DROP SHAFTS FOR NARRAGANSETT BAY COMMISSION CSO ABATEMENT PROGRAM, PROVIDENCE, RHODE ISLAND

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ABSTRACT

Seven pairs of drop and ventilation shafts, between two and nine feet in diameter, will convey combined sewer flow to a 230-foot-deep, 26-foot diameter storage tunnel. This paper will present case histories for each site. Discussion will include functional requirements, program and site access constraints, structural design, geology, the variety of excavation and lining construction methods used, and lessons learned. Noteworthy observations include the importance of assuring competent ground support at the soil-bedrock interface and of achieving tight verticality tolerance using both top-down and raise bore excavation methods.

PROJECT OVERVIEW

The Narragansett Bay Commission (NBC) is a regional sewer authority that serves 10 communities in the Providence, Rhode Island metropolitan area. From 1992 to 1999, the NBC developed a comprehensive facilities plan to abate Combined Sewer Overflow (CSO) pollution in the Upper Narragansett Bay. The plan underwent many major evolutions during this period, most notably the addition of a stakeholder's process by which NBC demonstrated a site-specific plan to control the pollutants and meet water quality standards. The favored solution consisted of deep tunnel storage with treatment at existing wastewater facilities. In 1999, a final plan was accepted which included two tunnels, five CSO interceptors, 12 sewer separation projects, a wetland facility, and a wastewater treatment facility upgrade. The program was to be constructed over 20 years in three sequential phases.

Phase 1 of the program included a 16,284-foot-long, 26-foot-diameter, 230-foot-deep storage tunnel; adits; drop shafts; ancillary facilities; and a pump station. Construction of Phase 1 began in 2001 and is expected to operational by 2008. Seven near surface sites to divert and convey combined sewer flow to the deep storage tunnel consist of diversion or interceptor relief structures, consolidation conduits, screening structures, approach and vortex structures, and drop and vent shafts.

In 1992 the NBC retained Louis Berger Group as Program Manager (PM) for the CSO Abatement Program. The PM team included Jacobs Civil Inc. as the primary designer assisted by CH2M Hill Inc. Haley and Aldrich provided geotechnical design and Gilbane/Jacobs Associates provided construction management services.

This paper focuses on design and construction of the drop and vent shafts.

DESIGN

Design Issues

During the design process, it was established that the program should encourage participation by local construction firms and, where possible, the construction contract scopes should be kept within the bidding range of smaller local contractors. To this end the work at each near surface site was to be packaged to bid individually and let out periodically in a series, rather than simultaneously. Appropriate milestones and constraints were thereafter established in the near-surface and tunnel contracts, and the program schedule organized to complete all but one pair of shafts using top down construction methods prior to excavation of the tunnel below.

Functionally, the near surface structures and shafts were designed to transfer up to the peak flows from a 1 year storm. Near surface structure configurations were based on the flow dependent guidelines established by the Iowa Institute of Hydraulic Research (IIHR) and scale model studies. The models dictated the geometric sizes and configurations for the approach channel, tangential inlet vortex generator, drop and vent shafts, deaeration chambers, and connecting adits. One of the shafts was also enlarged to act as an emergency overflow in the event that all gates closed when the tunnel was full (Figure 1).

Based on the hydraulic study and modeling, appropriate nominal dimensions were selected for each shaft and associated collection components. Four 5-foot, one 6-foot and two 9-foot diameter drop shafts were selected. Once the sizes had been established, it was important to consider installation requirements that would maintain the modeling assumptions.

The tangential inlet vortex configuration was favored over the plunge and helical configurations because of its proven record of energy dissipation and control of air entrainment. For the tangential configuration to function properly, it was critical for the verticality of the drop shaft to be maintained within prescribed limits. If the shaft deviated from plumb beyond these limits, the water would detach from the shaft walls and freefall into the chamber below, instead of swirling around the shaft as it descended. The freefall would have the negative effects of entraining additional air into the tunnel that would consume needed capacity, and accelerating long-term scouring of the deaeration chamber below by the erosive action of the falling water. Based on tolerances used for construction on previous shaft projects, the Contract Documents included maximum deviation from vertical of 3 inches in any 100-foot section and 6 inches in the overall depth of the shaft. Specific quality control measures were also established, such as verticality checks at the lesser of every 10 feet of drilling or once per day, and sizing of the excavated opening to meet the final tolerances based on the specific drilling and support methods chosen.

