12 Ft. ID Concrete Pipe Tunneling under Union Pacific Railroad Tracks
for the
Columbia Slough Consolidation Conduit
Portland, Oregon

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ABSTRACT
The City of Portland is constructing the Columbia Slough Consolidation Conduit as a part of its commitment to reduce combined sewer overflows into the Willamette River and the Columbia Slough. Known as “The Big Pipe,” the Conduit has an internal diameter of twelve feet and is about 3½ miles long. Construction Segment 1 of the project includes 814 feet of reinforced concrete pipe installed by boring and jacking. Five separate crossings were constructed beneath Union Pacific Railroad tracks and Columbia Boulevard, an adjacent arterial roadway. Four of them were twelve foot internal diameter reinforced concrete pipe. This paper describes the design and construction of these large crossings.

INTRODUCTION
Approximately six billion gallons of combined sewage and storm water are discharged annually into Oregon’s Willamette River and Columbia Slough through the City of Portland’s combined sewer system. The Columbia Slough Consolidation Conduit, also locally known, as “The Big Pipe,” is an important element of a project mandated for combined sewer overflow abatement. The Big Pipe is twelve feet in internal diameter and is about 3½ miles long. It is located in North Portland as shown in Figure 1.
The Conduit alignment follows Union Pacific Railroad right-of-way, North Columbia Boulevard (a major industrial thoroughfare) and runs parallel to an old monolithic concrete sewer interceptor. Geologic conditions along the alignment include recent river alluvium and fine-grained to coarse-grained catastrophic flood deposits with cobbles and boulders. This paper describes design and construction of four 172 in. bore crossings, one of the largest bored and jacked pipe installations completed in the region.

The City of Portland sewer system contains separated sanitary sewers as well as combined sanitary/storm sewers. The combined sewers were constructed prior to the 1940’s, when treatment of wastewater was not provided and the primary objective was sanitation and disease prevention. During periods of relatively low precipitation, the combined storm and sanitary sewers flow to the City of Portland’s wastewater treatment plants. During heavier precipitation, however, stormwater exceeds the capacity of existing combination sewers and interceptors. The excess flow, consisting of mixed sanitary sewage and stormwater, discharges directly into receiving waters at various outfalls. In recent years, the quality of the City’s surface waters has become a major concern of its citizens and environmental regulatory agencies. As a consequence, the City’s Bureau of Environmental Services has undertaken an extensive program to identify and separate the storm and sanitary sewers within the City. However, wet weather. Discharges into the Columbia Slough continue through a number of combined sewer outfalls. The outfalls that discharge into the Columbia Slough are located where combined sewer trunks are intercepted by diversion structures that direct low flow wastewater into an interceptor sewer pipeline running to the Columbia Boulevard Wastewater Treatment Plant. The diversion structures have overflow weirs that are overtopped by flow whenever storm water exceeds the capacity of the interceptor sewer. The higher flows overflow into the outfalls that discharge into the Columbia Slough.

Thirteen of these outfalls discharge into the Columbia Slough during wet weather, thus degrading water quality. In 1991, the City and the Oregon Department of Environmental Quality entered into a court-sanctioned agreement called a Stipulation and Final Order, to remedy this condition. Subsequent changes were included in an Amended Stipulation and Final Order that remains in force today. The Order’s objectives for the Columbia Slough drainage basin are to eliminate combined sewer overflow discharges in a typical year and to have no more than three discharge events in an average ten year period. The City is required to eliminate all untreated combined sewer overflow discharges to the Columbia Slough from winter storms with a five year frequency and from summer storms with a ten year frequency. The intent is to reduce the volume of discharges to a level representing 99.6 percent control.
Meeting the goals of the Amended Stipulation and Final Order requires the elimination of all combined sewer overflow from storm events equal to or less than a 5-year winter storm or a 10-year summer storm. The facilities to provide this level of combined sewer overflow elimination are required to be in place and operational by December 1, 2000. Included are the following elements:

- Columbia Slough Consolidation Conduit
- Influent pumping station
- Wet weather treatment facility
- Effluent pumping station
- Wet weather effluent outfall and diffuser.

The Columbia Slough Consolidation Conduit is a key element in meeting the Amended Stipulation and Final Order requirements. It will provide conveyance and nine million gallons of short-term storage for all combined sewer overflows produced in Columbia Slough basins.

