SECANT PILE SHORING – DEVELOPMENTS IN DESIGN AND CONSTRUCTION

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High groundwater levels combined with variable soil and rock profiles present challenges to the design and construction of deep excavation support systems. Increasingly, secant piling techniques are the preferred technical solution for shoring in these cases. Recent developments in drilling equipment, tooling and procedures allow cost-effective construction of deep, overlapped pile systems to tight tolerances in extremely difficult ground conditions.

This paper summarizes critical design considerations for secant pile shoring systems, detailing recent advances in installation procedures and verification techniques that allow secant piles to be used for an expanding range of project conditions. Technically- and commercially-viable secant pile shoring designs require that stringent drilling tolerances be achieved in order to successfully provide combined structural support and groundwater cutoff systems, particularly for unreinforced circular secant pile shafts acting in ring compression. Modern drill rigs and tooling can advance fully cased shafts in geotechnical conditions which range from cohesionless soils below the groundwater table to hard rock, within a single drillhole. Down-hole instrumentation provides verification that tolerance requirements are met and allow secant pile shoring to be used at sites previously considered unacceptably risky.

In California, secant pile shoring systems are being used for excavation depths of over 100 ft (30 m) on projects with challenging site conditions. Two case studies are presented detailing severe geotechnical conditions and excavation depths which represent the regional state of practice in secant piled excavation support. These projects provide real world examples of the design, construction and construction verification techniques that permit secant pile shoring to be used in more demanding geotechnical conditions and to greater depths than ever before.

Introduction

Secant pile walls are formed by constructing a series of overlapping “primary” and “secondary” concrete-filled drill holes. The primary piles are constructed first, followed by secondary piles, which are cut into the previously placed primary pile concrete. The amount of overlap required between the adjacent piles is a function of the structural design requirements and the installation tolerance that can be achieved.

Secant pile walls can be used for both excavation support and as a relatively impermeable cutoff wall. Although they tend to be more expensive than either sheet piles or deep soil mix (DSM) walls, secant piling techniques can be employed in geotechnical conditions which preclude these other types of shoring systems.

Design Considerations

The success of a secant pile system requires that the individual piles be structurally sound over their full length, and that adjacent piles be constructed to tolerances that maintain a reasonable overlap between the primary and secondary piles.

Secant pile walls for excavation support are designed to function in one of two ways. The typical design approach develops the structural capacity of the wall in the vertical direction. The wall spans between its points of support (e.g., cross-lot bracing or tiebacks) as a vertical beam. For this type of wall system, the primary piles are unreinforced, and the secondary piles are reinforced with either a wide flange section or a rebar cage. The primary piles are designed to act as lagging between the "structural" secondary piles, and the secondary piles are designed to have sufficient flexural and shear strength as beams in the vertical direction.

Secant pile walls can also be designed as ring compression structures. In this case, the piles are installed in a circular configuration and loads are resisted in circumferential compression. This type of structure is structurally-efficient because unreinforced concrete has significant compression capacity. Soil, groundwater and surcharge loads are resisted by thrust (compression) forces acting in the ring. The design compression strength of the unreinforced ring can be computed using ACI 318 provisions for unreinforced concrete, and, although rarely critical, the buckling capacity of the ring should also be evaluated.

For unreinforced ring compression structures the quality of the pile installation is particularly critical. The thickness of the "effective compression ring" that can be safely assumed for design purposes is directly related to the pile installation tolerance that can be achieved. Failure to achieve the minimum design overlap between the adjacent piles will compromise the structure's ability to perform as designed. For this reason, excavation depths for which secant pile compression ring structures have been employed have typically been limited to around 60 feet.

Recent improvements in drilling equipment and methods, combined with instrumentation to verify actual installation tolerances, are allowing deeper excavations to be supported using secant piles. These current practices are discussed in more detail with case history examples in the following sections of this paper.

