Construction and Design of Drilled Shafts in Hard Pinnacle Limestones

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Construction and design of drilled shaft foundations in hard pinnacle limestone requires flexibility from all parties involved due to the variability of the subsurface conditions. Strategies that have been found useful in the Birmingham, Ala., area are described. The importance of well-trained and experienced field personnel in these conditions is noted. It is also vital that engineers understand the construction challenges so as to provide both quality assurance and cost-effectiveness in design and in the specifications.

In the southeastern and eastern United States, many areas of the Valley and Ridge as well as the Cumberland Plateau physiographic regions are underlain by hard limestones and dolomites that have highly irregular surfaces due to weathering. These rocks generally weather to form clayey soils that typically fill the "slots," as shown on Figure 1 (*1*). Boulders often exist in the residual soil, and solution cavities can be present in the rock. The rock itself can be quite hard, with compressive strengths often exceeding 10,000 psi.

Foundation construction of heavy structures including highway bridges in pinnacle limestone is often accomplished using drilled shafts. Steel H piles are a common alternative to drilled shafts, but the very large load-carrying capacity of shafts founded on hard rock often serve to make drilled shafts more cost effective. Additionally, it is possible to inspect the shaft-bearing stratum, including probing beneath the bearing surface, so as to provide reasonable assurance that adequate bearing material is reached. The challenges to using drilled shaft foundations in these areas involve the erratic nature of the rock bearing surface, the difficulty in drilling the hard rock materials, and the need to make engineering decisions in the field.

GENERAL CONSTRUCTION CONSIDERATIONS

Overburden Soils

Because the residual soils tend to be cohesive, drilling through soil is typically performed in the dry with a casing set after rock is encountered. Although groundwater may be shallow in some instances, sand and/or gravels that would provide significant flows are not common. Groundwater is normally encountered in significant quantity upon reaching bedrock. Chert nodules and layers are sometimes present, and these cherts are extremely hard. Chert beds and occasional boulders may require rock excavation techniques.

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Rock Excavation

The hard limestones are quite difficult to drill with conventional rock augers, and southeastern contractors tend toward downhole drill and shoot methods. Blasting is performed using delayed charges, in which the charges in several center holes are shot first, followed by light charges around the periphery of the hole. Generally only about 2 to 3 ft of hole is advanced at a time. The steel casings are tipped with carbide for use as a core barrel, but coring is slow and expensive. After about 2 ft of rock is drilled and blasted with light charges, the casing is advanced by coring and the rock removed with a rock auger. Air-operated "cluster drills" are effective in dry environments but are not widely used where significant seepage is expected. The large volume of air used to lift cuttings has been known to blow into nearby shaft excavations. At least one southeastern contractor has rigged a bucket catcher above the cluster drill to catch cuttings and minimize the necessary air pressure and volume in deep holes.

In general, seepage of groundwater through slots, fissures, and fractures preclude advancing the hole without advancing the casing. The hardness of the rock material itself generally does not favor slurry drilling techniques, as drilling tools that are used with slurry tend to be less efficient and very costly at drilling hard rock. Slots, seams, and other rock surface irregularities are often filled with soil; excavation of this soil into a slot can often result in sudden large inflows of water, so this type of hand "dental work" is generally avoided.

DESIGN FOR AXIAL COMPRESSION LOAD

Design of drilled shafts for axial compressive loading in hard pinnacle limestones is generally based upon end bearing resistance in the hard rock. Because of the difficulties with forming a clean socket into massive rock, designers tend either to neglect rock socket friction or to use some extremely conservative value. Early attempts to construct and inspect a rock socket into pinnacle limestone in Birmingham, Ala., met with great difficulties due to seepage from the rock below the casing. In addition, Kulhawy and Goodman (*2*) have proposed that rock-socketed drilled shafts should generally be designed on the basis of socket side friction or end bearing, but not both simultaneously.