Geology

The region's lower surficial deposits consist of a basal glacial till overlain by discontinuous strata of glaciofluvial and glaciolacustrine cobbles, sands, and silts. Nearer to the surface are estuarine, alluvial, and urban fill deposits, which are generally thicker adjacent to the river and bay. The bedrock consists of a Devonian- to Pennsylvanian-aged sedimentary series that has been variably metamorphosed and deformed. In

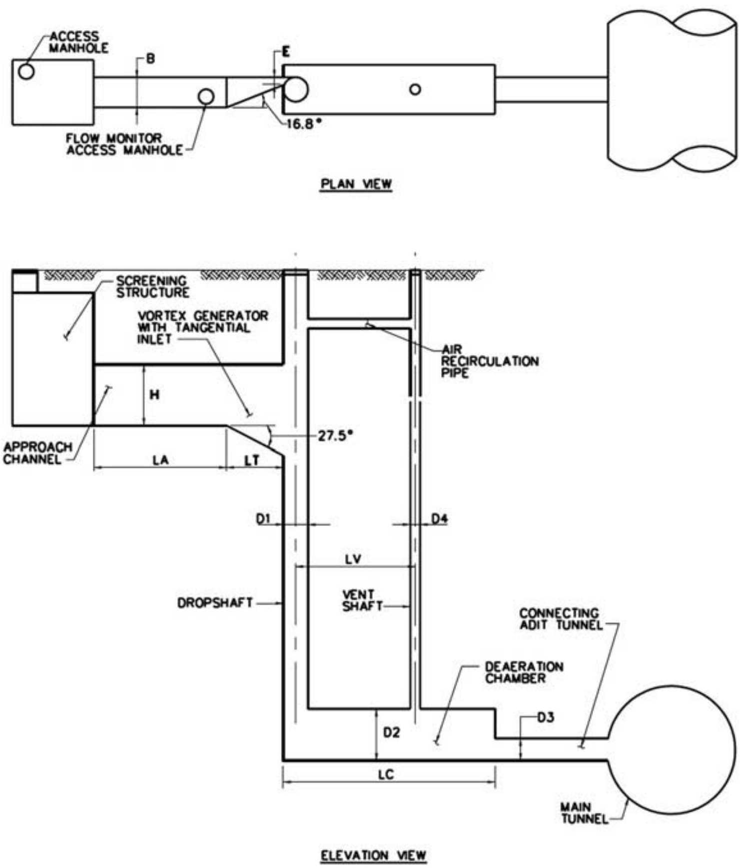

Figure 1. Components of collection system as described by the IIHR Model with critical dimensions identified (Jain and Kennedy 1983)

addition to relatively competent conglomerates, sandstones, siltstones, and shales with average UCSs of 10 to 13 ksi and a maximum UCS of 25ksi, there lay intermittent deposits of weak graphitic shales with UCSs of less than 1 ksi.

Bedrock topography is extremely variable with soil depths of 26 to 170 feet along the main spine alignment. The tunnel profile was selected so that the crown was two diameters below the lowest apparent top of rock elevation. Apart from regional variability, it was also documented that extreme localized irregularity existed both in the elevation and composition at the soil/rock interface. The thickness of overburden at the drop shaft sites varied between 60 feet and 120 feet, representing one-third to one-half the total depth of the shafts (220 feet).

Groundwater levels were generally within 10 feet of the surface. At a few locations along the alignment, hydrostatic readings in rock were found to be higher than in the soil, with one well at the north end becoming seasonally artesian.

A Geotechnical Baseline Report was generated for each pair of shafts. Special emphasis was placed on the need for sealing off soil at the irregular top of rock, anticipating high hydraulic conductivity in soil and rock, and coping with graphitic shale, weathered rock, and man-made obstructions. Discussions also included appropriate warnings to maintain verticality through the variably resistant rock and soil.

Contract Design

The Contract Documents for the drop and vent shaft linings called for a cast-in-place concrete lining with a minimum compressive strength of 4,000 psi. Drop shafts were to be reinforced with welded wire fabric (WWF) placed at the center of the minimum 6-inch lining. The vent shafts, which were 2 feet in diameter at all sites except one, which was 3.5 feet in diameter, were all unreinforced. The Contract Documents allowed for stay-in-place (SIP) forms, especially for construction of the smaller shafts where manned entry was not possible. Due to the corrosive nature of combined sewage, the SIP forms were allowed to be constructed only of specific non-corrosive materials. To facilitate compatibility of construction methods, the contractor was responsible for the initial soil and rock support design.

