Tunneling in Seattle – A History of Innovation

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ABSTRACT: The terrain and population growth of Seattle has prompted the construction of over 40 cumulative miles of tunnels in the last 110 years. The first tunnels, constructed prior to the turn of the century, were for transporting sewage away from lakes and out to Puget Sound. Subsequently, approximately 100 tunnels have been constructed for sewers, water lines, landslide stabilization, fiber optic lines, railroads, and more recently for transit systems. The evolution of tunneling technology in the Seattle area closely mirrors the various worldwide advances in tunneling technology and methods. Tunnels have progressed from hand-excavated tunnels with timber supports to innovative high-technology, closed-face, shield-driven tunnels utilizing chemical additives for soil stabilization, sophisticated computer systems to monitor machine operating characteristics as well as alignment, and gasketed, bolted and pinned, concrete segmental lining. This paper will provide a historical summary of the advances applied to the art of tunneling in the Seattle area.

1 INTRODUCTION

Development of the Puget Lowland in the Seattle area began in the 1870s. However, growth in the area has been constrained by a series of north-south-trending 200- to 500-foot-high glacially sculpted ridges that separate a series of valleys from Puget Sound. Early on, the City fathers recognized the need to modify the landscape to accommodate the growing population. Consequently, several major earth-moving projects were implemented in the first two decades of the 20th Century to alter the landscape. These included: 1) excavation of the Montlake Cut to join Lake Union to Lake Washington, 2) dredging of the Lake Washington Ship Canal to provide access to Seattle's inland lake system from Puget Sound, 3) Construction of the Hiram Chittendam Locks to preserve water levels in the lakes, 4) regrading portions of the steep ridges by lopping off up to 200 vertical feet and over 50 million cubic yards of soil that obstructed east-west traffic (Morse, 1989), 5) construction of a double-track mile-long railroad tunnel beneath downtown Seattle, and 6) construction of 21 miles of new sewer system (much of it in tunnels) to divert sewage away from inland waterways and out to Puget Sound. By any measure and in any decade of U.S. history, these nearly simultaneous construction projects comprised a monumental undertaking.

By 1900, the population of the Seattle area had grown to over 110,000. While the regrades provided new areas for development and prompted a population explosion in these plateau areas, there still remained numerous north-south ridges, up to 500 feet above sea level. This created a challenge for construction of sewage systems, and led to the installation of numerous raw sewage outfalls to lakes and rivers. By the turn of the last century, it was apparent that improvements were needed in order to allow discharge of sewage to Puget Sound rather than into the lakes. The only way to construct such a system was to build numerous tunnels beneath the major hills and ridges. Therefore, the first tunnels of record in Seattle were sewer tunnels carrying wastewater by gravity to Puget Sound.

Over the last 110 years, more than 100 tunnels totaling over 40 miles of tunneling have been successfully excavated in the Seattle area. These tunnels have been constructed through a wide range of geotechnical conditions, including rock, glacial soils, and non-glacial soils, and used various tunnel construction methods. While the techniques for excavating and supporting tunnels have undergone dramatic changes in these 100 years, the soil conditions that dictated the choice of tunneling methods have remained the same. Consequently, the experiences from local tunnels are pertinent to any construction approach that we might envision for future tunnels. Figure 1 presents a map of

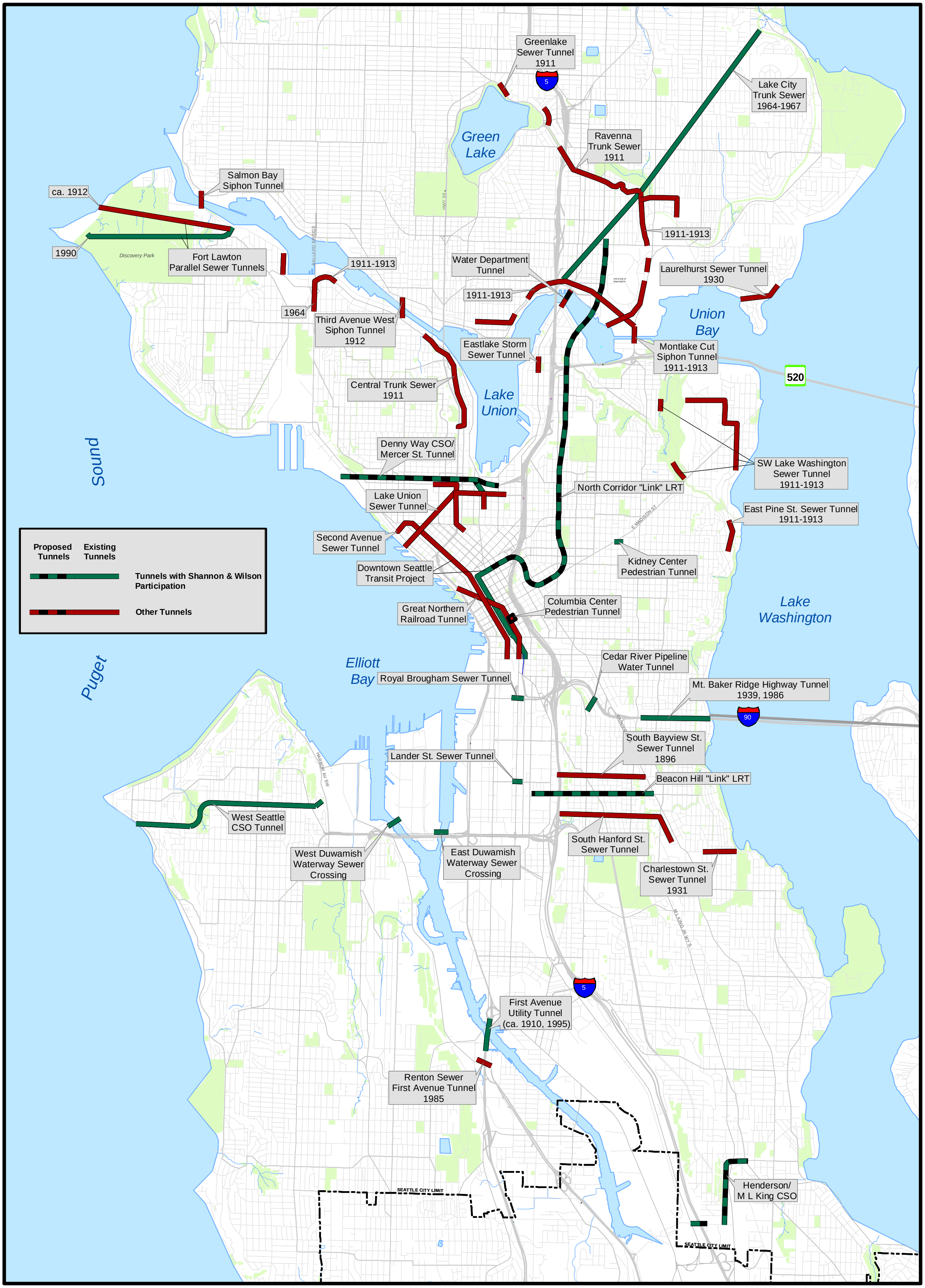

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Figure 1- Selected Seattle Area Tunnel Projects

selected tunnels constructed in the Seattle area. Table 1 presents a partial listing of these tunnels, along with brief discussions of their notable characteristics.

Tunneling technology in Seattle has reflected the development of new methods for soft-ground tunneling in other parts of the world. Early tunnels were hand-mined with initial timber supports and permanent linings of brick (e.g., Lake Union Sewer Tunnel, 1894). Early in the 20th Century, tunnels were constructed under compressed air (North Trunk Sewer, 1910). Beginning in the 1950s, more sophisticated technologies came into use and were applied to Seattle Tunnels as exemplified by:

- Silicate grouting (Ravenna Trunk Sewer Tunnel, 1957)
- Digger shield (2nd Avenue Sewer Tunnel, 1967)
- Stacked-drift compression ring liner (Mt. Baker Ridge Highway Tunnel, 1986)
- Waterproofing membranes (Seattle Bus Tunnel, 1987)
- Slurry pressure micro-tunneling (First Avenue Utilidor, 1995)
- Ground freezing for shaft construction (First Avenue Utilidor, 1995)
- Gasketed segmental linings (West Seattle Sewer Tunnel, 1995)
- Horizontal directional drilling (Henderson/M. L. King CSO explorations, 2001)
- Earth pressure balance machine (Denny Way/Lake Union CSO, 2002)

2 GEOLOGIC FRAMEWORK FOR TUNNELING

The geologic conditions of Seattle are highly variable and have had a major impact on the selection of construction methods and the ultimate success or failure of all tunnel projects in the Seattle area. While the techniques for excavating and supporting tunnels have undergone dramatic changes in the past 110 years, the soil conditions that dictated the choice of tunneling methods have remained the same. The geology of Seattle consists of: recent river, lake, beach, and landslide deposits; glacially overridden, very hard to dense interbedded glacial and interglacial sediments; and sedimentary and igneous bedrock.

