

BUILDING ON SHAKY GROUND



The southern 1 mi stretch of Route 99 in Seattle has been rebuilt as two adjacent viaducts that cross active rail lines, roadways, and utilities. But what challenged the design team most wasn't the built environment but the extreme seismic vulnerability of the site.



**By Monique Anderson, P.E., M.ASCE,
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THE 2.2 MI LONG Alaskan Way Viaduct, which takes motorists along downtown Seattle's waterfront, has always been controversial. Planning for the new highway began in the 1930s, and 15 years were to elapse before the double-deck reinforced-concrete structure was constructed. Not everyone was happy with it—and that sentiment endures today. Drivers love the fact that they can enjoy beautiful views of Elliott Bay and the Olympic Mountains as they drive along the top or the bottom deck. Pedestrians, however,



A project to replace a 1 mi stretch of the Alaskan Way Viaduct that serves an industrial area of Seattle, including the city's ports and sports stadiums, has resulted in a route that can now be used as a bypass during construction of the bored tunnel that is to replace the viaduct.

are bothered by the fact that they have to shout over traffic as they stand below the viaduct, and city dwellers lament the fact that the concrete structure creates a barrier between downtown and the popular waterfront.

In February 2001 the Nisqually earthquake (magnitude 6.8) shook downtown Seattle for more than 10 seconds. The epicenter of the earthquake was in Olympia, about 66 mi to the south. Many older structures were damaged, including the viaduct. The viaduct damage included cracking of the reinforced-concrete floor beams, joints, and girders. After shoring the structure, the Washington State Department of Transportation (WSDOT) carried out a vulnerability study

and found that if the shaking had lasted just a little longer or been a little stronger, portions of the viaduct could have collapsed. Thus began the latest phase in the controversial life of the viaduct: how to restore the seismic safety of the critical transportation lifeline that the viaduct supports. Hundreds of ideas were debated, including new bridges, new tunnels, retrofits of the existing structure, and an outright removal with rerouting of traffic to city streets.

The southern mile of the viaduct is south of downtown Seattle in an industrial area that supports the Port of Seattle, railroads, two sports stadiums, and other industries. In 2007, while debate about how to replace the central section of the viaduct along Seattle's waterfront continued, state leaders decided to replace the southern mile with new bridges that would run side by side. This project, completed in 2012, was referred to as the S. Holgate Street to S. King Street (H2K) viaduct replacement project. In 2009, when design of the H2K project was nearing completion, the debate about the remainder of the viaduct replacement to the north finally ended, and a bored tunnel was selected (see "Bored Tunnel Expected to Replace Alaskan Way Viaduct," *Civil Engineering*, March 2009). The H2K project design was modified so that it could be used as a major bypass route during tunnel construction and could incorporate a future connection to the bored tunnel section of Route 99. The H2K project involved the construction of two three-lane bridges roughly 1,890 ft long that run side by side and have 150 to 800 ft long approach embankments.

Seattle lies in a low area between the Olympic Mountains to the west and the Cascade Range to the east. Over the ages as many as five major glaciers traveled through this low area, leaving behind a varied mixture of soils that include clay, silt, sand, and gravel. In the intervals between the glacial advances and retreats, rivers and lakes appeared and disappeared. The weight of the glacial ice compacted the soils left behind by previous glaciers and those deposited during interglacial periods. After the last glacier receded to the north, the land rebounded and benefited from deposits from the marine environment, rivers, and landslides. The H2K project was carried out in the Seattle tidelands (mudflats) that once formed the main delta when the Duwamish (Dwamish) River emptied into Elliott Bay.

Prior to 1900 the primary industries of Seattle were lumber and shipping. To transport goods and lumber from other areas of Puget Sound, railroad trestles were constructed over the Seattle tidelands. Between 1889 and 1931 Seattle's engineering department began regrading the city by removing hills and sluicing the excavated material into the tidelands. More than 10 ft of fill was placed in the tidelands to raise the area above the high-tide line. The regrading projects made it easier to develop the downtown Seattle hills and created new opportunities in the tidelands. Because of the development fostered by the railroads and other industries, the tidelands quickly grew into what is now Seattle's industrial area.

The geologic and human history of the Seattle tidelands resulted in a distribution of more than 200 ft of loose to moderately dense sand and silt below the south ends of the bridges built in the H2K project. The upper 10 to 20 ft were deposited by human activity, the remainder deriving from the



Duwamish River and Elliott Bay environment. The water table is relatively shallow, being roughly 5 to 10 ft below the ground surface.

The proposed roadway configuration for the H2K project consisted of two side-by-side bridges, each about 50 ft wide. The proposed length of the bridges was about 1,890 ft with spans ranging from 120 to 210 ft. One bridge would carry three lanes of northbound traffic, and the other, three lanes of southbound traffic. The bridges had to be constructed in two stages so that traffic could be maintained along Route 99. First, the southbound bridge would be constructed along the west side of the viaduct. Traffic would then be moved to this new bridge, and the viaduct would be demolished. The northbound bridge would then be built along the alignment of the demolished viaduct. All of this had to be done in a way that would maintain traffic routes for the Port of Seattle and local industries.