In recognition of the variety of installation and design methods that would meet the design intent for the drop and vent shafts, the Contract Documents allowed for alternate liner designs. The alternate design liner criteria included most of the pertinent design assumptions that were used by the original designer, together with limits on material selection for the shaft liners (allowable materials were those that met previously described durability concerns). The contractor was responsible for designing several structural interfaces with near surface connections. The contractor was also required to show calculations that proved that the shaft lining installed would not require bearing support from below in the final condition, as the sequence of the program was such that the shaft would be constructed prior to the tunnel being constructed below. Alternate liner designs were required to be submitted as one package with the shaft excavation submittal to demonstrate that the methods were compatible.

Approved Alternate Lining Designs

At all but one of the seven shaft sites, alternate liners were installed. Two different alternate lining designs were used. One alternate lining concept, developed by GZA GeoEnvironmental of Providence, consisted of a High Density Polyethylene (HDPE) pipe as the inside surface, surrounded by a 4,000 psi grouted annulus. The annulus contained a ⅝-inch thick, ASTM A36 lining steel casing to replace the WWF. The vent shaft at these sites included only the HDPE and annular grout. The second alternate lining concept, developed by RT Group of East Providence, consisted of a prestressed cast cylinder pipe (PCCP) as the final internal lining with a 4,000 psi grouted annulus in both the drop and vent shafts. The drop shaft used an Embedded Cylinder Pipe (ECP), while the vent shaft used a Lined Cylinder Pipe (LCP). The embedded steel cylinder and prestressed steel strands in the PCCP pipes satisfied the reinforcing requirement.

CONSTRUCTION

Construction of the drop and vent shafts was accomplished by various drilling and lining installation methods. In addition to the subsurface conditions, such as top of rock elevation and thickness and density of glacial deposits overlying the rock, drilling methods were selected based on the diameter of shafts and accessibility to the connecting tunnel below. The alternate lining designs significantly reduced installation efforts.

Table 1. Summary results for drilling methods

Method	Drill Head	No. of Shaft Pairs	Finished Shaft Diameters (feet)	Drilled Hole/ Casing Diameters (inches)	Drilled Hole Verticality, feet out of plumb	Time to Complete One Hole (weeks)
Pile Top	Button Bit Rollers	3	2 and 5	48 to 84	2 to 5	4 to 15
Super Top	Cutting Casing/ Clam Shell	2	2, 5, and 6	72 to 98	0.5 to 2	3 to 8.5
Conventional	Augers, core barrels, telescoping casings	1	2 and 9	78 and 162	2 to 4	5 to 6
Raise Bore	Button Bit Rollers	1	3.5 and 9	72 and 144	1.3 to 1.5	8 (freeze) + 3 (pilot & raise)

Drilling Methods

Four different drilling methods were used to excavate the seven pairs of holes in which the drop and vent shaft liners were installed. At the six sites where shafts had to be installed ahead of tunnel construction, three different top-down drilling methods were employed. At the seventh location, the schedule allowed shaft installation after tunnel construction and the contractor chose to freeze the soil and use the raise bore method. Specialty subcontractors were hired by the prime contractors for each of the four methods employed. Table 1 provides a summary of the drilling methods used with production and verticality results for each method.

Drilling Method No. 1—Pile Top. Three pairs of shafts were excavated using "Pile Top" drilling rigs. Two specialty contractors—Treviicos of Boston, MA and New England Foundation Company (NefCo) of Hyde Park, MA—used pile top rigs manufactured by Wirth. These rigs were used to excavate, in the wet, both the overburden and the rock. The pile top rig, as the name suggests, is secured to a steel casing, which also provides the temporary support for the overburden. The steel casings were vibrated through 80 to 110 feet of overburden to the top of rock using large vibratory hammers. The drill head, rotated by a 12-inch-diameter hollow drill stem, is used to excavate the overburden within the installed casing and the rock below the casing. For these projects, the drill heads were relatively flat faced and tooled with button bit rollers. Soil and rock cuttings were removed through the hollow drill stems using an air lift system. The air lift system pushes high pressure air down to the drill head through 2-inch pipes attached to the outside of the drill stem. Immediately above the drill head the air is piped into a special fitting which turns the air 180 degrees back up and inside the drill stem, creating a vacuum affect that sucks the water and cut rock and soil from beneath the drill head up to the surface. This system necessitates relatively higher effort and larger surface space to set up, since it requires large sediment ponds, pumps and piping to remove the rock and soil from the water. Figure 2 shows a photograph of a pile top rig and a drill head as it is lowered into the casing to be connected to the drill on the rig.