The relatively high strength of the intact rock would feasibly allow extremely high bearing pressures at the tip, if the presence of an intact massive rock mass could be assured. In fact, designers in the Southeast tend to limit tip resistance in these rocks to the 100 to 200 ksf range; this range is only a fraction

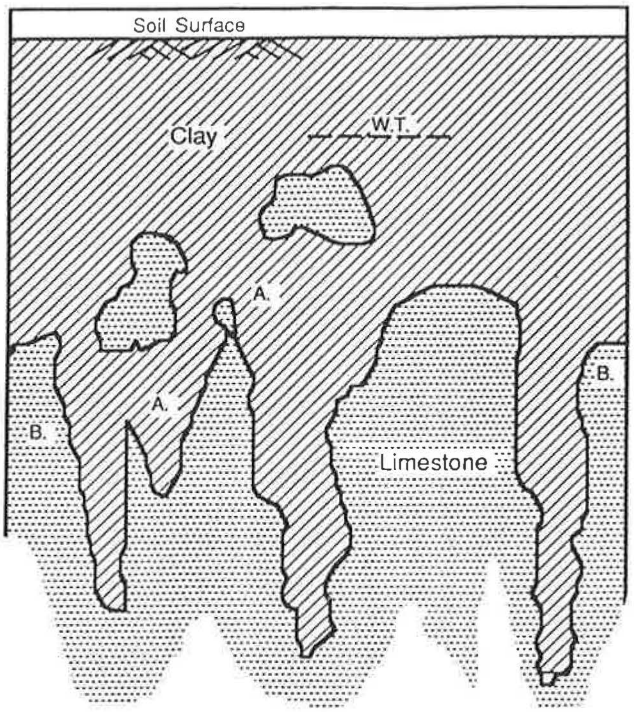

FIGURE 1 Profile of severely weathered rock (*1*).

of the rock's unconfined compressive strength. The reasoning behind these apparently conservative pressures is to allow field acceptance of a shaft on rock that provides less than full coverage of the bearing surface, as illustrated on Figure 2. In some areas of Birmingham, it has proven extremely difficult to place every shaft into intact rock even after excavating many tens of feet of rock.

Load tests of drilled shafts on hard limestone are extremely rare, and none are known to have been conducted to achieve failure. Because the compressive strength of the rock is typically greater than that of the concrete, it seems likely that geologic discontinuities that may be unknown at the time of design govern the ultimate bearing capacity of the foundation. The justification for the design bearing pressures is thus experience (lack of failures), and the emphasis is appropriately on inspection and evaluation of the bearing material at the time of construction.

Shafts in pinnacle limestone are designed for side friction in areas where fault zones or other geologic features have produced deep slots that have virtually no sound rock. The rock in these limited areas tends to be very fractured and prone to solution features, so that conventional rock bearing shafts are not feasible. Friction shafts tend to be used in groups in areas of a site where slots are present, and they are usually reinforced with a structural steel member because of the potential for concrete to flow laterally into cavities and seams. Unit side friction values used tend to be chosen as if the shafts were in soil, due to the erratic and unpredictable rock zones. At least some of the rock penetrated in these slots is likely to consist of isolated boulders.

INSPECTION OF THE BEARING STRATUM

Inspection of the bearing material is performed both by inspecting the bearing surface and by drilling one or more 2

