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Salvaging the Lessons Learned from a Difficult Microtunneling Project

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1. ABSTRACT

When a trenchless project fails it is bad for everyone involved on the project- the Owner, Designer, and Contractor. However, it is also bad for the entire trenchless industry. For the industry to move forward in a positive direction, we must take a hard look at project failures to determine why the project failed so that we can use the lessons learned to eliminate repeat failures. This paper details a forensic analysis of a failed microtunneling project that appeared to be ideal for the technology at the time of design. However, as the project was constructed, a unique set of circumstances, all of which could have been avoided with proper design and execution, resulted in project failure that included loss of line and grade to the extent that the pipe would not flow by gravity, flooded shafts, and broken jacking pipe. The paper presents the geotechnical conditions that were understood to exist at the time of construction, the details of the microtunnel construction, and the resulting microtunneling failure. The results of the forensic analysis will then be presented, including post-construction geotechnical work that was performed to determine the cause of failure. The lessons learned from the design and construction will be presented along with suggestions on how to prevent similar problems on future microtunneling projects. The lessons from this project will benefit the microtunneling design and construction industry.

2. INTRODUCTION

A large construction project was planned in California very near the Pacific Coast. The project included the construction of a new pump station that would replace a number of smaller lift stations. As part of the project, a new 24-inch microtunnel was designed at a very flat grade to carry sewage from a to-be-decommissioned lift station to the new lift station that was constructed as part of the project. The microtunnel was to be constructed in eight drives within a very sensitive wetland and would traverse beneath an environmentally sensitive inter-coastal canal. The authors of this paper were hired to analyze the project after the completion of five drives, at which point the Owner terminated the construction of the microtunnels. The project then proceeded into litigation which has subsequently been settled. Due to the sensitive nature of the issues, the names of the Owner, Project, and Designer are not presented in this paper.

3. DESIGN OF THE PROJECT

The project included the construction of a new lift station, followed by a series of eight microtunnels totaling 3,445 feet in length. The drives ranged in length from 316 feet to 581 feet. Drive 1 of the microtunnel project was to use the wet well of the lift station as a reception shaft, and the following seven drives were to move away from the lift station toward the Pacific Ocean, as can be seen in Figure 1. Of critical importance was Drive 6, which was to traverse beneath a channel within a critical wetland area with less than three feet of cover above the crown of the pipe on a very flat grade of 0.1%.

Figure 1. Plan view of Project Site showing Drive Numbers and Location.

The microtunnel project designers hired a geotechnical engineering firm to conduct a geotechnical investigation for the microtunnel design. Ten geotechnical borings were conducted along the microtunnel alignment, generally at the shaft locations, averaging one boring every 344 feet. The borings collected information on the soils to be encountered at the site. The geotechnical investigation revealed that the site soils consisted of layers of sand, silt, and clay. During the geotechnical investigation groundwater was discovered within 10 feet of the ground surface; however, no piezometers were installed during the design to track the groundwater levels or fluctuations in groundwater elevations during the design of the project.

The design documents allowed the Contractor to select between using vitrified clay pipe (VCP), Hobas, or Polycrete pipe material for the construction of the 24-inch microtunnel pipeline.

The design allowed the Contractor to select the type of shafts from a list provided in the specification. The list included sheet piles with internal bracing (although at some location the use of vibratory hammers was prohibited), corrugated metal pipe within a drilled shaft, interlocking grout columns (or secant piles), and interlocking soil-mixed columns. Although a geotechnical baseline report was not prepared for the project, the design documents listed each shaft by station and baselined the amount of fill that would be encountered at each shaft location. As the shafts were temporary shoring, the responsibility of the design was left to the Contractor.

The design required the microtunneling to begin at Drive 6 (the drive that traversed beneath the channel with minimal depth of cover); however, the design gave no information as to why the microtunnel had to start at this location.

Of interest in the design, the specification set a minimum depth of cover requirement for the microtunnel that was equal to two diameters or six feet; however, the drive beneath the channel had only 2.6 feet of cover over the crown of the tunnel. Another significant feature of the specifications that would play a large role in later litigation was that the specification required the Contractor to calculate the buoyancy of the pipeline and submit the calculations. Although all of the designed pipe options were buoyant under the design conditions, they were buried sufficiently deep to prevent flotation of the pipelines.

4. CONSTRUCTION OF THE PROJECT

Construction of the project began with the lift station. The Contractor began with a massive dewatering effort to lower the water table and allow the construction of the lift station; however, they encountered pressurized water in what was thought to be the Talbert aquifer which was known to exist beneath the site. The Owner acknowledged the existence of the pressurized aquifer and paid a sizeable change order to the Contractor to depressurize the aquifer to allow the construction. All of this activity took place prior to the construction of the microtunnel. Although the microtunneling contractor was referred to the geotechnical report for the lift station in the bidding documents, none of the information regarding the pressurized aquifer or the change order that was executed on the lift station contract was incorporated into the geotechnical documents or given to the microtunneling contractor during bidding or at any time during the construction.

The low bid contractor was awarded the microtunneling contract as the lift station was approaching completion. The Contractor elected to install 24-inch VCP with a 31-inch outer diameter (OD). The Contractor used a 30-inch Iseki Unclemole for the construction of the microtunnels. Shaft construction was completed using corrugated metal pipe with the drilled shaft method. Shaft construction began closest to the Lift Station and progressed toward the Pacific Ocean. Because the lift station wet well was approaching completion, the Contractor submitted an RFI asking if they could install Drive 1 first, microtunneling from Drive Shaft 2 to the lift station. Although the contract required Drive 6 to be installed first, the Construction Management team allowed the Contractor to proceed with the drive closest to the lift station first.