Woodward-Clyde Consultants performed a preliminary geotechnical investigation to aid initial selection of Conduit alignment. Many alternative alignments and permutations were considered. The initial investigation area included a corridor approximately one-half mile wide along N. Columbia Boulevard bounded by the Columbia Slough on the north, N.E. 14th Place on the east, and the City’s Columbia Boulevard Wastewater Treatment Plant on the west.

The final route selected for the Conduit shown on Figure 2 follows the route of a major existing interceptor sewer and is located on Union Pacific Railroad right-of-way for much of its length. The project begins at an influent pumping station under construction at the treatment plant. It runs east as a 144-inch conduit that parallels N. Columbia Boulevard, crossing from the north side to the south side of the roadway at Outfall 58. The conduit then continues in a tunnel-constructed section eastward along N. Columbia Boulevard to N. Argyle Way. It continues along N. Argyle Way and N. Argyle Street to Interstate 5 where it decreases to 72-inch internal diameter at a drop structure just west of the Interstate 5 overpass. The conduit continues eastward beneath Interstate 5 along the south side of the Union Pacific Railroad’s Kenton Yard. The 72-inch conduit ends at the intersection of N.E. 13th Avenue and Lombard Street.

The Conduit was divided into three major construction segments as shown in Figure 2. Segment 1 extends from an influent pump station under construction at the treatment plant to Outfall 58 and includes 2,712 feet of 144-inch internal diameter precast reinforced concrete pipe installed by the cut and cover method and by the bore and jack method. Segment 2 extends from Outfall 58 to Interstate 5 and includes approximately 8,361 feet of conventional tunnel with a 144-inch internal diameter reinforced concrete permanent liner. Segment 3 extends from Interstate 5 to N.E. 13th Avenue and Lombard St and includes 7,100 feet of 72-inch internal diameter reinforced concrete pipe installed by the cut and cover method.

Figure 2: CSCC alignment map
DESIGN OF THE COLUMBIA SLUGH CONSOLIDATION CONDUIT

The Conduit design included an alignment selection process and development of a predesign report; design submittals at the 30%, 60%, 90% and 100% design completion levels; and an independent value engineering study. The project design team was lead by Tetra Tech/KCM, Inc., an engineering consulting firm based in the Pacific Northwest.

Alignment Selection Process

During the conceptual development phase of the Conduit project, the number of primary alternative alignments was reduced from 25 to three. The three primary alignments were the Columbia Slough Alignment that closely paralleled the Columbia Slough, the Columbia Boulevard Alignment that followed Columbia Boulevard the full length of the project, and the Interceptor/Railroad Alignment that paralleled an existing interceptor and is located on Union Pacific Railroad right-of-way for much of its length.

The Tetra Tech/KCM design team conducted two workshops to assist the Bureau of Environmental Services with decision-making to identify a preferred alignment. The objective of the first workshop was to further analyze the Columbia Slough Alignment and the Columbia Boulevard Alignment options and recommend the better alternative from a technical perspective. During the first workshop, participants discussed concerns related to groundwater, boulder size, permit requirements, and seismic liquefaction and lateral spreading. The evaluation process consisted of comparing each alignment alternative against specific evaluation criteria. The result was a unanimous design team recommendation that the Columbia Boulevard alignment was preferable to the Columbia Slough Alignment.

The Bureau of Environmental Services and the design team conducted a second workshop to analyze the remaining two alignment alternatives and to select the better alternative from a technical perspective. Evaluation included consideration of permits, constructability, operations, right-of-way consideration, and public impacts. The group adopted the Interceptor/Railroad Alignment as the better of the two final alternatives. A key factor in adopting this alignment was the positive response of Union Pacific Railroad Company during initial discussions of the project.

Value Engineering Study

A value engineering study was conducted following the 30% design submittal. Ideas eventually adopted from this study included modifications to portions of the alignment and raising the profile two feet to reduce the construction impact of the seasonally fluctuating groundwater. The latter change proved to be especially valuable, especially during construction of Segment 1.

Constructability Considerations

During the design phase, several construction methods were considered for the 12-foot ID sections of the Conduit while allowing the contractor the option to select from several methods. Construction methods for Segment 1 included a combination of cut and cover installation with conventional steel plate lagged soldier pile shoring with boring and jacking beneath Union Pacific Railroad tracks and Columbia Boulevard.

