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# Slurry walls accelerate shaft construction in rock in Los Angeles

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ABSTRACT: This paper details the challenges associated with the design and construction of a "figure-eight" shaped, or dual cell shaft through soft ground and sedimentary rock for the Northeast Interceptor Sewer project in Los Angeles. The Humboldt Street Shaft was excavated as two cells, using a combination of both reinforced and un-reinforced concrete diaphragm walls. The Contractor chose to construct the diaphragm panels to full depth, using a Hydrofraise rather than sinking them only to the top of rock, thus eliminating the need for conventional rock support with shotcrete and ribs or dowels. This method of construction is unusual for sedimentary rock. The two cells varied in diameter and excavated depth, as each served a different purpose. The 21-m-diameter cell was excavated to a depth of 41 m to support tunneling operations and to allow construction of a junction drop structure and maintenance hole. The 12.5-m-diameter cell was only excavated to a depth of 19 m, allowing the construction of a stub-out connection to a future sewer. Other notable aspects of shaft construction included the use of rock anchors through the partition wall below the shallow cell and the use of weep holes through the shaft walls below the top of rock.

## 1 INTRODUCTION

### 1.1 *Project description*

The City of Los Angeles, Department of Public Works, Bureau of Engineering is presently undertaking two major construction projects to provide relief and redundancy for the aging North Outfall Sewer (NOS). These two projects are the Northeast Interceptor Sewer (NEIS) and the North Outfall Sewer – East Central Interceptor Sewer (NOS-ECIS). At the time this paper was written, the joint venture formed by Kenny, Shea, Traylor, and Frontier-Kemper (KSTFK) had completed tunneling for NOS-ECIS project. Meanwhile, a separate joint venture formed by Traylor, Shea, Frontier, and Kenny (TSFK) is currently mining the NEIS tunnel.

An overall vicinity plan for both projects is shown in Figure 1. The NEIS project involves the construction of an 8.5-km-long, 2.4-m-inside-diameter (ID) sewer pipeline in a 4.0-m-diameter excavated tunnel, three drop structures, and seven special maintenance holes. The project must be completed by November 30, 2004 in order to comply with a Cease and Desist Order (CDO) deadline imposed by the Regional Water Quality Control Board. When complete, NEIS will convey flows from existing sewers and the future Eagle Rock Interceptor Sewer southward to NOS-ECIS.

### 1.2 *Alignment*

NEIS will extend from a junction structure with NOS-ECIS at the intersection of Mission Road and Jesse Street, northward to the intersection of Division Street and San Fernando Road, in the Glassell Park area of Los Angeles, on an alignment roughly parallel to the east bank of the Los Angeles River. A project alignment map is provided in Figure 2.

### 1.3 *Site-specific description*

This paper focuses on the Humboldt Street work shaft, one of three work shafts being constructed for the NEIS project. The Humboldt Shaft is located on

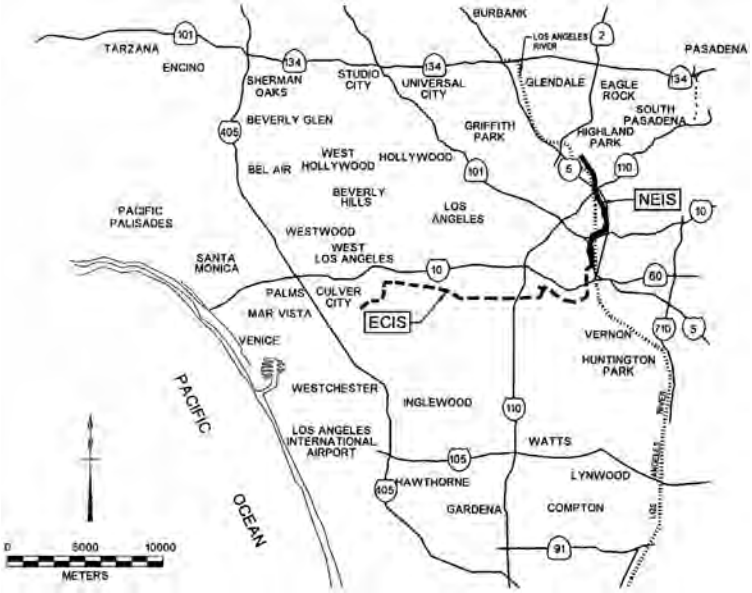

Figure 1. Vicinity map.