5. MICROTUNNEL DRIVES

Drive 1 was constructed in the month of October, and the 391-foot drive was completed without issue. The drive record showed that the pipe was installed within ½ -inch of line and grade. Line and grade tolerance was specified as +/- 1-inch of line and grade so the drive was installed well within the required tolerance. The machine was retrieved within the lift station wet well. Figure 2 shows the position of the laser relative to the target within the 24-inch machine during construction of Drive 1.

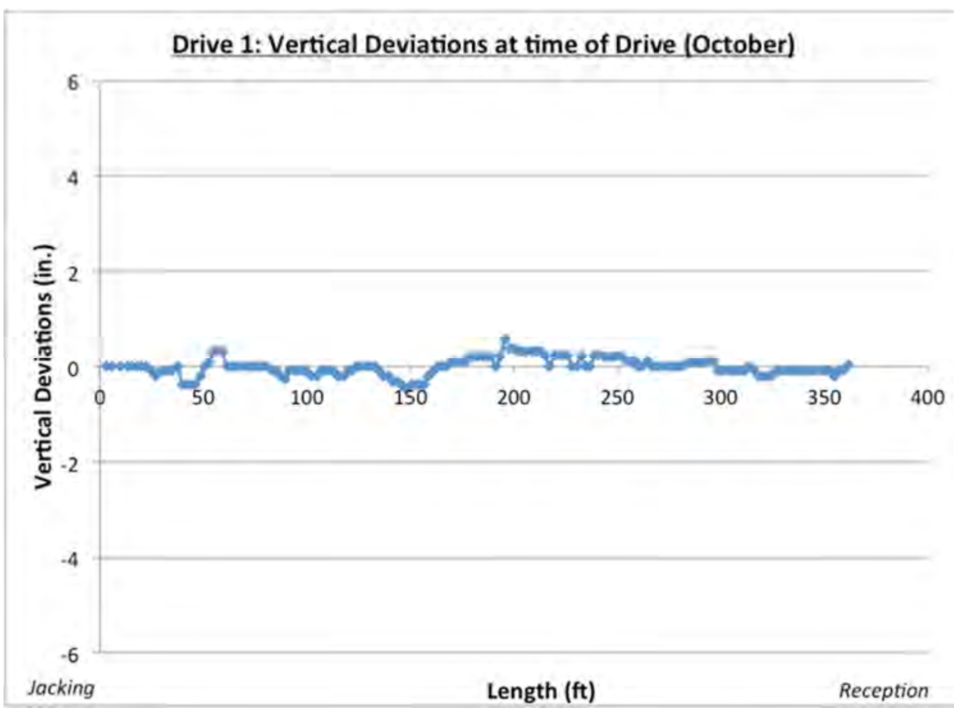

Figure 2. Vertical deviations measured during Drive 1.

After retrieval of the machine, the Contractor turned the machine within the shaft and started Drive 2 – the 524-foot drive toward the Pacific Ocean. This drive was constructed in the month of November and the vast majority of the drive was completed within ¼ of an inch of the design line and grade. At one location the grade was ½-inch low, which was the largest deviation from line and grade on the entire drive. Figure 3 shows the location of the laser relative to the target located in the 24-inch microtunneling machine.

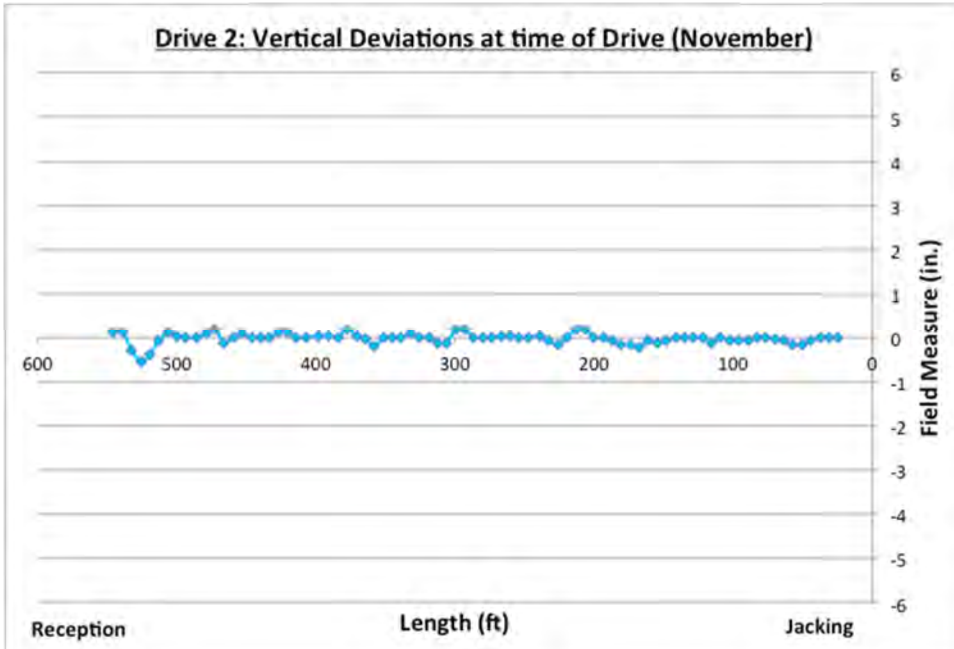

Figure 3. Vertical deviations measured during Drive 2.

In January of the following year, the Contractor moved the microtunneling equipment to the next jacking shaft to begin Drive 3, a 444-foot drive towards Drive 2. During the drive, the operator noted grade deviations of up to one inch at 110 feet and 220 feet into the alignment and was forced to move the laser to keep the laser on the target within the 24-inch machine. While pushing within 50 tons of the safe jacking capacity of the pipe (calculated with a safety factor of 2.5), the pipe broke at 460 feet into the drive. The breakage of the pipe was significant and allowed water to flow within the pipe. This water flooded the machine and the shaft, causing numerous problems and a significant delay. The microtunnel machine required retrieval from the surface and Drive 3 had to be completed by open cut excavation. Figure 4 shows the location of the laser relative to the target in the 30-inch microtunneling machine prior to the time the pipe broke and the drive was abandoned.

