HEAVY RAIL BELOW THE 100-YEAR FLOOD ELEVATION – INNOVATIONS IN DESIGN – A CASE STUDY

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ABSTRACT

To decouple the heavy rail entrance into the Port of Vancouver USA from a major north/south mainline of the nation’s rail system, a rail-under-rail grade-separation structure was designed along the northern bank of the Columbia River in Vancouver, Washington. To provide the required 23.5 foot (7.2 meter) clearance below an existing 100-year old rail bridge that crosses the river, the new rail line needed to descend more than 14 feet (4.3 meters) below the 100-year flood elevation. Because trains need to remain in operation during this flood condition, protection of the rail line from flood waters was required. Several innovative design solutions were developed to meet this design criteria in the most efficient manner.

This case study is of regional, national and international interest. The paper will discuss the project’s constraints, design challenges, and solutions utilized to meet the project criteria. The location and configuration of the structure posed special challenges and the solutions for this project will be of interest to practicing structural engineers as well as rail operators, owners, and land use professionals.

The rail structure itself, a 1,350-foot (411.5 meter) long portion of the new rail entrance for the port, is a partially elevated reinforced concrete structure that protects the rail from flood waters and supports it along the irregular river bank. To resist flood waters, a continuous reinforced concrete U-shaped trench was selected as the optimal solution. This selection of structure type was the first of many challenges for this project.

The superstructure borrows design innovations from the continuously reinforced concrete pavement industry to help eliminate expansion joints over the entire length of the structure. This helps minimize water infiltration during flood events and reduces lifetime maintenance costs. The substructure consists of closely spaced driven steel batter piles that support the majority of the rail trench structure and is extremely compatible with the expansion joint-free design.

The new rail trench structure provides a unique facility that meets the design challenges of the site, maximizes operational efficiency for the port, and relieves congestion at this critical location along the Pacific Northwest’s high-speed rail corridor.
INTRODUCTION

Located to the east of the Port of Vancouver USA, Project 16, better known as “the trench,” is one piece of a major capital improvement program called the West Vancouver Freight Access (WVFA) project. The WVFA project will provide a new connection to the east/west rail mainline that runs south of downtown Vancouver, Washington, and will relieve congestion along the north/south rail mainline that connects the Pacific Northwest to the rest of the United States, Canada, and Mexico.

The trench project, shown in Figure 1, creates a new decoupled rail entrance into the port along the north bank of the Columbia River by taking it below the existing north/south rail mainline river crossing known as the BNSF Bridge 9.6. A 1,350 foot (411.5 meter) long portion of this new rail entrance is a partially elevated concrete trench structure that protects the rail line from flood waters and supports it along the irregular bank of the river.

The project was designed to overcome site challenges, satisfy operational requirements of the port and the railroad, take advantage of staggered funding opportunities, and respond to environmental concerns. The project included three major design and construction phases and four construction contracts.

![Figure 1. Rail trench site plan.](image)

Because the rail line runs along the bank of the Columbia River and below flood elevations, this project employed both structural and mechanical flood protection measures to maintain uninterrupted train access into the port during high water events. The rail alignment connects to existing tracks on either end and provides a minimum vertical rail clearance of 23.5 feet (7.2 meters) beneath the existing BNSF bridge. The horizontal alignment extends beyond the Columbia River’s ordinary high water mark.
OHWM), but minimizes effects to the river environment and surrounding properties by siting the facility in a narrow strip of land that is just wide enough to construct the trench and allow for a future second track. The proximity to the river and the existing rail bridge is shown in Figure 2. Other significant challenges included surrounding active industrial properties, minimal construction access, and the widely varying environmental and geologic conditions of the site.

![Figure 2. Rendering showing the rail trench structure.](image)

This paper will outline some of the challenges and unique design elements of the rail trench structure, the background and reasoning behind the design and analysis, and the detailing done to provide a structure that will provide long-term performance despite the challenges posed by its location.

**DESCRIPTION OF STRUCTURE**

The rail trench structure is a 1,350-foot-long (411.5-meter-long), partially elevated U-shaped structure composed of a thick reinforced concrete slab with two reinforced concrete walls on either side to protect the rail line from river flooding. The majority of the structure (1,100 feet [335.3 meters]) is supported by a series of closely spaced four-pile bents. The pile supported portion ends where full-width ground support is available and where buoyancy uplift forces can be resisted by dead load alone. Figure 3 shows a developed elevation of the rail trench structure as pictured from the river.