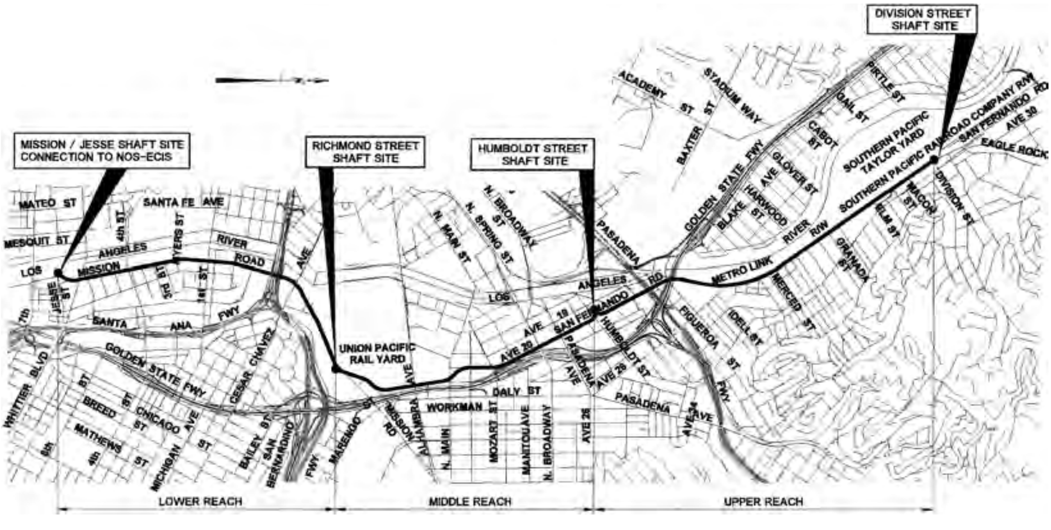

Figure 2. Alignment map.

the site of a former warehouse structure, near the intersection of Humboldt Street and San Fernando Road (see Figure 3). The shaft is 41 m deep on one side and 19 m on the other. The design team planned the shaft to serve three functions, as:

- drive shaft for the middle-reach earth pressure balance tunnel boring machine (EPBM), tunneling towards the Richmond Shaft;
- receiving shaft for the upper-reach rock tunnel boring machine (TBM) tunneling from the Division Street Shaft;
- work shaft for the stub-out connection tunnel for future tie-in to NOS.

The design specified that after the tunnels are mined and the carrier pipe is installed in each reach, a combined drop-and-junction structure with associated

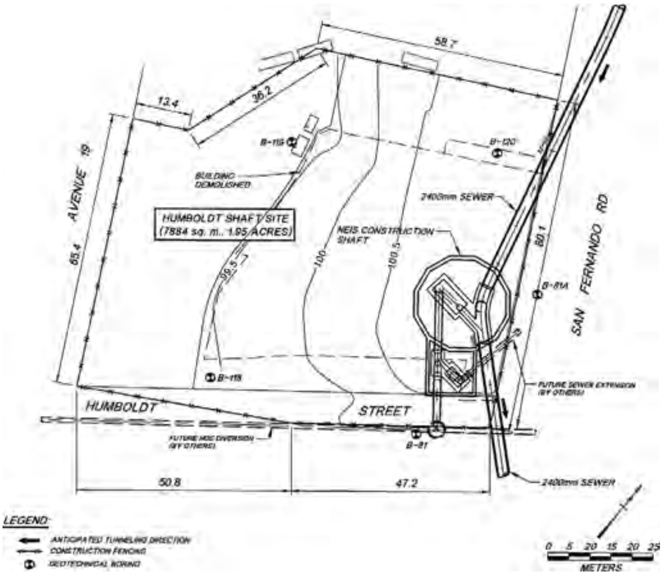

Figure 3. Site plan.

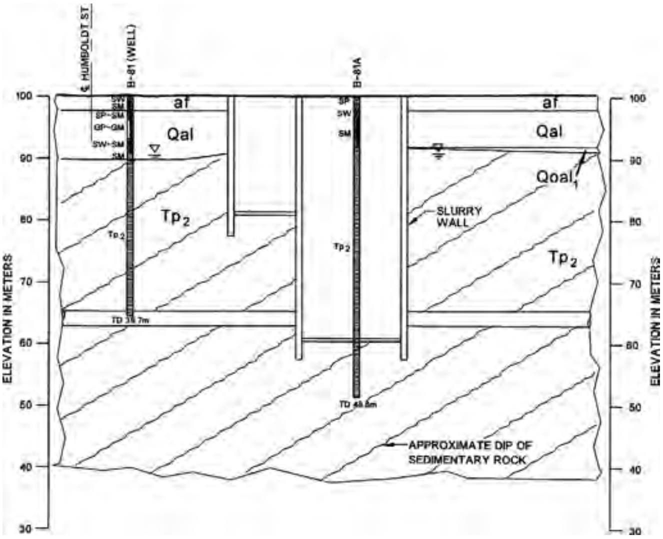

Figure 4. Geologic profile.

maintenance holes would be constructed in the deep shaft.