Secant Pile Construction

The requirements of cost and performance must always be evaluated when selecting construction methods for shoring systems. A wide array of techniques is offered within the foundation industry; however, in many cases excavation depth and geotechnical conditions limit the options that can be employed at challenging sites. The cost for secant piling typically exceeds that of deep soil mix, sheet pile or similar watertight shoring systems; however, the versatility offered by secant piling allows effective construction through highly variable ground profiles ranging from saturated cohesionless soils to hard rock, including advance through cobbles and boulders and even man-made obstructions.

For secant piling, installation tolerance is critical to project success and directly related to cost. When tight tolerances are maintained, pile spacing is maximized, reducing the number of piles required along an excavation perimeter. Once the permissible tolerance is defined, the pile installer must select construction procedures and equipment to satisfy this controlling performance criterion, while minimizing unit construction costs, typically by maximizing production rates.

Tolerance is evaluated in terms of both layout control and drilling verticality. Significant overall costs savings can be realized by using a guide trench and templates in order to ensure pile location is controlled at ground surface. For example, pile quantity can be reduced by 8% to 10% in a 40 ft (12 m) diameter shaft if location tolerance is controlled to within +/-1 inch (25 mm) in plan, compared to an industry standard of +/-3 inches (75 mm) for layout based on surface staking.

Figure 1: Guide Trench

Verticality tolerances of 0.5% (1 in 200) or stricter are typically necessary for secant piling projects, compared with standard requirements of 1% to 1.5% (ACI 336.1) for drilled piers. Pile spacing is maximized for economy, and therefore successful secant piling projects require exceptional attention to drilling procedures, equipment, and quality control to ensure overlap is maintained. Drilling methods and equipment selection are integrally linked in the construction process.

A range of techniques, including augercast and axial soil mixing, can be employed to install secant piles, provided plan layout is controlled and initial rig verticality is confirmed and verified. These high productivity systems combine technical performance, fast installation, and low cost and are suitable for excavations in soil and soft rock to depths of up to 45 ft (14 m). Pile diameters are limited to 24 to 36 inches (610 to 915 mm) for these installation methods, but potential installation rates are in the range of 500 to 1000 lineal feet (150 to 300 m) per shift. The double rotary system of “cased” auger drilling can increase viable secant piling depth to around 60 ft (18 m) while retaining the competitive benefits of augercast drilling.

For deeper excavations, layout control and drilling tolerance becomes increasingly critical. Increased pile diameter and improved verticality control can both increase the viable depth of a secant pile excavation support system. Diameters of 36 to 48 inches (915 to 1220 mm) are typically employed for 50 to 100 ft (15 to 30 m) deep shoring systems. However, due to increased unit costs associated with large diameter piles, the construction methods must aim to optimize verticality in order to minimize pile quantity and corresponding overall project costs.

Sectional heavy wall drill casing, advanced concurrently with the drill tool, performs the dual function of maintaining boring stability in cohesionless or unstable ground and stiffening the drill string in order to limit deviation at depth. Kelly drilling methods allow a range of soil and rock tooling to be employed within the casings such that different tools can be utilized to accommodate variations in ground type as the drill hole is advanced. Casing teeth configurations can be modified between or even within project sites to suit actual ground conditions.

Top drive rotary crawler drills are ideally suited to secant piling and can rapidly advance drill tools concurrent with 24 to 48 inch (610 to 1220 mm) diameter casing while maintaining strict verticality tolerances. Numerous commercially available rigs with torque in the range of 150 kip-ft to 195 kip-ft (200 to 250 kN-m) are suitable for pile depths up to 60 ft (18 m). Greater pile depths require enhanced equipment capabilities for efficient advance rates and handling of casing and drill tools. Machines with torque in the range of 260 to 295 kip-ft (350 to 400 kN-m) are usually employed for drilling to depths of 100 ft (30 m). Production rates can be in the range of 150 to 300 lineal feet (45 to 90 m) per shift.

In parallel with the evaluation of rig torque, drill selection should consider the weight of casing that can be efficiently handled by the machine. For depths exceeding 100 ft (30 m), and diameters in the range of 42 inches (1065 mm), oscillator attachments are required to assist casing advance and extraction due to the self-weight of the drill string. Oscillators increase the range of constructible pile diameters and depths, but limit production rates with resultant cost implications.