The presence of frequent large boulders was a major concern for installation by boring and jacking. Boulders encountered during geotechnical exploration suggested that access to the face of the boring machine was essential to remove boulders that could not be dislodged or broken up into smaller pieces. The fine-grained flood deposits in the area were classified as “slowly raveling” and the coarse-grained flood deposits were classified as “fast raveling” to “cohesive running” with a remote possibility of encountering “flowing” sand (The Tunnelman’s Ground Classification For Soils System, Heuer, 1974, and Heuer and Virgens, 1987). These classifications suggested that an open-face digger-type machine with hydraulic breasting boards was a viable alternative.
Slurry face tunnel boring machines and earth pressure balanced machines were considered inappropriate for this project because access to the face would be difficult when dealing with the cobbles and boulders that were anticipated. Tunnel machines consisting of shields without the capability to provide at least some face support were also considered inappropriate for this project because of the possibility of “flowing” ground and the obligation to protect track foundations while trains were passing overhead.

**GEOTECHNICAL AND ENVIRONMENTAL INVESTIGATIONS**

Extensive geotechnical and environmental investigation was conducted, including borings, large-diameter auger borings, test pits, and numerous sampling and analyses for determination of soil and environmental parameters. A geophysical survey was also conducted to further define site conditions. The result of this work was development of several documents to be used to establish geotechnical and environmental baseline conditions for bidding. The baseline contract documents include a Geotechnical Design Summary Report, a Geotechnical Data Report, an Environmental Design Summary Report, and an Environmental Data Report.

**Project Geologic Setting**

The Conduit project area lies within the Portland Basin at the north end of the Willamette Valley. There are several cultural features, such as roads and buildings along the Interceptor/Railroad Alignment. The ground surface along the Union Pacific Railroad and N. Columbia Boulevard is relatively flat, with local natural and man-made topographic breaks of less than 15 feet. A distinct break in topography occurs south of and parallel to N. Columbia Boulevard west of Interstate 5 and parallel to the Union Pacific Railroad tracks east of Interstate 5. Along this topographic break, ground elevations rise away from the Columbia Slough toward the southwest, from about 40 to about 80 feet City of Portland Datum in the western portion of the project area and about 60 feet to about 100 feet City of Portland Datum in the eastern portion. The increased elevation toward the southwest corresponds to the presence of a northwest-southeast linear ridge, most likely composed of flood deposits, which rises to the south in the residential areas south of N. Columbia Boulevard.

**Regional Geology**

Geology along the Conduit corridor generally consists of recent Columbia River alluvium overlying unconsolidated fine-grained and coarse-grained catastrophic flood deposits that in turn mantle partially lithified Troutdale Formation sediments.

**Geologic Units**

The Conduit project area is located in the western part of the Portland Basin, a broad, relatively flat basin underlain by Miocene Columbia River Basalt. Since late Miocene time, the ancestral and modern Columbia and Willamette Rivers and their tributaries have deposited alluvial sediments into the basin. The thickness of the sediments overlying the Columbia River Basalts exceeds 1,500 feet in the deepest portions of the basin. In the eastern portion of the basin, the alluvial sediments are interlayered with the basaltic Boring Lavas of late Pliocene and Pleistocene age. The upper portion of the alluvial deposits include varying thicknesses of sediments deposited by Pleistocene Age catastrophic floods originating in Montana and channeled down the Columbia River.

Geology along the Conduit corridor consists of recent Columbia River alluvium (Qal) overlying unconsolidated, fine-grained and coarse-grained catastrophic flood deposits (Qff and Qfc) which, in turn, mantle partially lithified Troutdale Formation (Tt) sediments. The recent alluvium is composed of variable amounts of fine sand, silt, and clay in continuous to discontinuous units filling the Pleistocene Columbia River channel. A geologic profile at the longest bored and jacked pipe crossing is shown in Figure 3.
Pleistocene-age catastrophic flood deposits overlying the Troutdale Formation are present across the entire Conduit project. Multiple high-energy turbulent floods (the Missoula Floods) that came down the Columbia River during glacial periods placed the deposits. They underlie the recent alluvium in the Conduit project area. The flood deposits range from silt and fine sands to sandy gravel with discontinuous layers containing cobbles and boulders. Throughout the project alignment, the flood deposits can generally be separated into two units: an upper fine-grained unit of sandy silt and silty sand (fine-grained flood deposits, Qff), and a lower coarse-grained unit of sandy gravel with varying amounts of cobbles and boulders (coarse-grained flood deposits, Qfc).