## 1.4 *Geology*

Three major geologic units are present at the Humboldt Shaft (see Figure 4). The following is a description of each unit, as described by the Los Angeles Bureau of Engineering's Geotechnical Engineering Division (GED) in the project's *Geotechnical Data Report* (GDR):

- *Artificial Fill* – Variable in soil type along the alignment, ranging from clayey silt to angular gravel and sand.
- *Recent Alluvium, (Qal)* – Fluvial and alluvial deposits (channel deposits, point bar deposits, and flood plain deposits) that have been deposited within

the past 10,000 years (Holocene age). It consists predominantly of cohesionless silty sands, poorly graded to well-graded sands with gravel, and sands with silt and gravel.

- *Old Alluvium, (Qoal)* – These deposits are generally considered to have formed between 10,000 and 700,000 years ago (upper Pleistocene age). Brown fine gravel with fine to coarse sand, containing scattered sand with gravel layers and scattered organic fragments in a clay/silt matrix.
- *Puente Formation, Unit 2 ($Tp_2$)* – The lower unit of the Puente Formation, an interbedded siltstone, claystone, and sandstone of Miocene age. The Puente Formation is divided into $Tp_1$ and the $Tp_2$ for the NEIS project. The major difference is that the beds of the $Tp_2$ are thicker and notably stronger than the thinner beds of the overlying $Tp_1$.

For the Humboldt Shaft the GBR indicated that up to 1 m of artificial fill could be expected, underlain by 8 to 9 m of medium dense to very dense recent alluvium, a thin layer (0 to 1 m thick) of older alluvium, then $Tp_2$ to the bottom of the excavation. The groundwater table lies at a depth of about 9 m.

None of the project borings around the Humboldt Shaft encountered gas, liquid oil, or tar within the $Tp_2$ or alluvial soils. However, natural hydrocarbons were found in several locations along the alignment. Oil and in this part of the Los Angeles Basin originates in the petroliferous $Tp_2$ and propagates up along the bedding planes through seams of sand and silty sand. Therefore, Cal/OSHA classified this shaft as "potentially gassy" during shaft excavation.

## 2 CONTRACT REQUIREMENTS

### 2.1 *Slurry walls*

The Contract Documents prohibit the Contractor from dewatering outside the limits of the Humboldt Shaft excavation. The reason for this restriction is to prevent migration of potential groundwater contamination and to minimize disruption to the natural groundwater flow. Therefore, the design team selected reinforced concrete diaphragm walls (slurry walls) to support the excavation through the alluvium and to prevent lowering of the groundwater table outside of the excavation. The conceptual design of the Humboldt Shaft shown in the Contract Documents is roughly circular in shape, with an adjoining shallow rectangular cell to the south. The conceptual design included 12 wall panels to approximate a ring and seven to enclose the shallow shaft for the NOS diversion structure (see Figure 5), tied together at the surface with a reinforced concrete cap beam. The design team determined the

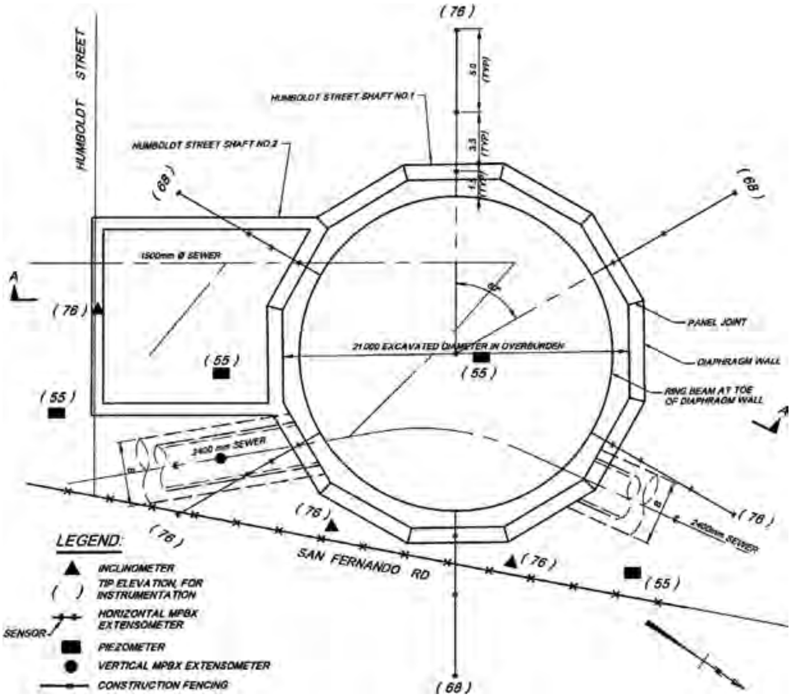

Figure 5. Plan view of conceptual shaft.

