The History of Tunneling in Portland—Rail, Highways, and the Environment

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ABSTRACT: Tunneling in Portland mirrors the industrialization and urbanization of America. Beginning with rail tunnels in the early 1900s, tunneling has evolved as a tool to protect the environment by reducing combined sewer overflows into the Willamette River. At least 14 tunnel projects exist in the Portland area, ranging from a 1909 rail tunnel to the East Side CSO Tunnel, currently under construction. The variety of tunneling methods used to construct these tunnels reflects the diverse local geology, ranging from basalt bedrock to open gravel and boulders to soft silt. Challenging ground conditions have led to tunneling innovation, including the first use of a slurry mixshield tunnel boring machine (TBM) in North America and the longest microtunneling drive in the United States.

INTRODUCTION

Portland tunnels have been built for heavy rail, highways, and light rail; however, some of the largest of the tunnels have been built to convey wastewater for treatment and to prevent combined sanitary/storm sewer overflows into the Willamette River and Columbia Slough. Diverse tunneling methods have been used to tunnel through Portland's complex geology, including excavating by drill and shoot, slurry TBMs and microtunneling tunnel boring machines (MTBMs), hard rock TBMs, and earth pressure balance (EPB) TBMs and MTBMs, TBMs run in open mode, shield, and hand excavation with and without ground freezing. Solving Portland's variable ground conditions has led to innovations that have benefited the tunneling industry.

PORTLAND'S OLDEST TUNNELS

Beginning in the 1860s and ending around WWI, Portland folklore tells of "Shanghai Tunnels" in Portland's Old Town, which conveyed men out through connected basement passageways to sailing ships moored along the Portland waterfront. The men, who had been allegedly drugged in illicit boarding houses, were forced to work onboard as sailors (Fraizer 2001). This creative use of subterranean passageways illustrates Portland's early recognition of the usefulness of tunnels.

Portland's two earliest excavated tunnels were constructed by the railroads to facilitate passenger and freight traffic in and out of the city. The Oregon Railroad and Navigation Company built the 1,654-m (5,425-ft) long Peninsula Railroad Tunnel in north Portland from 1909 to 1911 (Anderson 2005). This concrete-lined tunnel, which cuts through the north Portland highlands, shortens freight movement north over the Columbia River to Washington State. The Peninsula Tunnel was excavated through catastrophic glacial flood deposits of gravel and sand above groundwater. The tunnel and approaches cost $800,000 to construct at the time ($74 million in 2009 dollars); however, no record of the tunneling method can be found. The tunnel was subsequently acquired by Union Pacific Railroad (UPRR), and it is still in use 100 years later.

In 1921, the 425-m (1,395-ft) long Elk Rock Tunnel was constructed in south Portland by Southern Pacific for the Red Electric East Side local passenger train. Originally, the Red Electric crossed a trestle along the base of a steep rock cliff along the west shoreline of the Willamette River. Rockfall onto the trestle became unacceptable when Mrs. Ella Newlans, the wife of the president of the Oswego Cement Company, was hit in the forehead by a falling rock that crashed into her coach (*The Webfooter* 2008). Mrs. Newlans received several stitches, and the Elk Rock tunnel was excavated within the offending cliff to move passenger traffic out of harm's way. The Lake Oswego Trolley has used the Elk Rock Tunnel for many years, and it is currently being upgraded to expand Portland's extensive streetcar system to Lake Oswego.

These two early rail tunnels are precursors to the later wastewater, highway, and light rail tunnel projects that have been built along the east and west banks of the Willamette River, along the Columbia Slough, through the West Hills, and in east Portland.

PORTLAND’S UNIQUE GEOLOGY AND GROUND CONDITIONS

Portland’s unique and diverse geology has complicated the construction of both hard rock and soft ground tunnels over the last 100 years. Between 15 and 17 million years ago, Portland was inundated by thick Columbia River Basalt flows, which underlie the down-warped Portland Basin and the uplifted Portland West Hills (Tualatin Mountains). Approximately 13,000 years ago, the final catastrophic glacial flood scoured the Columbia River channel and the Portland Basin, leaving behind thick deposits of both coarse and fine flood deposits over most of the City’s lower elevations. These glacial flood deposits form steep bluffs that parallel the east bank of the Willamette River north and south of Portland’s downtown area. Portland is the only major metropolitan area in the continental United States that is populated by volcanoes. Interbedded volcanic cinders and basalt flows from these Boring Lava vents underlie potions of the West Hills and east Portland highlands. Thick deposits of windblown glacial loess, known as the West Hills Silt, blanket the Portland West Hills.

Since the end of the last glacial epoch, Portland’s ancient river channels and lowlands have been in-filled by sand and silt alluvium that has been deposited as the glaciers melted and sea level rose. Thick deposits of Quaternary Alluvium extend down to El. –42.6 m (–140 ft) beneath Portland’s central eastside riverfront and Swan Island in North Portland. Between the Columbia River Basalt flows and the glacial deposits and recent alluvium, the Troutdale Formation gravel and the Sandy River Mudstone document channel and overbank sediments of a much larger, ancestral Columbia River. These old alluvial units have been weathered and eroded and were later scoured by the catastrophic glacial floods.

Tunneling ground conditions in Portland are as unique and diverse as the local geology. The Willamette and Columbia rivers’ shorelines are underlain by very soft silt and sand that flows into excavations is prone to excessive settlement and complicates the maintaining of tunneling grade. Open matrix catastrophic glacial flood deposits below the groundwater level in lowlands preclude the use of EPB tunneling methods and cause excessive slurry loss with the use of slurry TBMs. Hard gravel, cobbles, and boulders in these deposits cause significant cutterhead and crusher wear. Cemented gravel horizons within the Troutdale Formation slow shaft excavation also cause excessive cutterhead wear. Weathered and faulted Columbia River Basalt in the West Hills contains highly fractured zones and closely spaced cooling, clay-filled joints that have a very short stand-up time.