**Fine-Grained Flood Deposits (Qff)**

The upper fine-grained flood deposits generally consist of silty clay, clayey silt, and fine sand with traces of gravel. The sand and gravel are composed primarily of feldspar, quartz, Columbia River Basalt fragments, and varying amounts of mica. In the Conduit area, the fine-grained flood deposits are geologically similar to the recent fine-grained river alluvium (Qal). They thicken toward the Columbia Slough and are stratigraphically above the coarse-grained flood deposits.

**Coarse-Grained Flood Deposits (Qfc)**

The coarse-grained unit of the flood materials is predominantly sandy gravel with varying amounts of cobbles and boulders. The cobbles and boulders are in discontinuous sloping layers in a sandy gravel matrix and are composed of quartzite and Columbia River Basalt. Openwork gravels are occasionally present as stringer-like bars and sheets within the coarse-grained flood deposits. Stratification or bedding of the deposits is the result of catastrophic flood deposit. The boulders observed within the coarse-grained flood deposits in the Conduit project area range from 12 inches to 48 inches maximum dimension and occasionally larger.

**Laboratory Testing**

A total of 476 geotechnical soil samples were taken for geotechnical laboratory testing, including 69 relatively undisturbed Shelby tubes. Geotechnical testing included visual classification, moisture content,
Atterberg limits, liquid limit and plastic limit, unit weights, grain-size analyses, both mechanical analysis (wet sieve) and hydrometer, shear strength estimates using a torvane shear device, direct shear tests, consolidated-undrained triaxial compression tests, point load tests on cobble samples, and compaction tests. Table 1 presents the geotechnical parameters that were used in the design.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>USCS Group Symbol</th>
<th>C – Cohesion</th>
<th>(\phi)° - Angle of Internal Friction</th>
<th>(\gamma) - Moist Unit Weight, Mg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill (F)</td>
<td>ML, SM, CL-ML</td>
<td>0</td>
<td>32</td>
<td>2.12</td>
</tr>
<tr>
<td>Silty Fine-Grained Flood Deposits</td>
<td>CL-ML, ML, SM</td>
<td>0</td>
<td>32</td>
<td>2.12</td>
</tr>
<tr>
<td>Gravely Coarse-Grained Flood Deposits</td>
<td>GP, GP-GM, GM, GW-GM, SP-SM, SW, SP</td>
<td>0</td>
<td>38</td>
<td>2.12</td>
</tr>
</tbody>
</table>

Table 1: Geotechnical design parameters

GROUND WATER CHARACTERIZATION

Ground water hydrogeology of the Conduit project area consists of a deep alluvial gravel aquifer, regional ground water and locally perched ground water. A total of 20 piezometers and eight ground water monitoring wells have been installed along an approximately 3½-mile corridor south of the Columbia Slough as a part of the Conduit project.

Perched Ground Water

Perched water was encountered at depths of 1½ to 2 feet in hand auger borings in the Segment 3 section. Seasonally perched water is present in designated wetlands and at other near-surface low elevation locations along the Interceptor/Railroad Alignment. The areas of perched ground water appear to be isolated from the deeper alluvial aquifer by a shallow fine-grained aquitard.

Regional Ground Water

A regional ground water table (aquifer) exists within the coarse-grained flood deposits. Measured ground water levels range from elevation 10 feet to 18 feet City of Portland Datum. These levels seasonally fluctuate above and below the invert elevations of the conduit in Segments 1 and 2. Segment 3 connects to Segment 2 at the high end of a drop structure at Interstate 5. It is thus considerably higher than the rest of the project and is entirely above the regional groundwater table.

Ground water slug tests and hydraulic conductivity measurements were also performed. The tests indicate that hydraulic conductivity in the fine-grained flood deposits range from about 80 feet per day in sandy soil to as low as 10 feet per day in deposits with significant silt or clay content. The hydraulic conductivity in the underlying coarse-grained alluvium was interpreted to be as high as 1,250 feet per day.