A typical section consists of an approximately 29-foot-wide by 4.5-foot-thick (8.8-meter-wide by 1.4-meter-thick) cast-in-place reinforced concrete slab and cast-in-place reinforced concrete walls that vary in height. The walls run the entire length of the rail trench structure and have a constant top elevation of 28.5 feet (8.7 meters) to protect the rail from a 100-year flood event (elevation 27.8 feet [8.5 meters]). The walls are a maximum of 1.5 feet (0.46 meter) thick at the base and taper to 1 foot (0.30 meter) thick at the top. Typical transverse cross sections of the pile-supported and at-grade portions
are shown in Figures 4 and 5, respectively. The overall layout of the substructure, combined with the stiffness of the superstructure, provide a uniform response to a variety of loads.

Figure 3. Developed elevation of the rail trench structure.

Figure 4. Typical cross section of pile-supported rail trench structure.

Figure 5. Typical cross section of at-grade rail trench structure.

Closely spaced transverse bents consisting of oppositely oriented transverse batter piles provide strength and stiffness. H-piles were used for the majority of the structure because of their overall structural performance and lower unit cost compared with pipe
piles. However, under the existing railroad bridge, steel pipe piles were used because of low-headroom pile-driving requirements (see Figure 6.) The low headroom necessitates double the number of pile splices compared to locations with unrestricted headroom. For this condition, pipe piles are more cost-effective as the cost per splice is less for pipes than it is for H-piling.

![Figure 6. Low-overhead pipe pile installation.](image)

The H-piles have well-defined strong and weak axes providing relative flexibility in the weak direction to attract less force during volume change displacements when compared to similar-weight pipe piling. The weak axis is oriented perpendicular to the structure alignment so that the H-piles move with the expansion and contraction of the structure in the longitudinal direction. The strong axes of the piles are aligned parallel to the rail trench centerline and the piles are battered for maximum resistance to transverse lateral forces (see Figure 7.) The H-piles, their layout and their orientation were all selected to maximize structural performance during all loading conditions while maintaining compatibility with the design criteria that required a low-maintenance water resistant structure.

The concrete superstructure was designed and detailed similar to waterfront structures and does not use expansion joints. This is achieved, in part, by providing a sufficient
amount of continuous longitudinal reinforcement similar to continuous reinforced concrete pavement systems.

The structure is designed for performance during all loading conditions required by the American Railway Engineering and Maintenance-of-Way Association (AREMA), Manual for Railway Engineering. Loads that control some facet of the design include dead and superimposed live loads (Cooper E-80 loading consisting of multiple sets of locomotives and 174 car trains), seismic and destabilized slope loading, buoyant uplift forces and hydrostatic pressures on the full height of the trench walls.

Figure 7. Partial H-pile installation.

Stormwater that enters the rail alignment’s catchment area is collected, treated, and conveyed to a permitted point of discharge. The trench catchment area includes the rail trench structure and the rail alignment runoff areas on either end of the structure that will drain towards it. A pump station located near the low point of the rail trench structure will discharge to an existing outfall located nearby.

STRUCTURE TYPE SELECTION AND DESIGN PHILOSOPHY

Selection of structure type. Early in the planning process, an extensive alternatives analysis was undertaken to explore various types of structures to support the rail line. A selection matrix was developed and included a variety of structure types and construction methods that would fit the constraints of the project and allow appropriate clearance beneath the existing bridge. The focus of the study was on evaluating the effect of each alternative based on such criteria as land use and environmental
permitting, construction scheduling and costs, structural and seismic performance, annual maintenance costs, flood operation behavior, and environmental impacts.

The alternatives evaluated included a ballasted trench structure inside bulkheads, a concrete trestle structure with no flood protection, a T-wall retaining wall system with no flood protection, and a pile-supported U-shaped superstructure. Options with structural flood protection included sub-alternates with wall heights corresponding to different degrees of flood protection (i.e., 10-year, 50-year, and 100-year flood stages.) This allowed for the comparison of different structure types, and also assigned a cost for flood protection that the port could evaluate versus the revenue that would be lost if it became necessary to use the old, less efficient rail entrance during a flood. The pile-supported structure with reinforced concrete walls high enough to protect against a 100-year flood was ultimately chosen as the optimal solution.

