Design Challenges of Deep Underground Shafts

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ABSTRACT
Deep shafts serve varying purposes in urban development: from egress, tunnel boring machine (TBM) launch/recovery to combined sewer overflow drop shafts and wastewater storage. The construction of a deep shaft may similarly involve a broad range of support of excavation (SOE) inclusive of ground freezing, slurry walls and secant piles. The geotechnical and structural parameters and analyses involved often require unconventional considerations and creative solutions. The installation of shaft structures is often a critical path activity necessary to commence other elements of the project. The analyses of these shafts must account for constructability without compromising efficiency. The design of shaft structures should consider unforeseen circumstances, uncertainty in ground conditions and provisions for subsequently constructed elements. The analysis of these structures is undertaken using creative closed-form solutions, soil-structure interaction and innovative finite element solutions.

INTRODUCTION
Deep shafts pose unique challenges which must be evaluated during design. Consideration should be given to the benefits and limitations of each shaft type and support of excavation based on required water tightness, ground stability and client-specific mandatory requirements prior to selection. Contrary to a shallow shaft, a deep shaft is usually always circular or oval-shaped more efficiently resist significant hydrostatic and earth pressures by hoop compression. In many cases, deep shafts may reach several hundreds of feet below grade. A deep shaft exhibits variable structural behavior relative to depth. Regions close to the interface with the base slab are affected by lining-to-slab connection details, tunnel openings or other specific loading such as TBM thrust frame support loads. Regions close to the ground surface are controlled by unbalanced construction surcharge loads and seasonal temperature variations. Bending strains are caused by temperature gradients across the lining. Mid-height regions are typically compression-controlled zones. The structural behavior of the lining must be considered for the installation of subsequently constructed internal structures to prevent significant increase in out-of-plane forces.

Design considerations should also account for deep shafts installed in mixed-ground conditions, which may require the use of different ground support systems and/or a soil-rock interface measures. Additionally, large diameter deep shafts installed in soil typically require large lining thicknesses, often impractical, for permanent ground stability or flotation resistance. Specific installation conditions must be considered to allow the SOE system to be utilized as a permanent structural element. Construction considerations are important due to unforeseeable conditions, quality control issues or general constructability. This includes special considerations for SOE repair work due to damage or improper installation, waterproofing, base slab construction, and utilization of instrumentation and monitoring systems.
SHAFT LOADING AND DESIGN CONSIDERATIONS

The selection of an adequate SOE system is often associated with the investigation of previous case histories and experience, as well as site-specific subsurface conditions. A reasonable assessment and selection may be achieved using relevant successful reference projects that have compatible characteristics including: subsurface conditions, shaft geometry (depth-to-diameter ratio), and construction site constraints such as equipment operation and mobilization, community impacts and disturbance limitations. In most cases, project-specific guidelines, the contractors experience, preferred method of construction and codes also influence the selection of shaft type. Therefore, it is imperative to understand the principal characteristics and limitations of each shaft type. Table 1 summarizes general considerations for shaft design.