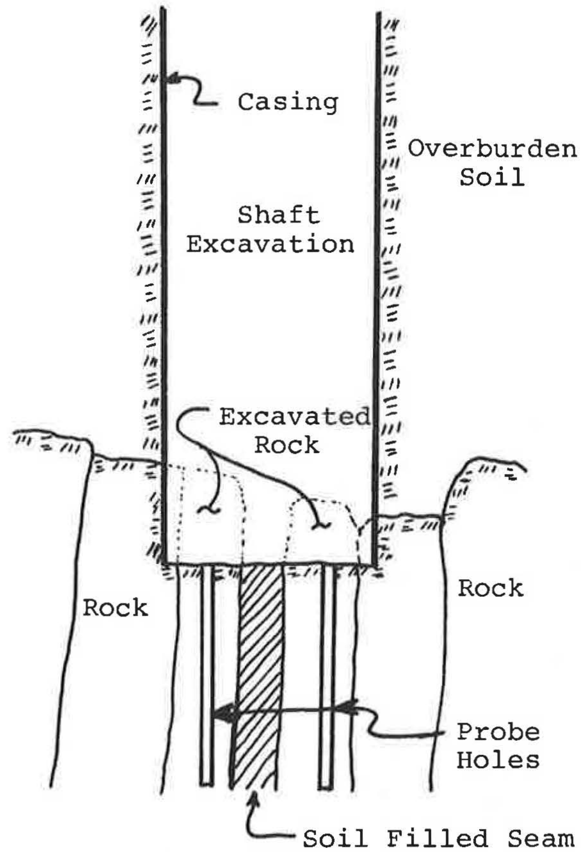

FIGURE 2 Shaft bearing over vertical soil-filled seam.

in. diameter probe holes to a depth of at least 2 shaft diameters below the bearing surface. Probe holes can be drilled expeditiously and economically down the hole using a hand-operated percussion tool. The hole is probed using a hooked rod, as illustrated in Figure 3, with which the inspector scratches the side of the probe hole in an attempt to locate discontinuities. Good communication between the inspector and the contractor's "hole man," who drills the probe hole, is important, because weak seams are easily detected during drilling.

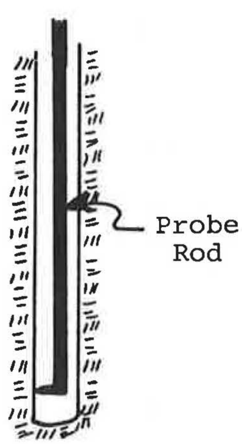

FIGURE 3 Rock probing tool.

More than one probe hole may be performed if a weak seam on the bearing surface is thought to represent a vertical feature, as shown on Figure 2.

Because of the importance of understanding the nature of the geologic discontinuities, as well as the need to make field decisions relating to the load-supporting capability of the foundation, it is vitally important that the inspector be a well-trained and experienced person. Optimum strategies and acceptance criteria may vary depending upon specific project needs, and the inspector should be a person capable of making such judgments.

STRATEGIES FOR CONSTRUCTION IN DISCONTINUOUS ROCK

Early attempts to construct drilled shafts in pinnacle limestones in Alabama involved the search for the elusive "sound rock," in which no discontinuities were present within two shaft diameters below the base. Some formations in Birmingham, such as the Ketona dolomite and areas of the Conasauga formation, are particularly prone to solution cavities and irregularities. The frequent result was removal (at great expense) of many tens of feet of rock, only to encounter limestone that was worse than that which had been drilled through. Additionally, the increasing water pressures with increasing depths make the construction work potentially more hazardous with respect to blowins. Stories abound in which a worker is chased out of a hole by a sudden spout of water or casings are floated out of the ground on the rock plug at the base. In one case a downhole worker who began to scream and shout for help was observed to be hanging onto a safety rope; the rock into which he was drilling a probe hole had dropped away into a cavern the size of a house!

Vertical Discontinuities

Where a vertical discontinuity or seam exists, as shown on Figure 2 or 4, the recommended approach is to probe the rock that is present over the base of the shaft (on both sides of the seam if the seam is within the shaft base). If sound rock exists except for a small area, it may be possible to accept the hole as adequate if the resulting bearing pressures are not excessive. Often, rock coverage over 75 percent or more of the shaft base is considered acceptable, provided that the rock that exists can be demonstrated to be sound. Some overdesign with respect to the allowable tip bearing pressures thus pays dividends during construction, in that less than a full bearing surface can be accepted. A nonvertical seam, as shown on Figure 4, should generally be detected by one of the probe holes and would necessitate additional drilling.