3 REGIONAL GEOLOGY

Seattle is located in the central portion of the Puget Sound Lowland, an elongated topographic and structural depression bordered by the Cascade Mountains on the east and the Puget Sound on the west. The Lowland is characterized by low-rolling relief with deeply cut ravines, river valleys, and lakes. In general, the ground surface elevation is within 500 feet of sea level.

The Puget Lowland was filled to significant depths by glacial and non-glacial sediments during the Pleistocene Epoch (2 million years ago to about 10,000 years ago); however, bedrock does outcrop at scattered locations throughout the area. Within the Puget Sound Lowland, bedrock outcrops are found south of an east-west line extending from Bellevue and Issaquah along the south side of Lake Sammamish, westward through the middle of Mercer Island and Lake Washington, on through downtown Seattle (along Interstate 90 and beneath the new baseball and football stadiums) and across Puget Sound to Bremerton. Within the last 15 years, this anomaly has been identified as the active Seattle-Bremerton Fault (Blakely, 2002). Outcrops of sedimentary and igneous bedrock are present at numerous locations in the Seattle area south of this fault. North of the Seattle-Bremerton Fault, the bedrock is buried over 3,000 feet deep beneath Pleistocene and Recent Sediments.

Geologists have generally agreed that the Puget Sound area was subjected to six or more major glaciations during the Pleistocene Epoch. Ice for these glacial events originated in the coastal mountains and the Vancouver Range of British Columbia. The maximum southward advance of the ice was about halfway between Olympia and Centralia. Ice thickness in the Seattle area may have exceeded 1 mile.

3.1 *Primary Soil Units*

The Pleistocene stratigraphic record in the central portion of the Puget Lowland is a complex sequence of glacially-derived and interglacial sediments. Partial erosion of some older deposits, followed by local deposition of more recent sediments, further complicates the geologic setting.

Explorations for several tunnel projects, such as the West Seattle/Alki Combined Sewer Overflow (CSO) Tunnel, Denny Way/Lake Union CSO (Mercer Street Tunnel), West Point Treatment Plant/Fort Lawton Sewer Tunnel, Mt Baker Ridge Highway Tunnel, Downtown Seattle Transit Project (Bus Tunnels) and current Sound Transit “Link” Light Rail Project, have all contributed greatly to our understanding of geology in the Seattle area. All indicate that much of the Puget Basin is filled to a considerable depth by glacially overridden dense to hard soils. These soils were deposited variously by several glacial advances and by streams or rivers and in lakes during intervals between glacial advances. Many of the ridges and hills have cores of older glacial and interglacial soils, extending back hundreds of thousands of years that have been

Table 1: Selected Puget Area Tunnel Experience

Tunnel	Date Done	Size	Length	Excavation Method	Support Method	Salient Features
Lake Union Sewer Tunnel	1894	72 in. I.D.	5,736 ft	Hand, wheelbarrows	Square Timber Sets-~9 ft square	Pump 200 to 300 gpm in sands. Only drilled borings in east half
South Bayview St. Tunnel	1894	~4'wide by 6' high ID	4,526 ft	Hand, wheelbarrows	Timber ribs, lagging, brick	263 ft shaft for ventilation by horse driven fan.
Great Northern RR Tunnel	1903 - 1905	38-ft by 38-ft O.D. horseshoe shape	5,141 ft	Multiple 10 to 15 ft drifts, hand excavated	Timber followed by brick	Severe local settlements up to 3 ft. damaging overlying new city library
Oregon and Washington RR (UPRR)	1907	38-ft by 38-ft O.D. horseshoe shape	900 ft	Multiple 10 to 15 ft drifts, hand excavated	Timber followed by concrete	Never completed - backfilled in 1921 and 1922 after a collapse at Yesler Way
1st Ave. Utilidor Tunnel	1910	~8' (est)	300 ft (est)	Compressed air, hand, wheelbarrows	Steel liner, concrete	Blowouts (air loss), several deaths,
4th and Connecticut Ave. Sewer (North Trunk)	1910	3-ft increasing to 6-ft I.D.	7,060 ft	Supported Trench	Reinforced concrete on timber piles	New sewers needed after reclamation of industrial area, and Denny regrade
Ravenna Sewer Tunnel (North Trunk)	1910	originally 80 in. relined to 66 in.	2,875 ft	Hand, wheelbarrows, rail cars, compressed air. Tried tunnel boring machine	Brick relined with pipe	Failed in Nov. 1957, 3500' steel lined, 16,000 cy fill, chemical grouting
Wallingford Tunnel (North Trunk)	early 1900s	9 ft I.D.	1,803 ft	Open cut and tunneling methods	Timber followed by concrete invert and brick arch	
Pacific St Tunnel (North Trunk)	early 1900s	9 ft I.D.	11,325 ft	Open cut and tunneling methods	Initial timber; final concrete & brick	
Lander St. Sewer	1910	4.5-ft to 9-ft I.D.	5,290 ft	Supported Trench,	reinforced concrete on timber piles	Connects to a sewer tunnel that runs eastward
Fort Lawton Tunnel (North Trunk)	1911	10 ft I.D.	9,720 ft	Hand, wheelbarrows, rail	Timber followed by concrete invert and brick arch	200 ft deep in hard clays
Montlake Siphon Tunnel (North Trunk)	1911	4 ft I.D.	2,005 ft	Hand, wheelbarrows	Timber ribs, lagging, brick	Dry Tunnel beneath Montlake Cut
Dexter and 8th Ave Tunnel (North Trunk)	1912	5 ft I.D.	9,315 ft	Hand, wheelbarrows	Timber ribs, lagging, brick	
Washington Park Tunnels (North Trunk)	1912	5 ft I.D.	4,052 ft	Hand, wheelbarrows	Timber ribs, lagging, brick	
Third Ave. West Siphon Tunnel (North Trunk)	1913	21 ft OD, 13 ft ID with twin 60 in. cast iron pipes	500 ft	Hand, wheelbarrows	Timber ribs, lagging, brick	Beneath Washington Ship Canal
Jackson St. Drainage Tunnel	1926	4 ft by 6 ft	1,500 ft	Hand tools, wheelbarrows, 35 psi compressed air	Timber ribs, lagging, brick	Drain wet ground along Washington

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South Hanford St. Tunnel	1930	9 ft. I.D.	6,055 ft	Hand, wheelbarrows	Timber followed by concrete	Replaced South Bayside Tunnel
Charleston Street Tunnel	1931	3.5 ft . I.D.	2,830 ft	Hand, wheelbarrows	Timber followed by concrete	130 ft deep
Henderson Trunk Sewer	1936	60 in. I.D. concrete and 48 in. brick	3,000 ft	Hand, wheelbarrows w/ compressed air	Timber followed by brick and concrete	
Laurelhurst Trunk Sewer Tunnel	1936	9 ft I.D.	1,850 ft	Hand, wheelbarrows	Timber followed by brick arch and concrete	130 ft deep
Ballard Sewer Siphon	1937	Twin 36 in I.D.	1,000 ft	Hand, wheelbarrows	Cast Iron Pipe in timber lining	Siphons beneath Lake Washington Ship Canal
SR-20 Mt. Baker Ridge Highway Tunnel	1938 - 1941	twin bores, 28 ft wide by 23 ft	1,330 ft	Stacked drifts, hand excav.	timber ribs, followed with concrete	Failure of column and severe settlement up to 3 ft.
WPA Slide Control Drainage Projects	1934-1942	4'w by 6'h	4,926 ft	Hand, wheelbarrows	Timber ribs	Over 20 tunnels used to drain landslides
Montlake Siphon Tunnel (North Trunk) Replacements	1963	42 in and 108 in. I.D.	586 ft	Hand, wheelbarrows	Steel ribs and lagging, cast in place concrete.	Dry tunnel beneath Montlake Cut
Elliot Bay Interceptor Sect. 6 Tunnel	1965-1966	8 ft I.D. 12.5 ft O.D.	1,750 ft	Shield, spaders	Steel ribs, lagging, cast concrete	Beneath Interbay Golf Course
Lake City Sewer Tunnel	1964 - 1967	8 ft I.D. 11 ft. O.D.	17,570 ft.	Close-face wheel excavator, dewatering, 15 - 30 psi compressed air, sodium silica chemical grouting	Steel ribs, boards, with cast concrete about 1000 ft behind face	1st use of closed-face wheel and sodium silicate grouting. Artesian flow, air loss, face and arch failures. Developed compressed air guidelines
2nd Avenue Sewer Tunnel	1967 - 1968	8.5 ft I.D.12.5 ft O.D.	19,900 ft	Digger shield, compressed air, chemical grout	Steel ribs and lagging, cast in place' concrete	1st use of Robbins digger shield. 3 to 18 psi air pressure.12 to 160 ft of soil cover
University of Washington Utilidors	1960s to present	various 5 ft to 10ft I.D.	50,000 ft	Various, loaders, roadheader, etc.	Timber, steel, shotcrete, cast conc.	Till may be cut by roadheader (like soft rock)
Kidney Center Pedestrian Tunnel	1975	10-ft horseshoe	120 ft	Bobcat Loader	Steel ribs, lagging, cast concrete	Less than 10 ft of glacial till cover