minimum shaft diameter of a circular shaft at this site to be 21 m in the alluvium and 19 m in rock. These dimensions were chosen to accommodate the permanent structures to be constructed within the shaft, as well as to minimize the amount of rock excavated.

The design of the circular cell assumes the walls act as a compression ring, carrying the load by thrust in the panels in the ring's plane, with no internal bracing required. The design of the rectangular shaft included internal steel bracing and additional reinforcing steel in the wall panels to resist bending stresses. Since slurry walls are very rigid and generally do not allow significant ground movement, the lateral earth pressure loading criteria in the contract documents are a triangular distribution based on averaging the active and at-rest earth pressure coefficients ($K_a$ and $K_o$ respectively). In addition to the triangular distribution, the design criteria included an apparent earth pressure envelope based on the same average K value, which was to be used only for the internally braced, rectangular cell.

### 2.2 *Rock reinforcement*

The geotechnical exploration program indicated that the Puente Formation is a very weak to moderately strong rock, with most unconfined compression test values falling below 5 MPa. The designers felt the rock strength was adequate to resist the compressive stresses due to hydrostatic and horizontal rock pressures in the rock mass around the circular shaft opening. However, to ensure a ring of intact rock would carry this load in compression, where joint sets and inclined bedding planes are present, additional rock support analyses were performed. These analyses assumed joint orientations and joint strengths developed from data contained in the GDR and GBR, as well as shaft geometry and locations of contacts between rock and soil. The designers calculated an apparent uniform rock loading, based on the force required to resist the movement of a wedge of intact rock sliding along the most prominent joint sets and/or bedding planes. The pressure diagrams in the Contract Documents included a uniform rock pressure of 67 kPa as a minimum requirement for the Contractor to design the rock support. The Contract Documents also required the Contractor to install strip drains with weep holes between the rock surface and the shotcrete to drain water-bearing joints around potentially unstable wedges that intersect the shaft walls. For this reason, the rock loading minimum design criteria did not include hydrostatic pressure for the design of rock reinforcement.

The conceptual design for rock reinforcement shown in Figure 6 included two alternatives for ground support rock:

- W8 ribs at 1.8 m vertical spacing, with 150 mm of steel-fiber-reinforced shotcrete.
- Rock bolts at about 1.8 m × 1.8 m spacing, 8.5 m long with 150 mm of fiber-reinforced shotcrete.

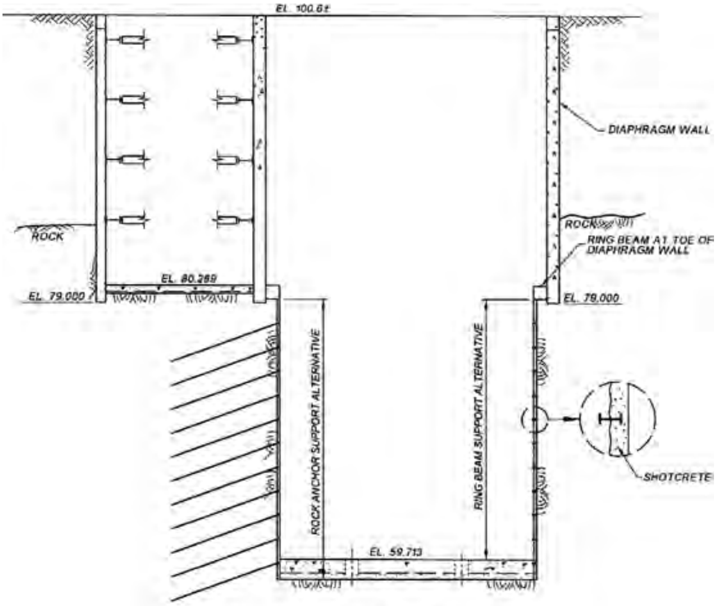

Figure 6 Section view of conceptual shaft.

These alternatives served as a basis for initial support, with provisions in the contract indicating that modification to these designs may be required, depending on conditions observed in the field.