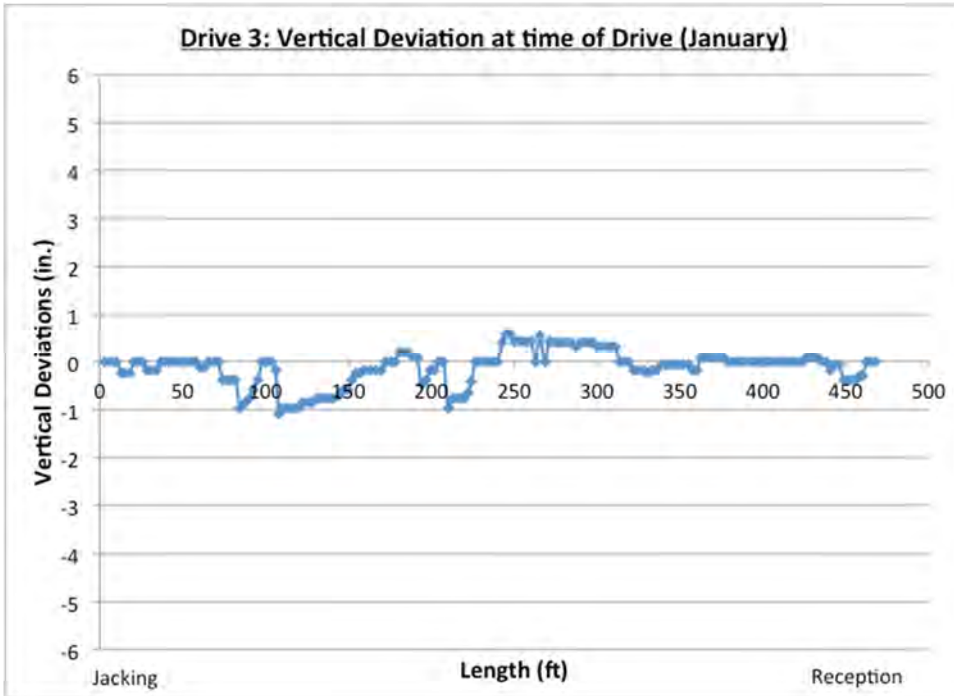

Figure 4. Vertical deviations measured during Drive 3 prior to abandonment.

Drive 4 began in April, at which time the Contractor rotated the equipment in the shaft and began the 316-foot drive toward the Pacific Ocean. The drive was completed with little incident and was completed successfully with less than ½-inch deviation on line and grade. Figure 5 shows the location of the laser relative to the target within the 30-inch machine during the drive.

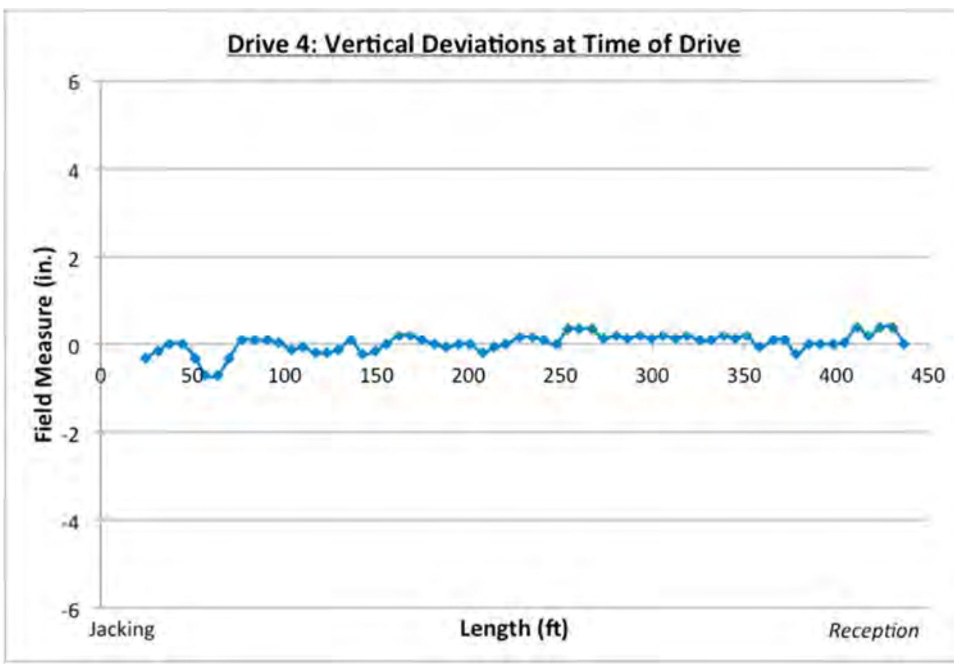

Figure 5. Vertical deviations measured during Drive 4.

For Drive 5, the Contractor relocated the equipment to the next jacking shaft and began the 445-foot drive towards Drive No. 4. This drive marked the beginning of a series of perplexing events that would ultimately result in the failure of the entire project. The drive began without incident and had progressed for approximately 300-feet when grade deviations in the pipe were noted at the pipes near the shaft. When these pipes were initially installed by the microtunnel machine, the microtunneling equipment guidance system showed that they were within the one inch line and grade tolerance; however, as the drive progressed, the pipes were beginning to increase in grade. This trend continued as the drive extended, as the pipes within 150 feet of the shaft rose upward and caused a hump in the pipe that deviated by as much as 13 inches from line and grade. The drive was finished with the machine at the appropriate line and grade; however, the 13-inch hump in the pipe was significant and would not allow the sewage to flow by gravity to the Lift Station. Figure 6 shows the grade deviations of the pipe as it was being constructed (i.e. the position of the laser relative to the machine target), along with the as-built survey of the pipe at the completion of the tunnel drive. It is important to note that by the end of the tunneling the operator was forced to move the laser to keep it on the target due to the large hump in the pipeline. These values were corrected on Figure 6 to reflect the actual position of the machine based on the operator's notes that kept track of the laser movement.