Table 1. Description of different shaft types

<table>
<thead>
<tr>
<th>Type (Temporary or Permanent)</th>
<th>Description</th>
</tr>
</thead>
</table>
| Slurry Wall (Temporary and Permanent Walls) | A slurry wall shaft involves the placement of a bentonite or polymer slurry to retain earth as it is excavated using a hydromill or clamshell. Once excavated, concrete is placed from the bottom up, with the tremie pipe(s) submerged in concrete as it is placed, displacing the slurry. Considerations involve:  
  a. Minimum panel overlap. The overlap should allow for maximum allowable vertical deviation while maintaining contact with the adjacent panel.  
  b. Verticality requirements, which add eccentric bending moments  
  c. Horizontal hoop force has sufficient bearing at panel ends — minimum panel-to-panel contact.  
  d. Glass fiber reinforced polymer (GFRP) may be used for any penetrations and TBM openings.  
  e. Base slab and intermediate floor/roof slab connection requirements |
| Secant Pile Wall (Typically used only for Temporary SOE) | A secant pile shaft wall involves installation of primary and secondary circular piles with either steel core beam or conventional reinforcement. The depth limitations of a secant pile shaft are less compared to slurry walls. Considerations include:  
  a. Pile alignment for deep shafts.  
  b. Weaker primary piles than secondary due to overlap required.  
  c. Difficulty keying base and intermediate slabs. The base slab must either rely on friction or on welded connections, or a temporary jet grout plug/tremie slab must be placed with tie-downs.  
  d. GFRP may be used for any penetrations and TBM openings. |
| Ground Freezing (Temporary SOE) | Ground freezing involves a circulation of brine or nitrogen via a freeze plant and pipe system. Nitrogen may freeze ground quicker, but is generally more expensive. Pipes are installed vertically to rock to provide groundwater cutoff. Considerations include:  
  a. Alignment of freeze pipes for deep shafts.  
  b. Energy costs for maintaining frozen ground for the duration of shaft construction and operation.  
  c. Sacrificial concrete for the face cast against frozen ground. 3” is the minimum recommended.  
  d. Mass concrete placement, such as the base slab, may generate heat enough to melt some frozen ground and diminish concrete quality. Water may also pool on top of the slab as it cures.  
  e. Skin friction is minimal and primarily from any dense sands — must be tested. |
| Slip-Formed (Permanent Shaft Structure) | A slip-formed shaft is typically done with fiber-reinforced concrete. The shaft is constructed away from the SOE as a free-standing concrete cylinder. A concrete infill is poured to fill the gap between the SOE and permanent shaft structure, putting the lining directly into compression. The forms slide up to expose the concrete just as it begins to harden. The lining is constructed top to bottom with no construction joints. Concrete mixes for the lining and for infill concrete need to be carefully developed. |
| Shotcrete (Temporary SOE) | Excavation support in rock will likely consist of shotcrete and rock anchors. In soft soil with ground improvements, it might consist of lattice girders and wire mesh. Consideration include:  
  a. Method and details for ground improvement.  
  b. If friction needs to be relied upon for buoyancy, the shotcrete smoothness criterion must be considered when determining the friction coefficient.  
  c. Lattice girders and wire mesh requirements for temporary loading.  
  d. Testing for shotcrete properties if in frozen ground. |
Shaft Structural Behavior and Design at Varying Depths

The design of the shaft permanent lining considers temporary loads (e.g., construction surcharge loads and TBM thrust loads) and long-term permanent. Generally, long-term loads in the lining include earth and water pressures that are uniform around the lining perimeter that increase with depth. For shaft excavation in rock, the rock pressure is typically a constant value but applied as unbalanced loads that vary around the perimeter of the lining based on potential rock wedge failure. During construction, the shaft lining is designed to resist construction surcharge loads imposed by equipment near the shaft. The depth of this lateral surcharge depends on the type of equipment, proximity to the shaft and any project-mandatory requirements. During the structural analysis, this load should be applied to half of the shaft or on opposing sides to simulate a “squeeze” effect.

The design of the permanent lining requires an understanding of the shaft’s variable structural behavior relative to depth. The lining may be divided into three regions based on its response to exterior loading. The bottom-most region is mainly influenced by the connection to the base slab and by the lining discontinuities for the excavation of a tunnel or adit. As shown Figure 1, significant vertical bending develops at the bottom of the lining due to the restraint of the base slab connection. This connection may be either fully rigid or pinned. For deep shafts with large diameters, a simple dowel connection is recommended to prevent large redistributed moments from the stiffer base slab. Tunnel openings also influence the behavior of the shaft. In cases where multiple openings are proposed, the two-way action of the lining is eliminated, increasing bending moments and decreasing the horizontal hoop forces. This condition may cause the lining to behave as a flexure-controlled member in the vertical direction. For the shaft shown in Figure 1, the bottom-most region extends for approximately 20% of the depth.

The lining’s structural behavior at the upper-most region is affected by unbalanced construction surcharge loads and temperature gradient loads due to seasonal variations during temporary condition. During construction, the shaft cover is not considered as a restraining member for the shaft lining and, instead, the shaft is analyzed considering a free end at the top. Horizontal bending deformation is expected to occur due to unbalanced construction surcharge loads, unbalanced surface live loads, irregular ground surface, and temperature loads. Additionally, at shallower depths, the hoop force decreases, which may cause the lining to behave as a flexure-controlled member in the horizontal direction. Bending strains due to the temperature gradients develop less vertical bending stresses than horizontal because of the free-end at the top which allows for movement.