SUMMARY OF PORTLAND TUNNEL PROJECTS

At least 14 tunnel projects have been built in Portland over the last 100 years. These projects include highway, heavy rail, light rail, and water/wastewater tunnels. Table 1 provides a summary of available information on Portland’s tunnel projects, including tunnel length, diameter, ground type, tunneling method, owner, contractor, and cost. Figure 1 shows the location of each of these tunnels. The following summaries provide highlights of each of the projects from the 1930s to present. The summaries highlight adaptations and innovations that were developed to mine through Portland’s complex ground conditions. The completion date or expected completion date for each tunnel or tunnel project is shown in parentheses next to its name in Table 1.

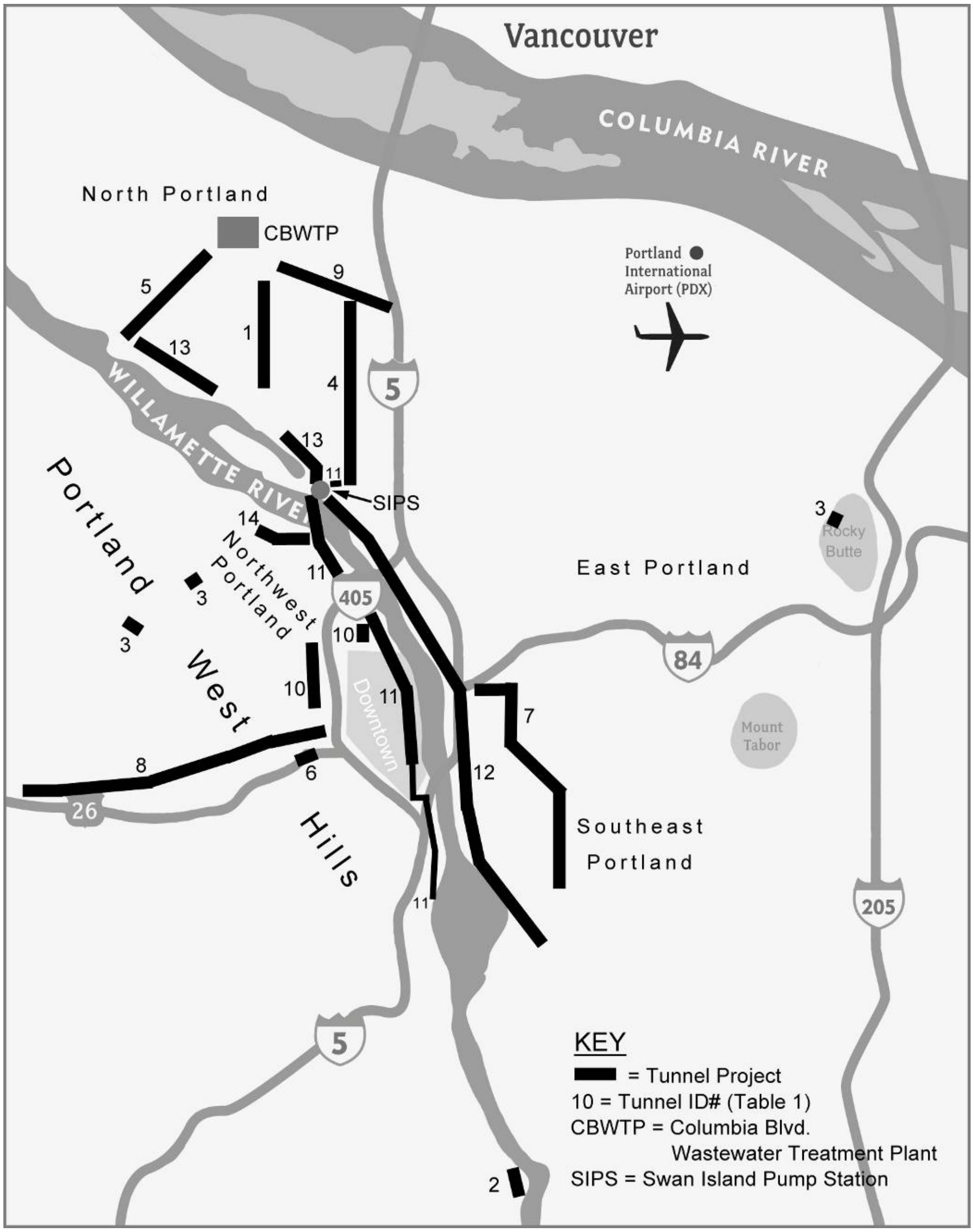

Figure 1. Vicinity map showing the location of Portland's tunnel projects

Early Portland Highway Tunnels (1939 to 1941)

The Federal Works Progress Administration (WPA) built three tunnels in Portland between 1939 and 1941 (Hadlow 2008). The West Burnside Tunnel and NW Cornell Road tunnels improved traffic through the Portland West Hills by straightening the roadways and removing steep grades. Rocky Butte Tunnel was built to improve residential and scenic access on Rocky Butte volcano in east Portland.

The Rocky Butte Tunnel, which took 16 months to complete, was excavated by WPA workers through Boring Lava cinders and basalt flows, using hand mining and drill and shoot methods, respectively. Tunnel muck was removed in one-cubic yard "Swede" cars on light-gauge rails, pulled by cable on a stationary winch. The portals of the curved

114.3-m (375-ft) long Rocky Butte Tunnel almost overlie each other due to the steep (5 percent) grade on the volcano. Special traveling steel forms were used to apply a 50.8-cm (20-in.) thick reinforced CIP concrete lining over the timber initial support.

The 74.4-m (244-ft) long West Burnside Tunnel was excavated through clay (decomposed Columbia River Basalt and/or West Hills Silt). Two 1.8 to 2.4 m (6 to 8 ft) high sill drifts and one crown drift were driven before the remainder of the tunnel was excavated by hand using “Swede” cars. The two 76.2-m (250 ft) and 152.4-m (500-ft) long NW Cornell Road tunnels were excavated through highly weathered Columbia River Basalt using drill and shoot methods. “Swede” cars on rail were used to remove tunnel muck. Both the West Burnside and NW Cornell Road tunnels were lined with CIP reinforced concrete.

