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STARTING OFF ON THE WRONG FOOT - PROBLEMS WITH MICROTUNNELING SHAFTS

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ABSTRACT: Microtunneling shafts are much more than starting and ending points for microtunnels. When designed and constructed correctly, they create the foundation for a successful microtunneling project. If selected or built poorly, they can be a recipe for disaster. This paper explores problems with microtunneling shafts, why problems occur, and how problems can be avoided.

1. INTRODUCTION

Shaft design and construction are typically secondary to the selection of pipe materials, pipejacking methods, and alignment design on a microtunneling project. However, the cost and risks associated with microtunneling shaft construction can exceed those of the microtunneling on some projects, particularly in the cases of deep microtunnel installations. This paper details the critical considerations that must be addressed in designing microtunneling shafts, and problems that can occur when shaft selection is not properly suited to actual site conditions or when construction operations compromise shaft integrity. Case studies serve to further illustrate complications with microtunneling shafts.

2. MATCH SHAFT TYPES TO GROUND CONDITIONS

Each type of microtunneling shaft has specific advantages and disadvantages that determine its suitability for specific projects. Jacking and receiving shaft types may be different as the required characteristics of each are extremely different. Jacking shaft dimensions are governed by the combined length of the thrust block, entry ring, jacking frame, and pipe or microtunneling machine. In addition to length requirements, the jacking shaft must also withstand jacking forces and provide a stable, relatively dry working platform. Reception shafts can typically be smaller than, and not as robust, as jacking shafts since their primary function is to facilitate retrieval of the microtunneling machine and allow for tie in of the new utility pipeline.

Shafts in soil are most commonly constructed using soldier piles and lagging, sheetpiles, auger drilling, concrete caissons, ground freezing, secant piles, liner plate, or slurry walls. Each method is best suited to specific conditions but relative cost usually becomes an important selection factor. Improper shaft selection or construction can lead to significant problems during microtunneling operations.

Selection of the shaft types for a specific project can be determined by the engineer and specified in the contract documents. Predetermining shaft types is advisable when the site conditions are suitable for only specific types of shafts, when the shaft will become an integral part of a permanent structure, or when schedule restraints dictate shaft selection. Alternatively, selection of shaft types can be left to the contractor and may result in a lower cost for shaft construction and use of shafts that the contractor is proficient at constructing. In either situation the contractor should be required to submit shop drawings and construction methods stating design assumptions. Requiring the contractor to design the shaft shifts responsibility onto the contractor to ensure that construction and microtunneling operations are completed within the designed limitations of the shafts.

3. COMMON SHAFT CONSIDERATIONS

Selection of the proper shaft type is the first step towards a successful microtunneling project; however, there are common considerations for all jacking and receiving shafts that should be addressed. The following discussion and case studies will illustrate several examples of shaft problems and the potential solutions.

Shaft Break in and Break out (Entry and Exit)

A critical design aspect for all shafts is “break in” and “break out” of the microtunnel boring machine (MTBM). These shaft wall penetrations create an unsupported face of soil that may be susceptible to collapse under high groundwater and soil pressure. Groundwater and unstable soil can flow into the shaft through the penetrations if the penetrations are not properly planned and executed.

Launch and retrieval of the MTBM through sheetpile, lagging shaft walls, or any shaft that requires manual cutting of portals in the shaft wall, requires some form of ground stabilization on the outside of the shaft prior to launch or retrieval of the machine if microtunneling in unstable soils. Unstable soils present the risk of cave-in once the shaft wall is removed for launch or retrieval of the MTBM. Soil cave-ins pose a safety hazard to workers and create a void outside of the shaft wall that can result in surface settlement or settlement of nearby existing utilities. Soil improvement methods that can be used include grouting, ground freezing, and dewatering.

Excessive Disturbance on the Perimeter of Shafts

One of the common problems with many shaft types is the creation of excessive disturbance on the outside of the shaft during construction. This is especially true with shafts constructed with soldier piles and lagging, trench boxes, some caissons, and some sheet pile shafts, depending on the excavation scheme. This can create tremendous difficulty for the microtunneling operations during launch of the machine including loss of the slurry circuit, inability to maintain line and grade, machine diving, or loss of material into the shaft during launch.