The rail trench superstructure was developed to include the previously mentioned thick slab with side walls in a U-shaped section. This cross section was chosen so the rail line remains operational during a 100-year flood event. The sidewalls were designed to resist flood water up to an elevation of 28.5 feet (8.7 meters), as well as balanced and unbalanced hydrostatic loading, including a trench full of water with receded surrounding floodwaters following an event greater than the 100-year flood.

The proposed vertical and horizontal alignments of the rail trench structure were also studied, in particular the structure’s location relative to the river. During concept development, the alignment was adjusted to maximize construction flexibility in relation to the expected water levels while still providing sufficient room to build the project within the available right-of-way.

**Design philosophy.** The rail trench as configured is more similar in design and construction to typical waterfront structures such as fixed piers and wharves when compared to vehicular bridges. Piers and wharves typically consist of continuous pile-deck systems without expansion joints and are often over 1,000 feet (305 meters) long. Such a design makes for easier detailing, construction, and maintenance.

Waterfront structures are supported by an array of uniformly spaced, similar stiffness pile bents forming the substructure. Vehicle bridge structures, by contrast, are typically designed with a minimal number of discrete foundation elements that are relatively stiff and spaced as far apart as possible. These foundation elements must resist significant vertical and lateral forces and attract load from a large tributary area. Expansion joints on bridges are used to accommodate movement due to shrinkage, creep, and temperature variation while the stiff foundation elements stay in place during these displacements.

Expansion joints require ongoing maintenance during operational conditions and require repair or replacement after seismic events. Therefore, current bridge design and construction practices typically endeavor to minimize the number of joints. The Washington State Department of Transportation (WSDOT) Bridge Design Manual (BDM) specifies limits on allowable bridge lengths and construction types that do not require expansion joints.
DESIGN ELEMENTS

Flood water resistance. The flood characteristics of the Columbia River at the project location are such that historically high water levels are only present for a short duration. Because of this, the structure was designed to be water resistant, not water tight. Water that enters the inside of the structure (see Figure 8), through seepage or rain fall, is removed by a nearby dedicated pump station.

Because the rail drops 9.6 feet (2.9 meters) below the 100-year flood level and the bottom of the structure is 4.3 feet (1.3 meters) below the river’s ordinary high water mark, infiltration of flood waters into the trench is possible during high water events. Thus, concrete cracking due to structure thermal movement, shrinkage-induced displacements, and normal operating loads were examined. The structure is the first line of defense against water intrusion and minimizes infiltration by limiting crack widths using continuously reinforced concrete paving (CRCP) design methods for the longitudinal reinforcing, and by eliminating expansion joints along the entire length of the structure. Ancillary to this, a project specific concrete mix and a redundant water stop system at all construction joints were specified. A dedicated pump station and drainage system with the capacity to remove rain and flood water that enters the trench structure was provided as a second line of defense against water entering the trench structure.

Figure 8. Inside of the rail trench structure prior to installation of ballast, ties and track.
By calculating an expected crack width and pattern based on the CRCP design, it was conservatively predicted that the amount of water that could infiltrate into the trench through the structural concrete would be a maximum of 153 gallons (579 liters) per minute, at the 100-year flood stage. This is less than 25% of the flow that would enter due to a design rain storm (2-year) event. This seepage flow rate met the criteria for water resistance. The pump station was designed to remove the storm and seepage water so trains can continue operating.

**Continuously reinforced concrete paving design strategy.** With the selection of a cast-in-place reinforced concrete structure, the superstructure was further simplified by implementing elements of CRCP design. The CRCP design uses continuously and closely spaced longitudinal reinforcing bars to minimize the width of transverse cracks and to more evenly space the cracks along the entire length of the structure. Instead of concentrating the movement of the structure at widely spaced points where an expansion joint would be installed, the movement is designed to occur in small amounts over the entire length of the structure. While the trench structure is still expected to crack, the methods used in design provide for a more predictable pattern of tightly closed cracks, which will minimize water infiltration.