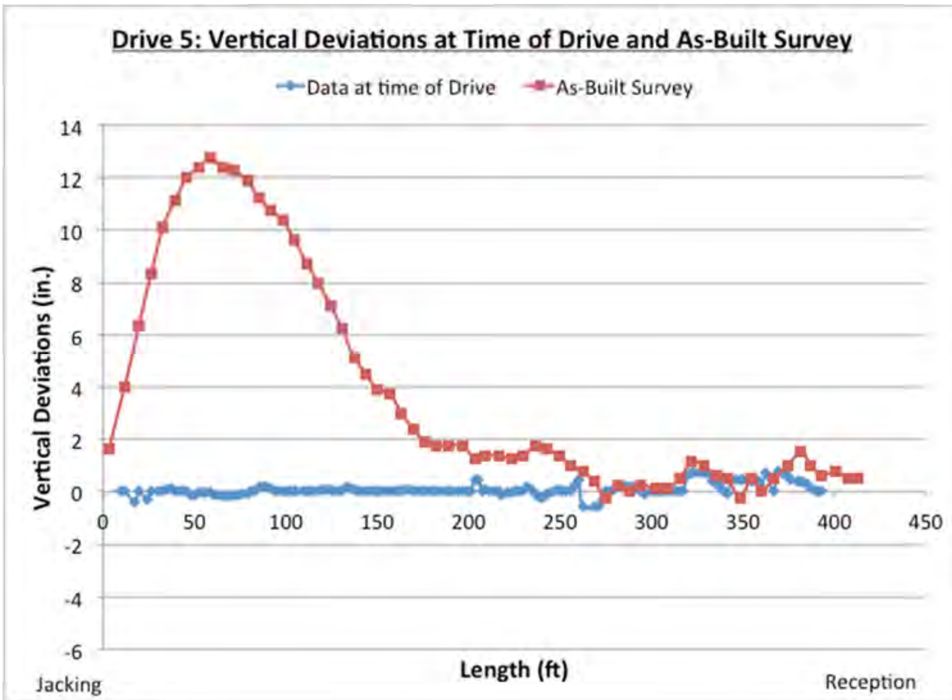

Figure 6. Vertical deviations measured during and post-construction of Drive 5.

It was unclear at this point why the pipe had risen during jacking as there was no indication of encountering an obstruction or any object that would have caused the machine to rise – in fact, the machine was on line and grade during the excavation of the first 275 feet. The rise in the pipe occurred after excavation, but the question was – why?

6. INVESTIGATING THE PROBLEM

After the pipe on Drive 5 had risen, it was decided to go back and re-survey the other microtunnel drives (1 through 4) to determine their exact locations. The results of the surveys were astonishing. Drive 1, which had originally been installed within the specified line and grade tolerance at the time of construction, had shown significant movement. In fact, there were locations where the pipe exhibited humps that were five and four inches out of tolerance, as shown in Figure 7. With the tight grades specified on the project, the areas exhibiting the deviations were significant enough that they would require repair to allow the sewer to flow by gravity.

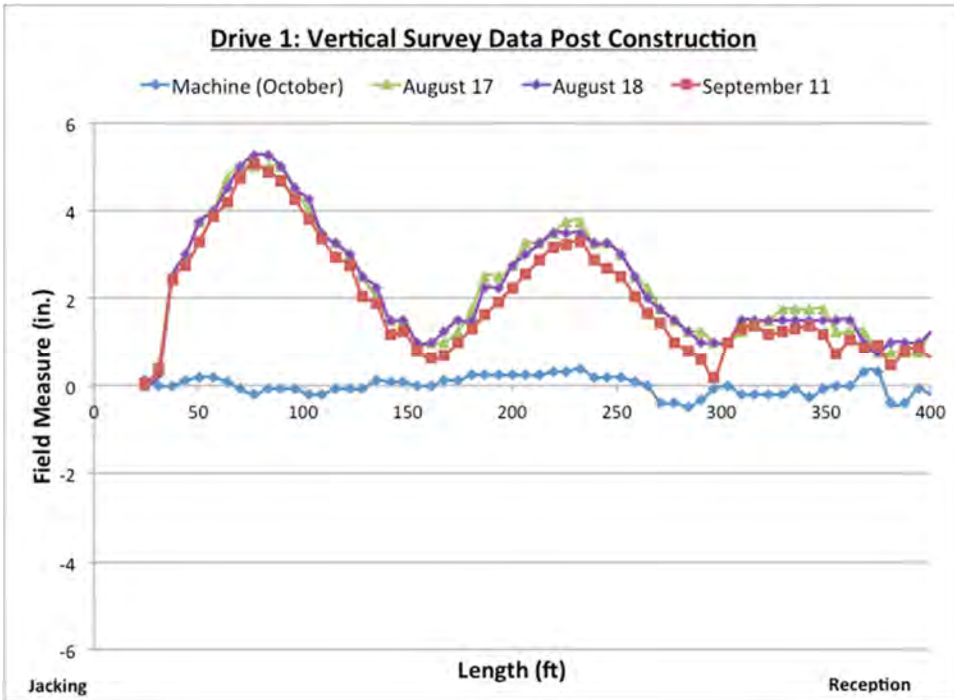

Figure 7. Vertical deviations measured during and post-construction of Drive 1.