Even in the early planning stages, the WSDOT's bridge engineers knew that the side-by-side bridges would need to be supported on deep foundations. Their preferred foundation called for reinforced-concrete piles cast in drilled holes (drilled shafts). The WSDOT had used drilled shafts with diameters up to 6 ft and depths reaching 100 ft on many of its bridges throughout the state. The engineers planned to construct the bridge approach embankments from gravel borrow; the vertical sides of the embankments would be supported by mechanically stabilized earth (MSE) walls, which also are widely used throughout the state. Unfortunately, the soil conditions in the old tidelands of Seattle were such that

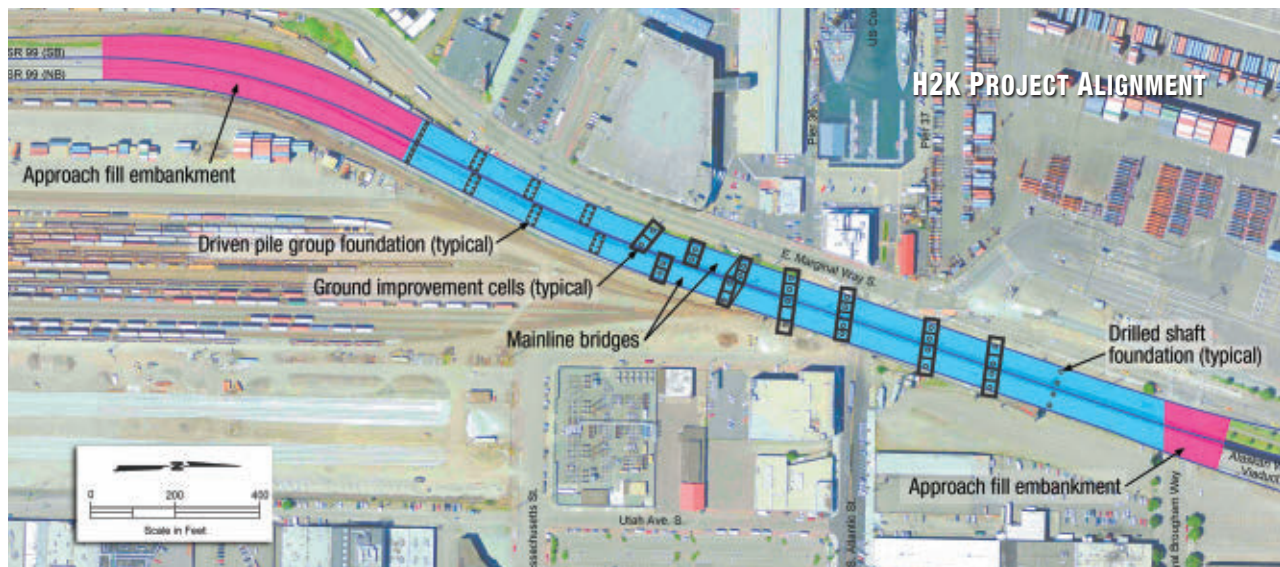
Twin side-by-side bridges were constructed next to the existing viaducts as part of the S. Holgate Street to S. King Street (H2K) project.

standard approaches were not going to work.

When the subsurface explorations revealed loose soils extending to depths of more than 200 ft along the south ends of the bridges, the engineers went back to the drawing board. Drilled shafts had not routinely been installed to depths exceeding 120 ft. The engineers had to decide whether it would be feasible to go 200 ft or more. In the end, no engineer, expert, or contractor could convince the WSDOT that it could be done without a high risk of construction problems. Therefore, WSDOT engineers selected driven, open-end pipe piles 5 ft in diameter to support the south ends of the bridges. In areas where the soft soils were less than 150 ft deep, they selected 10 ft diameter drilled shafts, much larger than what they had used for most other bridges. The drilled shafts had to be temporarily cased to prevent soil from caving in during drilling.

Early in the project, the WSDOT drew on the expertise of seismic specialists at Shannon & Wilson, Inc., of Seattle, to perform a probabilistic seismic hazard analysis that took into account the number and activity of the various earthquake faults in Seattle. One, the Seattle Fault, runs just south of the project area and is capable of producing earthquakes as large as magnitude 7.2. The results of the probabilistic seismic hazard analysis were used to develop ground motion recommendations for the design of the new bridges. The WSDOT decided that the project's seismic design criteria would include ground motion with a 7 percent probability of exceedance in 75 years, that is, a 1,000-year return period. This selection was based on guidelines issued by the American Association of State

WSDOT



Highway and Transportation Officials. The WSDOT also decided that it would use a “life safety” performance objective, meaning that the structures could suffer significant damage and service disruption but could not collapse.