The tendency for shear failure of the rock into the seam can be reduced by excavating the soil into the seam and backfilling with concrete, a technique sometimes used for shallow foundations on rock. This practice is not recommended in deep shafts drilled below the groundwater table because of the possibility of large and uncontrolled seepage into the shaft through such an excavated seam. Note that it is generally necessary to keep the casing seated into the base of the shaft to minimize seepage. If there is concern about the integrity

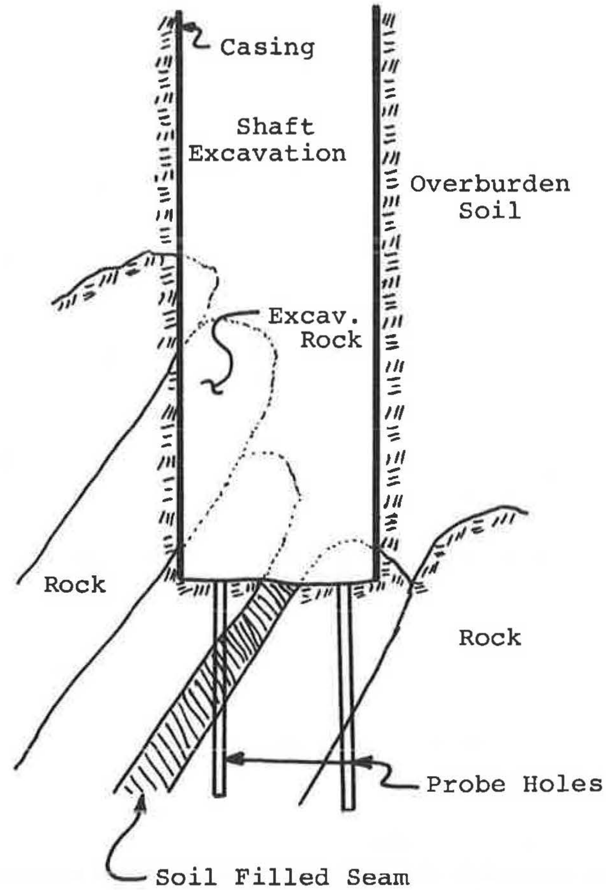

FIGURE 4 Nonvertical soil-filled seam.

of the adjacent rock, the hole should be deepened or other measures taken to provide additional support.

Once the shaft excavations exceed about 70 ft or so below the groundwater level, additional drilling becomes much more difficult due to seepage concerns, and alternative solutions should be considered. Alternatives include the use of driven piling within the shaft excavation and the use of rock anchors installed as described below. In some cases it has even been deemed necessary to place additional shafts and use grade beams to transfer load from the problem shaft to adjacent units.

Composite Piling

Deep slots are often encountered where geologic discontinuities such as fault zones have produced exceptional rock irregularities (often called "ratty rock"). Where deep slots make it impossible to attain adequate bearing material, one solution that has been used is to drive steel H piles into the slot to form a composite pile and provide support for the missing portion of the bearing surface. The difficulty with using this technique is that the piles may not achieve good bearing until a great length of piling is driven, and so this approach is not common.

Another use of composite piling where poor rock is encountered to great depth is to simply drill a shaft designed to provide capacity by side friction. The composite shaft is formed by placing a structural steel member, such as an H pile or a wide flange section, into the fresh concrete. The structural steel is used because of the tendency for lateral loss of concrete into voids and cavities, which could potentially disrupt a rebar cage during concrete placement. Because these shafts may not have the high capacity of shafts bearing on sound rock, it may be necessary to install several composite shafts to replace one conventional shaft. Composite piling tends to be used only in those areas of a site where a large deep slot is present, with conventional shafts on rock used where possible.

On sites where the need for composite piling is anticipated, it is generally advisable to drill a pilot hole at each and every foundation location to determine in advance which type of foundation is most appropriate. The pilot hole could be a conventional soil boring, but for reasons of economy is more often a small-diameter percussion-drilled hole. If the pilot hole does not encounter sound rock at a particular location, that foundation is planned as a group of composite piles designed to carry load in side friction. Small-diameter shafts on the order of 18 in. in diameter are most common, with reinforcement provided by a single H pile placed after the concrete. These shaft groups are more expensive than conventional shafts and thus are used only where necessary.