Lack of Communication Between Shaft and Microtunneling Crews

Often on microtunneling projects, the contractor who builds the shafts and the contractor who constructs the microtunnels are not the same. As a result, there are opportunities for miscommunication, especially in regards to launch of the microtunneling machine. An example of this is when the contractor building a concrete caisson or secant pile shaft leaves the steel reinforcing in the portal area through which the microtunnel machine should launch. When the microtunneling contractor arrives on site, they then have to remove the steel reinforcing prior to launching the machine. This process results in delays and can compromise safety.

4. SPECIFIC SHAFT TYPES AND CASE STUDIES

Soldier Pile and Lagging Shafts

Soldier pile and lagging shafts are common on trenchless construction projects. They are especially common on pipejacking projects above the groundwater where the soils are typically strong and relatively stable. Attention to details on soldier piles and lagging shafts is even more critical when groundwater is present, the soils are weak, or when utilities cross through the shaft.

A soldier pile and lagging shaft is constructed by either driving, or pre-drilling and grouting in place, steel H-piles at a predetermined spacing and to a designed depth, prior to excavation. Once the soldier piles are in place around the perimeter, excavation of the shaft begins. As the excavation progresses, lagging (typically timber or steel plate) is placed between the solider piles and pushed or driven to the bottom of the excavation to prevent soil from sloughing into the shaft as the excavation is advanced. Wales and struts are placed around the inside perimeter as necessary during the excavation progress to support the soldier piles, preventing deflection of the shoring due to external soil pressure as shown in Figure 1. Alternatively, on very large excavations tiebacks can be installed to anchor and support the shaft.   Once the excavation is complete and the lagging or sheets are fully in place, wedges are driven between the lagging and the flanges of the soldier piles creating positive contact between the lagging and the soil. Pea gravel or contact grout may be placed behind the lagging to fill any void space. Finally, the shaft bottom is finished with a concrete working slab, or a layer of crushed rock, depending on the application and specification requirements.

Figure 1. Soldier pile and steel plate lagging shaft used on an Interstate crossing

Soldier pile and lagging shafts are typically a more economical alternative to other types of shoring systems such as sheetpiles, auger-drilled shafts, or caissons. However, soldier pile and lagging shafts should only be used in soils that are stable enough to allow for placement of lagging without caving or raveling. This type of shaft should not be used in permeable soils with high groundwater since the interfaces between lagging and soldier piles are never watertight and piping of soil into the shaft can occur, creating voids behind the shaft walls and potential surface settlement. Despite these limitations, soldier pile and lagging shafts are sometimes necessary, even in unstable soils, as the only alternative to deal with utilities that cannot be avoided in the shaft footprint. Because of the flexibility of lagging installation, this shaft type can work around penetrations in the shaft walls.

A recent microtunneling project involving soldier pile and lagging shafts provides insight into two potential problems with this type of shaft. The first problem was excessive disturbance and deformation of the soil mass outside the shaft and the second was poor workmanship and lack of communication between the general and microtunneling subcontractor when constructing the thrust block. The project consisted of twin 72-inch steel casings to be installed by microtunneling beneath an Interstate highway. The drives were 350 feet long and had approximately 25 feet of vertical cover between the casing crown and the Interstate embankment crown, but only 10 to 12 feet of cover at each shaft. The soil conditions consisted of medium dense to dense, clean, poorly graded sand, above the water table. The soils were self-supporting for short spans and time periods and were therefore considered borderline for what can be successfully supported using soldier piles and lagging. However, with careful workmanship the shaft could have been successfully constructed.

A critical factor for success on any microtunneling project is good communication between the microtunneling contractor and the contractor that is constructing the shafts. Because few microtunneling contractors perform their own shaft construction, the shaft work is often done by a contractor that may not be aware of the critical shaft elements as they pertain to microtunneling. For this project, the general contractor built the jacking shaft well in advance of the microtunneling work and without much advice or oversight from the microtunneling subcontractor. Unfortunately, full-time construction inspection did not start until the microtunneling subcontractor mobilized, so little was known by the owner or engineer about the shaft construction workmanship, until the microtunneling was in progress.

The general contractor began by drilling the holes for the soldier piles and encasing the bases of the piles in concrete. There was some caving of the sand into the drilled holes during the first few holes, so the drilling contractor began filling the excavations with water, which kept them stable long enough to place the soldier piles. After all of the soldier piles were installed the shaft was excavated with a hydraulic excavator. In the cohesionless soils, it was extremely important to keep the steel lagging sheets pushed into the soils ahead of the excavation progress. Unfortunately this was not done and the unsupported excavation was advanced too far below the lagging at both the front and back of the shaft, causing circular shear failures where several yards of sand sloughed into the shaft. The failures progressed until chimneys reached the surface outside the shaft. There were no critical features near the shafts and the sloughing did not result in any damage. However the contractor proceeded to fill the holes by dumping the sand back into the void without any compaction, which would later cause significant problems during the microtunneling.