Mason Ralph Curcio and his crew designed and built beautiful masonry portals for all three tunnels using Rocky Butte basalt (Boring Lava). Mr. Curcio, an Italian immigrant who learned masonry in Europe, is responsible for the spectacular masonry work along the historic Columbia River Gorge Highway, the Crown Point Vista House, Multnomah Falls Lodge, and Timberline Lodge (Hadlow 2008). Figure 2 shows the masonry portal at the West Burnside Tunnel.

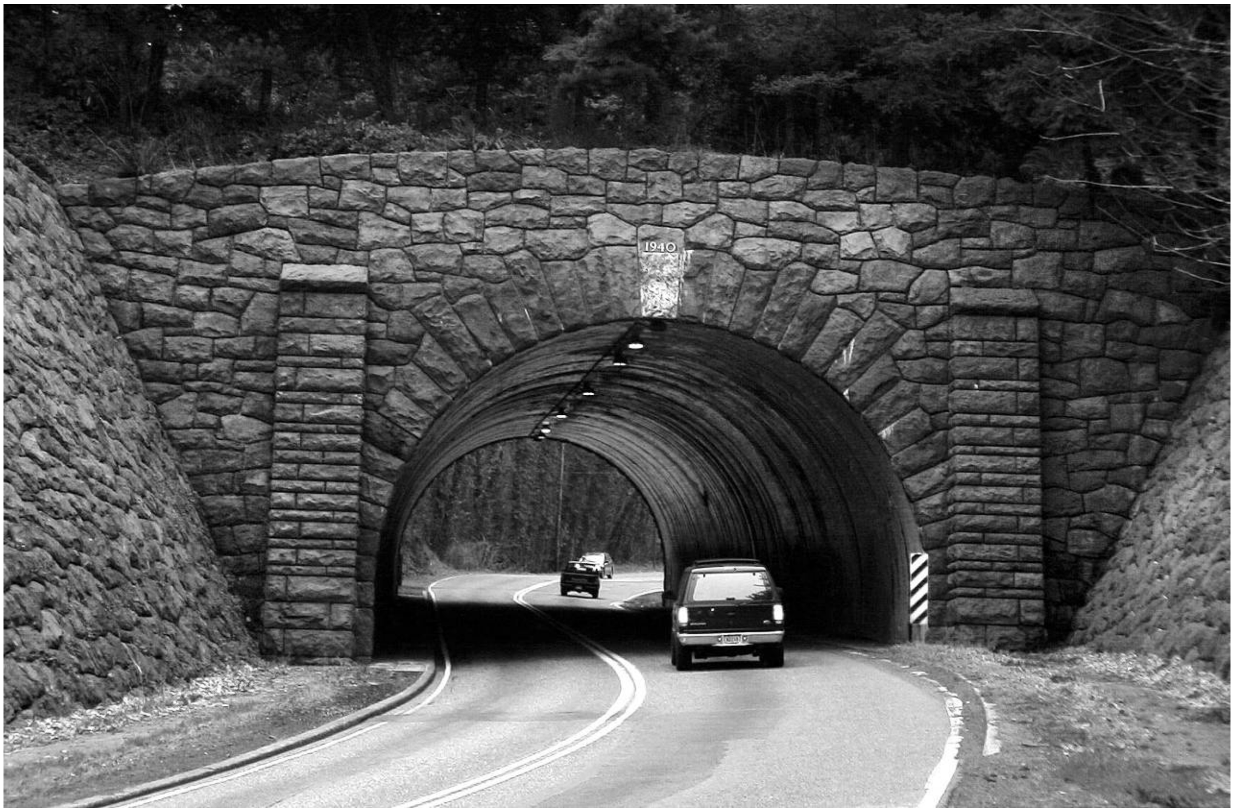

Figure 2. West Burnside Tunnel showing historic WPA stone masonry portal (photo used with permission of Robert Hadlow)

Peninsular Tunnel (1950)

An interconnected tunneled and open-cut sewer pipeline was built in the 1950s along the east side of the Willamette River to convey flows from southeast Portland to the Columbia Boulevard Wastewater Treatment Plant in north Portland. The pipeline consists of three elements (from south to north): the Southeast Interceptor, the Central Eastside Interceptor, and the Peninsular Tunnel. The 5,059-m (16,600-ft) long and up to 50.3-m (165-ft) deep Peninsular Tunnel, which cuts east west through the north Portland highlands, was both the longest and deepest Portland tunnel until the 1990s. The tunnel was excavated through Catastrophic Glacial Flood deposits consisting of sand, gravel, and boulders above groundwater. Breastboards were required for tunneling to prevent running ground.

The tunnel was excavated by placing permanently located steel ribs with timber spiling over the ribs and breast boards on the heading. Tunnel excavation was initially supported using ribs and boards. Collapsible steel forms were used to construct the CIP concrete horseshoe-shaped lining for the 244-cm (96-in.) finished diameter tunnel. Initially, a double pumping system was employed to deliver concrete to the lining forms. This method was abandoned when the line plugged; concrete was then delivered to the form via a rail-mounted car pulled by a small locomotive. The entire project was completed in 554 days, mining simultaneously from both portals.

Portsmouth Tunnel (1967)

The Portsmouth Tunnel was constructed in north Portland to convey sewer flows through the highland along the east side of the Willamette River to the Columbia Boulevard Wastewater Treatment Facility. The tunnel was excavated using an open-face pneumatic shield with an overhanging canopy and conveyor belt. Figure 3 shows a photograph of the shield outside the tunnel.

Figure 3. Front view of Portsmouth Tunnel open-face pneumatic shield with overhanging canopy (photo used with permission of the City of Portland Archives and Records)

The 2,179-m (7,149-ft) long tunnel was excavated through fine-grained catastrophic glacial flood deposits above the groundwater table in sand that was “so clean that it was sold as aggregate” (*The Oregonian* 1967). The tunnel was supported during construction by steel sets and wood lagging (Figure 4) and was completed with a circular CIP concrete lining. Tunnel excavation took eight months to complete, and five men worked at the heading during each of the three shifts per day.