### 2.3 *Geotechnical instrumentation*

The contract required the Contractor to install the following three sets of geotechnical instruments around and within the Humboldt Shaft:

- three inclinometers (shown as ▲ on Figure 5);
- four piezometers (shown as ■ on Figure 5);
- twelve horizontal multiple-point borehole extensometers.

The inclinometers and piezometers are considered typical, minimum instrumentation for a shaft of this size and depth. The horizontal multiple-point borehole extensometers are specified for the portion of the shaft in rock. Their primary purpose is to measure lateral ground movement and warn of potentially large block movements. If the maximum lateral movement of 25 mm were exceeded, additional rock anchors or steel ribs would be installed to arrest ground movements and maintain stability of the rock mass.

## 3 CONTRACTOR’S REVISED DESIGN

### 3.1 *Shaft geometry*

The conceptual design consisted of two shafts adjacent to one another. The small, shallow shaft consisted of slurry walls with waler and strut supports. It was intended that the shallow shaft would carry lateral loads by flexure, which necessitated walers and struts for support. The large, deep shaft was comprised of two different support types. In the alluvium and fill, the deep shaft would carry lateral loads by hoop compression. In the Puente Formation, rock anchors and fiber-reinforced shotcrete would carry the loads directly, or ring beams could be used in hoop compression.

Using the variety of support systems as described above would have added time and complexity to the Contractor’s operations. Therefore, the Contractor elected to use a “figure-eight” or dual-cell slurry wall shaft (shown in Figures 7 and 8), similar to the concept used for the Richmond Shaft. The small cell is approximately 19 m deep, and the deep cell is approximately 39 m deep. Ed (Itzig) Heine P.E., and Steve Blumenbaum of Alpha Corporation designed the dual-cell shaft for this joint venture.

### 3.2 *Radial walls*

The radial walls were designed by the hoop stress method and were considered to be unreinforced compression members. Only the circular band of concrete inscribed within the limits of the slurry wall panels was considered effective in compression. The Hydrofraise (French for hydro-mill) construction method chosen by the Contractor resulted in average chord lengths of 2.4 m. The contractor-proposed chord lengths were much shorter and therefore more efficient in hoop compression than anticipated in the conceptual design.

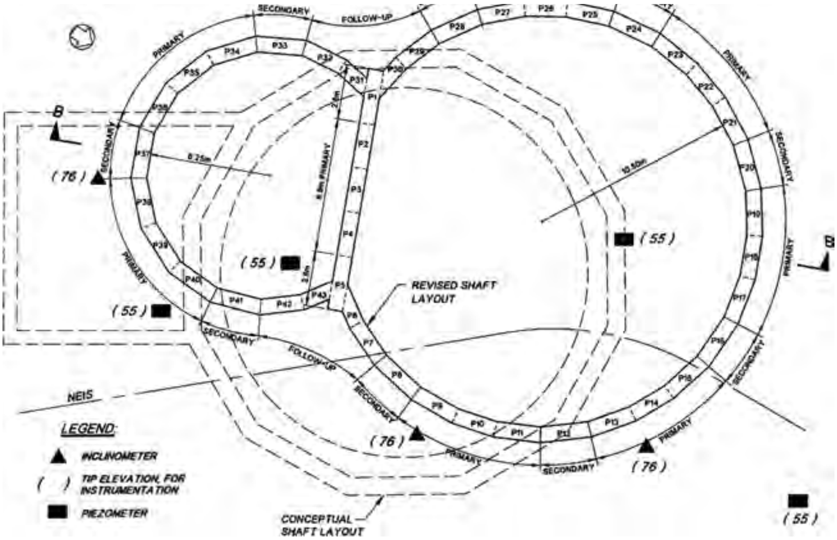

Figure 7. Plan view of contractor’s revised geometry.

The short chord lengths afforded the opportunity omit a cap beam. When long chord lengths are used, a reinforced concrete cap beam is often used at the top of the shaft to provide continuity and resistance to deformation. But with the close approximation of a circle provided by the shorter panels, a cap beam is not required.

Steel reinforcement was not needed for the purpose of resisting lateral loads. However, contingency reinforcing was installed, in case the panels were not installed within the specified tolerances. In that event, the panels could span vertically to remedial ring beams or walers.

In the Puente Formation, drain holes were provided in the slurry walls to relieve any groundwater pressures. This was mostly precautionary, given the relative impermeability of the formation.