The next problem occurred while constructing the thrust block. Again, the general contractor performed this work well in advance of the microtunneling subcontractor’s mobilization to the site. Therefore the block was formed the entire width of the back wall and poured parallel to the back wall. When the microtunneling equipment was set up in the shaft to exact line and grade, two problems were discovered. First, the general contractor had placed the soldier piles incorrectly and one of the soldier piles was located in the tunnel horizon. A quick adjustment had to be made to the alignment and the jacking frame was moved to a new location, a few inches to the side. However, the microtunneling subcontractor then discovered that the thrust block was not poured perpendicular to the alignment. When the jacking frame was set in place a two-inch gap was left between the jacking plate and the concrete wall on one side. To rectify this situation, steel shims were placed behind the jacking frame to fill the gap, attempting to distribute the jacking load to the thrust block.

Finally, the jacking frame was set and the microtunneling subcontractor was ready to cut a portal in the steel lagging and begin the drive. However, when the 76-inch hole was cut in the lagging sheet, approximately 10 cubic yards of sand that had been loosely placed by the general contractor after the sloughing failure, came pouring into the shaft (Figure 2). The microtunneling subcontractor had to remove the sand, jack the MTBM through the launch seal out into the void outside the shaft, and then replace the sand in the void. This time the sand was compacted as it was backfilled around the MTBM. The sloughing event cost the Contractor a day of work. If the soil had not been so dramatically disturbed during shaft construction, and had the contractor driven the lagging ahead of the excavation, there would likely have been only minor sloughing that would have been easy for the crew to handle, avoiding a day of delay. If a soldier pile and lagging shaft were used again in these conditions, it would be wise to specify soil improvement at the exit location and have full-time construction inspection during shaft construction. Specialty inspection is essential to ensure that the shaft contractor follows sound construction practices to avoid excessive disturbance on the outside of the shaft and to require the contractor to properly compact any material placed around the shaft perimeter to repair any over-excavation. On this project, soil improvement using permeation grouting would have been very effective in the clean sandy soil and would have prevented any soil movement during break-out.

Figure 2. Loss of approximately 10 cubic yards of soil into the soldier pile and lagging shaft during cutting of portal for launch of MTBM

Once the microtunneling drive started, problems with the thrust block, and the soil failures behind it, became evident. With the first drive advanced less than 200 feet, cracks began to develop in the thrust block. Because almost all of the sand behind the shaft was in a loose state, there was no support behind the 2’ 6” thick concrete thrust block. Additionally, because the thrust block was skewed to the alignment, the loading was not evenly distributed. In addition, the microtunneling subcontractor was not adequately lubricating the pipe resulting in very high jacking forces, further complicating the problem. As the thrust block continued cracking and the shaft began deforming, line and grade control became extremely difficult. The MTBM was being loaded unevenly, and the shaft movements were causing the laser setup to move. As the drive progressed, the microtunneling operator was able to reduce the jacking loads through increased lubrication and the first drive was finished, but with significant horizontal deviation.

Before the second drive commenced, the general contractor performed permeation grouting behind the thrust block to provide adequate support for the jacking forces. Grouting was not done at the break-out location however, and just as with the previous bore, several yards of sand sloughed in when the hole was cut in the shaft. The grouting behind the thrust block was successful as there was only minor cracking in the thrust block for the second drive, and steering control was much improved.

Overall, this project was completed successfully. However many headaches could have been avoided if more care had been exhibited during shaft construction. If the general contractor had been more careful to keep the lagging ahead of the excavation, the excessive sloughing would not have occurred. Additionally, better communication between the general and the microtunneling subcontractor could have resulted in a better quality shaft. Requiring the microtunneling subcontractor to review and approve shaft drawings and construction submittals would ensure that shaft design and construction issues specific to microtunneling have been expressed.

On the owner’s side of the project, on-site inspection during the construction of the shaft may have prevented the soil failures into the shaft, or at least made the problems known to the microtunneling subcontractor who could then have initiated grouting before the first drive. Additionally, in hindsight, the design team should probably have specified that ground improvement and stability checks be used at the break-out locations to prevent any sloughing of soil when the MTBM was launched. For example, before cutting the full-sized hole for the MTBM, a small hole should first be cut to evaluate stability as shown in Figure 3. If raveling or running began, then ground improvement would be required. Successively larger holes would then be cut to evaluate stability before the full size hole was cut.