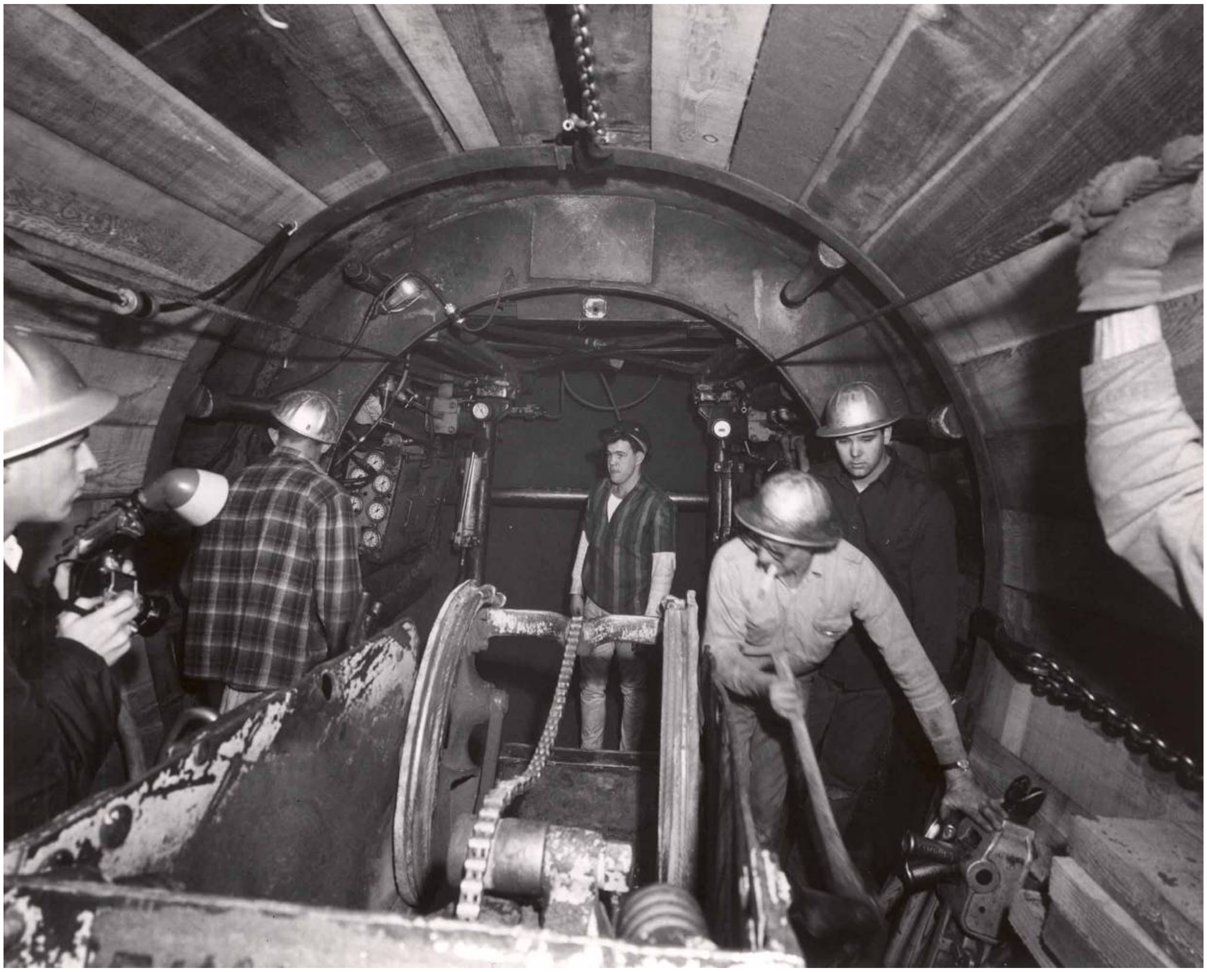

Figure 4. Workers inside the Portsmouth Tunnel shield during tunnel excavation (photo used with permission of the City of Portland Archives and Records)

Vista Ridge Tunnel (1969-1970)

The Vista Ridge Tunnel was built through the eastern edge of the Portland West Hills to significantly increase traffic flow between Portland to the Tualatin Valley. The tunnel connects I-405 (Stadium Freeway) with US 26 (Sunset Highway). The curved Vista Ridge Tunnel consists of a three-lane, 305-m (1001-ft) long eastbound tunnel, and a three-lane, 289-m (949-ft) long westbound tunnel. The Oregon State Highway Commission contracted the construction of a pilot tunnel near the crown of the proposed eastbound three-lane tunnel prior to awarding the contract for final tunnel construction (Hadlow 2004). Contractors were allowed the opportunity to study the Columbia River Basalt rock structure within the pilot tunnel as they prepared their bids. Since the tunnels are described as two “semi-circular bores” (Hadlow 2004), they were most likely heading and bench excavations using drill and shoot methods through basalt bedrock. The tunnels were finished with CIP concrete linings, ceramic tile interiors, and daytime lighting systems (Hadlow 2004).

Southeast Relieving Interceptor (mid to late 1980s)

The Southeast Relieving Interceptor was built in four phases to convey overflows from the original Southeast Interceptor (Singleterry 2009). The tunnel portion of the pipeline alignment extends approximately 5,550 m (18,200 ft) through southeast Portland northward to the Sullivan Pump Station, located in Sullivan Gulch beneath the I-84/I-5 elevated interchange.

The Southeast Relieving Interceptor was constructed in Phases 1, 2, 3, and 4, from north to south. Part or all of Phases 2, 3, and 4 include tunnel sections with tunnel cover ranging from 12.2 to 24.4 m (30 to 80 ft). A 3.7-m (12-ft) diameter open face shield was used to excavate Phases 2 and 4. Phase 3, the only section located below groundwater, was excavated with a close-faced shield in conjunction with dewatering wells. Rib and board initial support was used for all three phases. Concrete CIP final linings were constructed in Phases 2 and 4, while the Phase 3 lining consists of pulled-in reinforced concrete pipe (RCP).