Figure 2: Drill Rig and Casing Oscillator

Secant piling systems are rarely employed for excavation support at depths exceeding 100 ft (30 m). In order to maintain overlap while accounting for drilling deviation at this depth, large pile diameters are required, and in turn secant piles become prohibitively expensive. However, modern drilling equipment such as the Bauer BG50, with 350 kip-ft (470 kN-m) of torque and 130 kip (600 kN) winch capacity, can construct piles to a depth and diameter exceeding any conventional commercial limitations. The recent Transbay Terminal test program in San Francisco demonstrated the current limit state of practice by constructing 7.2 ft (2.2 m) diameter secant piles to a depth of 230 ft (70 m). The sectional casing was advanced using a rotator system, with 150 ton excavation and support cranes employed to achieve a production rate of approximately one pile per week.

Installation Verification

Until recently, there was no ready means of evaluating the verticality of a drill hole prior to it being exposed in an excavation. Therefore, it was necessary to make reasonably conservative assumptions about the verticality tolerance on which a design could be based.

Downhole survey techniques that permit measurement of both the diameter and plumbness of a drill hole are now available. For example, the Sonicaliper® is a sonar device that provides a 360 degree profile of the drill hole at any depth. It can be used for surveying drilled shafts as well as slurry wall panels. The instrument is able to make measurements in a dry hole, under water, or even through polymer or bentonite slurry. Survey readings can be taken in a cased or uncased hole.

Figure 3 is an example Sonicaliper® measurement at a depth of 70 ft (21 m) in a 36-inch (900 mm) drill hole. The dashed green line and light crosshairs illustrate the theoretical position and diameter of the hole. The surveyed hole location and diameter are shown by the blue circle and dark crosshairs. In this example, the downhole measurements indicate that the hole is offset from its theoretical location by 1.9 inches (48 mm).

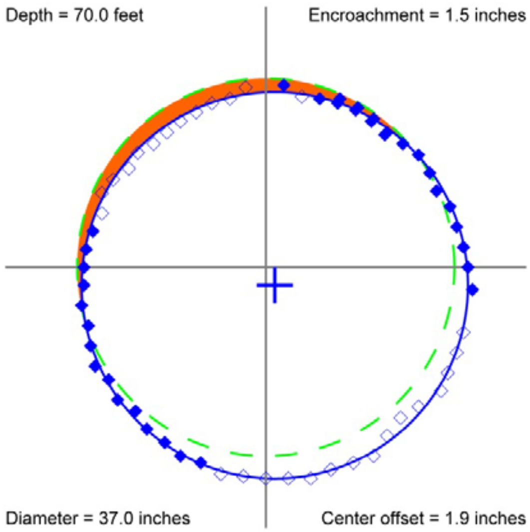

Figure 3: Sonicaliper Measurement

The Inclination Measuring Instrument (inclinometer) manufactured by Bauer provides an alternate means of surveying cased drill holes. The instrument is similar to an inclinometer probe that is used for measuring lateral ground movements in a small diameter slotted casing, although at a much larger scale.

Downhole surveys permit tighter installation tolerances to be used for design because the as-built pile locations can be confirmed prior to excavation. If the surveys indicate a potential problem, holes can be redrilled or other proactive corrective action can be taken at a specifically targeted location.

Recent Projects

Mormon Island Auxiliary Dam Key Block

The Mormon Island Auxiliary Dam (MIAD), located about 20 miles (32 km) northeast of Sacramento, is a 4800 ft (1460 m) long, 110 ft (34 m) high earthfill dam that helps impound the American River to form Folsom Lake. The United States Department of Interior, Bureau of Reclamation has concluded that some of the downstream foundation soils are susceptible to liquefaction during a large earthquake. The Bureau designed a “Key Block” to mitigate the potential problems resulting from this liquefaction. The Key Block is a 55 ft (17 m) wide by 900 ft (274 m) long area at the toe of the existing dam from which the foundation soils will be removed down to and keyed into bedrock and then replaced with lean concrete and engineered fill. The Key Block excavation is specified to be performed in segments not exceeding 150 ft (46 m) in length with no less than 300 ft (91 m) of unexcavated length in between. Hence, the Key Block will be constructed in a total of seven excavation bays; a test bay followed by six longer production bays.