Figure 3. Soil stability checked by cutting small holes in steel plate prior to cutting full sized portal for MTBM launch or retrieval

Auger-Drilled Shafts

Auger-drilled shafts can be constructed rapidly and safely, to meet constrained construction schedules. Due to limitations on maximum diameter, auger-drilled shafts are most commonly used as reception shafts, but can be used as jacking shafts, if jacking equipment and jacking pipe are carefully selected. Auger-drilled shafts become cost-effective for river crossings with nearby sources of groundwater recharge, and for deep applications in potentially unstable soils. It should be noted that there are a very limited number of contractors capable of constructing auger drilled shafts in the diameter necessary for microtunneling applications. It is therefore typically advisable to bid them against other types of shaft construction methods to keep the costs of the shafts competitive if the geotechnical and other constraints allow.

Auger-drilled shafts are constructed as outlined in the simplified steps below. Attention to detail is essential during every step to ensure success.

1. Set-up auger drill rig and excavate a 6 to 8-foot diameter pilot hole to the full depth of the shaft. Maintain the hole filled with thick polymer to stabilize the hole.
2. Fabricate a starter or outer corrugated metal casing by bolting together curved panels or segments.
3. Enlarge the pilot hole using reaming wings and a muck bucket. For deep shafts, the reaming process may be completed in two or more stages with each stage including the setting and grouting of telescoping casings, as shown in Figure 4.
4. Install an outer casing and grout the annulus between the outer casing and the soil. The outer casing typically extends 2 to 3 feet above ground surface to provide additional counterbalancing slurry pressure, and to act as a safety barrier.
5. The next reaming stage is carried out within the outer casing. A slightly smaller diameter casing is set and grout is placed between the inner casing and the soil when reaming and cleanout are completed to the design invert elevation. The excavation typically extends several feet below design invert elevation to allow space for the tremie plug.
6. Place tremie plug to resist uplift. Grout annulus of corrugated metal casing. Dewater when tremie plug and annular grout has reached sufficient strength.

Figure 4. Large diameter auger-drilled reception shaft constructed for a microtunneled drive adjacent to a river

There are several problems that can occur with auger drilled shafts. These potential problems include:

1. Raveling of collar and undermining of drill rig outriggers and surface features.
2. Loss of polymer through open-work gravels and cobbles.
3. Uplift or boiling of invert.
4. MTBM cannot excavate through annular grout.

Each of these potential problems is discussed below, along with measures that can be used to avoid or overcome the problems.

1. *Raveling of the collar:* On a recent river crossing, raveling of the collar occurred when the polymer level was allowed to drop below ground surface in sands and gravels. Left unchecked, the raveling could have undermined the outriggers of the drill rig or other surface features. The rig could have toppled, or nearby utilities or road surfaces may have been damaged. To avoid this problem, polymer levels were increased to the ground surface and viscosity and gel strengths were increased to support the soils. On another project in highly permeable soils, it was very difficult to maintain polymer levels at the ground surface. In this case, a stabilizer ring was constructed before drilling began on the second shaft. The stabilizer ring was constructed by excavating a circular trench approximately 3 to 5 feet deep and 3 to 5 feet wide, tapering to the outside. The ring was positioned outside the outside casing diameter. Un-reinforced concrete was placed into the trench to act as a barrier to raveling and sloughing of surface soils. The stabilizer ring also enhanced worker safety when working near the edge of the auger-drilled excavation.

2. *Loss of polymer through open-graded gravels and cobbles:* On a subsequent crossing of the same river, open graded gravel and cobble layers were encountered above groundwater and excessive polymer loss to the formation occurred. This was especially troublesome because the open graded materials were encountered at substantial depth and because the pressure head exerted by the full column of polymer was large. If the polymer level is lowered to reduce the pressure head the polymer losses will usually decrease. However in this case the collar of the shaft would have become unsupported and would have raveled, as described above. A starter casing was required to stabilize the near-surface soils, allowing the polymer levels to be lowered, lowering the pressure to mitigate polymer losses. The starter casing can extend below and bridge the open graded materials if they are shallow, or may simply extend a few feet below surface, as done on this project, to allow polymer levels to be lowered.