Drive 2 was re-surveyed but showed essentially no change in grade from the original installation to the re-survey. Drive 3 could not be surveyed because it contained the as-yet unfixed broken pipe, allowing water into the excavation and making entry unsafe. When Drive 4 was re-surveyed, significant deviations in line and grade appeared, even though it had been installed within line and grade tolerances only three months prior to the re-survey. Drive 4 showed grade deviations of four-inches and two and 1/2 - inches at the near-shaft locations, as shown in Figure 8.

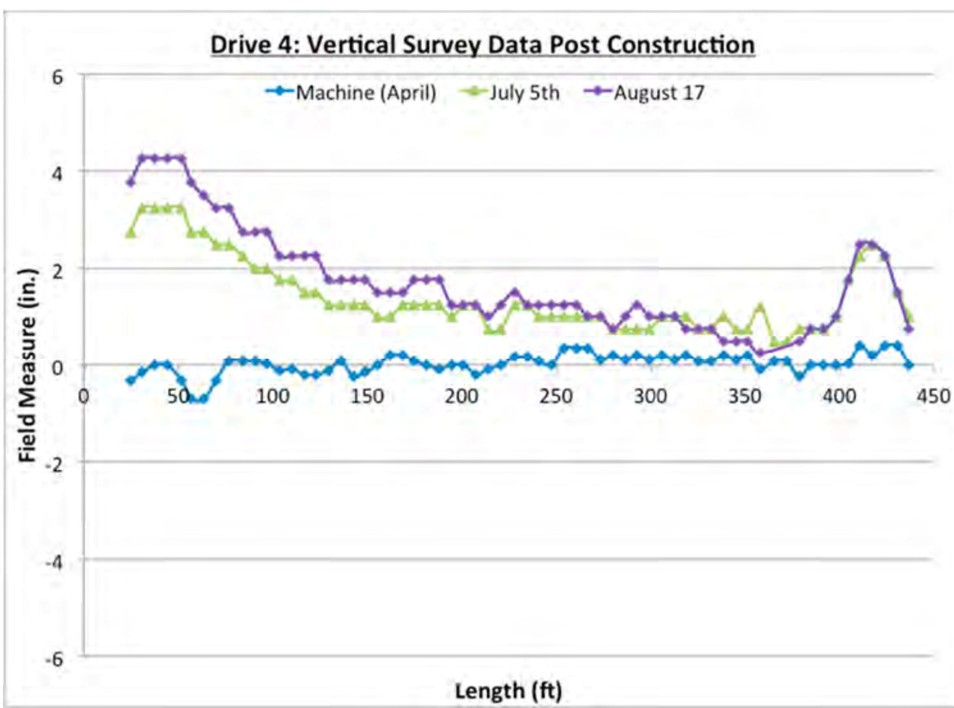

Figure 8. Vertical deviations measured during and post-construction of Drive 4.

At this point the microtunneling was stopped. There was no sense in microtunneling beneath the channel because the deviations in line and grade were of such significance that gravity flow could not be achieved in the remainder of the pipeline. In addition, the Contractor was very concerned that the machine would "daylight" within the channel due to the shallow depth of cover.

7. DETERMINING THE CAUSE OF FLOTATION

There were many theories as to the cause of flotation, several of which focused on the buoyancy of the pipe. There was no disagreement that the pipe was buoyant; however, there was disagreement over what had occurred during tunneling to cause flotation of the pipe when the depth of the pipeline was sufficient to prevent upward movement due to buoyancy forces.

Some theorized that over-excavation had taken place during microtunneling operations; however, there was no evidence of over-excavation in the jacking record. In addition, over-excavation would not have explained the flotation. In order for over-excavation to occur, the soil must be loose/soft enough to flow into the face of the machine. If this scenario exists, the soil will also collapse over the machine and subsequent pipe. If the pipe is sufficiently deep that the overburden forces are higher than the upward buoyant force of the pipe, the pipe will not float. If the soil was stiff enough to hold a competent hole, keeping the overcut open, the pipe could float by means of the upward buoyant force to the limits of the overcut; however, over-excavation would not occur because the soil would need to be sufficiently stiff to hold the overcut, and therefore collapsing of the soil into the face of the machine would not occur.

There were some that theorized that the microtunneling machine had liquefied the loose granular soils, causing flotation of the pipeline; however, liquefaction would have caused the microtunneling machine to sink. During the microtunnel drives, the microtunneling machine had no difficulty with maintaining grade and did not encounter any areas where bearing capacity of the soils beneath the machine were of any issue. In addition, the maximum rotation of the machine was eight revolutions per minute, well below the frequency that would be necessary to cause liquefaction of the soil.

To determine the cause of the flotation it was necessary to take a critical look at the geotechnical conditions along each of the drives. It was discovered early in the analysis that the Contractor for the Lift Station had encountered pressurized water during the dewatering process. Once this was discovered, monitoring well records from the local County agency were requested for analysis to determine if pressurized groundwater conditions existed historically. Those records revealed several dewatering wells within close proximity to the construction site (one well was only 256 feet from one of the microtunnel drives). The monitoring well records revealed that there were three main aquifers at the site: a shallow aquifer that contained perched water near the ground surface that was referred to as the "Shallow Aquifer System or Layer 1"; an aquifer that was below the shallow aquifer system known as the "Primary Aquifer System or Layer 2" which would become seasonally pressurized; and a third aquifer referred to as the "Deep Aquifer System or Layer 3." All of the aquifers were separated by aquitards or layers of clay. Of critical importance was Layer 2 as it was where the microtunnel was located.