The soil conditions at the Key Block consist of dredged alluvium overlying a thin layer of clayey colluvium, which in turn overlies variably weathered amphibolite schist bedrock. Historically, the alluvium was dredged a number of times for its gold content. The majority of the dredge tailings are poorly graded to silty sand and gravel with cobbles and occasional boulders; however, finer-grained silty sand with some gravel and clay is found near the base of the deposit. Bedrock is anticipated to be encountered at depths ranging from about 52 to 78 ft (16 to 24 m) below grade. The groundwater table at the Key Block is near the ground surface, and the project design criteria require the shoring system be designed assuming groundwater at grade.

Previous attempts at improving the seismic performance of the downstream foundation soils included the installation of thousands of stone columns, and a test section in which an attempt was made to treat the soils with jet grout. The stone columns and jet grouted mass will be encountered during the construction of the Key Block.

A reasonably dry, shored excavation is required so that the moderately weathered bedrock at the Key Block subgrade can be cleaned and inspected prior to the placement of the lean concrete. Further, the excavation shoring system must accommodate excavation of up to 8 ft (2.4 m) into bedrock. Therefore, the shoring wall is required to penetrate into bedrock for both toe support and groundwater cutoff. The two diaphragm wall options that were considered feasible for the challenging soil and rock conditions at this site are secant piles and slurry walls. A secant pile wall was determined to be the most cost-effective solution for this project.

The shoring wall design is based on 3.28 ft (1 m) diameter secant piles installed at either 2.25 ft (690 mm) or 2.0 ft (610 mm) center-to-center spacing, depending upon the depth to bedrock. The design assumes that a verticality tolerance of 0.5% is achievable. The 2.0 ft (610 mm) pile spacing will be employed in locations where the depth to bedrock exceeds 70 ft (21 m) to allow for drilling tolerance and to increase the structural capacity of the wall where the excavation will be deepest. The primary piles are unreinforced 3000 psi (21 MPa) concrete and the secondary piles are reinforced with W24x94 sections over their full depth. The design considers the wide flange beam acting compositely with its surrounding concrete.

The design loads for the shoring system are soil pressure (including the substantial lateral surcharge from the adjacent dam), groundwater pressure, construction surcharge, and a seismic increment based on an earthquake with a peak ground acceleration of 0.20g.

Up to five levels of crosslot bracing will be installed in each excavation bay. The bracing frames have bolted wale splices and strut-to-wale connections so the frames to be easily assembled and disassembled and the components can be used in different size bays. Figure 4 is a typical cross-section through the full depth Key Block excavation.

Work on the secant pile wall at the test bay started with the construction of a cast-in-place concrete template in order to accurately define the geometry of the secant pile wall at the ground surface. A total of 96 secant piles were installed at the test bay. A Bauer BG40 drill rig advanced flush bolted sectional casing into bedrock. Concrete was placed using the tremie method, and then casing was extracted. The W24 reinforcing beams were wet set into the concrete-filled secondary piles.

Drilling conditions proved to be extremely challenging at the test bay. Cobbly soil, existing stone columns, and hard rock conditions resulted in exceptional levels of wear on the drill tooling. Casing through the cohesionless, saturated alluvial soils was essential.

At the test bay, bedrock was encountered at depths of between 53 and 61 ft (16 to 18.5 m), and the secant piles were drilled to a total depth of 71 to 80 ft (21.5 to 24 m).

Excavation commenced after the secant pile concrete was allowed to cure for a minimum of two weeks. Figure 5 shows the test bay excavated to a depth of 52 ft (16 m) with the fourth level of bracing in the process of being installed. The as-built secant pile wall has proven to be relatively watertight, with only minor local weeping at the interfaces between adjacent piles. As the secant piling is exposed, the accuracy of drilling and layout control has been confirmed by observation and performance of the system.