BID PACKAGING

The Conduit project was separated into six separately contracted construction segments. The main conduit work was broken into three segments. Segments 1 and 2 included 12-foot internal diameter conduit and Segment 3 included 6-foot internal diameter conduit. Segment 5 was a sewer relocation project that preceded the Segment 2 work. Segment 4 is a landscaping and community enhancement project. Segment 6 is an odor control facility to be constructed where Segments 2 and 3 connect. The intent of this sort of bid packaging was to encourage greater participation by local businesses in the Conduit project, especially by historically underutilized businesses.
DESIGN OF SEGMENT 1 (CUT AND COVER AND BORED AND JACKED PIPE)

The design of Segment 1 included 2,712 feet of 12-foot reinforced concrete pipe of which four 126 foot to 222 foot sections were to be installed by boring and jacking. The work also included approximately 190 feet of jacking 6-foot steel casing and 331 feet of 5-foot reinforced concrete pipe, two cast-in-place concrete structures, and manholes and other appurtenances.

The work included crossing Union Pacific Railroad mainline tracks at five locations, four with 12-foot conduit and one with 6-foot conduit. The last 12-foot conduit crossing and the 6-foot crossing also included crossing Columbia Boulevard, a major industrial thoroughfare serving Portland’s port facilities. The bored and jacked pipe also crossed existing utilities including 16-inch and 12¾-inch natural gas transmission lines. Two of the crossings were located in close proximity to an existing 102-inch x 102-inch monolithic concrete sewer interceptor serving most of Portland. Boring and jacking was the required construction method for the last two crossings and optional for the other three crossings. See Figure 4.

Installation by the boring and jacking method was selected for the following reasons:

- Crossing of very active Union Pacific Railroad mainline tracks was necessary.
- Interruption of railroad service could not be tolerated for more than 24 hours.
- The alignment also crossed a major thoroughfare in combination with the track crossings.
- Relocation of several buried utilities within the alignment would have been required for conventional cut and cover installation.
- The settlements produced by boring and jacking were expected to be controllable and tolerable.
- Experience elsewhere indicated boring and jacking very large reinforced concrete pipe could be successful given the proper equipment, installation techniques, and favorable soil conditions.

Where boring and jacking was to be used to install the 12-foot conduit, direct reinforced concrete pipe jacking was required on a 24-hours per day basis until completed. Close coordination with Union Pacific Railroad operations was necessary because shutdown and breasting of the face was required whenever the excavation face was within 25 feet of the centerline of the tracks and a train was passing overhead. The equipment specifications required steerability and full-face control capability. At the 12-foot Columbia Boulevard crossing (Crossing 4 on Figure 4), the local natural gas utility exposed the two gas lines noted above before boring and jacking operations began. This unloaded the pipes during jacking to limit the impact of settlement. The contract required instrumentation installation and monitoring during boring and jacking work. Compaction grouting was required for this crossing to mitigate settlement on the roadway and utilities. Figure 5 from the design drawings shows the profile of this part of the work.
Figure 5: Profile of Bored and Jacked Crossing 4

SEGMENT 1 CONSTRUCTION (OPEN CUT AND BORED & JACKED):

The pipe was installed using the cut and cover method except for five bored and jacked crossings under Union Pacific Railroad tracks and Columbia Boulevard. The Segment 1 construction contractor was Robison Construction, Inc., of Sumner, WA. The contract documents conditionally allowed three of the five Union Pacific Railroad crossings to be performed using the cut and cover method. Due to the constraints and risks of the open cut option, the contractor elected to use boring and jacking to install all five of the crossings. The boring and jacking subcontractor was Northwest Boring Co. of Woodinville, WA. It selected equipment manufactured by Akkerman Equipment, Inc., of Brownsdale, MN, for the four 12-foot and the one 6-foot jacked crossing.

The balance of this paper will focus on the fourth and final 12-foot jacked crossing beneath active Union Pacific Railroad mainline tracks and Columbia Boulevard. At 222 feet long, it was the longest crossing and was installed with the benefit of fresh experience from three earlier shorter crossings. The general contractor for the project proposed a shift in the alignment just ahead of the fourth jacked crossing in order to install jacking pit shoring clear of overhead Union Pacific Railroad signal wires. The owner accepted the proposal and agreed to participate in increasing the length of the jacked Crossing 4 from 210 feet as designed to 222 feet as installed.