Phase 3 crosses through the historic Hawthorne Slough, which was filled during the urbanization of east Portland. Geology along the entire alignment includes artificial fill, Quaternary Alluvium, Catastrophic Glacial Flood Deposits, and Troutdale Formation. Sand lenses in the Troutdale Formation ran into the tunnel excavation, while the cemented gravel had excellent stand-up time.

Westside Light Rail Transit Tunnels (1996)

The twin 4,542-m (14,900-ft) long, 6.4-m (21-ft) diameter Westside Light Rail Transit Tunnels were built to convey commuter trains through the Portland West Hills between downtown and the Tualatin Basin suburbs (Gildner et al. 1997). The project also included the construction of the deepest commuter train station in North America, to date. The tunnels and station shaft were excavated through the Grande Ronde Basalt Member (GRB) of the Columbia River Basalt Group, Boring Lava basalt, and Sandy River Mudstone. Numerous fault zones and associated highly fractured rock were encountered during tunneling.

The tunnels were excavated in three reaches: A, B, and C (from west to east). Reach A, approximately 1,585 m (5,200 ft), was mined using drill and blast techniques for the rock and earth excavation equipment for the soft ground due to extremely variable ground conditions. Contract Documents precluded TBM use in this reach of the tunnels (Gildner et al. 1997). Reaches B and C, approximately 2,970 m (9,750 ft) combined, were mined primarily through the GRB using a full-face hard-rock TBM. The geologic conditions in these reaches included units of the GRB that were considered less variable than those encountered in western portions of the alignment.

During mining of the first tunnel with the TBM, stand-up time in the first unit of the GRB (Sentinel Bluffs) proved inadequate for TBM operations. Raveling ground conditions created up to 6-m (20-ft) high voids above the TBM. Additionally, the hard basalt caused excessive wear to the cutterhead and cutters. To correct these problems, the contractors modified the TBM by redesigning the grippers, adding reverse rotation, increasing torque, adding protective wear plating to the cutterhead, and installing a “poor man’s EPB” system to stabilize the heading (Gildner and others 1997).

During the excavation of the Washington Park Station, the soil-nail excavation for the headhouses encountered excessive ground movements in the soil (Portland Hills Silt). The excessive movements were tied to the station excavation being located within a massive landslide. The contractor had to install a series of long horizontal drains to lower the groundwater conditions in order to control soil movements prior to completing the excavation.

Columbia Slough Consolidation Conduit (2000)

The Columbia Slough Consolidation Conduit (CSCC) was constructed in north Portland to reduce combined sewer overflows into the Columbia Slough as part of Portland’s state-mandated CSO abatement program. The project included a 2,560-m (8,400-ft) long, 3.7-m (12-ft) diameter tunneled section that was excavated by a mixed-face wheel EPBM that was modified to erect ribs and lagging as initial support (Feroz et al. 2000). The contractor installed a hood on the TBM, and after modification to prevent diving, the hood mitigated raveling ground and gauge cutter overcut (Feroz et al. 2000). The final lining consisted of CIP reinforced concrete.

The tunnel was excavated through Quaternary Alluvium and Catastrophic Glacial Flood Deposits that consisted of slow raveling sand and fast raveling gravel above groundwater. Tunneling was complicated by the presence of oversized boulders within the coarse-grained Catastrophic Glacial Flood Deposits.

Tanner Creek Stream Diversion Project, Phases 2 and 5 (2002)

The Tanner Creek Stream Diversion Project was built to convey creek flows and storm water from Portland's West Hills directly to the Willamette River (Klein et al. 2001). The project, also part of Portland's mandated CSO abatement program, was constructed in five phases through the north side of downtown. Phases 2 and 5 included microtunneled sections through the historic Tanner Creek channel, which was filled with debris during the urbanization of Portland. The 1,158-m (3,800-ft) long Phase 2 alignment passes close to over 100 existing buildings, including brick and masonry structures. Phase 5 extends 457 m (1,500 ft) through an industrial area beneath several mainline railroad tracks. The 183-cm (72-in.) (ID) microtunnels were excavated below groundwater through extremely variable ground conditions including artificial fill, soft silt marsh deposits (Quaternary Alluvium), and Fine-grained Catastrophic Glacial Flood Deposits (Klein et al. 2001).

Artificial fill, which had been dumped to fill in the historic Tanner Creek channel, consisted of a heterogeneous mixture of soil and debris, including bricks, boulders, concrete, wood, and other manmade materials (Klein et al. 2001). The designer conducted ground penetrating radar (GPR) investigations and large-diameter borings to locate and characterize potential buried obstructions. Historical research identified buried timber planked roads supported by timber piles crossing the microtunnel alignment. Portland's first geotechnical baseline report for microtunneling was prepared, which set baselines for project ground conditions and obstructions.

To reduce construction risks, the contractor was required meet the following requirements:

- Provide an MTBM that was equipped to handle large, hard obstructions and fibrous wood debris
- Use a slurry MTBM to reduce ground settlement associated with tunneling
- Complete microtunneling through fill deposits containing obstructions that could damage the MTBM after all other microtunneling has been completed.
- Install watertight support for Phase 5 shafts through fill deposits that contain buried obstructions

Even with these required precautions, buried obstructions were encountered during both tunneling and shaft excavation that delayed the project and increased the cost. The MTBM hit a buried tree stump in the artificial fill during Phase 2 tunneling that was too large to ingest. The MTBM continued "plowing" the stump off line and grade until the ground fractured to the surface and the construction of a recovery shaft was required to rescue the MTBM. Similarly, a buried tree is thought to have caused deflection of Phase 5 sheet pile shaft support that allowed flowing sand to enter the shaft excavation and caused excessive settlement of NW Front Avenue, adjacent rail lines, and buried utilities beneath Front Avenue.