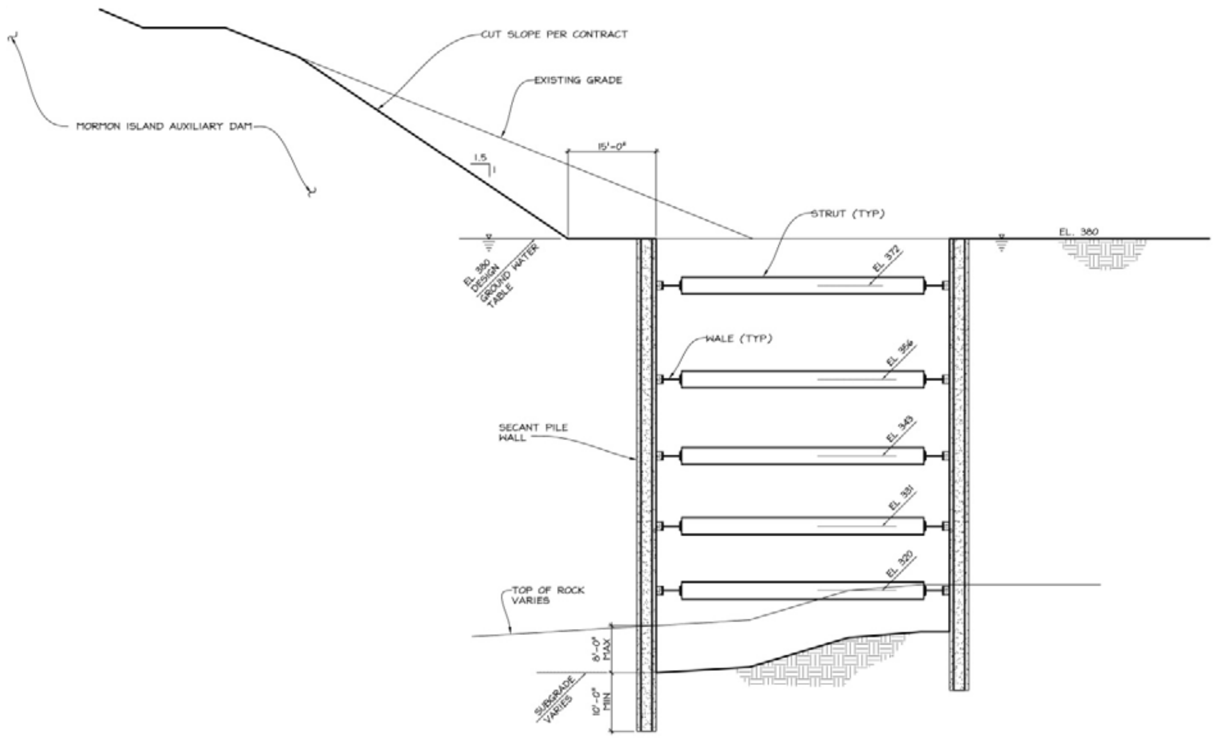

Figure 4: Typical Section at Key Block

Figure 5: Key Block Excavation at 52 ft (16 m)

<u>New Irvington Tunnel Vargas Shaft</u>

The 3.5 mile (5.6 km) long New Irvington Tunnel will provide a seismically sound alternate to the existing conveyance tunnel connecting the San Francisco Public Utility Commission's (SFPUC) water sources in the Sierra Nevada and Alameda County to the Bay Area's water supply systems. The project includes a 41 ft (12.5 m) inside diameter, 115 ft (35 m) deep temporary shaft to create access for 13 ft (4.0 m) diameter tunnel drives in two directions. The shaft is adjacent to the I-680 freeway at Vargas Road in Fremont, California.

The soil profile at the shaft consists of 20 to 35 ft (6 to 11 m) of fill and colluvium (sand with gravel and cobbles and medium stiff clay) overlying bedrock. The groundwater level was anticipated around 14 feet below the top of shaft elevation. Bedrock was expected to be intensely to moderately fractured, weak to moderately strong, with shear zones.