The geotechnical conditions at the site were analyzed to compare the flotation of the pipe with the locations of the aquifers and the records at the monitoring wells. The geotechnical conditions for Drive 4 are shown in Figure 9. The geotechnical conditions revealed that the microtunnel was designed just below an aquitard that separated the Shallow Aquifer System and the Primary Aquifer System.

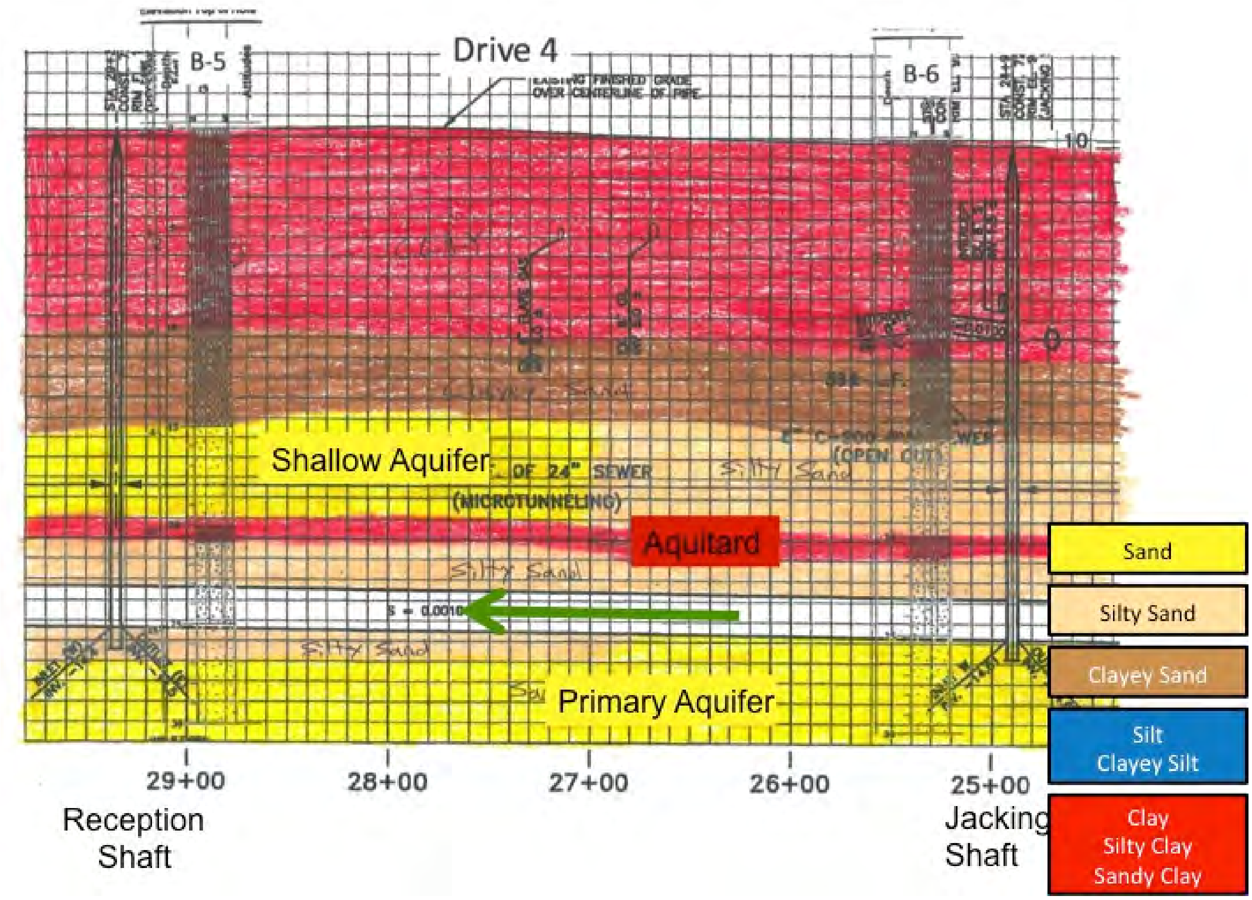

Figure 9. Geotechnical Conditions along Drive 4 showing the Shallow and Primary Aquifer.

An examination of Drive 4 revealed that at the time of construction, the water in the primary aquifer was not pressurized, according to the County monitoring wells. However, within a month after construction, the primary aquifer became pressurized and some wells exhibited artesian pressures. Figure 8 showed that the flotation effects were the highest nearest the shaft locations. It was then determined that the shafts had breached the aquitard during construction and were not completely sealed at the interface, creating a pathway between the shallow and primary aquifers. Since the pipe was designed only a few feet beneath the aquitard, the critical gradient to cause piping of the sandy soils between the shallow and primary aquifer was very low. When the pressure in the primary aquifer began to rise above that in the shallow aquifer, the water began to migrate upwards into the shallow aquifer. Nearest the shafts where the aquitard had been breached, the movement of water took soil particles with it, removing the soil from above the pipeline. Since the pipe was buoyant, the pipe floated into the space that was vacated by the soil that had moved into the shallow aquifer due to soil piping. These effects were not seen on Drive 4 during construction because the primary aquifer was not pressurized at the time of construction.

However, on Drive 5, the primary aquifer was pressurized during the time of construction. In fact, as they were microtunneling, the primary aquifer was pressurized to the point that the critical gradient was reached near the jacking shaft location. This caused the soil above the pipe to begin piping/moving above the aquitard (clay) layer during the installation of the pipe. Although the Contractor was installing the pipe to the design line and grade, the pipe began to float during the installation because of the pressure gradient between the Shallow and Primary Aquifers. Figure 10 shows the geotechnical conditions on Drive 5 during construction.