### 3.3 *Center wall*

The center wall was designed for different load conditions depending on depth. Where it is a common wall between the two cells, the center wall was designed for compressive horizontal loads coming from the radial loads in the two cells. It was also designed to accommodate a 1.5 m differential soil loading between elevations in each cell. Reinforcement in this area was designed to limit buckling. At elevations below the bottom of the shallow shaft, the center wall behaves differently. It is subjected to lateral earth loads as well as compressive loads coming from the radial wall of the deep cell. In this area, the wall spans vertically, and reinforcement is used for flexural strength. This load condition controls the design of the center wall reinforcing. The wall spans between 9 m long rock anchors, which are installed on 2 m × 4.5 m centers. Reinforcing cages were only terminated at the top of rock in the circular portion of the shaft.

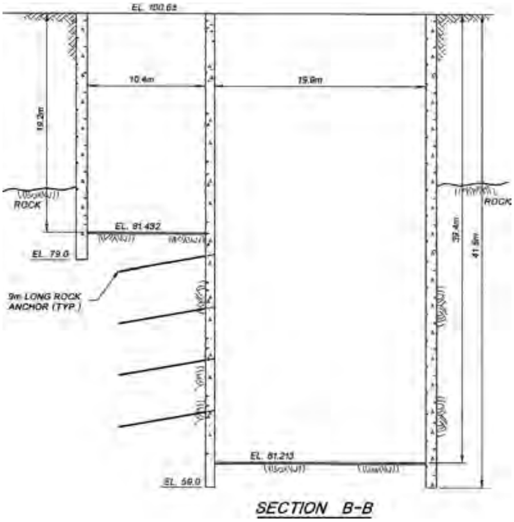

Figure 8. Section view of contractor's shaft.

At all elevations, the ends of the radial walls were poured integrally with the end panels of the center wall, and reinforcement was provided across the center/radial wall joint. In this way, shear transfer across the joint is ensured.

### 3.4 *Groundwater considerations*

In the fill and alluvium, the slurry walls were designed for the combination of earth and hydrostatic pressures. In the Puente Formation, the slurry walls were designed only to support wedges of rock. In rock, the slurry walls confine the rock mass and the ground to support the horizontal rock and hydrostatic pressures present deeper in the rock mass. Hydrostatic pressures behind the slurry wall and in water-bearing joints around potentially unstable wedges intersecting shaft walls are relieved through the use of weep holes drilled horizontally through the slurry walls. Weep holes were not drilled through the walls above the rock to prevent dewatering of the overlying alluvium. The slurry in the alluvium provides a water barrier that the designers did not want to compromise.

### 3.5 *Summary of advantages*

There are several advantages to using the dual-cell, full-depth, slurry wall shaft instead of the conceptual design. First, the construction methods were simplified and shortened by using one excavation method. Second, Hydrofraise construction allowed the designer to eliminate the cap beam. The shorter chord lengths also minimized the need for panel reinforcement. Third, replacing the rectangular small shaft with a circular one minimized the need for reinforcement and eliminated the need for walers and struts in the small shaft. Fourth, no setback was required to change from slurry wall to rock anchor support. This not only reduced the footprint of the large shaft, but it also eliminated the need for a cast-in-place ring beam at the transition from slurry wall to rock support.

## 4 CONSTRUCTION MEANS AND METHODS

### 4.1 *Advantages of hydrofraise method for slurry wall construction*

The TSFK Joint Venture selected Soletanche Inc. as their slurry wall subcontractor and chose the Hydrofraise excavation method for several reasons, which are described below:

1. *Schedule Advantages* – Time restrictions placed on the Contractor by the CDO required that shaft construction be expedited.
2. *Achieving Tight Tolerances at Depth* – The real-time data supplied to the operator from the fraise allows precise alignment of each panel which assures tight vertical joints at depth.
3. *Versatility of the Hydrofraise* – The Hydrofraise is able to excavate through all types of materials with minimal modification to the cutting tools.
4. *Minimal Impact on Environment* – The Hydrofraise method imposes minimal impact on the surrounding environment, which was a necessity in the densely populated vicinity of the shaft site.

The operating principle of the Hydrofraise is similar to that of a slurry shield TBM, in which the excavated opening is supported by a pressurized suspension that balances the earth and water pressure of the excavation. In most cases, this suspension is a bentonite and water slurry. The slurry acts not only as a support fluid, but also as a transport medium. The ground excavated by the cutting tool is mixed with the support fluid slurry near the excavation face, where it can then be pumped to the surface. A separation plant, usually on the surface, then separates the support fluid from the ground, and the fluid is again pumped to the excavation face. Fresh bentonite can be added as slurry properties dictate.