Overall, this drilling method worked well for excavating both the overburden and the rock. The first site where this system was used provided valuable information about

Figure 2. Wirth pile top rig

which methods worked and which did not. However, the geology varied enough from site to site that there were more lessons to be learned at the second and third sites. Lessons learned include:

- Trained and well-informed operators are critical to the successful operation of the drill rigs. The first hole drilled with this method achieved twice the production rate of the remaining holes, but the resulting hole was five feet out of plumb, which was too great a deviation to allow installation of the liner within tolerance. The operator had been bearing down with the hydraulic jacks of the drill slide to increase downward pressure on the head in an attempt to achieve higher penetration rates. The correct approach to achieve better tolerance was to allow only the weight of the drill head and stems to apply downward pressure.
- Vibrating the casing to the top of rock proved to be one of the more difficult tasks. A proper seal between the casing and rock was critical to prevent overburden material from running or flowing into the uncased rock excavation. At one site the softer glacial deposit, overlying weathered rock allowed the casing to be installed and seated securely in rock with relative ease. At this location the installation of 100 feet of temporary overburden casing took only one day, with most of the time spent on casing welding. At a different site, denser and thicker glacial deposits overlying a sloping top of rock made it difficult to install the casing and seat it properly in the rock. At this location, repeated cycles of drilling and advancing the casing to properly seat the casing within the rock was required. For each cycle, this involved removing and reinstalling the pile top rig to allow the vibratory hammer to advance. The casing and installation of the casing took several weeks to complete.
- Achieving the desired verticality tolerance with this drill was difficult. However, Contract verticality tolerances could be and were achieved by simply drilling larger holes that would allow the liner to be installed within tolerance. This lesson not only applied to this specific method, but to all subsequent top-down drilled shafts.

Figure 3. Super top drill rig

The time to excavate a single shaft with this method varied considerably (refer to Table 1). The shortest duration (four weeks) was achieved at two shaft locations where there were no delays and work was performed in two shifts per day. Observations indicate that drilling production rates were *not* dependent on the shaft diameter. At approximately one foot per hour, the penetration rate through rock and soil was consistent for all the shafts except the first shaft, as noted, which averaged double this rate. While the penetration rate in the rock was dependent on the ability of the drill head to break up the rock, the penetration rate for soil excavation was restrained intentionally to avoid plugging the drill stems with spoils. The most significant delays to production were due to either trouble installing steel casing to the top of rock and/or hampered efforts in achieving the verticality tolerance.

Drilling Method No. 2—Super Top. One contractor—Raito of Woburn, MA—used a "super top" drill rig. This drill rig sits on the surface, uses hydraulic grippers to grip the outside of steel casings, and spins and pushes the casings into the ground. The casings are fitted with carbide teeth and spun at approximately one rpm. The soil within the casing is removed using a clam shell while maintaining an appropriate plug of soil and water level within the casing to avoid bottom instability. Rock excavation was also completed with a clam shell after a rock chisel was used to loosen/break up the rock. The welded overburden casing consisted of 40-foot-long 1-inch-think steel sections. The casings used in the rock were slightly smaller in diameter to fit inside the overburden casing and flush-bolted to ease removal prior to installation of the final liner. Spoil handling required less effort than the methods that used air lift systems, since significantly less water was removed along with the soil and rock. Additionally, the excavated rock ranged from small cobble-sized chips to bolder-sized chunks, as opposed to the silty sandy consistency produce by the selected roller bits of the pile top method. Figures 3 is a photograph of this drill rig in operation.