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Tunnel	Date Done	Size	Length	Excavation Method	Support Method	Salient Features
Mt. Baker Ridge I-90 Tunnel	1983-1986	24 stacked drifts (9.5 ft)- 65 ft I.D.	1,330 ft	Digger Shields	Expanded Concrete Segments with Mass Concrete Backfill	Largest diameter soil tunnel in the world
Beacon Hill Waterline, Cedar River Pipeline	1984	12 ft diam.	150 ft	Loader, pneumatic spaders	Shaft w/ shotcrete and ribs, tunnel with liner plate followed by cast concrete	Excavated down 12% grade through ancient landslide beneath I-90
Columbia Center Pedestrian Tunnel	1985	14 ft diameter horseshoe	280 ft	Loader, pneumatic spaders	Steel ribs and shotcrete	First use of shotcrete for tunnel liner in Seattle
Virginia Mason Hospital Pedestrian	1985	10-ft horseshoe	120 ft	Bobcat Loader	Steel ribs, lagging, cast concrete	Less than 10 ft of glacial till cover
Renton Sewer Tunnels ETS-4A	1986	8 ft. I.D. 12 ft O.D.	2,403 ft	Drill and shoot	Rock bolts, steel ribs, lagging, grouted pipe	40 ft below Interstate 5
ETS-4B	1986	8 ft. I.D. 12 ft O.D.	620 ft	Digger Shield	Steel ribs, lagging, filter cloth	400 ft crossing under Interurban Ave. S. and 240 ft crossing under E. Marginal Way. S
ETS-5	1986	8 ft. I.D. 12 ft O.D.	1,820 ft	Drill and shoot	Rock bolts, steel ribs, lagging, grouted pipe	Beneath Pacfic Highway and W. Marginal Way
ETS-6	1986	8 ft. I.D. 12 ft O.D.	1,056 ft	Partial EPBM (flood doors, pressure relieving gate, no auger, no soils conditioners	Steel Ribs and Lagging w/ grouted pipe	First Seattle use of EPBM, big settlements forced use of sodium silicate and polyurethane grouts
Downtown Seattle Transit Project (Bus Tunnel)	1987-1988	twin 21.25 ft. O.D.	13,624 ft	Digger Shield, Dewatering, Compaction and Chemical Grouting	Expanded Segments, PVC membrane, Unfreinforced Cast concrete	First use of PVC waterproofing membrane in US
West Point Sewer/ Fort Lawton Parallel Tunnel	1990	12 ft. I.D., 15.5 ft O.D.	8,400 ft.	Lovat partial EPBM with backloading cutters, flood doors, pressure relieving gates, muck ring and triple brush tail seals	Steel ribs and lagging with filter fabric, short sections of gasketed steel liner plate, final cast-in-place concrete	TBM never converted to full EPBM. 2 short shutdowns for methane. Best advance rates of 109 ft/shift, 217 ft/day, 797ft/week
Royal Brougham St. Sewer Tunnel	1993	8 ft I.D. 10 ft O.D.	300 ft	Pipe Jacking with well point drainage	Reinforced concrete pipe	Jacked beneath active BNSF RR tracks
Lake Washington Canal Siphon	1993	3.3 ft O.D.	1,518 ft	Iseki Unclemole slurry pressure microtunnel, 13 in. boulders capacity	3.2 ft steel pipe in 10 ft lengths with welded joints	596 ft at 12 deg. down, and 218 ft at 29 deg. down. First Slurry Microtunnel in Seattle
Lander St. Sewer Tunnel	1995	8 ft I.D. 10 ft O.D.	130 ft	Pipe Jacking with well point drainage	Reinforced concrete pipe	Jacked beneath active BNSF RR tracks

Table 1: Selected Puget Area Tunnel Experience

Tunnel	Date Done	Size	Length	Excavation Method	Support Method	Salient Features
1st Avenue Utilidor Tunnel	1995	10-ft O.D.	~500 ft	Microtunneling, frozen shafts	Reinforced concrete pipe	Difficulties sealing one of frozen shafts
West Seattle/Alki Sewer Tunnel	1995-1997	13 ft. O.D.	10,500 ft	Partial EPBM with belt conveyor	Bolted, gasketed concrete segment	First use of polymer conditioners in Seattle
Eastlake Storm Sewer	1997	3.5 ft O.D.	475 ft.	Slurry microtunneling	Jacked concrete pipe	Tunnel alignment 19.3 ft off course
Justice Center Tunnel	2001	15 ft horseshoe	200 ft	Loader and pneumatic spaders	Sodium silicate grouting, ribs and lagging, CIP concrete	Excavated through logs and debris from old "skid road" log flume
Denny CSO/Mercer St. Tunnel	2002	14.7 ft I.D. 16.8 ft O.D. storage tunnel	6,212 ft.	EPBM w/ conditioners	Bolted, gasketed concrete segment	First complete EPBM in Seattle. Alignment within + 6 in. Average advancement at 40 ft per 10 hr shift
	2001			Microtunnel	Jacked concrete pipe	Jacked beneath BNSF RR tracks through sand fill and rock riprap
Henderson CSO Tunnel	2002	14.7 ft I.D. 16.8 ft O.D.	3,105 ft	EPBM w/ conditioners	Bolted, gasketed concrete segment	Storage Tunnel
	2002	3 ft I.D.	260 ft	Microtunneling	Gasketed concrete pipe	
	2002	6 ft I.D.	740 ft	Microtunneling	Gasketed concrete pipe	
	2002	6 ft I.D.	700 ft	Microtunneling	Gasketed concrete pipe	
	2002	6 ft I.D.	185 ft	Microtunneling	Gasketed concrete pipe	Explored conditions with HDD and tomography under I-5 and railroad

successively incised and mantled by more recent deposits.

The most recent geologic map (Galster and Laprade, 1991) of surface exposures indicates that between the north end of Lake Washington and Puget Sound, the surficial soils are primarily dense to hard, Vashon-age (13,000 to 15,000 years old), glacial till and sandy glacial outwash. Our recent work on the Alki Sewer Tunnel, Mercer Street Tunnel, and "Link" Light Rail Transit (LRT) indicates that Seattle geology is much more complex and varied than envisioned 20 years ago.

Glacial Till - The till (locally known as hardpan) is a gravelly, silty to clayey sand with cobbles and scattered boulders. Unweathered till will stand in near-vertical bluffs up to about 70 feet high and may have strength characteristics equivalent to that of very soft rock or lean concrete. Consequently, tunnel contractors have used a variety of soft rock excavation techniques, including heavy-duty toothed rippers, roadheaders, disc cutters on soil tunnel boring machines, and even light blasting.

Glacial Recessional and Advance Outwash – The outwash sand generally consists of dense to very dense, clean to silty, fine to medium sand with traces and lenses of coarse sand, gravel, and cobbles. Where outwash soils are saturated, they yield large amounts of groundwater, and have been used as water sources. Saturated outwash sands will tend to flow as a viscous liquid unless dewatered prior to tunneling or stabilized during the tunneling process.

Glaciolacustrine Clay – Over-consolidated, hard clay and clayey silt soils underlie much of Seattle, interbedded with various outwash sands and till-like units. These clay units have been a major soil component in many of the tunnels in Seattle. The clays make one of the best tunneling medias in Seattle; they tend to be relatively dry, and contain only scattered cobbles and boulders. Thin seams or lenses of sand and gravel may provide small quantities of seepage when encountered in a tunnel heading. However, the brittle and fractured nature of this silt and clay soil unit often presents challenges to tunneling, depending on the localized extent of fracturing as well as the size of the opening being considered.

Glaciomarine Drift – This is a mix of glacially derived debris consisting of a clay and silt matrix with variable quantities of sand, gravel and boulders deposited in a marine environment. This over-consolidated soil type spans the gamut of characteristics from glaciolacustrine clay to till. Due to the variability of this soil unit, it may require both soil and soft rock excavation techniques.

Interglacial Deposits – Lacustrine and fluvial clay, silt, sand, peat, and gravel layers are interspersed between the various glacial units. Because these soil units have also been glacially overridden, they are of a hard to very dense consistency.

3.2 *Geotechnical Issues*

The following paragraphs discuss subsurface conditions, associated with the soil units discussed in the previous few paragraphs that have proven to have a significant impact on the selection of tunneling methods and the likelihood of success of tunnel construction in the Seattle area.

Boulders and Cobbles – Most of these soil units are likely to contain scattered cobbles (3 to 12 inches in diameter) and boulders (greater than 12 inches in diameter) of varying diameters and concentrations. The highest percentages of boulders are likely to occur in the till, glaciomarine drift, and glacial outwash units. Boulders and cobbles also occur as dropstones in the glaciolacustine silts and clays. Boulders tend to be concentrated along contacts between soil units. Most boulders encountered on prior tunnel projects were in the 1- to 3-foot-diameter range. However, a few boulders ranging from 3 to 10 feet in diameter were encountered in the Bus Tunnels and Mt. Baker Ridge Tunnel. The Chambers Creek Sewer Tunnel near Tacoma encountered so many boulders in a till unit that the tunnel boring machine (TBM) (a rotating wheel cutter in a shield) was unable to excavate or displace them. Subsequently, a shaft was excavated so that the TBM could be removed and replaced with an open-face shield enclosing a hydraulic digger, which provided better access for breaking up and removing the boulders.