West Side CSO Project (2006)

The West Side CSO Project consists of a 5,541-m (18,180-ft) long, 4.3-m (14-ft) diameter tunnel, three microtunneled pipelines, and six major shafts, including the 42.7-m (140-ft) diameter, 50.3-m (165-ft) deep Swan Island Pump Station shaft located at the tunnel's northern terminus (McDonald 2007). The West Side CSO Project is one of two large CSO abatement projects included in the Willamette River CSO Program. The approximately 30.5-m (100-ft) deep tunnel parallels the Willamette River's west shoreline through downtown and northwest Portland before crossing beneath the river channel to connect to the Swan Island Pump Station in north Portland. The 2,246-m (7,370-ft) long Southwest Parallel Interceptor (Segment 3) pipeline conveys CSO flows from southwest Portland into the tunnel, while the 420.6-m (1,380-ft) long Tanner Extension collects CSO flows from Tanner basin directly north of downtown. The 997-m (3,270-ft) long Peninsular Force Main pipeline conveys flows from the Swan Island Pump Station to the existing Peninsular Tunnel.

Geologic units encountered during project excavations included artificial fill, Quaternary Alluvium, Fine and Coarse-grained Catastrophic Flood Deposits, and the Troutdale Formation (Fong et al. 2002). The Sandy River Mudstone, which is located 45.7-m (150 ft) below the base of the Swan Island Pump Station shaft, was used as an impervious layer for groundwater cut-off for a jet grout curtain. Extensive historical research was conducted during project design to identify and baseline potential buried obstructions along the tunnel and pipeline alignments and within shaft excavations. The tunnel and shaft locations were realigned because of the discovery of abandoned bridge foundations, abandoned steel dolphins, and buried foundations and contamination associated with a demolished flourmill.

The West Side CSO Project was the first large tunnel in North America to use slurry mixshield TBMs, which were utilized to tunnel through open gravel, cobbles, and boulders in the coarse-grained Catastrophic Flood Deposits and the cemented gravels of the Troutdale Formation. Similarly, slurry MTBMs were required for microtunneling through the same material. The tunnel has a reinforced concrete, gasketed, segmented liner to withstand up to three bars of groundwater pressure. To meet the tight project deadline, two 4.9-m (16-ft) (OD) TBMs were launched in either direction from the tunneling shaft to provide schedule flexibility for the construction of the Swan Island Pump Station. The TBMs were required to handle mixed-face ground conditions that often included soft silt and sand over open gravel with up to 36.6 m (120 ft) of groundwater head. The contractor experienced significant difficulty separating the bentonite slurry from the silt and fine sand alluvium during tunneling, causing increased bentonite usage. Tunnel muck was barged to Ross Island in south Portland, where it was used to partially fill an abandoned gravel pit in the Willamette River.

Slurry walls and secant pile walls were constructed as watertight support for tunnel and microtunnel shafts, respectively. Break-in and breakout areas outside the shaft walls were jet grouted to seal the shafts during tunneling into and out of shafts with significant groundwater head. Even with these precautions and the use of a seal at the tunnel eye, groundwater inflows and limited ground loss due to flowing silt and sand alluvium occurred at the tunneling shaft, endangering the TBM. The excavation of the Swan Island Pump Station shaft was delayed by six months because of the difficulty in achieving groundwater cutoff. Remedial jet grouting was performed, and limited dewatering was conducted before shaft excavation could be completed. To get back on schedule, the pump station was redesigned to move the Operations and Maintenance Building off the top of the structure. This move permitted concurrent construction of both structures. That, coupled with accelerated shaft excavation, brought the project back on schedule.

As expected, timber piles and Catastrophic Glacial Flood boulders were encountered during shaft excavation and microtunneling. A boulder, similar to those shown in Figure 5, fell into a slurry wall panel excavation at the Swan Island Pump Station shaft before concrete was placed to fill the panel. When this boulder was removed from the wall during shaft excavation, it created a hole that allowed groundwater to enter the shaft. The shaft was then flooded and repaired using jet grout.

Figure 5. Catastrophic Glacial Flood boulders encountered within the Swan Island Pump Station shaft excavation (photograph by Sue Bednarz, Jacobs Associates)

West Side CSO microtunneling innovations included the use of a slurry MTBM equipped with an airlock to permit face interventions during tunneling. The airlock was used to access and remove an unidentified steel pile obstruction that was supporting an electrical duct bank along the Southwest Parallel Interceptor alignment, eliminating the need to construct a costly rescue shaft. Microtunneling costs were also reduced by using a single MTBM that was retrofitted on site for 183-cm (72-in.), 213-cm (84-in.), and 243-cm (96-in.) (ID) microtunneling. Timber piles and logs encountered by the MTBM were handled, and microtunneling through very soft silt did not significantly impact line and grade. Controlled density fill placed inside steel “top hat” enclosures was used at the tunnel eye during microtunnel shaft break-ins to reduce the potential for groundwater inflow and flowing ground.

East Side CSO Project (2011)

The East Side CSO Project, which is the largest project in the Willamette River CSO Program, is currently under construction along the east side of the Willamette River. The 8,918-m (29,260-ft) long, 6.7-m (22-ft) diameter tunnel extends from southeast Portland to the Swan Island Pump Station. Five microtunneled outfall diversion pipelines, ranging from 76.2 to 914.4 m (250 to 3,000 ft) long, convey CSO flows into the main tunnel. Seven shafts have been built along the tunnel alignment, which extends up to 51.8 m (170 ft) below the ground surface. The shafts permit TBM access at atmospheric conditions and provide drop structures for the diversion pipelines. Tunneling is being conducted in two directions from the Opera Shaft using a single 7.6-m (25-ft) diameter slurry mixshield TBM. The tunnel is supported by a gasketed, segmented liner of reinforced concrete. To reduce costs, steel fibers are being used to reinforce segments installed within the dense Troutdale Formation, while rebar cages are being used for segment reinforcement through the soft sands and silts and at shaft connections.