These design concepts were implemented into the reinforcing layout of the trench slab and walls. The photograph in Figure 9 shows a typical layout of the top mat of steel in the slab.

![Figure 9. Typical reinforcing of slab section.](image-url)
After the strength requirements were met, the longitudinal reinforcing was configured to provide a 0.7 to 1 percent of the cross-sectional area as longitudinal reinforcing bars spaced at 6 to 9 inches (152 to 229 mm) on center. In this way, the cracks widths are expected to be limited to 0.008 inches (0.203 mm), which translates to a more water resistant and durable structure. With the flow of water through a crack proportional to the cube of the crack width, the amount of infiltrated water is expected to be minimal and easily removed by the pump station that is sized for much larger flows.

Supplementing the design and detailing of the rail trench structure with CRCP standards allows for a structure that will provide reliable structural performance and require minimal lifetime maintenance. The rail trench is a long concrete structure (Figure 10) and utilizes the closely spaced longitudinal reinforcing, closely spaced pile bents, and flexibility of the piles to allow for temperature-induced deformations to be carried by the reinforcing without the need for expansion joints.

Figure 10. Rail trench structure as seen from the river.

**Longitudinal internal forces and displacements.** Forces arising from temperature changes on the long structure were calculated during design. Per Table 8-2-1 of the AREMA 2010 Manual, the structure is considered to be located in “Moderate Climate” and needs to be designed to resist stresses for a temperature rise of 30 degrees Fahrenheit (F) (17 degrees Celsius [C]) and temperature fall of 40 degrees F (22 degrees C.)
For structural analysis and design, the temperature forces were applied within a computer structural model in the following ways.

- As a global temperature differential load on the steel piles.
- As a global temperature differential load on the reinforced concrete trench walls and slab.
- As a temperature differential between the top and bottom surfaces of the reinforced concrete.

The trench slab and wall analysis results showed additional axial force demands on the concrete components due to temperature-induced strains. These forces are resisted by the reinforcing steel for tensile forces and by the concrete for compressive forces. Transverse volume change demands were found to be insignificant.

The total deformation demand on the trench structure is then a combination of shrinkage and thermal effects. These effects were estimated using the American Concrete Institute’s (ACI) ACI 209R-92 Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures and the WSDOT Bridge Design Manual. Per these methods, the ultimate shrinkage strain of the walls was found to be approximately 230 millionths while the ultimate shrinkage strain of the base slab was estimated at around 90 millionths. For temperature, a coefficient of thermal expansion of 0.000006/F (0.000010/C) was used to estimate approximate strains of 240 millionths for the entire cross-section.

For the total system consisting of the trench slab and walls, the ultimate total strain was approximately 400 millionths. This comprises ultimate shrinkage strain of around 150 millionths and ultimate temperature strain of around 250 millionths.

Because the stiffest substructure elements are located at the midpoint of the structure, the ends will experience the greatest temperature and shrinkage displacement. From the computer models, the maximum displacement at the outermost pile bent in the longitudinal direction is estimated to be approximately 0.5 inch (12.7 mm.) This displacement demand is significantly lower than the estimated displacement capacity of the H-piles which is approximately 3.5 inches (88.9 mm.) The substructure configuration ensured predictable displacements that were easily managed by the reinforcing.

**CONCLUSION**

The nature of any port facility is such that constraints imposed by water bodies, transportation modes, and surrounding communities present challenges for any major expansion project. Through careful design and a combination of innovative methods and technologies borrowed from the waterfront, concrete, and paving industry, a one-of-a-kind rail trench structure was constructed with a low life-cycle cost, and will be operational essentially 100% of the time, despite its location below the 100-year flood elevation.

By using a specific deep pile foundation system composed of steel H- and pipe piles and detailing the reinforcing so that the performance of the structure is as predictable
as possible, the goal of a new and separate rail entrance into the port was realized. The new rail trench structure provides a unique facility that meets the all structural requirements, maximizes operational efficiency for the port, and relieves congestion at this critical location along the Pacific Northwest’s high-speed rail corridor.

REFERENCES


American Concrete Institute (ACI), ACI 209R-92 Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures, Reapproved 2008.


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