Rock Anchors for Nonvertical Discontinuities

Where concern exists that there may be fractures or sloping bedding planes within the rock, rock anchors may be used to provide continuity and load transfer across nonvertical discontinuities, as shown on Figure 5. Rock anchors generally consist of No. 10 or 11 high-strength steel bars such as Dywidag, grouted into a hole 2 to 2¼ in. in diameter and 10 to 12 ft in length. Larger diameter holes have been used but require the use of surface drilling equipment; the 2 to 2¼ in. size holes can be more economically installed downhole using handheld air impact equipment. A specific rock anchor plan must be developed in the field after investigation of the existing geologic conditions, and thus the need for field personnel capable of designing such a plan.

Rock anchors may also be used across thin-seam horizontal discontinuities, as shown in Figure 6. However, simple horizontal fractures in flat-bedded limestone generally would not require any additional treatment and may not even be detected by simple probing operations. In general, probing is intended to detect significant soft seams or the presence of cavities within a reasonable distance of the bearing surface.

CLASSIFICATION FOR PAY PURPOSES

One of the key elements to successful use of drilled shafts in pinnacle limestone is the structure of the bid document related to drilled shaft pay items. Because of the considerable uncertainty involved in this geology, there will undoubtedly be uncertainties in the quantities of cost items. The most cost-effective approach to foundation construction is to identify these cost items and to price the job on a unit cost basis for each item. This is the approach that has evolved in the Birmingham market, and it is a key element in the acceptance

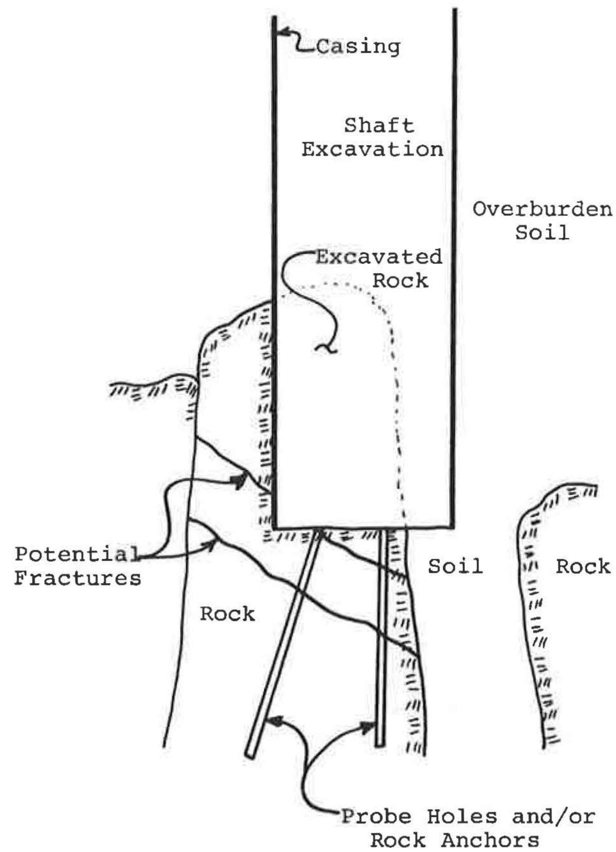

FIGURE 5 Rock anchors on fractured rock.

and use of drilled shafts on a widespread basis. The general items identified for unit costs are the following:

- Earth augering, with unit costs for each diameter anticipated.
- Rock augering, with unit costs for each diameter anticipated. Augerable rock includes shales and sandstones that can be excavated with a rock auger but not an earth auger. Sometimes this item is even listed as shale excavation.
- Hard rock drilling, with unit costs for each diameter anticipated. This rock includes most of the hard pinnacle limestones and is defined as that rock that cannot be excavated with a rock auger but requires blasting or other special drilling tools.
- Concrete, per cubic yard and based on dray tickets.
- Steel reinforcement, per pound.
- Test holes, per linear foot.
- Mobilization.
- Any other special items, such as rock anchors, composite piles, etc.