3. *Uplift or boiling of the invert:* Auger-drilled shafts are often selected for deep river crossings because they can be constructed under high groundwater conditions. The occurrence of high groundwater pressures and a nearby source of recharge can make dewatering impractical. Therefore, the base of the shaft must be designed to safely resist uplift and boiling. The first requirement is to conservatively establish the maximum groundwater elevation for design against uplift, based on historic flood events. The 100-year recurrence event is often used to establish maximum groundwater elevations. Potential consequences have to be considered as well. A thick concrete tremie plug is typically used to resist uplift. The tremie concrete is placed using a tremie pipe inserted through the polymer. The plug may be designed to resist uplift using dead weight of concrete alone. This approach is safe but conservative. More commonly, the tremie plug is designed to act with the shaft walls to mobilize shear friction between the grouted CMP walls and the soil. Attention to details during construction is essential if the design takes credit for shear friction acting along the walls as a component of the resisting force. In this case, the tremie plug must be structurally connected to the shaft walls, using horizontal reinforcing steel welded or bolted to the casing near the top of the tremie concrete. Dowels must extend a sufficient distance into the concrete to safely resist shear. A secondary mat of reinforcing may be required in the tremie concrete to resist bending moments caused by the uplift pressures. Annular grouting must be carefully completed to ensure intimate contact between the shaft and soil. Even if all these measures are taken into account, prudent practice dictates that not more than 1/3 to 1/2 of the calculated value of shear friction can be relied upon to resist uplift, due to variability in the soil, uncertainties about actual soil friction properties, and irregularities in grouting.

4. *MTBM cannot excavate through annular grout:* MTBMs that have been designed to excavate soils are not efficient when attempting to excavate through concrete or high strength grout. High strengths are not necessary for an annular grout. Therefore, the best solution to this potential problem is to avoid high strength grouts. The use of fly ash or other cement substitutes can significantly reduce concrete strengths. Bentonite may be added to reduce strength and permeability and control inflows. The MTBM must be capable of excavating through the annular grout. Therefore, upper bound unconfined compressive strengths should not exceed 500 psi for microtunneling applications if the microtunneling machines are not fitted with rock cutters.

Concrete Caisson Shafts

Caissons can be extremely effective for jacking and reception shafts for deep crossings with rechargeable sources of groundwater, i.e. river crossings. It may be impossible or impractical to lower groundwater for river crossings. The caisson can be sunk in place to provide a (nearly) watertight, stable support system. Caissons provide excellent jacking capacity, and are easily converted into permanent structures such as wet wells.

Typically, a caisson is cast in 8 to 20 foot lifts, with a cutting shoe fabricated of steel at the base. When the first lift of concrete has cured sufficiently, the forms are stripped and excavation begins inside the caisson. The caisson sinks under its own weight as the soil inside is excavated. When the caisson reaches design depth, a tremie plug is cast to resist uplift and boils, and the caisson may then be dewatered. Figure 5 shows a concrete caisson during construction and once constructed being used as a jacking shaft.

Figure 5. Concrete caisson shaft during construction (left) and being used as a jacking shaft (right) for river crossing projects

Typical problems that can occur with caissons include:

1. Caisson will not sink due to geotechnical conditions.
2. Caisson will not stop sinking due to geotechnical conditions.
3. MTBM can't excavate through walls.
4. Uneven sinking or tilting as they sink.
5. Uplift.

1. *Caisson will not sink due to geotechnical condition:* Caissons generally sink well in sands and gravels and soft to medium clays and silts. However, when caissons encounter stiff to hard clay or silt, as occurred on two recent river crossings, they may not sink under their own weight. This occurs when the bearing capacity of the soil exceeds the effective bearing pressure exerted at the base of the cutting shoe. A number of factors contributed to this problem on the river crossing projects. First, the skin friction between the outside wall of the caisson and the soil was high. This was exacerbated by the contractor dumping the excavated soil and water from the interior of the caisson near the outside walls of the caisson. The excavated water and soil ran into the annulus, creating high frictional resistance. Secondly, hard silt was encountered below the cutting shoe, with very high bearing capacity. The deadweight of concrete was inadequate, and buoyancy reduced effective bearing pressures. Measures to reduce or eliminate one factor adversely affected other factors. For example, reducing water levels inside the caisson reduced buoyancy, and increased effective bearing pressure. However, frictional resistance increased due to increased loading conditions.

