with a permanent casing or liner through the zone of rapid groundwater flow, discounting side resistance in that zone. GL and UST provide the best chance of detecting this type of defect.

Other design-related defects, not shown in Figure 9, include placing bearing stresses on unreinforced bells that are too large, producing tension cracks in the concrete, misinterpreting the strength and compressibility properties of the intended base bearing stratum, specifying an inappropriate concrete mix design (inadequate flow properties; not resistant to leaching, sulfate attack or other environmental factors at the construction site), and gross errors in establishing the cross-section to take lateral or tension loads leading to significant tension cracking. LST methods are sometimes able to distinguish tension cracks in the concrete. Effects of other design errors may become evident only from the ultimate integrity test, distress in the superstructure.

PERSPECTIVE

Although the subject of this paper is defective drilled shafts, most drilled shafts, when designed properly, are constructed as designed and without incident when competent contractors are employed. Sliwinski and Fleming (*6*) reported a study of LST-type integrity tests on 5,000 drilled shafts in the United Kingdom during 1982. That study is summarized in Table 1.

Only about 1 shaft in 200 developed a detectable defect (covering perhaps one-quarter of the cross section) during drilling and concreting. Of these, the vast majority of defects occurred within 5 m of the surface, which would make their inspection by EVI and CD feasible in many instances. Only about 0.1 percent had detectable deep-seated defects that would require more sophisticated investigation techniques.

The present state of the art, however, does not permit the inference of small defects, unless they are fortuitously encountered by cores or happen to develop around access tubes

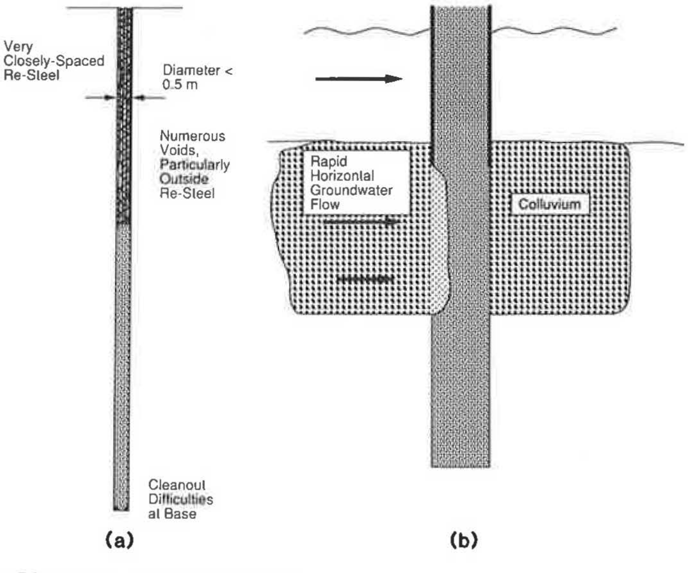

FIGURE 9 Design problems.

TABLE 1 CLASSIFICATION OF DEFECTS IN 5,000 DRILLED SHAFTS CONSTRUCTED IN THE UNITED KINGDOM IN 1982 (*5*)

Type of Defect	No. of Shafts Encountered
Soil contamination in top 2 m	18
Soil contamination or necking for depths of 2 - 5 m	7
Poor quality concrete somewhere along shaft	4
Voids adjacent to shaft with loss of concrete	2
Defects due to trimming top of shafts or to traffic on site	42
Total No. of Defects	73 (1.5%)
Total No. of Defects Excluding Post-Construction Trimming and Damage from Traffic	31 (0.6%)

for GL tests or UST, or are uncovered by meticulous EVI. Despite advances in the state of the art of nondestructive evaluation of drilled shaft integrity, it is important that construction defects be minimized and critical that they be essentially eliminated on drilled shaft foundations that afford no redundancy. This requires expert and diligent inspection that can only be achieved by teaching drilled-shaft inspectors to be wary of situations, such as those discussed in this paper, that produce defects. The Association of Drilled Shaft Contractors and the Deep Foundations Institute (*7*) and Greer and Gardner (*8*) provide excellent references for training and for use in the field by DOT inspectors.

For an organization, such as a state DOT, that has no record of experience in drilled shaft foundation performance, it is recommended that a nondestructive evaluation scheme be selected and applied to a representative number of drilled shafts on each construction project. Frequency of testing should be dictated by the risk of foundation failure that is acceptable for an individual project. For example, every drilled shaft for single-shaft bents in a major interchange connection (no redundancy), every fifth shaft in a normal bent or abutment in a major bridge, or the first drilled shaft constructed on a minor structure might be tested routinely. A policy of testing shafts nonroutinely in which inspectors observe evidence of the potential defects discussed here should also be implemented. As the confidence level in an organization grows, routine tests could be conducted less frequently. One possible routine testing scheme would be to use LST, possibly in a form suitable for detecting near-surface defects, followed by CD when potential defects are indicated. Nonroutine tests could encompass any or all of the methods described here, depending on the nature of the suspected defect.

SUMMARY

A number of relatively common situations that produce defects in drilled shafts have been identified, and general methods that may be appropriate for investigating those defects, illustrated in Figures 2–9, have been suggested. Other defects are possible, as are other integrity testing methods. At present, no definitive method or combination of methods can be recommended for detecting all defects. The subject remains an important research topic.

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