The reinforced concrete pipe manufactured for the large jacked crossings was designed in conformance with design loading requirements for moments and thrusts given in the construction documents. The design requirements for the pipe took into account Cooper E-80 railroad loads, earth loading and side support, and internal surcharge components. The large reinforced concrete pipe had an inside diameter of 144 inches with a 13-inch wall thickness. The outside diameter of the pipe was a uniform 170 inches. The normal pipe length to be jacked was 12 feet long. Each section of pipe weighed approximately 81,000
pounds including about 5,000 lbs. of steel reinforcement. This 144-inch pipe is at the practical upper size limit for precast concrete pipe to be transported over the road.

The pipe was manufactured by PIPE, Inc., of Portland, OR, which fortunately had a plant on N. Columbia Boulevard less than two miles from the jobsite. The pipe had bell and spigot joints sealed by twin confined rubber O-ring gaskets. This system created an annular space between the gaskets that could be quickly pressure tested immediately after joint assembly to verify joint seal. This was a “go - no go” test procedure to qualify further incorporation of each joint into the work. The pipe also was produced with a set of three 1½ inch diameter grout ports located every 6 feet. The ports were located such that one was located at the pipe crown and the other two were halfway between the invert and each pipe springline. The ports were initially used for injection of bentonite slurry lubrication during the jacking operation and for subsequent contact grouting after the jacking was completed. The allowable force for jacking the pipe was limited to one-third of the 28-day compressive strength of the concrete used in the pipe. Given the required minimum 5,000 psi concrete strength and the area of the spigot portion of the joint, the pipe’s allowable capacity was on the order of 2,300 tons. The boring and jacking subcontractor used a 150-ton crane to handle and lower the sections of pipe into the jacking pit for assembly.

The boring and jacking subcontractor selected an Akkerman Pipejacking EX 168 shield, a fully articulated shield with full-face breasting doors. The shield was equipped with an Akkerman Model EX 50 Backhoe Excavator. Both the full-face breasting doors and the EX 50 Excavator were hydraulically operated. Each door could be individually opened or closed to control the face if necessary. The hydraulic pumps powering the shield were driven by electric motors powered by an on-site diesel generator. The pipe jacking shield was sized to create a one inch overcut for steering capability resulting in a bore diameter of 172 inches, two inches larger than the outside diameter of the pipe. This overcut was essential for allowing the shield articulation to make minor adjustments to line and grade but introduced an annular void that created the potential of two inches of settlement. The open face of the shield allowed for handling and removal of boulders as necessary.

The jacking system consisted of four 300-ton telescoping jacks, resulting in a total jacking capacity of 1,200 tons. The jacking frame was manufactured to accept another two jacks that the boring and jacking subcontractor had on hand if needed. The subcontractor also constructed an intermediate jacking station to be used if jacking forces exceeded the allowable jacking force. The subcontractor used one inch thick oriented strand fiberboard as a cushion material between successive pipe sections.

The jacking and receiving shafts were constructed as soldier pile cells with steel plate lagging. The jacking shafts each had a nominal dimension of 32 feet long by 20 feet wide with a typical depth of about 27 feet. The receiving shafts were nominally 20 feet long by 20 feet wide with a depth of up to 30 feet. The jacking shaft design included evaluation of E-80 railroad loads as well as apparent earth loading and nominal surcharge loads with a design deflection not to exceed ¾ of an inch. Because the Crossing 4 receiving pit was in close proximity to an existing 102-inch x 102-inch interceptor, the soil design parameters for it were more stringent and used at-rest earth loading and nominal surcharge loads with a design deflection not to exceed 0.375 inches. The boring and jacking subcontractor used two 5 inch thick steel plates in front of a 12 inch thick concrete wall cast against the back wall of the jacking shaft as a backstop for the main jacks. In addition, the subcontractor excavated and poured a three foot thick concrete wall parallel to and about ten feet behind the reaction wall of the jacking pit for Crossing 4. It extended the full depth and width of the jacking pit.