In the glacial deposits, the cobbles and boulders were carried in by advancing ice from Canada and the Cascades. Consequently, these cobbles and boulders, as well as the smaller gravel and sand-sized granular material, have very high unconfined compressive strengths, generally ranging from 20,000 to more than 40,000 pounds per square inch (psi). These high strengths make these materials difficult to break up with conventional soil excavation equipment, and make them highly abrasive to tunnel excavation and muck handling equipment.

In glacial tills or glaciomarine drift, the cobbles and boulders may account for an estimated 2 to 10 percent of the unit. In glaciolacustrine clays and outwash sands, these coarse materials may account for an estimated 2 percent or less of the excavated volume. Non-glacial units may also contain cobbles and boulders, many of which have eroded out of the glacial soils.

Most TBMs can be sized to handle large cobbles or small boulders (up to 2-foot-diameter) by using rock

crushers or large enough openings in the cutterhead and conveyor system to transport these boulders. Boulders can purportedly be handled with disc cutters mounted on the cutterhead. However, there is a definite risk that some large hard boulders could remain in front of the tunneling machine, causing overexcavation and possibly excessive surface settlement. These large resistant boulders will have to be cut up and removed, which will require personnel access to the face. This may require the use of compressed air and/or grouting to stabilize wet sandy or silty soils in order to permit safe access.

Buried Logs – Logs embedded in soil deposits have been encountered by several tunnels in the Seattle area. Records of construction for the Great Northern Railroad Tunnel beneath downtown Seattle mention the presence of a "buried forest" in interglacial soil deposits. Where these logs occur in older Pleistocene deposits, they are often decayed sufficiently so that they can be readily cut up by an advancing tunnel boring machine. However, they may still foul or clog filter screens and pumps in a slurry boring machine or horizontal directional drill. A microtunnel constructed beneath the Duwamish River as part of the West Seattle Sewer Tunnel Project encountered logs that were sufficiently decayed that they turned to wood chips during excavation and only proved to be a nuisance in the mud tanks and slurry filtering system.

Where the logs are embedded in more recent alluvial, fluvial, or beach deposits, they may still be relatively fresh and provide a major impediment to tunnel advance. Several microtunnel projects and horizontal directional drilling projects have been seriously delayed or stopped by the presence of nearly fresh buried logs. A TBM tends to tear off long strips of wood from these logs, which may clog the boring machine head. In a slurry-based tunneling system, these long strips of wood will tend to clog the slurry lines, filters, and pumps.

Man-made Obstacles – Man-made obstacles that may be encountered during tunneling include temporary tiebacks for building shoring, steel and timber piles, riprap armored old shorelines, random fill in man-made embankments, well casings, sunken logs, and steel cable associated with logging mills and other industrial facilities and other man-made debris. These objects can pose serious impediments to tunneling, unless they are anticipated and planned for. The Bus Tunnels encountered several hundred abandoned temporary steel tiebacks that had to be cut off as each was encountered beneath Third Avenue in downtown Seattle. As with most obstacles, the real challenge was in anticipating their presence and then in controlling and stabilizing the soils while exposing the tiebacks. Also, the original construction of the tiebacks had disturbed the outwash sands, in some cases to such an extent that large and damaging surface settlements occurred when the soils were further disturbed by tunneling. Several local tunnels have encountered timber piles or logs from sawmills that have drastically slowed advance, and in some instances required the excavation of a shaft to rescue and repair the tunnel machine. Most of these obstacles can be predicted based on a careful historical research of the alignment.

Abrupt and Irregular Soil Contacts - In general, the contacts between the various glacial and non-glacial soil units tend to be relatively abrupt and non-horizontal. Consequently, tunnel excavations may encounter a mixed-face condition as they pass abruptly from wet flowing outwash sands into relatively dry, very hard glacial till or hard glaciolacustrine clays. Typically, the contacts between various units are undulating and non-planer due to the erosive processes that contributed to the deposition of each successive layer. The undulations will tend to trap or hold groundwater, making complete dewatering of a wet sandy unit overlying a till-like or clay unit, very difficult to impossible. Consequently, tunneling equipment must be designed to accommodate a wide range of soil and groundwater conditions, as well as abrupt transitions from one type of soil to another. In particular, mixed-face tunneling, where a looser or wetter soil overlies a harder unit, can make tunnel machine alignment control difficult, and may aggravate ground losses and resulting surface settlements. Careful explorations can provide a degree of predictability for these contacts.

Perched Groundwater Levels - Due to several magnitudes of variation in permeabilities for the various soil units, and the complex interlayering of the many soil units that have been observed in the Puget Sound Lowlands, it is common to encounter wet silt and sand units located above, below or interbedded with much less permeable clay and till-like units. Consequently, tunnels rarely are excavated completely in dry soils, but almost always are excavated at least partially in wet, flowing soils. Such was the case for the Bus Tunnels and the West Seattle Sewer Tunnel. The Bus Tunnels used dewatering systems and chemical grouting to reduce groundwater and soil inflows. The West Seattle Sewer Tunnel used dewatering at the portals and a closed-face tunneling machine with soil conditioning additives to control groundwater inflows.

Highly Permeable Sands and Gravels – Numerous wells in the Puget Sound Lowlands were drilled to tap groundwater from the various glacial outwash, interglacial, and recent alluvial sand layers. Flows from these wells are generally very high, on the order of several hundred gallons per minute. Similar sand and silt units have required either major dewatering pro-

grams (Bus Tunnels) and/or caused significant delays where the water was either unanticipated or not sufficiently dewatered (Lake Union Sewer Tunnel and Lake City Trunk Sewer Tunnel).

Fractured to Sheared Clays – Stress induced fracturing and shearing have been noted in pre-Vashon age glaciolacustrine clays and glaciomarine drift in several projects in the Puget Lowlands (Mt. Baker Ridge Tunnel, Bus Tunnels, and pending Link LRT Tunnel). The fractures and shear zones cause these very hard soils to behave more like a fractured soft rock than soils. Excavations for the Bus Tunnels and Mt. Baker Ridge Tunnel experienced some slabbing and isolated wedge failures. Fracturing or shearing of the clays is generally only a potential problem when using open-faced tunneling methods.

Methane – Methane gas has been encountered in borings and several tunnel projects throughout the Puget Sound Lowland (Lake City Trunk Sewer Tunnel, West Seattle Sewer Tunnel, Fort Lawton Sewer Tunnel, and pending Link LRT Tunnels). In most cases the methane inflows were controlled with normal tunnel ventilation and were minimized with single-pass bolted and gasketed lining systems and closed-face tunnel boring machines. Most recent tunnels in the Seattle area have been classified as “potentially gassy” based on exploration data and in accord with Occupational Safety & Health Administration (OSHA) standards. This OSHA classification requires numerous gas monitoring sensors, appropriate lighting and electrical systems, increased ventilation and automatic shutdowns of tunnel equipment in the event that significant methane is encountered. The Fort Lawton Sewer Tunnel and the West Seattle Sewer Tunnel both experienced a few brief gas-related shutdowns, which generally lasted less than a few hours, until the tunnel was adequately ventilated.

4 TUNNELING IN THE SEATTLE AREA

About 100 or more tunnels have been constructed in the Seattle area over the last 110 years with a total estimated length of over 40 miles. A partial tabulation of these tunnels is included on Table 1 and known locations of selected tunnels are shown on Figure 1. Not all tunnels are included on the list and map, since historical records are incomplete and not necessarily well organized with regards to tunneling in the Seattle area.

Necessity has indeed proven to be the mother of invention for tunneling in the Seattle area. The hilly topography has generally been the motivation for considering tunneling. Once a tunnel alternative is under consideration, the next step is to evaluate the geologic conditions, including the factors discussed above. As technology has advanced in a wide range of fields, including metallurgy, lasers, computers, hydraulics, concrete additives, etc., there have been creative suppliers, contractors, designers, and owners willing to try new and innovative means and methods of tunnel construction to cope with difficult ground conditions, and speed up the tunneling process. Many of these new developments in tunneling have found application in the Seattle area.

A wide range of tunnel diameters and lengths have been used for a variety of infrastructure applications. By far the largest aggregate length of tunnels to date have been constructed for sewers. Recent government mandates for reductions in weather induced combined sewer overflows into surface waters have fostered a need for new storm and sewer tunnels. However, a fair number of tunnels have also been driven for railroad and highway transportation routes. Recently, small-diameter tunnels have been used for gas pipelines, water lines, feeder sewers, power lines, and fiber-optic cables. Many short tunnels have also been constructed for pedestrian access. Several major projects are planned for the near future that will incorporate significant lengths of tunnels for a light rail system, major sewer expansion, and improved highway transportation alignments.