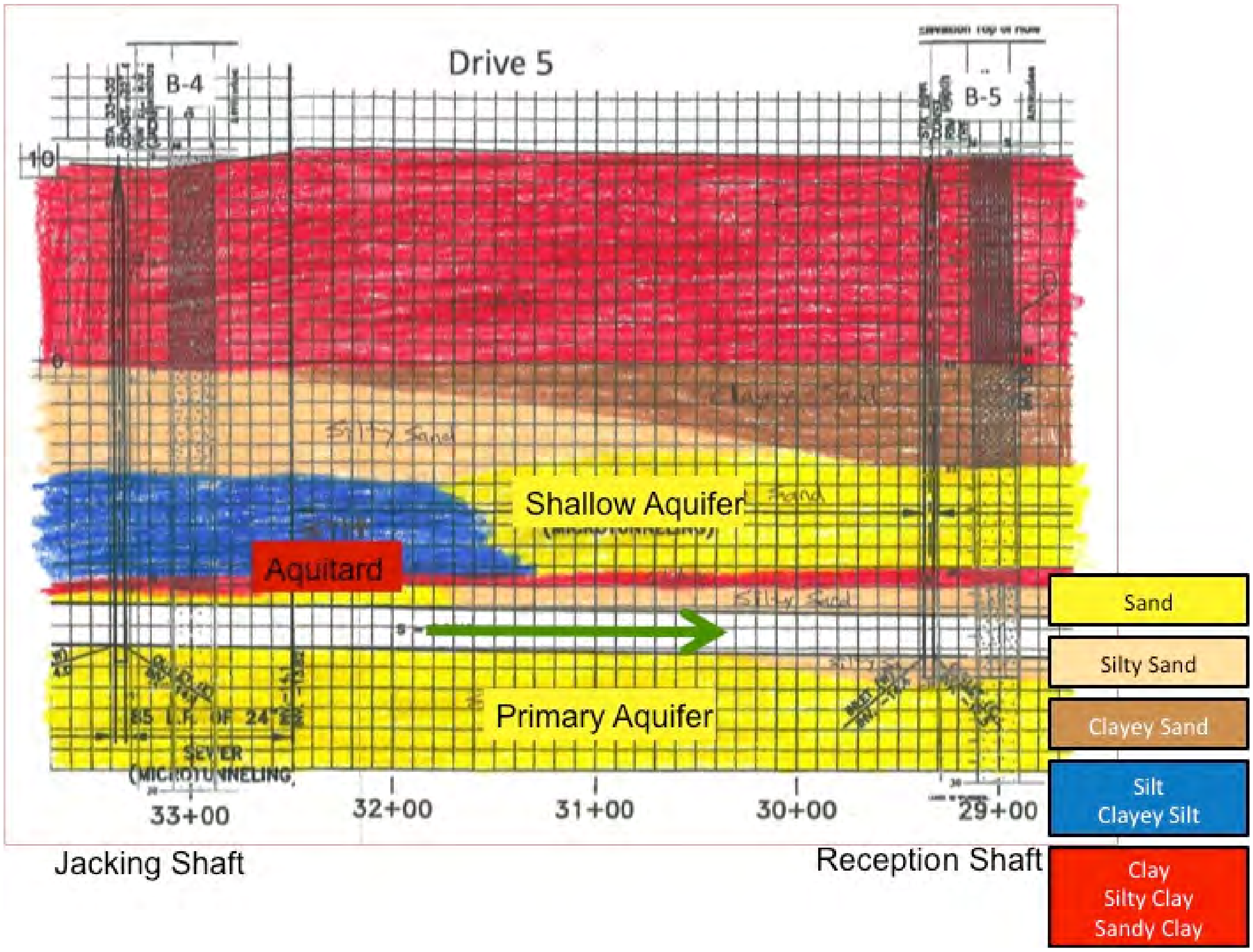

Figure 10. Geotechnical Conditions along Drive 5 showing the Shallow and Primary Aquifer.

Of note on Drive 5 was the fact that the aquitard is significantly thick in the area where the piping occurred, resulting in flotation of the pipe; however, beyond approximately 250 feet into the drive, the aquitard shrinks to less than 6 inches thick. In Boring B-5, the aquitard is seen only as a thin layer of clay, which has been interpreted to stretch along the drive. It is therefore possible that the aquitard is in fact discontinuous, allowing the pressures to equalize during tunneling, and eliminating the potential for pipe flotation in that area.

Drive 1 showed a similar pattern to Drives 4 and 5 with an aquitard within a few feet of the pipe, sandy soils above the pipe that were susceptible to piping, and flotation of the pipe near the shaft locations where the aquitard was breached by the shaft construction. However, of equal importance was Drive 2 where no flotation was observed during or post construction. The geotechnical conditions for Drive 2 are shown in Figure 11.