A typical equipment spread for the Hydrofraise method is comprised of a modified crane, a fraise cutting tool, a bentonite slurry mixing and storage facility, a separation/de-sanding plant, and one or two support cranes. The specific layout of the Hydrofraise used in this project can be seen in Figure 9.

### 4.1.1 *Schedule advantages*

The Hydrofraise can shorten the construction schedule because of its ability to continuously excavate. The tool is lowered under its own weight into a pre-built concrete guide wall, with the cutting wheels turning. It continues excavating until it reaches the desired depth. In conventional clamshell excavation, the continual raising, lowering, and dumping cycles are time consuming. However, as with any sophisticated piece of equipment, the Hydrofraise is susceptible to mechanical and electrical downtime, whereas the clamshell can be kept running with a minimum of specialized maintenance, tools, and equipment. However, on the NEIS project, the Hydrofraise experienced minimum downtime and was therefore able to keep the project on schedule. Slurry wall panel construction at the Humboldt Shaft lasted 49 days, with the crew working two 10-hour shifts. The approximate area of the slurry wall panels is 3,381 $m^2$, in elevation.

Figure 9. “The Hydrofraise evolution II” by Soletanche, Inc.

### 4.1.2 *Achieving tight tolerances at depth*

One of the major reasons the Contractor chose the Hydrofraise method was due to its precise excavation control. The design assumptions of shaft geometry are dependent upon the construction tolerances that the equipment can achieve. The cutting tool is equipped with inclinometers and tilt meters that are linked to a computer screen in the operator’s cab. The operator is able to read the information provided by the instrumentation in real-time and make corrections as needed. Several features are available to the operator for steering purposes. First, each of the two rotating cutting wheels can be run at variable speeds to correct for left and right misalignment. Second, the entire cutting head can tilt up to 1.5° in the vertical plane of excavation to correct for front and back misalignment. Such precise control over tool guidance enabled the Hydrofraise to excavate panels on the NEIS project within a tolerance of 0.3%, which equates to a variance of only 125 mm from the designed vertical alignment, over a depth of 42 m.

### 4.1.3 *Versatility of the Hydrofraise*

The Hydrofraise cutting tool can quickly and easily adapt to changes in ground conditions with modifications to the cutters. Both of the cutting wheels can be removed and replaced in a single shift, which allows the Hydrofraise to perform in almost any ground

Figure 10. Photo of broken teeth.

Figure 11. Excavation in rock.

condition. As an example, at the Richmond Shaft site, which was the first of three slurry walls constructed for NEIS, the Hydrofraise was equipped with self-cleaning cutting paddles to deal with the soft claystone and mudstone present in the area. However, when harder sandstone was encountered at the Humboldt site, the slurry wall Sub-Contractor quickly replaced the paddles with carbide tipped picks. The carbide picks performed well; the only problem was chipping of the carbide tips in the hardest layers of the $Tp_2$ as shown in Figure 10. It was the versatility of the Hydrofraise that enabled the Contractor to further accelerate the schedule by extending the slurry walls through the Puente Formation and eliminating rock bolting and shotcreting from the shaft excavation activities.

### 4.2 *Panel construction sequence*

The circular shape of the shaft was approximated with short chords because the Hydrofraise is limited to excavating rectangular shaped sections. The chord length for the Humboldt slurry wall ranged from 1.804 m to 2.448 m. The wall was constructed in 43 "bites," with each bite being one pass of the cutting tool. The wall was also constructed in 19 "panels," which were either: a primary panel comprised of three bites, a secondary panel comprised of one bite, or a follow-up panel of five bites. A secondary panel separated each primary panel and the follow-up panels were used to create the joint between the two cells.

Each primary and follow-up panel was excavated and concreted first, before the secondary panels were excavated. Tight joints between the primary and secondary panels were constructed by spacing the primary panels so that the Hydrofraise cut into the previously poured concrete of the primary panels, while it was excavating the secondary panels. The cutting of the primary panels produced a rough surface for the concrete of the secondary panels to bond to, thus producing a strong and relatively watertight joint. The concrete was poured using dual tremie pipes in the primary and follow-up panels and a single tremie pipe in the secondary panels.

### 4.3 *Shaft excavation*

Because the shaft was originally classified as "gassy" by Cal/OSHA, the Contractor chose to drill a test hole prior to excavation of the shaft for the purpose of drawing gas samples. It was hoped that the Cal/OSHA would reclassify the shaft based on favorable results from these samples, and thus allow the use of conventional equipment for the shaft excavation. The shaft was indeed reclassified to "potentially gassy" with special conditions, based on the gas samples, and the Contractor was allowed to proceed with conventional equipment.