The boring and jacking subcontractor requested waiver of the requirement to jack on a 24-hours per day basis. This change was approved by the owner and Union Pacific Railroad after verifying that soil conditions were better than expected. As part of the change, the subcontractor assumed all additional risks resulting from the change. This change proved to be wise because it allowed the work to be done entirely during daylight which greatly enhanced productivity, worker safety, and coordination with Union Pacific Railroad.
Crossing 4 began on August 10, 1998 with normal long shifts of twelve hours each day. Production rates ranged between 0.6 feet and 3 feet per hour. The average production rate for the entire drive was about 2 feet per hour, and the jacking was completed in ten consecutive days. During the jacking operation, it was determined that neither the two additional jacks nor the intermediate jacking station would be necessary. Settlement was monitored both at the railroad tracks and along the Columbia Boulevard crossing. Observed settlement exceeded the specified criteria of half an inch several times over but proved to be quite tolerable. The design tolerances for line and grade were 0.1 foot for grade and 0.4 foot for line. The installation was well within the allowable tolerances as it holed out within a quarter of an inch of the design grade and only three-quarters of an inch off line.

On the second day of the jacking process, the contractor began injecting a bentonite slurry into the annular space created by the shield overcut as a lubricant to help to reduce the total jacking resistance. The calculated annular space volume for the jacking was 17.4 cubic yards. A total of cubic 28.8 cubic yards of bentonite slurry was injected during the drive. The ratio of the cumulative lubricant used to the annular void created by boring is shown with a plot of production versus jacking force on Figure 6.

![Figure 6: Production versus jacking force](image)

In this figure it can be seen that at about 125 feet of production, the amount of lubricant used exceeds the theoretical overcut volume. Vertical jumps in jacking force at specific points represent increases in resistance that developed between shifts. The jacking data shown are a composite of information collected by both the subcontractor and the owner. Note that a significant increase in jacking force occurs at about 165 feet into the drive. This distinct increase may represent the point where the shield and pipe string began to be influenced by cobbles and boulders in the coarse-grained flood deposits. The composite information plotted in Figures 6 and 7 indicates a total of about 249 feet of total jacking. This includes the length of the crossing, launching and retrieval of the boring shield, and short lengths of pipe overhang into the shafts for transition to the adjacent structures.

Another way to look at the data is by comparing production with the unit jacking resistance. This is illustrated in Figure 7. Also shown on this figure is the theoretical volume of annular space created and
the total lubricant used. The unit jacking resistance is initially high at around 0.35 tons per square foot at the end of the first shift. After about 75 feet of production, the unit jacking resistance drops to between 0.9 and 0.13 tons per square foot with an end value of about 0.10 tons per square foot. After about 125 feet of production, the amount of lubricant injected exceeded the theoretical volume of the annular space created. This may be due to lubricant permeating open-graded native gravels and filling voids created during boring, and also losing bulk due to water migration.

Figure 7: Production versus unit jacking resistance

Construction Monitoring

Damage to existing structures and utilities was to be prevented during construction. Criteria were established during the design phase to control damage due to settlement. These criteria were monitored during the construction phase by conventional surveying and a network of geotechnical instrumentation. This offered an opportunity to mitigate settlement damage if it exceeded the established allowances.

Settlement Instrumentation

Instrumentation was installed to monitor ground movement during and after construction of the conduit and other appurtenant facilities. The instrumentation program was designed to assure that the work was proceeding as expected and to identify behavior different than anticipated. Instrumentation is especially necessary on an urban project such as the Conduit because existing infrastructure, buildings, and structures along the alignment need to be protected against ground movement. The instrumentation consisted of the following:

- Fixed Point End Anchors (4)
- Free End Drive Point Anchors (36)
- Structure/Surface Settlement Points (20)
Data from the instrumentation was collected several times a day and was analyzed and reported on a daily basis. Settlement monitoring was considered to be so important that the general contractor and the owner each took readings and reported the results to each other.

**Settlement Results**

The four 144-inch crossings were completed working ahead on station (west to east), which coincidentally was in order of increasing length and difficulty. Measured maximum settlements at the pipe centerline exceeded the allowable maximum of half an inch in all cases and ranged from 1-1/8 inches to 2-5/8 inches. It is believed that this variation is due to differences in rail traffic, soil characteristics, and pipe string lubrication technique among the crossings. Total rail settlement at each 144-inch crossing is shown in Table 2.