Tunnel construction methods have included: hand mined and timber supported tunnels; shielded tunnel machines with compressed air and/or dewatering; earth pressure balance tunnel boring machines; gasketed, bolted and pinned concrete segmental lining; slurry pressure balance tunnel machines with jacked pipe; a wide range of augered pipe jack and microtunnel systems; and most recently horizontal directional drilling techniques for a variety of conduits and pipelines up to 4 feet in diameter and over 2,000 feet long.

5 SELECTED TUNNELS FROM 1890 TO 1950

Tunnels constructed prior to about 1950 were generally excavated using mechanical means (such as shovels and hand spades, pneumatic spaders, steam shovels, and front-end loaders) without the benefit of a protective shield. Many of the earliest tunnels were excavated with pick and shovel, and the muck removed with wheelbarrows or by rail mounted cars pushed by men, pulled by mules, or hauled by electric or diesel locomotives. Ventilation, if used, was powered by mules or horses at ground surface. Dewatering was accomplished with pipes driven into the tunnel heading. Initial support was provided with timber or steel ribs, timber lagging, steel rail or timber spiling and forepoling. Final support was provided with a lining of brick and/or concrete.

Lake Union Sewer Tunnel – The earliest known record of a tunnel in Seattle is the Lake Union Sewer

Tunnel, constructed over a period of several years and by several contractors in the 1880s and 1890s (City Engineer's Report, 1893). The roughly 8-foot by 8-foot tunnel extended for a length of 5,400 feet from the south end of Lake Union southwestward to Elliott Bay. Excavation was with hand-held spaders and shovels, wheelbarrows, and narrow gage muck cars. A hoist at the center shaft was powered by horses or mules. Excavation support was provided by timber and steel rail forepoling and timber sets, followed by a brick and mortar lining.

The tunnel reportedly passed through saturated outwash sands, till, glaciolacustrine clay, and flowing silt. Groundwater inflows were reported to reach over 400,000 gallons per day. One reported roof fall amounted to over 1,400 cubic yards (cy) of soil. In one instance, an abrupt blow-in of the tunnel heading killed one of the miners and injured several others. To counteract these adverse conditions, the contractors employed several techniques: 1) they drove the tunnel from four headings (from the two ends and in both directions from a shaft mid-way along the alignment); 2) they hammered steel pipes into the heading to relieve water pressures; 3) in certain areas they reduced the heading size to as little as 4 feet by 4 feet, which apparently enhanced stability; and 4) they used timber and steel rail spiling hammered out ahead of the advancing face.

North Trunk Sewer – This major sewer construction program was prompted by a typhoid epidemic and fears of a cholera outbreak, caused by contamination of drinking water sources by the discharge of raw sewage directly into the lakes and streams. The project involved about 21.7 miles of new sewers, much of it in tunnel, and constructed at a cost of about $3.5 million (Dunbar, 1911). The project took 6 years to complete, from 1908 to 1914. Construction problems were encountered with swelling or squeezing glaciolacustrine clay, high water flows, and flowing sand in the outwash deposits. Production rates were reported at about 1 cy per worker per day, or 3 to 100 feet per week, using shovels and placing initial timber support and a final brick lining.

One of the unique portions of this project included the 3,500-foot-long Ravenna Trunk Sewer Tunnel driven beneath Ravenna Creek from the present-day site of University Village to Green Lake. Due to the presence of wet flowing fine sand along most of the alignment, construction proved difficult. A shielded boring machine was tried in 1911, well ahead of its time, but did not prove capable or effective in controlling the flow of the saturated sands. In addition it had various mechanical problems. Subsequently, a compressed air lock was installed and the tunnel was hand excavated under an air pressure of 18 to 22 psig. These high air pressures would likely have resulted in numerous cases of the "bends" unless construction shifts were limited to allow for compression time, which seems unlikely. Brick lining was installed close behind the excavated face, in order to minimize air loss. Overall advance rates for the Ravenna Creek Tunnel were reported to be 3 to 100 feet per week, and averaging about 50 feet per week.

Other major tunnels constructed as part of the North Trunk Sewer included: Montlake Boulevard Siphon Tunnel, Fort Lawton (West Point) Sewer Tunnel, Laurelhurst Sewer Tunnel, Fremont (West 3^{rd} Avenue) Siphon Sewer Tunnel, Wallingford Sewer Tunnel, Pacific Street Sewer Tunnel, Lander Street Sewer Tunnel, Dexter Avenue Sewer Tunnel, and Washington Park Sewer Tunnel. All of these tunnels were primarily excavated with pick and shovel in glacially overridden soils and supported with an initial timber lining followed by a brick lining, as shown on Figure 2.

Figure 2 – Brick Lining Being Placed Against Timber Supported Hard Clay Soils of the Fort Lawton Tunnel (photo courtesy of City of Seattle Photo Archive).

In 1957, a portion of the Ravenna Creek Tunnel failed due to piping of sand through joints in the brick lining, which compromised the support for the lining and led to its collapse. The lining collapse led to the formation of a 150-foot-diameter by 50-foot-deep sinkhole. Old tunnel timbers, collapsed brick lining, and 20,000 cy of soil from the sinkhole plugged the tunnel. Removal of the debris plug and reconstruction of the lining required that the soils be stabilized. Stabilization was achieved, in part, with the use of sodium silicate grout. This was the first use of this grouting method in Washington (Morse, 1997). The lining was rebuilt and a steel pipe liner was grouted in place

through distressed portions of the tunnel. About 17,000 cy of backfill was used to fill the sinkhole. Repairs took about 1 year, and included the placement of a temporary pump station and 5,400 feet of steel pipe sewer at ground surface. At the time, this was considered to be one of the most expensive sewer repairs in U.S. history.

Great Northern Railroad Tunnel – Between 1903 and 1905, a double-track railroad tunnel was constructed beneath downtown Seattle through a wide range of glacially overridden soils. About half of this 5,141-foot-long tunnel passes beneath 4th Avenue with a soil cover ranging from 20 feet at the south portal to about 110 feet near mid-point at Spring Street. The tunnel was constructed using the multiple drift method: several small 8- to 15-foot-rectangular openings were excavated and timber-lined; these were combined to form a larger final horseshoe-shaped tunnel opening that was about 30 feet wide by 28 feet high, as shown on Figure 3. The excavated tunnel was supported with cast-in-place concrete about 4 feet thick. No construction records.

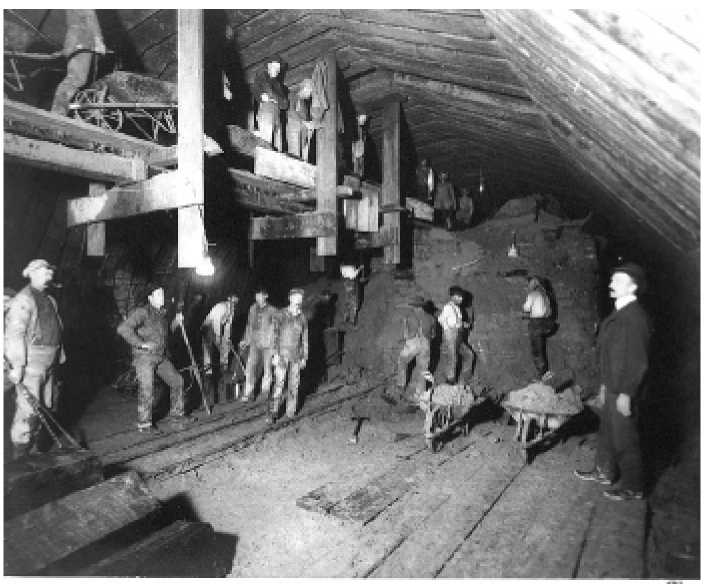

Figure 3 – Excavation of the Upper Heading of the Great Northern Railroad Tunnel Beneath Downtown Seattle (photo courtesy of the University of Washington Photo Archive).

are available for this tunnel, although photos and drawings show the multiple drift methods with a large number of men using shovels and picks, wheelbarrows, and small rail mounted muck cars with electric locomotives. A 1915 lawsuit, involving a new Public Library Building that experienced up to 3 feet of settlement, provides much of the background information. To minimize continued long-term settlements, an adit was excavated over the crown of the tunnel to remove timber blocking that was rotting out and replace it with concrete backfill.

The tunnel was constructed through a wide range of overconsolidated soils including sands and gravels, "blue" clay, and "hardpan" (till) with local large water inflows. In the vicinity of 4th and Marion Street, the tunnel encountered a "prehistoric forest" with one tree measuring over 3 feet in diameter embedded in the blue clay. Sand and gravel units with heavy inflows of water were encountered between Cherry and Marion Streets, and from University to Pike streets.