The first 5.2 m of the shaft, which consisted mostly of artificially backfilled sand and alluvial sand and clay, was excavated from the surface by a Caterpillar 325 excavator. For the next 4 m of excavation, the CAT 325 excavator was placed in the shaft where it then loaded two 3.8 $m^3$ circular muck skips, which were hoisted on a single line by a 125-ton-capacity American 9260 crane, as shown in Figure 11. The crane was previously factory modified for deep tunnel operations. This 4 m of excavation consisted mostly of alluvial sand and clay. At an approximate 7.6 m depth, the soil became sticky and produced a strong hydrocarbon odor. A chemical analysis of the excavated material revealed that the soil contained a high concentration of natural petroleum hydrocarbon, which is not uncommon in the Los Angeles Basin. The soil was classified as "Contaminated" and was removed and dealt with by the Contractor's environmental subcontractor.

The $Tp_2$ Formation was encountered at a depth of 9.1 m, at which point the CAT 325 was no longer able to freely excavate the material with a bucket. Consequently, a 53 kN hoe-ram was attached to the CAT 325 to break the hard layers of the $Tp_{2,}$, while a CAT 312 excavator was put into service to load the broken material into muck skips. The production rate of each piece of equipment was quite evenly matched so that the two excavators could follow each other around the shaft, one breaking material and one loading material. The efficiency of the operation led to a production rate of about 550 $m^3$ per shift, which equated to approximately 1.2 m (in depth) per shift in the large cell. The CAT 312 excavator was utilized in the small cell, since the shaft was not large enough to accommodate the CAT 325. With aggressive bucket teeth, the CAT 312 was able to excavate nearly all the material down to a depth of 26 m unassisted. Where it was not able to dig, a smaller hoe-ram attached to a Case 580 loader assisted the operation by breaking the harder material. With these production rates, the shaft was sunk in 39 working days, utilizing two 8-hour shifts per day.

### 4.4 *Rock anchor installation*

The rock anchor scheme in the straight center wall of the shaft consisted of four rows of anchors with five anchors per row and a vertical and horizontal spacing of 4 m and 2 m, respectively. The design specified 9 m long, 35-mm-diameter, 1,030 MPa Dywidag Threadbar anchors, which were to be installed in a 70 mm hole and encapsulated in cementitious grout. The Contractor chose to use a Gardner-Denver PR 123 rock drill mounted to an ATD 3800 Air Trac drill carrier (as seen in Figures 12 and 13) for the drilling in the relatively soft rock of the $Tp_2$ Formation, 10-m-long, 100 mm diameter holes could be drilled in a matter of minutes. Shorter holes drilled as weep holes yielded some water immediately after drilling and periodically during a relatively dry rainy season in 2002.

Contract Specifications stated that shaft excavation was not allowed more than 1 m below a row of anchors until each bolt was pull tested. In order to gain high early strength and a quick turnaround on the pull test, a prepackaged non-shrink rock anchor grout formulated by Euclid was initially selected for the cementitious encapsulation. It was to be batched and pumped by a Hany IC 310 colloidal mixer. A prepackaged product was selected with the hope that it would reduce batching times and improve quality assurance of the grout, since the Contractor could not afford to halt shaft sinking production in order to reinstall a failed anchor. However, after a number of unsuccessful attempts to mix and pump the prepackaged product, it became apparent that the Euclid material was not compatible with the Hany equipment at the water-to-cement ratio the Contractor needed to achieve. It was decided that a switch would be made to a traditional cement-and-water grout mix. Master Builders MEYCO Fix Flowcable was added to the mix to reduce water requirements, increase pumpability, and provide non-shrink properties. After this change was made, the Hany mixer and pump performed flawlessly. Each anchor was pull tested approximately 20 hrs after installation, with all anchors passing, except the last one.

Figure 12. Drilling weep holes in the slurry wall.

Figure 13. Drilling for rock anchor installation.

Figure 14. Weep holes drilled through the slurry wall.

The anchor failure is believed to have been caused by a transient water flow which washed grout out of the hole. Another anchor was installed immediately and passed pull testing.

## 5 CLOSING REMARKS

Excavation of the Humboldt Shaft ended on March 28, 2003. The shaft excavation was never on the project's critical path. This can be attributed to the successfully planned and implemented slurry wall operation devised by the TSFK joint venture and their subcontractor, Soletanche Inc. The joint venture kept the project on schedule through shaft construction, despite the rigorous demands dictated by the CDO.

## ACKNOWLEDGEMENTS

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