Ground support for the shaft was originally envisaged as secant piles penetrating a few feet into bedrock, below which rock dowels and shotcrete were to be installed in a top-down manner. However, when the first secant pile was drilled it became evident that the installation of rock dowel and shotcrete support would be very challenging to a depth of approximately 95 ft (29 m). The shaft support design was modified to extend the secant piles into competent bedrock, essentially drilling to the full depth of the shaft. The resultant use of unreinforced secant piles as a stand-alone compression ring shoring system for a 100 ft (30 m) deep excavation is unprecedented.

A total of 76, 3.28 ft (1 m) secant piles at 1.83 ft (560 mm) center-to-center spacing form a compression ring as shown in Figure 6. The secant piles are unreinforced 3000 psi (21 MPa) concrete. A 1.5 ft (460 mm) minimum thick effective compression ring is required to provide sufficient capacity to resist the specified shaft design loads. This requires a minimum overlap between the adjacent piles of around 5 inches (130 mm). To ensure sufficient pile overlap at a depth of 80 ft (24 m), the piles were specified to be installed within 1 inch (25 mm) of their theoretical location at the ground surface and with a deviation from plumb of no more than 0.5%. Even tighter tolerance needed to be demonstrated in order for the shaft support to function beyond a depth of 80 ft (24 m).

A guide trench was provided to set the secant pile locations at the ground surface. A Bauer BG40 drill rig was used to drill 115 ft (35 m) deep holes that were cased to a depth of 100 ft (30 m). The BG40 proved to be up to the task of cutting through the structural concrete primary piles during the installation of the secondary piles. The concrete mix was modified during the installation process in order minimize early strength gain while maintaining the specified minimum compressive strength.

Every hole was surveyed using the Sonicaliper® at depths of 60 and 100 ft (18 and 30 m). The downhole surveys indicated that all the holes were well within the specified verticality tolerance.