WPA Slide Control Drainage Tunnels– During the economic depression of the 1930s, the federal government organized a slide stabilization program under the WPA to build drainage trenches and tunnels into selected hillsides to attempt to dewater or at least depressurize landslides and or landslide prone areas. Over a dozen drainage tunnels, ranging in length from 100 to 1,000 feet, were constructed for a cumulative length of nearly a mile. All of these tunnels were hand-mined and timber rib supported to about 4 feet wide by 6 feet high. Most were constructed in glacially overridden soils. Bell and spigot 6-inch and 12-inch pipes were placed in the tunnels, which were then backfilled with gravel and crushed rock.

Mt. Baker Ridge Tunnel – These twin two-lane highway tunnels were constructed in the early 1940s through a ridge of overconsolidated hard glaciolacustrine silt and clay, overlying a dry, clean outwash sand. In response to prior reports of "heavy ground", a stacked-drift method of construction was used in an attempt to control ground loss and reduce surface settlements. The stacked drift method, shown on Figure 4, was constructed using a series of seven roughly rectangular 6 feet by 8 feet drifts braced off a central core of soil. The final concrete liner was cast within the interconnected stacked drifts. The resulting excavation was about 34 feet in diameter and the finished concrete lined tunnel had an inside diameter of about 29 feet.

The fractured condition of the glaciolacustrine clays resulted in high loads on the timber support system. Cave-ins resulted in partial collapse of at least 20 feet of wall drift. Heavy soil loads caused settling of the wall posts and the arch by as much as 8 inches. Locally, the 12-inch by 12-inch timber wall sill plates were crushed down to as little as 2 inches thick. Surface settlements averaged about 12 inches resulting in damage to streets, utilities, and buildings. Excavation for both portals resulted in landslides covering a block or more.

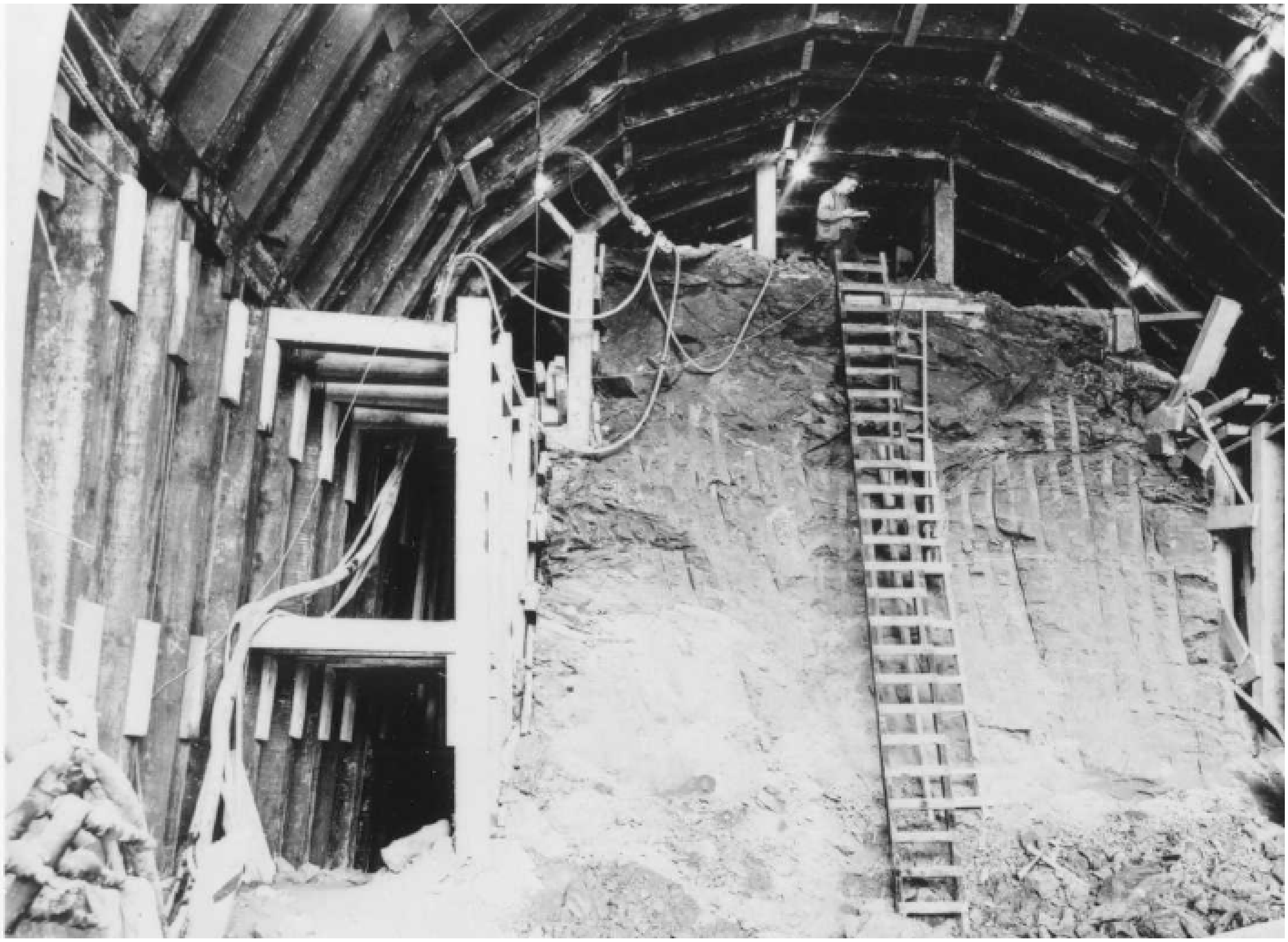

Figure 4 – Construction of Mt. Baker Ridge Tunnel ca. 1940 Using a Stacked Drift Construction Method. (Courtesy of Washington State Department of Transportation.)

6 SELECTED TUNNELS FROM 1950 TO 1980

Over the three decades from 1950 through 1980, numerous advances in the mechanization, safety, and efficiency of tunneling prompted the construction of a number of tunnels that had not previously been considered to be feasible. Movable steel barrels or "shields" were used to protect the workers and support the tunnel face as the tunnel was advanced. TBMs with rotating cutterheads were used more frequently for soil and rock tunnels. Muck was removed by small rail-mounted muck trains pulled by diesel locomotives. Ventilation using fans and metal ducting was carried forward with the advancing tunnel. Safety rules disallowed the use of gasoline powered engines for tunnel construction in order to reduce carbon monoxide concentrations. Due to the increased use of compressed air in tunnel construction, and the attendant increase in related injuries and deaths, new compressed air regulations, implemented on the Lake City Sewer Tunnel discussed below, were adopted as a state and then as a national standard. The following examples of tunnel construction in Seattle over three decades were selected to exemplify the application of some of these advances to Seattle ground conditions.

2nd Avenue Sewer Tunnel – This 12-foot outside-diameter (O.D.) tunnel was constructed for a length of 10,900 feet by Constructors PAMCO in 1968 through glacially overconsolidated sands, gravels, clays and tills. PAMCO designed and built a steel shield, with an attached hydraulic backhoe "digger" and hydraulic actuated "breasting" doors.

This unique "digger shield" was subsequently used on a number of tunnels in the northwest, including the Seattle Bus Tunnels, and the patents eventually sold to the Robbins Co. for use around the world. Compressed air pressures of 3 to 6 psig were typically used, however, higher pressures of up to 17 psig were used with the highest pressures in the saturated sands and gravels. Even with these air pressures, groundwater inflows on the order of 30 to 40 gallons per minutes (gpm) were recorded at several locations, and inflows of up to 75 gpm were measured at a few locations. Tunnel support was provided by steel ribs and lagging followed within about 1,000 feet by a cast-in-place

concrete liner to limit air loss. Settlements along the length of the tunnel were generally small to negligible, except at the southern end where the cover was shallow and soils were soft to loose fills. In this area, in the vicinity of Yesler Avenue and King Street, up to 18 inches of settlement occurred.

Lake City Sewer Tunnel – This extremely challenging tunnel was constructed with a one-of-a-kind closed-face wheel excavator, built by the contractors, Kemper Construction Co. and Rocco Ferrera & Co. specifically for this tunnel. The 17,000-foot-long, 11-foot O.D. tunnel trends northeast from the north side of Portage Bay at 7th Avenue E. to Mathews Beach on Lake Washington. A total of 21 borings were used to define the geology and groundwater conditions. At a spacing of about 800 feet, the borings missed two deep sand filled valleys, which caused severe compressed air losses and groundwater inflows. Partial dewatering was accomplished along long stretches of the tunnel in order to reduce compressed air requirements to 15 to 30 psig. Extensive portions of the tunnel were solidified by sodium silica chemical grouting to reduce groundwater inflows. Tunnel support was provided by steel ribs and timber lagging followed by cast-in-place concrete within about 1,000 feet of the advancing tunnel heading to reduce compressed air loss. Methane was encountered at several locations. The compressed air guidelines developed for this project by Jack Smith were eventually adopted by Washington State and ultimately by OSHA.