   In hardpan soils, ultimate bearing capacity is at least 5 times the undrained shear strength of the soil. Undrained shear strength of a hard silt or clay may be 4,000 psf or higher, resulting in an ultimate bearing capacity of 20,000 psf or more. The bearing pressure of the concrete is 150 psf times the height of wall above groundwater, and is 87.6 psf times the height of wall below groundwater. (Notice that the thickness of the caisson wall is not a factor in bearing pressure. The weight is simply spread over a larger area. Therefore, increasing wall thickness has no beneficial effect on sinking of the caisson.) The table of calculated bearing pressures below clearly shows that a concrete caisson cannot be expected to sink under its own weight in hard soils, even if the caisson is 100' deep, side friction is ignored, and no groundwater acts to reduce effective weights. Stiff clay would be expected to have a minimum ultimate bearing capacity of 2,500 psf. Approximately 17 feet of concrete above groundwater or 30 feet of concrete below groundwater is required to sink the caisson through stiff clay with 2,500 psf ultimate bearing capacity. These examples illustrate that other measures are necessary if caissons must be sunk through stiff to hard silt and clay. Such measures may include pre-drilling of perimeter holes beneath the cutting shoe, use of steel beams or other dead weight above the caisson, or hand excavating beneath the shoe. Each of these measures was used by the contractor on the recent river crossings. Pre-drilling of perimeter holes is usually the safest and most effective solution.

Height of concrete wall	Bearing pressure above groundwater	Bearing pressure below groundwater
10'	1,500	876
20'	3,000	1,752
40'	6,000	3,504
80'	12,000	7,008
100'	15,000	8,760

2. *Caisson will not stop sinking due to geotechnical conditions:* Soft to very soft clay or silt would be expected to have an ultimate bearing capacity of approximately 1,250 psf or less, if embedment depth is ignored and a simplified model is used for bearing capacity. In soft to very soft clays and silts, and in loose sands and gravels, the weight of the concrete may significantly exceed bearing capacity of the soil. Once moving, the caisson may continue to sink until firmer ground is encountered. The solution is to first, understand ground conditions, and second, limit lift height to reduce bearing pressures. To increase bearing capacity, maintain an unexcavated plug of soil inside the caisson above the cutting shoe (embedment depth increases). Maintain water inside the caisson reduce effective weight of concrete walls. External collars have been used but are cumbersome and reduce production. Secure attachment is a challenge, and the collar must be removed to continue the sinking process.

3. *MTBM cannot excavate through concrete walls unless fitted with rock cutters designed specifically for the concrete strengths anticipated:* MTBMs that have been designed to excavate soils (or soft ground cutting heads) are very inefficient or unable to excavate through concrete. The drag bits or bullet bits rapidly wear or are damaged, and the overcut created by the gage cutters decreases. The damage or wear can result in excavation problems throughout the microtunnel drive. Jacking forces may increase, as a result of the reduced overcut. Damaged teeth may break off and be ingested by the MTBM, causing damage to slurry pumps, shaker screens, or other components. Alternatively, these broken teeth can get locked in the cutterhead and cause the machine to stall. The solution to the problem is to incorporate a soft eye into the caisson wall at the entry point. The soft eye should be comprised of cellular or low-strength concrete with no reinforcing steel. To alleviate concerns about the survivability of the unreinforced soft eye as the caisson is sunk, a steel plate may be bolted to the inner wall, and removed just prior to installation of the entry ring. A common, but labor intensive and slow solution, is to hand-excavate through most of the caisson wall. Special care must be taken to protect the workers against wall failures due to the soils and groundwater forces on the outside of the caisson.

4. *Uneven sinking or tilting as they sink:* This problem is common, but usually not serious. Measures to correct tilt and prevent tilt in the first place include excavating evenly and removing any high spots at or beneath the cutting shoe. Guide beams and concrete control rings are typically not very effective. If the caisson tilts, the guide beams are simply pushed outwards and the control ring cracks. Sufficient lateral support cannot be mobilized to correct or halt the tilt.

5. *Uplift resistance:* This issue was covered under auger-drilled shafts, and applies to any watertight shaft where high groundwater pressures may be experienced. However, uplift can be a serious problem during caisson excavation. When high groundwater and high permeable soils are present, it is important that the caisson excavation takes place “in-the-wet” as lowering the water level inside the caisson will result in unbalanced loading between the inside and outside of the caisson. On a recent project, in well-graded gravel and sand, the contractor advanced the excavation inside the caisson, lowering the water level inside the caisson well below the groundwater level outside the caisson. Lowering the water level inside the caisson resulted in high seepage forces beneath the cutting shoe and a catastrophic uplift failure occurred, affecting the soil in a 30-foot radius around the caisson. The surrounding ground immediately adjacent to the caisson settled on the order of two to three feet, significantly affecting the stability of the crane that was adjacent to the caisson. Luckily no injuries were sustained during the event.