Geologic units and ground conditions are similar to those encountered during the construction of the West Side CSO Tunnel. The majority of the main tunnel is located in dense, sometimes cemented Troutdale Formation gravel with sand lenses. Soft silt and sand Quaternary Alluvium was encountered in ancient river and stream channels that cut across the alignment. Open gravel, cobbles, and boulders in the coarse-grained Catastrophic Flood Deposits were encountered in the Opera Shaft excavation and along a segment at the north end of the tunnel alignment. The tunnel and shaft flooded, and ground loss occurred during the breakout of the Opera Shaft at the start of tunneling. The TBM was damaged, and construction was delayed. To mitigate against future groundwater inflows and ground loss, intermediate tunneling shafts are flooded prior to TBM break-in.

Buried obstructions, including timber piles, abandoned building and bridge foundations, rip rap, and logs were identified and baselined during project design. Ground penetrating radar was used during design to locate deep steel piles supporting the Interstate 5/Interstate 84 interchange within an ancient channel. The main tunnel was realigned when a deviating steel pile was detected within the tunnel horizon.

Microtunneling costs were reduced when the owner selected a single pipeline diameter (213 cm [84 in.]) for all outfall diversion pipelines, preventing the need for an additional MTBM. One of the microtunneling drives on the East Side CSO Project won an award as the longest microtunnel drive in the United States (916-m [3,005 ft]). The owner chose to take the risk associated with lengthening the drive to avoid the cost of constructing an intermediate jacking shaft. The drive was successful, even though the MTBM advanced through wood debris, timber piles, and large steel spikes beneath a railroad yard and historic dock area.

Portsmouth Force Main (2011)

The Portsmouth Force Main, which is currently under construction, is part of the City of Portland’s Willamette River CSO Program. The force main will convey flows through north Portland from the Swan Island Pump Station north to the Portsmouth Tunnel. The project is divided into two segments. Segment 1 is primarily an open-cut pipeline through the Swan Island lowlands, but also includes a microtunneled section. Segment 2 is a tunneled section through the highland bluff that borders the east bank of the Willamette River.

An 899-m (2,950-ft) long, 213-cm (84-in.) diameter microtunnel is under construction through sand fill and soft silt Quaternary Alluvium along the south end of Segment 1. The remainder of the Segment 1 force main will be installed in an open-cut excavation. A 168-cm (66-in.) diameter steel carrier pipe will be installed within the Segment 1 excavations. The Segment 1 microtunnel and shafts were located to avoid large buried obstructions, including a demolished flour mill and three 122-cm (48-in.) diameter, 173.7-m (570-ft) long large drainage pipes. Smaller obstructions, including timber piles, logs, abandoned dredge pipes, and rip rap, have been quantified based on a detailed review of historic maps and photographs.

The 1,783-m (5,850-ft) long Segment 2 tunnel extends up to 42.7-m (140 ft) deep through sandy Catastrophic Glacial Flood Deposits and Troutdale Formation gravel between the south portal shaft and the north connection shaft. A 264-cm (104-in.) diameter TBM run in open mode above groundwater is being used to excavate Segment 2 through potentially raveling ground. Temporary support consists of steel ribs and timber lagging. A 168-cm (66-in.) Hobas carrier pipe will be installed following tunnel excavation. Although extensive research was conducted to identify Segment 2 buried obstructions, unidentified cobbles and boulders were encountered beneath the bluff slope at the start of tunneling. At the time of this paper, this has resulted in project time loss due to boulder removal complicated by soft sands flooding the machine face.

Balch Consolidation Conduit (2011)

The Balch Consolidation Conduit is currently under construction in the industrial Guilds Lake area of northwest Portland. The conduit will convey sewer and stormwater flows from the Guilds Lake area into the West Side CSO Tunnel. The conduit crosses beneath historic Guilds Lake and the site of the 1905 World's Fair. After the fair, the lake was filled and an incinerator was constructed to burn Portland's trash.

The project consists of a 1,951-m (6,400-ft) long, 213-cm (84-in.) diameter microtunnel through fill, soft silt lake deposits (Quaternary Alluvium), open gravel, cobbles, and boulders (Catastrophic Glacial Flood Deposits), and Troutdale Formation gravel. Shafts are located to avoid buried obstructions and contamination associated with the incinerator site. The contractor is installing a soil mix wall for shaft support using a cutter soil mixing (CSM) machine. A slurry MTBM was selected to facilitate tunneling through open gravel, cobbles, and boulders. Based on experience with the West Side CSO Project, an airlock has been installed in the project's MTBM to permit access to the face for obstruction removal. A secondary steering joint has also been installed for better steering control in the soft silt lake deposits.

CONCLUSIONS

Portland's long history of tunnel projects has produced innovations in tunneling, microtunneling, and shaft construction that have benefited the tunneling industry. These innovations have been developed to handle the unique and diverse geology and ground conditions encountered in the Portland area. Although Portland's large Willamette River CSO Program tunneling projects will be completed by 2011, future projects will continue Portland's tunneling tradition.

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Table 1: Summary of 100 years of Portland tunnel projects