Seahurst Sewer Tunnel – This is the tunnel that was never built. Explorations for the Renton Effluent Transfer System by Metro in 1982 identified saturated sand and gravel soils at depths of over 200 feet beneath SeaTac airport. At the time, these conditions challenged the capabilities of available tunneling technology. Tunneling methods and equipment had not yet been developed to handle boulder-laden glacial soils and groundwater heads in excess of 100 feet, particularly where dewatering was not feasible. Tunneling under compressed air was not feasible for this tunnel, because water pressures exceeded the 90 feet allowable under OSHA regulations for worker safety. Gasketed segmental concrete liners were just being tried for the first time on the Baltimore Subway to permanently accommodate groundwater pressures. Due to a lack of experience on other projects, use of gasketed concrete liners was not considered a “proven” technology. As a result of technical and political questioning of the feasibility of this project, it was abandoned. However, the tunneling technology currently in use on many tunnels in the Pacific Northwest and around the U.S. would now make this tunnel feasible.

University of Washington (UW) Utilidors – It is estimated that over 20 miles of tunnels have been constructed on the UW campus for sewers, utilidors, and pedestrian passageways. About half of these tunnels have been constructed by cut-and-cover methods, but over 10 miles of tunnels have been constructed through the hard glacial till that caps the University area to a depth of up to 50 feet. Due to the hardness of this soil, excavation has often been challenging and initial support has generally been light consisting of steel ribs and light timber lagging, followed by a cast-in-place concrete lining. Recent tunnels have been excavated with roadheaders to cut through the soft rock-like glacial till, followed by a shotcrete lining.

7 SELECTED TUNNELS FROM 1980 TO 2002

A wide variety of new tunnel methods and equipment were developed and introduced in the 1980s to present. Most notable with regards to Seattle tunnels was the introduction of earth pressure balance (EPBM) and slurry pressure balance (SPBM) tunnel boring machines for water-laden flowing silts and sands, with groundwater heads of up to 200 feet. Further advances in the 1990s included the addition of rock disc cutters on these soil machines to grind up boulders (Dowden and Robinson, 2001) and the use of bolted, gasketed segmental lining and polyvinyl chloride (PVC) waterproofing membranes in a two-pass concrete or shotcrete lining. Advances in geotechnical exploration systems such as the use of vibro-core drilling techniques and borehole tomography have enhanced the information gained from explorations. Changes in the contracting formats to allow for a greater degree of risk sharing (escrowed bid documents, labor and energy escalation clauses, design summary and geotechnical baseline reports, and disputes review boards) have contributed to a fairer and more equitable tunnel contracting approach. The following examples of tunnel construction in Seattle in the last two decades were selected to exemplify a wide range of excavation methods.

Mt. Baker Ridge Tunnel (MBRT) for I-90 - The MBRT is the largest diameter soil tunnel in the world (Robinson et al. 1987). The triple-deck, five-lane highway tunnel was constructed from 1983 to 1986 by the Guy F. Atkinson Co. using a unique form of the stacked-drift method, as shown on Figure 5, to form a semi-flexible 65-foot inside-diameter (I.D.) compressive ring liner. The compression-ring liner is comprised of 24 individually excavated concrete backfilled drifts. Behavior of the liner was modeled using one of the first applications of the finite element method to tunneling. Concepts and formulas for the stiffness and flexibility ratios for tunnels were developed on this

Figure 5 – Excavation of the 63.5 ft Diameter Soil Core From Inside the 24 Drifts of the Mt. Baker Ridge Highway Tunnel on Interstate 90.

project. The project was also unique in its complete application of innovative risk sharing contracting methods proposed by the U.S. National Committee on Tunneling Technology (1974). Risk sharing approaches included: geotechnical baseline report, Disputes Review Board, escrowed bid documents, and a sharing of potential construction price increases due to changes in the cost of labor, materials and energy. These design and contracting approaches resulted in a low bid of $38.3 million (significantly below the engineer's estimate of $78.9 million) and a final construction cost that was actually $1.8 million below the bid price.

Downtown Seattle Transit Project (DSTP) – The DSTP (Robinson, et al, 1991) travels beneath Pine St and Third Ave. through the central business district, past numerous high-rise buildings. The 1.3-mile alignment includes five stations (International District, Pioneer Square, University Avenue, Westlake Mall, and Convention Center). The Guy F. Atkinson Co. began tunneling on May 29, 1987 and was completed on March 24, 1988. The twin tunnels passed within 5 feet under the Great Northern Railroad Tunnel and about 3,000 feet further on crossed about 10 feet above the old tunnel. The twin 21.3-foot O.D. tunnels were driven with double-articulated Robbins Co. digger shields with orange-peel breasting doors. Initial support was provided by an expanded segmental lining, followed by a waterproofed final 12-inch-thick concrete lining. To our knowledge, this was the first use of the PVC membrane in combination with a completely unreinforced concrete final lining, as shown on Figure 6.

Figure 6 – Final Unreinforced Concrete Lining Being Cast Against a PVC Waterproofing Membrane Inside the Downtown Seattle Transit Project.

The DSTP was constructed through a complex sequence of hard to dense, glacially overridden interglacial and glacial sediments, with multiple perched groundwater levels. The tunnel alignment passed adjacent to several high-rise buildings, and consequently passed through over 500 steel tiebacks as well as numerous glacially deposited cobbles and boulders up to about 5 feet in diameter.

Settlements were held to less than ¼ inch along building fronts and less than 2 inches along project centerline by a combination of deep well dewatering, eductor-ejector well dewatering of silts, compaction grouting, chemical grouting, and jet grouting.

Columbia Center Pedestrian Tunnel – A 180-foot-long, 14-foot-wide by 14-foot-high pedestrian tunnel was constructed in 1985 beneath the intersection of Columbia Street and 5th Avenue from the 76-story Columbia Center to the Gateway Tower. The tunnel was excavated through hard glaciolacustrine laminated clay under a soil cover of 20 to 30 feet. Excavation was complicated by the presence of six fully grouted tieback anchors. The Frank Coluccio Construction Co. excavated this short tunnel using handheld pneumatic spaders and a small front-end loader. To eliminate the time-consuming need for forming a cast-in-place liner, 4 to 6 inches of steel mesh reinforced shotcrete with 4-inch by 13 lb/ft steel ribs spaced 2 feet was used for the first time for the struc-

tural support of a Pacific Northwest tunnel in soil. Surface settlements were less than ½ inch.

West Seattle/Alki CSO Tunnel – This 2-mile-long, 11-foot I.D. tunnel was completed by the McNally Tunnel Construction Co. in 1997. The tunnel extends from the Duwamish River, up to 400 feet beneath West Seattle and out to Alki Point (Oatman, et al., 1997, and Webb, et al., 1997). Tunneling was accomplished using a Lovat convertible earth pressure balance machine (EPBM) with an outside diameter of 13.25 feet. The TBM was never used in full earth pressure mode, but was used in partial earth pressure mode with pie-shaped flood doors, muck relieving gate, muck ring, and chemical soil conditioners. Tunnel support was provided by a single-pass, gasketed, bolted, segmental lining, its first use in Seattle.

Ground conditions along the alignment consisted of hard glacial lacustrine clay in the east half of the tunnel, and interglacial sand, gravel and cobbles in the western half of the alignment. Boulders were infrequently encountered, with less than 8 hours of down time attributed to break-up and removal of boulders. However, the very abrasive nature of the granular soils resulted in work stoppages for two underground repairs involving partial resurfacing of the cutter-head, and weekly to daily replacement of selected cutter teeth. Groundwater levels ranged from 60 feet above tunnel crown in the clays, and 0 to 14 feet of groundwater head in the granular soils. Methane was detected in several borings. During tunneling there were several temporary automatic shutdowns of the TBM until the ventilation system could clear the air. Landslide disturbed soils are present over both portals and required special portal stabilization procedures as well as heavy reinforcement of the first 300 feet of tunnel at the east portal.

The success of an EPBM project depends not only upon the capabilities of the TBM but also almost equally on the appropriate use of soil conditioners to control face stability, reduce abrasion, and develop a plastic soil plug capable of resisting the external soil and groundwater pressures. Due to the variable nature of the granular soils, continuous adjustments were required in the concentration and nature of the conditioners that included water, foam, polymer, and bentonite.

Denny CSO/Mercer Street Tunnel – Construction of this 6,212-foot-long, 16.8-foot O.D. tunnel by the Frank Coluccio Construction Co. beneath Mercer Street comprised the first use of a fully functional Lovat EPBM in the northwest (Abramson, et al., 2002). Soil conditions along the alignment consisted of glacially over-consolidated till, glaciolacustrine clay, glaciomarine drift, outwash sand and gravel, and interglacial fluvial and lacustrine sands, gravels, silts and clays. Groundwater levels ranged from 20 to over 60 feet above tunnel crown. An EPBM was required to adequately limit ground losses and resulting settlements. Chemical additives, including foam and polymers, were used extensively in the granular soils to control excavated soil quantities and maintain pressures on the tunnel face. Alignment and EPBM properties were continuously monitored by the machine operator as well as the construction management team with a computerized TACS guidance and data acquisition system. Support of the tunnel was provided by a gasketed, bolted and pinned, segmental concrete lining, as shown on Figure 7.