Figure 1. Profile of typical deformed shaft
The mid-region over the lining height may be classified as the region of the lining less impacted by lining discontinuities and/or boundary conditions. In this region, the lining behaves as a compression-controlled element with minimal out-of-plane deformations. For compression-controlled regions, minimum reinforcement should suffice. The reinforcement requirements for shaft structures vary by code interpretation. For example, the minimum reinforcement may be per Chapter 14, Walls, of ACI with a slight modification. Vertical walls of buildings have vertical compression and horizontal tension due to potential wind loads. Since the lining would have horizontal compression, the requirements must be flipped. Similarly, it may be interpreted that the shaft lining is a compression member requiring minimum 1% reinforcement. This is a common overconservative consideration as this excerpt of the code also requires tie reinforcement, which is typically not provided for shaft linings outside of beams. Further, the code allows minimum reinforcement requirements to be waived if the reinforcement provided is one-third greater than required by analysis. Reinforcement optimization must be performed during final design.

**Loading Due to Temperature Variations**

Shafts that are open at ground surface for long periods of time, such as TBM retrieval/launch shafts, are subject to seasonal temperature changes at the ground surface. These temperature variations cause deformations that induce out-of-plane bending stresses. The temperature loading due to seasonal variations is applied as a gradient; a function of change in temperature in the inner and outer faces of the shaft divided by the thickness of the lining as shown in Figure 2. The temperature drop across the concrete lining is calculated by considering material parameters such as coefficients of thermal conductivity, thickness and average seasonal temperature variations. The following considerations may be used to derive the temperature gradient variation along the lining height:

a. Consider seasonal average maximum and minimum ground temperatures specific to the region where the shaft is constructed.

b. Outside the shaft, it may be assumed that the seasonal temperature decreases/increases linearly as a function of depth. Existing scientific research shows that at depth of approximately 30-ft below the surface, the temperature outside the shaft becomes constant based on average ground

![Figure 2. Derivation of temperature gradient along shaft lining](image)
temperature and any fluctuation of the earth temperature may be considered negligible.

c. Inside the shaft, it may be assumed that the temperature decreases/increases linearly as a function of depth along the full height of the shaft. The temperature at the bottom of the shaft may be assumed to be equal to the average normal ground temperature to maximize the temperature gradient effect at regions closer to the surface during the temporary condition.

d. Thickness of the SOE wall may considered as part of the overall thickness used to calculate the temperature gradient as this is a temporary condition. The resultant temperature gradient is applied to the permanent lining only using a finite element software.

Internal Structures

Deep shafts may have a variety of applications such as combined sewer overflow, stairs for egress, utility/ventilation chase, among others. They often require the installation of permanent, wall-mounted internal structures (ventilation chambers, drop pipes, floor slabs etc.). These installations may contribute to the increase of localized out-of-plane stresses due to forces transferred from the internal structures' connection into the lining. To preserve the simplicity of the lining structural design, the following general considerations may be made:

- Detail connections that reduce unfavorable out-of-plane forces transferred between the lining and the internal structures, and
- Evaluate the locations (shaft elevations) at which the internal structures will be mounted to the lining.

Wall-mounted internal structures may be connected to the lining using reinforcement with mechanical couplers able to resist tension and shear forces due to load eccentricity. This connection not only prevents transferring additional bending forces from internal structure but, concurrently, prevents external loading on the shaft such as unbalanced surcharge loads, seismic deformations or lining deformations due to temperature gradients, from influencing the internal structures design. If the shaft lining is analyzed using a finite element model and including mounted internal structures, their connection should be modeled as pinned connections, constraining only translational degrees of freedom (DOFs) to prevent any out-of-plane bending moment to be transferred between the lining and the internal structures. In finite element software, these connections may be modeled as “weld constraints.” These constraints generate multiple body constraints that are applied locally to a set of joints within a given tolerance. As shown in Figure 3, the connection of the internal structure is modeled at a distance less than one inch away from the CIP lining shell elements while the constraint tolerance is set to one inch. Only translation DOFs are constrained, preventing any other out-of-plane forces to be transferred between the CIP lining wall and the internal structures.