Tunnel Name (Purpose)	ID #	Year Completed[1]	Length	Diameter	Ground Type	Method	Current Owner	Contractor	Construction Cost (Millions)
Peninsula Tunnel (Freight rail)	1	1911 (tunneling started in 1909)	1,658 m (5,438 ft)	6.9 m (22.5 ft) high (ID) 4.9 m (16 ft) wide (ID)	Soft ground (no groundwater)	Steel ribs and timber spiling were placed over ribs and breast boards. Finished as a concrete-lined horseshoe.	UPRR		$0.8
Elk Rock Tunnel (Passenger rail)	2	1921	425 m (1,395 ft)	7 m (23 ft) high (ID) 5.5 m (18 ft) wide (ID) horseshoe tunnel	Hard rock	Drill and shoot	City of Portland	Southern Pacific	Unknown
<u>Multnomah County Highway Tunnels</u> Rocky Butte, West Burnside, and NW Cornell Road Tunnels	3	1939, 1940, 1941	70 to 152 m (230 to 500 ft)	8.2 m to 9.6 (27 to 31.5 ft) wide (ID)	Hard rock, soft rock, and soft ground.	Mixture of hand dug and drill and shoot. Reinforced CIP lining constructed with special traveling slip forms. WPA masonry portals.	City of Portland	WPA laborers and Ralph Curcio (masonry)	$0.5 (Rocky Butte Tunnel)
Peninsular Tunnel (Sewer)	4	1950	5,060 m (16,600 ft)	2,438 mm (96 in.) (ID) horseshoe tunnel	Soft ground (no significant groundwater)	Excavated using breastboards, rib and board support, CIP concrete lining.	BES	NA	NA
Portsmouth Tunnel (Sewer)	5	1967	2,179 m (7,149 ft)	2.4 m (8 ft) (OD), 1.8 m (6 ft) (ID)	Soft ground (no groundwater)	Horseshoe open-face pneumatic shield, with steel sets and wood lagging, CIP concrete liner.	BES	NA	NA
Vista Ridge Tunnel (Highway)	6	1969–1970	EB: 305 m (1,000 ft) WB: 151 m (494 ft) (curved)	4.8 m (15.6 ft) high (ID) 12.5 (41 ft) wide (ID)	Hard rock	Drill and shoot (assumed)	ODOT	Coat Contractors (pilot tunnel), Donald M. Drake and Winston Brothers (main bores)	$4.2 (EB) $3.7 (WB)

Tunnel Name (Purpose)	ID #	Year Completed[1]	Length	Diameter	Ground Type	Method	Current Owner	Contractor	Construction Cost (Millions)
Southeast Relieving Interceptor—Phases 2 through 4 (Sewer)	7	1980s	5,547 m (18,200 ft) (total length of tunneled section in Phases 2 through 4)	1,981–2,591 mm (78–102 in.) (ID).	Soft ground (with and without groundwater)	3.7 m (12 ft) diameter open face shield, circular rib & board support, CIP concrete lining (Phases 2 and 4). 2,896 mm (114 in.) diameter close-faced shield, circular rib & board support, RCP final lining (Phase 3).	BES	Dick Schumann (Phase 2 and 4) Frank Coluccio Construction Co. (Phase 3)	$25 (includes open cut work)
Westside Light Rail Transit Tunnel (Light rail)	8	1994 and 1996	4,542 m (14,900 ft) (twin tunnels)	6.4 m (21 ft)	Hard rock and soft ground (groundwater)	Hard Rock TBM (modified), drill and shoot	TRIMET	Frontier, Kemper/Traylor Brothers	$190
Columbia Slough Consolidation Conduit - Segment 2 (CSO)	9	2000	2,548 (8,360 ft)	4.6 m (15 ft) (OD) 3.7 m (12 ft) (ID)	Soft ground (no groundwater)	4,597 mm (181 in.) wheel EPB TBM (mixed face—modified for erecting ribs and lagging) CIP reinforced concrete final liner	BES	Frank Coluccio Construction Co. (Phase 3)	$25.5
Tanner Creek Stream Diversion Project, Phases 2 and 5 (Stormwater)	10	2002	1,158 m (3,800 ft) (Phase II) 457 m (1,500 ft) (Phase 5)	2,261 mm (89 in.) (OD) 1,829 mm (72 in.) (ID)	Soft ground (groundwater)	Slurry MTBM with RCP	BES	Robison Construction Inc.	$13
WSCSO Program WSCSO Tunnel, SWPI Segment 3, Peninsular Force Main, and Tanner Extension (CSO[2])	11	2006	6,706 m (22,000 ft) (tunnel) 2,246 m (7,370 ft) (SWPI) 997 m (3,270 ft) (PFM) 421 (1,380 ft) (TE)	4.3 m (14 ft) (tunnel) 2,134 & 1,829 mm (84 in. & 72 in.) (SWPI) 2,438 mm (96 in.) (PFM) 1,829 mm (72 in.) (TE)	Soft ground (groundwater)	Slurry TBM with one pass segmental liner MTBM with RCP (SWPI & TE) Steel casing with carrier pipe (PFM)	BES	Impregilo/Healy Joint Venture	$80 (main tunnel) $50 (micro-tunnels) $70 (shafts) $105 pump station (shaft)

Tunnel Name (Purpose)	ID #	Year Completed[1]	Length	Diameter	Ground Type	Method	Current Owner	Contractor	Construction Cost (Millions)
ESCSO Program ESCSO main tunnel with connected Outfall 28, 37 and 38, 40, 41, and 46 diversion pipelines. (CSO)	12	2011[1]	8,918 m (29,260 ft) (tunnel) 76 to 914 m (250 to 3,000 ft) (pipelines)	7.6 m (25 ft) (OD), 6.7 m (22 ft) (ID) main tunnel Five 2,134 mm (84-in.) (ID) microtunnels	Soft ground (groundwater)	Slurry TBM with one pass segmental liner, MTBM with RCP, conventional mined connection through frozen ground	BES	Kiewit/ Bilfinger Berger	$220 (main tunnel) $35 (micro-tunnels) $105 (shafts)
Portsmouth FM Project (Segments 1 and 2) (CSO[2])	13	2011[1]	1,782 m (5,848 ft) (Segment 2 tunnel). 899 m (2,950 ft) (Segment 1 microtunnel)	Segment 2: 2,642 mm (104 in.) (OD) circular tunnel Segment 1: 2,134 mm (84 in.) (OD) microtunnel. Both segments: 1,676 mm (66 in.) (ID).	Soft ground (groundwater)	Segment 2: TBM run in open mode, ribs and boards. Segment 1: slurry MTBM with RCP. Both segments: 1,676 mm (66 in.) (ID) Hobas carrier pipe.	BES	Michels Tunneling (Segment 2). Mountain Cascade, Inc. (Segment 1).	$19.4 (Segment 2) $28 (Segment 1)
Balch Consolidation Conduit (CSO)	14	2011[1]	1,951 m (6,400 ft)	2,134 mm (84 in.) (ID)	Soft ground (groundwater)	Slurry MTBM with RCP	BES	James W. Fowler Co.	$57

[1] Project is currently under construction. Estimated completion date is listed.

[2] Combined Sewer Overflow.