Figure 7 – Gasketed Segmental Lining Installed Behind Tailing Gear at Lovat Earth Pressure Balance Machine in the Mercer Street Tunnel.

Advance of the EPBM averaged about 33 feet per 10-hour shift, with a peak daily advance of 80 feet in a 10-hour shift and a peak of 356 feet tunneled in a five-day work week. Advance rates showed marked improvements as the crew gained experience with each of the soil types. Abrasion of the cutterhead and cutters stopped the machine after about 2,800 feet of advance for resurfacing of the perimeter of the cutter-head and replacement of all cutters. EPBM advance rates in the highly abrasive till and outwash soils over the next 3,300 feet of tunnel were high, due to increased usage of soil conditioners, improved quality and robustness of the carbide cutters, and weekly to sometimes daily changing of worn cutters.

Settlements were low to negligible along most of the alignment due to the very capable use of the EPBM, along with the application of soil conditioning foam and polymer additives. Settlements during initial startup were as great as 3.75 inches across Elliott Avenue, due, in part, to the normal learning curve and also due to the very shallow soil cover of less than 20 feet in landslide disturbed clayey soils.

FUTURE TUNNEL POSSIBILITIES

Several major tunnel projects are planned in the Seattle area over the nest 10 years. None of these projects would be possible without the recent state-of-the-art advances in geotechnical exploration, tunnel design, tunnel excavation technology, tunnel support systems, and ground improvement techniques that have occurred over the last 20 years.

North Corridor Transit Tunnel – Six miles of twin subway tunnels are planned as part of the North Corridor section of the "Link" LRT. The alignment is currently being re-evaluated but will likely include three deep mined stations with twin-tube diameters of about 45 feet, two shallow cut-and-cover stations, a shallow underpass beneath Interstate 5, and a 1,300-foot-long crossing about 130 feet deep beneath Portage Bay. The tunnel alignment passes through a wide range of highly variable soil conditions consisting of glacially overridden silt, sand, clay, and till. Multiple perched groundwater heads of up to 200 feet, combined with isolated pockets of methane further complicate construction requirements. A wide variety of soil exploration techniques have been used to assess ground conditions. Conventional explorations have included mud rotary drilling with split spoon and Dames & Moore sampling. However, this exploration system reveals only a small portion of the soil conditions. Explorations with a vibro-core drill rig yielded continuous samples, which helped to better define soil conditions along shaft depths and provide details on geologic transitions and variations that could not otherwise be determined except by tunnel and shaft construction.

A relational database was used to tabulate and coordinate all drilling, field testing, and laboratory testing data (Ward, et al., 2002), providing access for numerous simultaneous users. Up to eight drill rigs were used concurrently to perform explorations.

Beacon Hill Transit Tunnel – A 1-mile-long twin-bore tunnel will pass beneath Beacon Hill, south of downtown Seattle, as part of the Link Light Rail System. The 20- to 21-foot O.D. tunnels and deep mined station will be excavated through highly overconsolidated, interbedded, glacial and inter-glacial soils with multiple perched water tables. The deep mined station will likely be constructed using the Sequential Excavation Method (SEM) that permits the excavation of large complexly shaped underground openings. Several vibro-core borings were used to provide continuous sampling of these complex soils. Rock coring techniques were also used in the very hard soils to obtain relatively undisturbed samples for laboratory testing. Geophysical tomography was used in several borings to provide a 3-D assessment of soil conditions between borings.

Henderson CSO – This project includes a 3,100-foot-long, 15-foot I.D. storage tunnel as well as connector tunnels beneath Interstate 5 and beneath mainline Burlington Northern and Union Pacific railroad tracks and several connector tunnels beneath city streets. The storage tunnel will be excavated with an EPBM through over-consolidated glacial and interglacial soils. Tunnel support will be provided by a gasketed, bolted/pinned, segmental concrete lining. The connector tunnels beneath the freeway and railroad alignments posed a unique exploration problem due to very limited access. Consequently, exploration below these alignments was accomplished with a triangular array of 200- to 300-foot-long horizontal directional drill holes spaced about 12 feet apart in which cross-hole tomography was used to determine the location of buried timber piles and rock or concrete obstructions.

Brightwater Sewer Project – King County's adopted Regional Wastewater Services Plan calls for a new regional wastewater plant in south Snohomish County to serve customers in that area. Although a site has not yet been selected, it is apparent that a collection system facility will be needed to transfer untreated wastewater to the new plant and transfer treated flows to a new Puget Sound outfall. The various components of the collection facility will extend from the north end of Lake Washington westward out to Puget Sound. The hilly topography makes tunneling an obvious solution for long portions of the 10- to 20-mile-long gravity feed sewer system beneath up to 400 feet of topographic relief. A variety of tunnel and trench alternatives are being assessed to select alignments that minimize impacts to the community while ensuring the lowest overall construction and operations/maintenance costs. As with most tunnels in the Seattle area, soil conditions are expected to be highly variable, and groundwater levels of up to 250 feet above the tunnels are anticipated.

Alaska Way Viaduct Replacement – A double-deck elevated highway along the west-side of downtown Seattle, built in the 1950s, was damaged by the magnitude 6.8 earthquake that occurred in western Washington on February 28, 2001. As a result, the Washington State Department of Transportation along with the City of Seattle and King County, are assessing several alternatives for replacing this critical and vulnerable highway with a combination of large-diameter tunnels and cut-and-cover alternatives. The existing double-deck viaduct carries six lanes of traffic, which could require up to twin 50-foot-diameter tunnels through the up to 200-foot-high bluff that boarders Puget Sound and downtown Seattle.

9 NEEDED TUNNELING INNOVATIONS

The Seattle area is unique among major U.S. cities in its highly variable topography coupled with a wide range of soil and groundwater conditions. Soils may range from glacial till and hard clays with excellent excavation characteristics to saturated sands and silts that require stabilization during excavation and support. Toward the south end of the City, bedrock consisting of sandstone, shale, and dikes or sills of andesite/basalt may be encountered. Based on recent experience in the Seattle area, there are a number of areas in which advances and improvements could greatly enhance tunnel productivity and reduce the risk of encountering unforeseen ground conditions. A partial list of suggested innovations is as follows:

- Improved hardened surfaces and cutter design for highly abrasive hard glacial tills and dense sands with extremely hard cobbles and boulders.
- Improved means for assessing cutter and head wear and replacement requirements.
- Improved tail seals, bearing seals and other sealed tunnel components to accommodate groundwater pressures of 250 to 400 feet (7.5 to 12 bars).
- Improved capabilities of EPBM and SPBM to excavate and process timber piles and logs.
- Improved means of locating and identifying obstructions such as isolated boulders, logs, timber piles and other obstructions from the ground surface to depths of 400 feet.
- Improved dewatering methods for fine sand and silt soil units.

10 CONCLUSIONS

The Seattle area has proven to be a hotbed for innovation and testing of tunneling technology over the last 110 years, due in part to the difficult and challenging geologic and topographic conditions in the area. Innovations such as compressed air regulations, sodium silicate grouting, waterproofing membranes, finite element method analyses for tunnel design, Disputes Review Boards, Geotechnical Baseline Reports, soil tunnel support with shotcrete, and large-diameter stacked drift semi-flexible tunnel linings have all been pioneered and/or tested in the Seattle area. Recent innovations in soil tunneling technologies, such as EPBMs, SPBMs, computerized monitoring of TBM operations and laser guidance, and gasketed and pinned/bolted segmental concrete linings have also been brought by several tunnel contractors to projects where they have been tried, tested and proven in Seattle's challenging terrain and glacial soils.

Numerous challenges lie ahead for the tunnel industry in the Seattle area. Deeper and longer soil tunnels are planned for the Seattle area, for the Link LRT program and for several sewer tunnels. Large-diameter bores for deep subway station tubes and for portions of the Alaska Way Viaduct replacement will require the application of the SEM for larger diameters and more difficult ground conditions than have been accommodated thus far anyplace in the world. Consequently, numerous advances are still needed in tunneling technology to accommodate future tunneling needs as owners, designers, and contractors continue to push the existing state-of-the-practice and advance the state-of-the-art of tunneling.

11 ACKNOWLEDGEMENTS

A number of owners, engineers, geologists, and construction firms have blazed the trail for innovations in tunneling technology in the Seattle area. Without the foresight, expertise, risk taking, and risk sharing offered by these agencies, companies, and individuals, the amazing succession of advances that we have recorded over the last 100 years would not have been possible. Local tunnel design and construction innovators have included:

R.H. Thompson, City Engineer from 1884 to 1914
Gene McMaster, Lead Engineer with Metropolitan Engineers
Constructors PAMCO
Frank Coluccio Construction Co.
Guy F. Atkinson Construction Co.
Robbins Machine Co.
City of Seattle
King County
Municipality of Metropolitan Seattle (Metro)
Washington State Department of Transportation

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