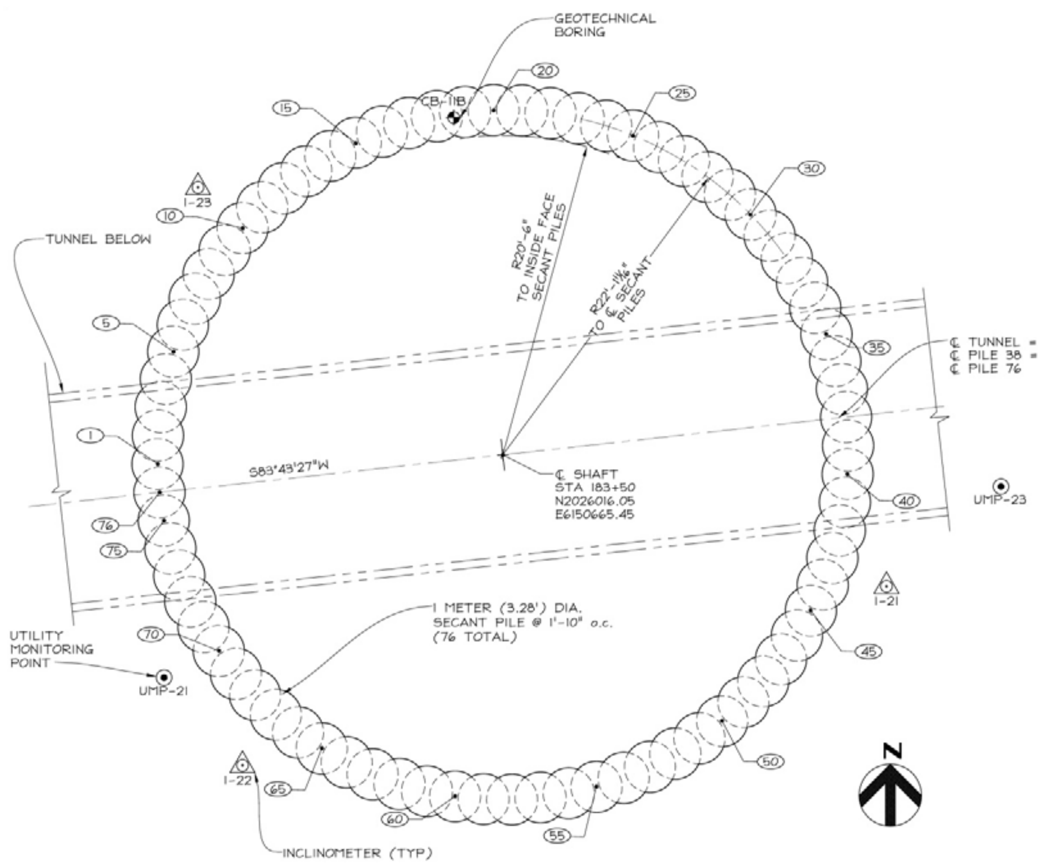

Figure 6: Vargas Shaft Secant Pile Layout

The secant piles were tremie concreted with the casing progressively extracted as the concrete was placed. The volume of concrete placed at each hole was typically around 45 cubic yards (34 cubic meters), which is about 25% more than the theoretical volume of a 115 ft (35 m) deep, 3.28 ft (1 m) diameter hole.

During excavation, observations of the as-built piles indicated that, for the most part, installation tolerance was outstanding. The shaft was successfully supported to a depth of 100 ft (30 m) using secant piling without supplemental support.

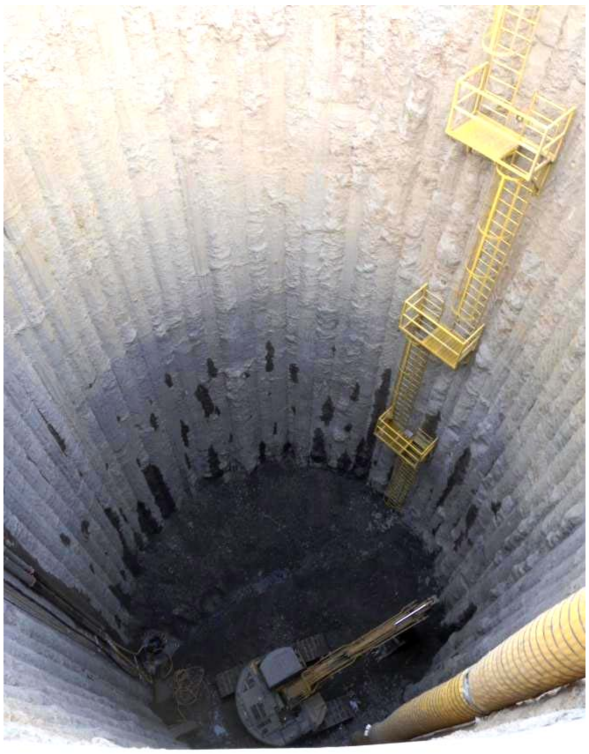

Figure 7: Vargas Shaft at 90 ft (27 m)

Recent construction at the Deephams Sewage Treatment works in England employed 4 ft (1.2 m) secant piles to form a 62 ft (19 m) diameter shaft to a depth 79 ft (24 m) (Hayward, 2011). The Deephams project included reinforcing cages within secondary piles, and supplemental cast-in-place concrete compression rings within the shaft, in contrast to the stand alone unreinforced pile system constructed at the Vargas Shaft. Both shafts were constructed using the same type of drilling equipment, a Bauer BG40 rig working with sectional heavy wall drill casing.

Conclusions

Recent project experience has proven that appropriate drilling equipment and methods can achieve installation tolerances that allow secant pile shoring systems to be used in geotechnical conditions and for excavation depths previously considered to be infeasible. Modern drill rigs and tooling allow cost effective installation of secant piling excavation support systems suitable for depths of up to 100 ft (30 m). State of the art equipment enables construction of piles with diameters and depths that far exceed limitations of currently commercial viable projects. Downhole survey techniques allow designers to confirm critical tolerances are met, refining design efficiency and enhancing cost-effectiveness of secant piling solutions.

At the Mormon Island Auxiliary Dam Key Block project, secant piles were installed successfully through saturated, cohesionless soils with cobbles, boulders and into hard rock. The work completed on that project to date demonstrates that secant piling can be utilized in extreme geotechnical conditions which precluded the use of almost all other foundation techniques. At the Vargas Shaft, an unprecedented excavation depth was supported using an unreinforced secant pile compression ring without supplemental support.

References

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