Ground Freezing Shafts

Ground freezing can be used to construct shafts by freezing the in-situ groundwater which bonds with the soil to form a solid soil-water matrix that is impermeable to water. Freeze shafts are created by drilling and installing small diameter (typically 1 to 2-inch) pipes to the desired shaft depth around the perimeter of the shaft to allow for circulating the cooling medium as shown in Figure 6. Typically a brine solution is used as the cooling medium, although if rapid freezing is required, liquid nitrogen can be used at a significant cost penalty. The cooling medium is housed in a refrigeration unit and circulated through the piping system. Over time, ice columns build around each of the freeze pipes. The cooling medium is continually circulated through this closed loop system until the ice columns “grow” together forming the desired shaft wall thickness. This process can take several weeks or even a few months, depending on the ground conditions. In addition, it is important to note that if groundwater velocities are relatively high, it may not be possible to establish a freeze. Therefore, it is extremely important to have a geotechnical engineer with ground freezing experience evaluate the insitu soil and groundwater conditions prior to attempting ground freezing techniques.

With the frozen shaft walls established, shaft excavation can take place. The freeze system must remain in operation and be maintained throughout the entire duration of the project. Insulating blankets and concrete shaft linings are often used to maintain the freeze walls and protect the shaft walls from melt. Upon completion of the project the circulation of the cooling medium is stopped and the frozen ground thaws. The circulation pipes can then be removed. This process induces essentially a “freeze-thaw” cycle in the ground and can potentially cause ground heave during freezing, followed by localized settlements during thaw.

Figure 6. Cooling pipes freezing groundwater prior to shaft excavation (www.cryocell.com)

Freeze shafts have been used successfully on a few microtunneling projects due to their ability to create a watertight environment in high groundwater conditions. However, they require significant expertise to construct, ongoing monitoring to ensure the shaft walls remain solid, and intense, careful pre-planning for the entry and exit of the shafts to ensure that the freeze walls are not compromised during launch and retrieval of the MTBM. Many of the freeze shaft problems associated with microtunneling operations have resulted from improper launch and retrieval techniques that resulted in erosion of the freeze walls that eventually led to flooding of the shaft and catastrophic failure. Special care must be taken to avoid damage to the shaft walls when mounting launch and reception seals, for example. In addition, it is very important to keep the machine and pipeline moving forward and not stop forward progress for long periods of time as the machine or pipe can become frozen into the wall if left for long periods of time. The case history below illustrates these points

A 60-inch microtunneling project used freeze shafts at both the jacking and receiving shaft locations. Failure of the reception shaft occurred during attempted retrieval of the MTBM. The microtunneling machine had been driven to just outside the reception shaft. In lieu of mounting a reception seal, the contractor elected to use a specialized grout mixture and attempted to grout into the annulus as the machine was driven into the freeze shaft. However, as the machine was driven into the ice wall, the groundwater (which was under approximately 85 feet of head) pressurized the annular space. As the cutterhead of the machine entered the inside of the shaft, the pressurized groundwater blew all of the grout into the shaft and quickly began to erode the ice wall. Within a very short time frame, the eroded area around the microtunneling machine was allowing large volumes of soil to enter into the freeze shaft causing the entire shaft to fail.

On another project a 62-inch MTBM was launched through a freeze shaft wall that was approximately 12 feet thick. However, when the machine was only 5 feet into the wall, problems occurred with the hydraulic motor in the MTBM that required repair. The repair took approximately three days. The contractor did not pull the machine out of the ice wall because they did not want to damage the launch seal (the shaft designer analyzed the case and advised the contractor that they could safely remove the machine without breaching the shaft wall due to the thickness of the freeze wall that remained). Instead, the contractor left the machine in place, approximately 5 feet into the ice wall. When the contractor tried to move the machine they discovered that it was frozen into the ice wall. To rectify the situation, they elected to heat the inside of the machine with large heating units. This proved to be very dangerous as the heaters melted the bond between the machine and the freeze wall. However, the heat also melted the bond between the launch seal and the freeze wall, creating a path for the groundwater to flow. Once the machine exited the frozen zone and into the native ground (which had approximately 60 feet of groundwater head), the pressurized groundwater flowed around the machine and back to the melted path around seal, into the shaft. Erosion of the ice wall quickly occurred and within minutes the launch shaft completely flooded.