This method also worked well for excavating the overburden and the rock. Holes drilled with this method provided the best verticality results of the four methods (see

Table 1). The primary lesson learned with this method is that it relies heavily on the competency of the ground on which the drill rig is founded. These rigs have limited ability to adjust shaft verticality for an uneven foundation. This was evident where the drill rig experienced some differential settlement during drilling the overburden and caused the drilled hole to be too far out of plumb. The contractor had to backfill the hole and install temporary foundation piles to better support the drill rig. Although it would appear that this method would be well suited for securing a good seal between the soil casing and the top of rock, for one shaft a complete seal was not made, resulting in significant loss of ground. Two conditions that contributed to this are: (1) top of rock was sloped and (2) because of the rig differential settlement problems discussed above, the overburden portion of this particular shaft had to be redrilled through the grout-filled abandoned hole. The combination of these two conditions caused the casing to bind and jam, exceeding the torque limitations of the drill rig and casing left above the top of rock.

Achieving good production rates with this method required good operators trained in the art of using a clam shell and chisel within steel casings. Excavation rates for this method did depend somewhat on the size of the hole that was being excavated. Refer to Table 1 for production rates.

Drilling Method No. 3—Telescoping Casings and Auger. One pair of shafts was constructed using conventional telescoping casings with auger excavation under slurry for the overburden. The rock portion was excavated using an A-frame mounted air lift drill, which was tooled and operated in similar fashion to the pile top rigs. The specialty contractor for this method was Case Foundation of Broomall, PA. The drop shaft for this pair of shafts was a nine-foot-diameter shaft and required a larger drilled hole than the locally-available pile top and super top rigs could drill. For the overburden, slurry was used to excavate below two telescoping casings. The crane-mounted drill used a kelley bar and cross bar to install the casings. The drill tools used were augers, core barrels, and toothed buckets ranging between 20 inches and 10 feet in diameter. This shaft excavation method had the most difficulty in drilling through boulders and obstructions.

The overburden excavation was riddled with difficulties related to excavation of boulders and man-made obstructions, including loss of approximately 90 cubic yards of ground from outside the casing. Penetration rates for the rock portion of the shafts were similar to those on the pile top method—1 foot per hour. Verticality of holes drilled with this method was similar to those achieved with the pile top rigs.

Drilling Method No 4.—Raise Bore with Ground Freezing. At one location the tunneling contractor was able to schedule construction of one pair of drop and vent shafts after tunneling was completed below. The tunneling contractor, Shank/Balfour Beatty (Shank), chose to subcontract with Moretrench of Rockaway, NJ to freeze the 160-foot depth of soil, and with Dynatec of Richmond Hill, Ontario to raise the bore through rock and soil. Freeze holes were drilled from the surface on 4-foot centers along the circumference of both shafts, with additional freeze holes drilled inside of the drop shaft. Raise bore operation consisted of a pilot hole to the tunnel and then reaming the pilot hole up from the tunnel to the surface. Excavated material dropped into the tunnel and was removed with the existing tunnel mucking systems. The verticality achieved at the excavated shafts was largely a function of the verticality achieve by the pilot holes (see Table 1). Figure 4 shows a photograph of the raise bore reamer in the tunnel.

The excavation rate for this method was significantly faster than for the other three. Once pilot holes were established, each shaft took less than one week to excavate. Although ground freeze pipes had been drilled around and within the shaft excavation envelope, one large steel obstruction went undetected and stalled the pilot hole

Figure 4. Raise bore reamer (144-inch) prior to commencing drop shaft excavation

and reaming operations at the drop shaft. Except for this occurrence, this operation was completed with little delay. Refer to Table 1 for overall production rates.

Difficulties Encountered at Top of Rock

Using Methods 1, 2, and 3, repeated difficulties were experienced related to unstable conditions at the transition between soil and rock. Principally the problems related to insufficient seating of the casing into the irregular, fractured, and weathered horizon at the top of rock. At four of the seven drops shafts this led to significant loss of surrounding soil, backfilling the excavation, and redrilling through the stabilized zone. Only one of these incidents prompted a request for change due to differing site conditions, and that request has been disputed.

Liner Installation

The three types of shaft liners are described in detail above. This section describes liner installation. The precast concrete pipe liner and HDPE-steel composite liner were installed for the shafts that were drilled prior to tunnel construction and used the water that filled the drilled holes to ease the installation process. The cast-in-place shaft liner was installed using slip forming by the tunneling contractor that had access to the tunnel.