While the location of the internal structures depends on its function within the shaft, as part of a holistic approach at preliminary shaft planning and early stage design, its construction may benefit from properly detailing its structural behavior at the internal structure connection points. For instance, shaft elevations near the surface or close to the base slab, are typically designed with suitable flexural reinforcement to resist out-of-plane bending moments induced by external loads. These are regions with positive reinforcement that can accommodate such connections without altering the overall design at those elevations. Conversely, at mid-elevations of the shaft, or
compression-controlled shaft elevations and locations where flexural reinforcement might not be required by design, out-of-plane forces should be limited. These considerations are of greater importance for deep shafts where properly defined regions along the shaft height may ultimately reduce the cost and time of advanced design and commencing construction.

**TBM Thrust Support Loads**

A major consideration in TBM launch shafts is the analysis of TBM thrust frame loads. Conventionally, TBM thrust frames use a base slab for support as shown in Figure 4(a). This requires a slab suitable for high concentrated uplift forces and with enough tensile capacity to resist pull-out forces from the anchorage connections. This condition may be more significant in the design of a base slab for a deep shaft as it acts in the same direction as hydrostatic pressures. An alternative installation method, shown in Figures 4(b) and 4(c), consists of using the lining to resist the TBM thrust load with a set number of support points depending on the lining strength and project specific TBM thrust frame capacity requirements. Shear forces are prevented from transferring into the base slab by introducing a concrete block at the bottom of the support confined with the lining. The analysis of the lining capacity under this loading condition includes checking for flexural strength, punching shear and bearing capacity. In most cases, project-specific provisions allow the SOE system to be accounted for to resist the TBM thrust load in conjunction with the permanent lining as this is a
temporary loading condition. Additionally, the TBM thrust load should be combined with actual external loads during construction to obtain an accurate net load acting in the lining to prevent unconservative results. A finite element model of the shaft is the preferred method of analysis to include additional resistance from the surrounding ground stiffness.

The SOE System as a Permanent Structural Member

Deep, large-diameter shafts, especially those shafts excavated in deep soils, often require a large permanent lining thickness to ensure long-term strength and serviceability requirements are met. Project-specific codes allow the use of the SOE system as a permanent structural member if specific provisions are followed. This allows for decreasing the permanent lining thickness significantly by sharing the external permanent load between the SOE and the CIP inner lining proportionally based on their stiffness. Alternatively, the SOE may be designed and installed as a permanent component to resist the earth pressure while the permanent cast-in-place lining resists the water pressure only.

An important consideration in the design of any shaft is checking it against buoyant forces. For large-diameter and depth shafts, the buoyancy capacity may rely on the SOE wall. If a slurry wall SOE system is utilized, block-outs may be used in the slurry wall panels to form a key between the invert slab and the SOE wall. For other shaft types, concrete cast against concrete, provided the surface is roughened to a ¼-inch amplitude in accordance with ACI, will generally obtain a satisfactory bond. Where the surface would not properly adhere, a positive doweled connection may be provided as well. The relative deflection of each concrete medium be it initial support or permanent lining, if utilized long term, should be checked relative to stiffness to determine if they will deflect away from each other as the support of excavation may extend deeper to provide groundwater cutoff. A support of excavation system installed prior to excavation such as slurry wall or secant piles may also utilize skin friction with the surrounding ground, which is a function of the friction angle of each stratum. In the case of constructing a shaft with frozen ground, testing is required to consider and demonstrate skin friction of the thawed ground, which would otherwise be zero. Ground freezing in this instance would be a vertical application around the shaft perimeter. Soils with large void ratios and inherently higher water contents are most susceptible to impact due to ground freezing. A dense stratum, like sand, is less impacted due to a low void ratio. A staged finite element analyses is needed to simulate this analysis with test results. When frozen ground is used for support of excavation, shotcrete may be applied for short-term structural stability and to prevent water ingress. Testing is needed to verify the elastic modulus when shotcrete application is to be considered. When other options are not possible, resistance against buoyant forces may also be achieved using tiedown ground anchors; either temporary for construction or permanent (Parkes and Castelli 2017).

Shaft Design Under Mixed Ground Conditions

Any support of excavation system installed from the surface in mixed ground involving rock does not need to necessary extend the depth of the shaft so long as rock provides adequate groundwater cutoff and is sound. The SOE can be keyed into rock and set back from the face of the rock excavation. A perimeter ring beam (or toe anchors) may be installed to provide lateral stability as needed based on bedrock quality. The permanent lining design at soil to rock interface may involve a stepped transition or a smooth transition as shown in Figures 5(a) and 5(b). In a stepped transition, an
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additional permanent ring beam can be designed as shown in Figure 5(c). This flat ring beam must resist the reactions from the dowels connecting the lining in the soil and rock. Waterstops should be provided at each construction joint. Table 2 lists some characteristics and limitations for each type of interface design.