**Table 2: Total rail settlement at 144-inch pipe centerline, Feet**

<table>
<thead>
<tr>
<th>Location</th>
<th>Grout date</th>
<th>Near rail</th>
<th>Far rail</th>
<th>Traffic</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Crossing #1</td>
<td>6/26/98</td>
<td>-0.11</td>
<td>-0.09</td>
<td>Light</td>
<td>Jacked track and tamped ballast after contact grouting</td>
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<tr>
<td>Crossing #2</td>
<td>7/9/98</td>
<td>-0.21</td>
<td>-0.20</td>
<td>Heavy</td>
<td>Jacked track and tamped ballast after about half of settlement was experienced, and again after contact grouting</td>
</tr>
<tr>
<td>Crossing #3</td>
<td>7/16/98</td>
<td>-0.22</td>
<td>-0.21</td>
<td>Heavy</td>
<td>Jacked track and tamped ballast immediately after these final readings were taken; contact grouted the next day</td>
</tr>
<tr>
<td>Crossing #4</td>
<td>8/24/98</td>
<td>-0.10</td>
<td>-0.10</td>
<td>Heavy</td>
<td>Subcontractor improved lubricant injection monitoring; jacked track and tamped ballast after contact grouting</td>
</tr>
</tbody>
</table>

Rail traffic at Crossing 1 was very light, about one train per week. This allowed settlement to develop slowly without train loading until contact grouting largely arrested it. Settlement at Crossing 1 was thus about only about 1¼ inches, well under the total overcut of the boring machine. Settlement at Crossing 2 was twice that experienced at Crossing 1. However, it was in the same order of magnitude of track settlement from high traffic and heavy operating loads that was observed elsewhere in the Penn Junction area. Heavy rail traffic caused Crossing 2 settlement to be surprisingly greater and to appear much more quickly than at Crossing 1. A change in soil characteristics and a delay in starting lubricant injection were probably exacerbating factors. Union Pacific Railroad maintenance personnel regraded the track once as settlement developed and again after contact grouting. Close coordination with Union Pacific Railroad proved to be essential. Crossing 3 settlements were roughly the same as those experienced in Crossing 2 despite the exercise of greater care and timely lubrication. The tracks at Crossing 3 are in a curve so train traffic was correspondingly slower. This allowed regrading of the track to be deferred to one operation immediately after completing and grouting the crossing.

Crossing 4 operations were much improved over previous crossings and came much closer to meeting settlement requirements. The average settlement measured on the tracks and on N. Columbia Boulevard pavement averaged slightly less than an inch. Settlement observed on the mainline track was greater than on the adjacent siding and developed more rapidly due to heavier train traffic. Settlement observed on the Columbia Boulevard pavement was less than that observed on the Union Pacific Railroad tracks due to
lighter vehicular loads, use of compaction grouting, and the tendency of the unusually thick pavement to bridge.

**Table 3: Crossing 4 Structure Settlement in Feet**

<table>
<thead>
<tr>
<th>Time</th>
<th>UPRR Siding</th>
<th>UPRR Mainline</th>
<th>North Columbia Boulevard</th>
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<tr>
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<td>North rail</td>
<td>South rail</td>
<td>North rail</td>
</tr>
<tr>
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<td>-0.03</td>
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</tr>
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<td>-0.05</td>
</tr>
<tr>
<td>8/14/98</td>
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<td></td>
<td></td>
</tr>
<tr>
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<tr>
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</tr>
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**CONCLUSIONS**

The design and construction of this project was based on risk sharing principles between the owner and the contractor. Baseline documents were a basis for the bidder to select construction means and methods to be compatible with the subsurface conditions anticipated. This approach provided the owners with a reasonable low bid with the risks for the unknown being assumed by the owner. The owner, the general contractor, and the boring and jacking subcontractor all entered into a working partnering agreement before the work. The contract also provided for a Dispute Review Board to help resolve issues arising from differing site conditions or other changes short of litigation. To date, no issues have been referred to the Dispute Review Board. The bids for Segment 1 were about 16% under the engineer’s estimate and the final contract cost is expected to be about 14% under the Engineer’s estimate.

Boring and jacking method of installation provided the following benefits:

- The installation method reduced the impact on the environment.
- This method resulted in minimal surface disturbance.
- Major traffic disruptions, road closures, and traffic delays along Columbia Boulevard for trucks, communities, and businesses was avoided.
- Disruption and delay of Union Pacific Railroad traffic was avoided.
- High cost of pavement removal and replacement along Columbia Boulevard and removal and reinstallation of Union Pacific Railroad tracks was avoided.
- The cost of disruption or damage to existing underground utilities was avoided.
- The working environment was safer compared to other methods.
REFERENCES