Note that the excavation items almost always include casing, shoring, and pumping, rather than listing these as a separate item.

The engineer provides an estimate of these quantities, but actual payment is based upon unit costs for the quantities used on the job. Rock excavation typically runs 4 to 5 hole diameters on average, but can vary significantly from job to

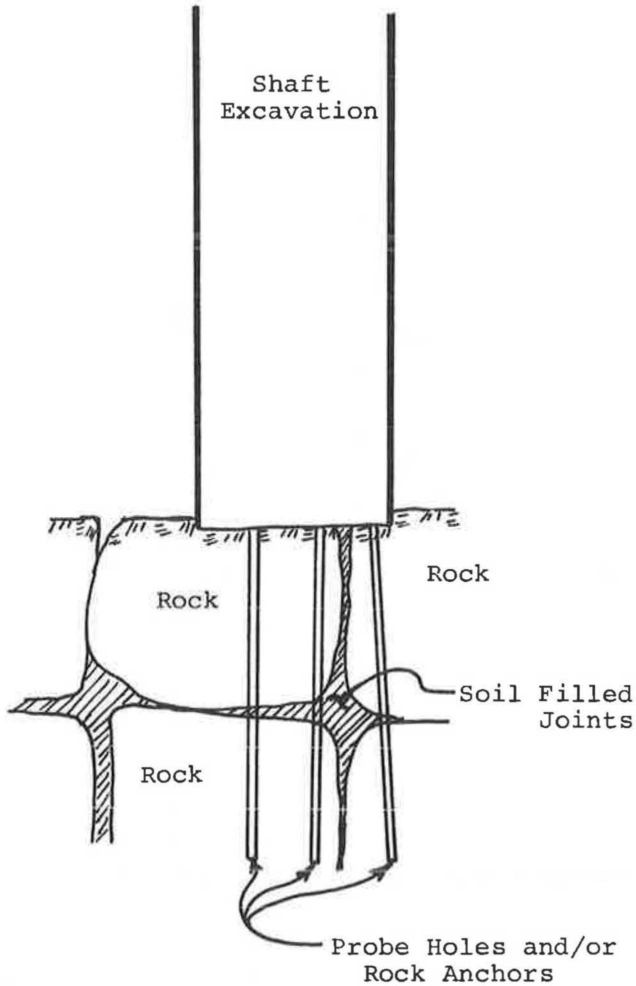

FIGURE 6 Rock anchors on flat-bedded rock with discontinuities.

job. It is particularly important to separate items such as concrete placed in the hole from the cost of excavating the hole; because of cavities and irregularities in the rock, the amount of concrete needed often ranges from 150 to 300 percent or more of the theoretical volume of the hole. In some parts of the United States, concrete is lumped into the linear foot rate for excavation; in these formations such a practice would put all of the risk of concrete overruns onto the contractor and thus necessitate a conservative estimate of concrete quantities on his part at bidding time. Some state highway departments provide for no cost differential between earth and hard rock drilling, but in pinnacle limestones it is extremely difficult to estimate how much rock excavation will be needed. With the unit cost approach, the contractor is neither penalized nor unfairly rewarded when directed to carry the hole deeper. In general, contractors, engineers, and owners have found this system to be fair and cost effective for all concerned.

SUMMARY

Drilled shaft foundations can provide a very cost-effective and high-quality foundation alternative in areas of hard pinnacle limestone. However, the uncertainties associated with this type of geology necessitate some special considerations with respect to construction and design. Particularly important is the requirement for flexibility in the specifications and bid documents. It is also essential to have well-trained and experienced personnel on site who are capable of making decisions relating to foundation capacity and construction. Attempts to construct rock sockets into sound hard limestone has not been a successful strategy; however, other strategies have evolved and are identified in the paper. The evolution of the local bidding structure into unit cost pricing is seen as a key element in the widespread acceptance and use of drilled shafts in these formations.

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