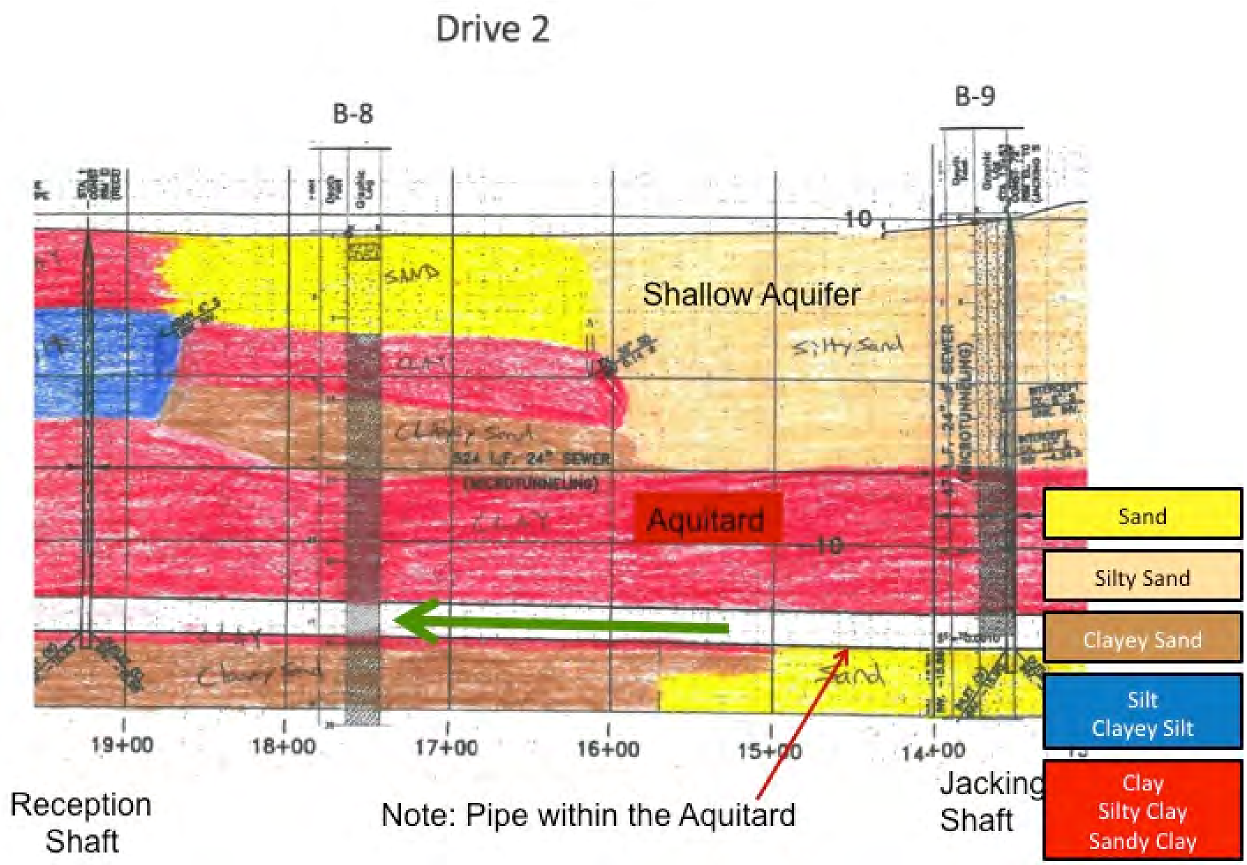

Figure 11. Geotechnical Conditions along Drive 2.

Drive 2 was constructed almost entirely within clay. At no point along the drive was there a condition where there was sand above the pipe as the alignment was completely within the clay aquitard. Because of this fact, there was no soil above the pipeline that was susceptible to piping. Although the primary aquifer became pressurized on this drive, as with all the other drives, piping of the soils did not occur as clay is not susceptible to piping under the pressure gradient that was measured in the monitoring wells. Therefore, there was no flotation of the pipeline. This proved to be the case as the post construction surveys revealed that no flotation had taken place on Drive 2 after the pressurization of the aquifers.

8. CONCLUSIONS AND LESSONS LEARNED

There were many valuable lessons learned on the project. The most prominent lesson learned was the importance of gathering groundwater information on microtunneling projects. Although it was widely known to the designers that the groundwater table was close to the ground surface at the project site (which was one of the main reasons that microtunneling was the chosen method of construction), piezometers were not installed at the site to measure the groundwater fluctuations over the course of the design. Had the designers had access to piezometer data, they surely would have seen the fluctuations in the groundwater pressures and could have changed the design accordingly.

If pressurized water was known to exist at the site, it would have been critical to include a grouting program with the shaft design to completely seal the shafts so that no piping could have occurred at the location of the shafts. Alternatively, the pipeline could have been deepened below the aquitard so that the critical gradient was much higher and would not have been reached with the water pressure fluctuations that were expected in the local area.

Another valuable lesson learned from the project was the importance of sharing information from the lift station contract with the microtunneling contract. Although this would have taken some coordination on the part of the construction management consultant and design consultant, the fact that the lift station Contractor was aware of the pressurized aquifer in the year preceding the microtunneling construction was tremendously valuable information.

Had the coordination taken place and the information been included in the microtunneling contract, it would have certainly resulted in a higher bid price for grouted shafts; however, the City would have ended up with a pipe that would not have floated and would have flowed by gravity.

Another lesson learned was that the microtunnel design utilized such a flat slope that there was absolutely no room for error. Had the lift station been deepened, even by two to three feet, it would have allowed for some deviation in the grade of the microtunnel pipe without failure of the project. It is understood that microtunneling is advertised to be accurate to within one-inch on 1,000 feet; however, conditions are not always perfect and it is often wise to incorporate some flexibility into the design to allow for some construction difficulties.

The channel crossing was never constructed; however, had it been constructed, the project may have had additional problems. With a very small amount of ground cover over the crown of the pipeline, it is likely that the machine would have day-lighted in the canal, causing a host of problems. Had this occurred, the environmental regulators on the project could have shut the project down causing significant delays. The risk of this crossing was extremely high and could have been mitigated by deepening the pipeline to the “standard rule” of two diameters of cover. This would have resulted in a slightly deeper lift station; however, this would have lowered the risk for the overall project.

This project was disastrous for the City who had never used microtunneling on a project before, and will likely never use microtunneling again. As a result, it hurt the entire microtunneling industry. The authors were hired as claim analysts to help determine the cause of loss and participate in mediation hearings and preparation for litigation. Although these stories can be “ugly,” it is critically important that this industry shares our failures as well as our successes so that we can grow as an industry and learn lessons from the projects that do not go well. We applaud those who gave their permission to have this story told and respect those whose names have been omitted from this text for the sake of privacy.