Concrete Pipe Liner Installation. Concrete pipe was used to line shafts of 2, 5, 6 and 9 feet in diameter. The pipe string was made of 40-foot-long pieces. The lower piece was fitted with an end cap to allow controlled “sinking” of the pipe string to the bottom of the hole. To accomplish this, water was pumped into the pipe to make it heavier than the water it displaced within the drilled hole. The installation was facilitated with a pair of specially fabricated full circumference clamps, each with four support wings. One clamp would hang pipe in the drill hole while the second clamp was used to lift the subsequent pipe. Before lowering into the drill hole, pipe joints were welded and pressure-tested using the integral external joint test nipples. The interior joints were patched prior to submerging. Once the full length of pipe string was in the drill hole, special care was used to level the top of the pipe by shimming the “hanging”

Figure 5. Welding 5-foot diameter concrete pipe liner installation—note clamps "hanging" pipe vertically

clamp support wings. Figure 5 depicts installation of a 5-foot-diameter concrete pipe. Once the pipe was in place, the annulus between the concrete pipe and the rock or overburden casing was filled with grout to complete the installation.

This liner was the preferred liner by the contractors due to ease of installation. At one location, after the tunnel contractor completed the connection to the base of the completed shaft, a 20-foot-long section of shaft liner failed. The inside mortar and the thin steel cylinder sandwiched between the inside mortar and prestressed strands crushed inward. After some investigation it was theorized that the lower piece of shaft liner pipe experience some damage—although it was not evident at the time—during drill-and-blast tunnel excavation and/or contact grouting after the tunnel liner was installed. It is believed that this damage compromised the pipe integrity. The failure occurred shortly after tunnel liner completion and ground water pressure recovery. More careful, controlled blasting and grouting was done at subsequent connections.

HDPE and Steel Composite Liner. This liner was used for two pairs of shafts with 2-feet and 5-feet diameters and was among the first to be installed at pre-tunnel construction sites. It was installed in similar "sinking" fashion as the concrete pipe liners by including bottom caps on the steel and HDPE casings. First, a welded steel casing was lowered with 3-inch external spacers to ensure proper concrete coverage. Steel wings were welded to the top of this steel casing and shimmed on a level frame to position the liner vertically. An inclinometer tube with large centralizers was then lowered into the casing to confirm that verticality tolerance was achieved. Grout was then tremied to fill the annulus outside the steel casing. The HDPE casing had centralizers that were tight to the inside diameter of the steel casing such that when it was lowered into the steel casing it was deemed to match the confirmed verticality of the steel casing. The annulus between the HDPE and steel casing was tremie-grouted to complete the installation. Refer to Figure 6 for a photograph of this liner installation.

Slip Formed Cast-In-Place Liner. The two shafts drilled using raise bore methods were cast in place using slip forms. Forms were fabricated on site and raised through the excavated holes using hydraulic cable jacks while placing concrete between the forms and the rock or frozen overburden. The average rates of concrete installation at the drop and ventilation shafts were 2.1 and 2.5 feet per hour, and slip forming was completed with little difficulty. The tunneling contractor lined three larger working shafts on this same site using the same method.

Figure 6. HDPE being installed as the inner member of composite liner

Liner Tolerances. Except for drilling Method 2, all excavation methods struggled to maintain verticality that would result in the achievement of finished lining tolerances. Although attempts were made to excavate larger diameters, many of the shaft liners were installed with greater-than-specified deviations from plumb. With the assistance of Dr. S.C. Jain, who originated the vortex system, the design team scrutinized the hydraulic assumptions and parameters used to define the nominal shaft sizes and concluded that additional deviation could be tolerated in the drop shafts. The allowable deviation ranged from 6 inches to 2 feet, depending on the site-specific flows and the shaft-to-shaft distance at the base.

CONCLUSIONS

The seven pairs of shafts were constructed by four different specialty drilling companies and lined by six different prime contractors. Four distinctly different drilling methods were successfully used to complete the shaft drilling.

The nominal verticality tolerances could not be met by using these methods. However, the use of larger excavations and application of site-specific tolerances enabled the achievement of the functional requirements. The inclusion of performance criteria to encourage alternate lining materials and techniques in lieu of cast-in-place liners significantly aided the top-down construction. Allowing alternate designs for shaft liners proved to be an effective means of meeting both the contractor's individual installation preferences and the owner's ultimate goal of a cost-effective, functional drop and vent shaft system.

REFERENCE

Jain, S.C. and Kennedy, J.F., "Vortex-Flow Drop Structures for the Milwaukee Metropolitan Sewerage District Inline Storage System," IIHR Report No. 264, Iowa Institute of Hydraulic Research, July, 1983.