Improper launch and retrieval methods caused failure of both jacking and receiving freeze shafts on the projects described above. As with any shaft type, freeze shafts require consideration of the limitations of the shaft and what potential actions that could breach the integrity of the shafts. The infrequent and specialized use of freeze shafts means that very few microtunneling contractors have experience with freeze shaft and they may be unaware aware of the shaft limitations.

Sheetpile Shafts

Steel sheetpile shafts are commonly used for microtunneling shafts. Because of their modular nature they can be installed to almost any shape, and with the proper wales and struts, to very large sizes. Additionally, they can be installed to provide a nearly watertight shaft in a variety of ground conditions. This makes them extremely useful for projects in loose and soft soils below the water table.

Sheetpile shafts are constructed by either driving or vibrating individual sheet sections into place around the perimeter of the planned shaft. Steel sheets are typically interlocking using a ball and socket connection to link adjacent sections. Adjacent sheets are advanced in an alternating sequence a few feet at a time to help ensure the sheets remain interlocked. It is best to install continuous sheets for the full depth of the shaft, but for very deep excavations, shorter sheets can be driven and spiced together as the shaft is lowered. Once the sheets have been installed to depth, excavation can commence. As with soldier pile and lagging shafts, wales and struts are typically installed to resist soil pressure as the excavation progresses (Figure 7). When the final depth is reached, a concrete working slab is typically poured to finish the excavation.

Figure 7. Sheetpile jacking shaft prepared for launch of the MTBM (left) and a shaft that flooded during construction with split interlocks allowing high inflow of water (right)

When steel sheetpiles are used in areas of high groundwater it is extremely important to keep the sheets interlocked during placement. If the sheets are driven too far ahead of each other, the interlocks can split during installation and the seal will be compromised. Additionally, if the soil contains large amounts of gravel, it may be difficult to maintain the interlock during installation as rocks can get into the socket and disrupt the jointing. Interlocking is also very difficult to achieve in soils with cobbles and boulders present, and is generally not recommended. Even in soils without rocks, it is often not possible to make the interlock between the first and last sheets due to spacing issues. Any corners that cannot be properly interlocked need to be sealed after excavation by welding a patch panel of steel between the adjacent sheets.

As with other watertight shaft types, such as auger-drilled shafts and caissons, a thick concrete slab must be poured to prevent groundwater from entering through the bottom of the shaft and to prevent uplift of the finished shaft. This can be accomplished with a tremie slab as described in other sections of this paper. Alternatively, if a layer of soil exists below the shaft bottom that will act as an aquitard, the sheets can be driven into this layer to break the flow path of the surrounding groundwater. At this point a thin concrete slab will be adequate to finish the shaft. Using sheetpiles in hard or dense soils may require pre-drilling around the perimeter of the shaft to loosen the soils and allow them to be driven or vibrated to full depth.

The most commonly experienced problem with sheetpile shafts and microtunneling is during exit and entry of the shafts. When the microtunneling machines exit or enter the shafts, the steel sheets must be removed or cut away at the portal to allow the machine to penetrate the shaft. It is important to stabilize the soil behind the shaft wall at the portal to allow for removal of the sheets without allowing soil or groundwater to flow into the shaft. This can be accomplished by grouting, ground freezing, or dewatering techniques in conjunction with exit and entry seals. As discussed previously with steel beams and lagging shafts, small holes should always be cut in the sheets to prove that the ground behind the portal is stable prior to opening large holes in the shaft. Once the engineer is convinced that the soil behind the shaft wall has been sufficiently stabilized, the contractor should then be allowed to completely remove the steel supporting the portal for launch and retrieval of the machine.

5. CONCLUSION

Proper shaft design and construction is essential for a successful microtunneling project. Each type of shaft has advantages and limitations that must be addressed. Several case histories illustrate many different problems that can occur with microtunneling shafts. Many of the situations could have been avoided or prevented if proper shaft design and construction techniques were used. An understanding of the site conditions and full knowledge of the different shaft types is essential to ensure that the most appropriate shaft type is used on a microtunneling project. Construction of the microtunneling shafts requires coordination between the engineer, the microtunneling contractor, and the contractor constructing the shaft. Properly designed and constructed shafts help get a microtunneling project off on the right foot and well on its way to success.