**Table 2. Types of lining soil-to-rock interface design**

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth transition</td>
<td>a. Simpler shaft construction</td>
</tr>
<tr>
<td></td>
<td>b. Increased lining durability (increased outer reinforcement cover)</td>
</tr>
<tr>
<td></td>
<td>c. Eliminates “ring beam” (step) for lining transition at soil-rock interface; fewer joints at interface will reduce the potential for water infiltration from the rock-soil interface</td>
</tr>
<tr>
<td></td>
<td>d. Shortens span of shaft cover</td>
</tr>
<tr>
<td></td>
<td>e. Allows contractor to use one set of forms for the entire height of the shaft</td>
</tr>
<tr>
<td></td>
<td>f. May not be a practical solution for large variations in shaft diameter</td>
</tr>
<tr>
<td></td>
<td>g. Requires additional concrete which may increase material costs</td>
</tr>
<tr>
<td>Stepped transition</td>
<td>a. Analysis of shaft along soil and rock may be done independently.</td>
</tr>
<tr>
<td></td>
<td>b. Lining reinforcement provided may be independent for each section (soil and rock).</td>
</tr>
</tbody>
</table>

SHAFT CONSTRUCTION CONSIDERATIONS

Shafts designs often need to be re-evaluated during construction due to unforeseen circumstances, quality control issues or general constructability. Evaluations may consider provisions of the American Concrete Institute (ACI) code that deals with existing structures based on the as-built conditions and concrete strengths of shaft elements that have already been placed.

A shaft lining or SOE system may require repair. However, the structure, typically under high compression forces, must be assessed prior to performing repairs. Part of the assessment involves using data from available instrumentation and monitoring data. A vibrating wire piezometer allows for determination of the groundwater table elevation while a stress cell will provide the soil and pore pressure readings. Based on these two values, the lateral pressure and equivalent at-rest earth pressure coefficient may be determined. Using this information, the circumferential hoop force may be calculated. If part of the SOE requires concrete removal, the extent of that removal will be governed by the ability of this force to span around the opening. The control of groundwater inflow and ground loss must be considered when developing repair measures.

For large diameter shafts, reinforcement traversing the circumference (horizontal hoop bars) may not be exactly plumb. The reinforcement may jog in and out of horizontal construction joints. For reinforced concrete to maintain continuity, bond strength and adhesion, cementitious paste must be placed within the area where reinforcement protrudes from the joint up to a point where the clear distance between the

Figure 5. (a) Stepped transition section; (b) smooth transition section; (c) permanent ring beam for a steeped transition
reinforcement and construction joint is 1.5 times the maximum aggregate size as illustrated in Figure 6. For example, for \( \frac{1}{4} '' \) aggregate, the required distance is \( 1 \frac{1}{8} '' \). This must be done prior to the subsequent pour. Spacers or standees may be utilized, but due to the variability of placement height in large diameter shafts and concealment of the top behind formwork, often this issue is unavoidable.

**Base Slab Installation**

Base slabs cast in multiple lifts due to thickness or temperature control requirements must act as a composite flexural member. A positive connection should be provided between lifts to transfer horizontal shear. While dowels may be used, a more efficient concept would be to utilize standees, or reinforcement cage chairs. Standees should be considered similar to ties providing shear reinforcement. Surfaces need to be clean, free of laitance and roughed to \( \frac{3}{4} '' \) amplitude in accordance with guidelines for surface preparation provided in American Concrete Institute (ACI) 318 or 350. A shear key may be used to provide support for the base slab connecting it to the shaft. It is recommended to have the top of the base slab be a minimum 1-ft above the top of the shear key to account for required concrete consolidation within the keyway. The depth of the keyway depends on the required bearing area. It is recommended to utilize keyways, when possible, as opposed to a more rigid connection. Depending on the diameter of the shaft, the moment transferred to the SOE may be high and inefficient towards reinforcement requirements on a temporary structure. In the temporary condition, where the SOE provides support for the base slab, the shear design should

![Figure 6. Horizontal reinforcement at construction joint](image)

![Figure 7. Base slab connection to SOE, final lining and lifts](image)
be based on the height, or keyway height, applicable, for maximum direct shear at the face of the support. In the permanent condition, the shear plane is shifted to the inner face of the final lining and, therefore, the full thickness may be considered for shear capacity. Shear-friction reinforcement may be provided as required.

**Waterproofing**

Most projects mandate a maximum allowable ingress or dampness criterion. Examples of typical waterproofing accessories are presented in Table 3. A waterstop should be placed at every shaft permanent construction joint. It is generally preferred to not form a shear key as, often, it is mound-formed by hand and allows for water to circumvent the waterstop if done incorrectly. At the interface between the shaft lining and base slab, detailing becomes critical. Ideally, the reinforcing mat is depressed or bent around the outer perimeter to allow for the waterstop installation with required vertical clearance from the mat. However, since base slabs are often governed by the hydrostatic uplift force, it is not always efficient to do so. An option here is a retrofit waterstop as shown in Figure 8(a). At shaft penetrations, a hydrophilic waterstop, as shown in Figure 8(b), should be added to a PVC waterstop for added protection. At TBM openings, hydrophilic waterstops are recommended in addition to a grout hose to seal the interface and provide a remedial measure in case there is still leakage. Support of excavations, such as slurry walls or secant piles, maintain some degree of water tightness through the structural interlock formed by overbites.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description and Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard Waterstop</strong></td>
<td>Made of PVC and available in a variety of sub-categories: ribbed, ribbed with center bulb or flexible ‘U’. Generally used at construction joints</td>
</tr>
<tr>
<td><strong>Retrofit Waterstop</strong></td>
<td>Made of PVC with flat bottom anchored into concrete and a vertical ribbed piece embedded in subsequently cast concrete.</td>
</tr>
<tr>
<td><strong>Hydrophilic Waterstop</strong></td>
<td>Made of chloroprene rubber, the waterstop expands up to 8 times when exposed to water. Placing it within a slight groove will help against displacement when concrete is cast on top or against.</td>
</tr>
<tr>
<td><strong>PVC Membrane</strong></td>
<td>Membrane placed against a smooth surface and compartmentalized via water barriers. For example, it would be placed against SOE prior to casting the permanent lining. Water barriers would outline sheets of membrane, welded together, with a prescribed square footage to not diminish the post-grouting capability in case of leakage.</td>
</tr>
<tr>
<td><strong>Re-injectable Grout Hose/ Contact Grout Tube</strong></td>
<td>PVC Hose system embedded in concrete to allow grouting seal at construction joints.</td>
</tr>
</tbody>
</table>

![Figure 8. (a) Retrofit waterstop; (b) hydrophilic waterstop](https://example.com/image-url)
Shafts and Mining

Instrumentation and Monitoring

Any deep shaft construction should include robust instrumentation and monitoring. Prior to construction, baseline readings must be taken and instruments calibrated. Instrument readings are particularly important for mitigating risk to any adjacent structures, but also critical for construction activities that may arise: a slurry wall panel or secant pile may not be constructed with the proper overlap, an incorrect concrete strength may be used due to poor quality control, or an unforeseen penetration may be required within the shaft. While undertaking any construction phase mitigation/design modification it is critical to understand earth and water pressures, differences between current readings and baseline readings and their relation to design load considerations. For example, while a slurry wall panel or secant pile may have deviated more than allowable, for the temporary system, earth pressures of groundwater readings may be lower than anticipated required less bearing. These conditions should not be relied upon, but are tools to utilize. Table 4 presents typical instruments that may be utilized for shaft construction.

CONCLUSION

The design process of a deep underground shaft involves a multitude of considerations. The constructability, while not entirely predictable, may be mitigated through careful consideration of anticipated issues and utilizing available data to efficiently adapt the design to suit means and methods. The general recommendations presented are adequate for shaft sizing and additional considerations for shaft type. However, limitations on lift lengths due to temperate control or concrete truck availability, attachments for shaft access, TBM launch thrust block and frame layout among other construction issues should be considered in any final design.

REFERENCES

1. American Concrete Institute (ACI) 318—Building Code Requirements for Structural Concrete.

2. American Concrete Institute (ACI) 350—Code Requirements for Environmental Engineering Concrete Structures and Commentary.