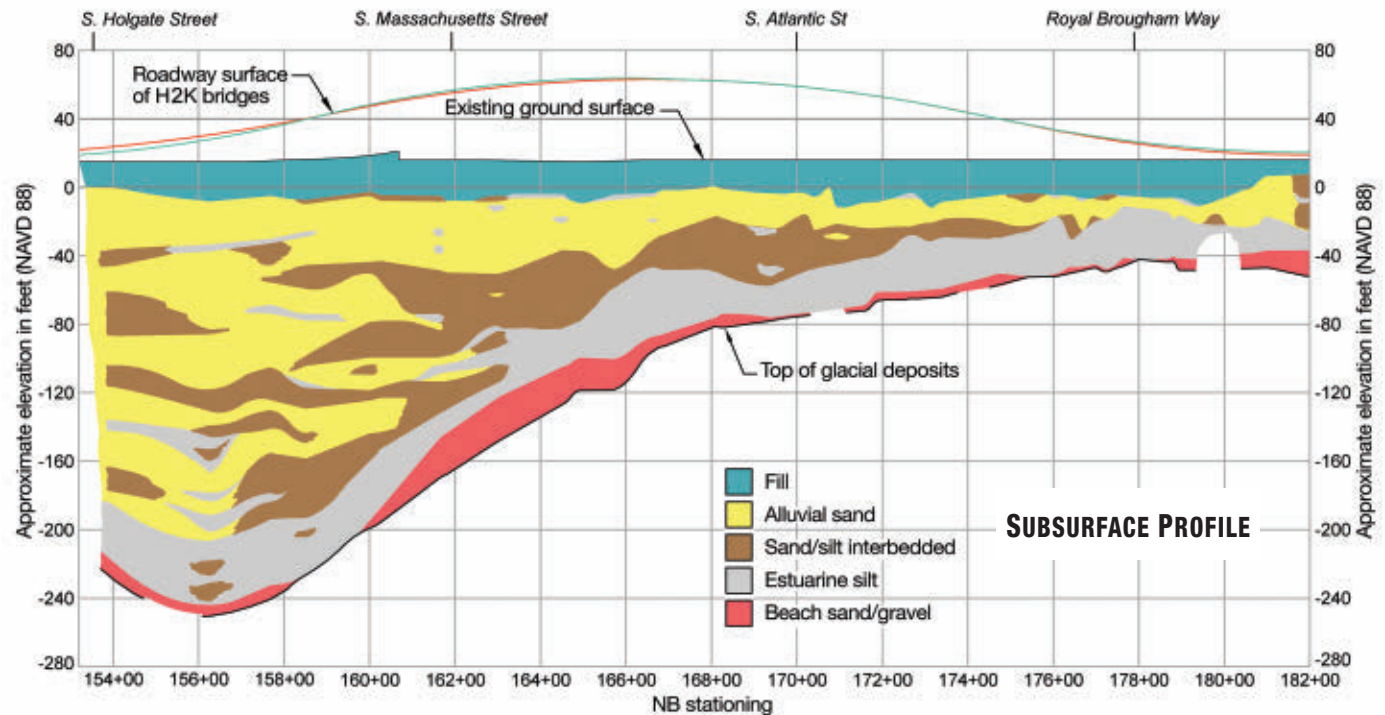
Once the seismic design criteria were developed, the engineers performed analyses to see how the design ground motions would affect the soil at the site. They estimated that the soil liquefaction would extend in various submerged sand and silt layers to depths of as much as 120 ft based on a nonlinear effective stress analysis.

Soil liquefaction occurs in loose, saturated, sandy soil when the water pressure in the pore spaces increases to a level that is sufficient to separate the soil grains from one another. This phenomenon occurs during ground shaking and results in a reduction of the shear strength of the soil. The amount of strength loss depends on the degree and extent of the liquefaction. The potential effects from ground liquefaction include ground set-

tlement and lateral ground movement, and they can reduce the vertical and lateral capacity of bridge foundations.

The engineers determined that the greatest risks in this case were twofold, the first being the deep foundations being loaded by downdrag from the liquefied soils or pushed sideways as the liquefied soils try to flow toward the bay and the second being a failure of the approach embankments because of the underlying liquefied soils.

Initially, the engineers considered various methods to improve the ground and reduce the possibility of liquefaction. However, such an approach was deemed to be too expensive because of the large lateral extent and depth of the potentially liquefiable soils. Next they checked to see if the structural design could be revised to accommodate the soft ground behavior. The planned pile and shaft sizes were already the largest and deepest that local contractors could confidently construct, and adding to this would significantly



SHANNON & WILSON, BOTH

complicate the structural design. The engineers then rolled up their sleeves and tackled each problem by considering all potential solutions, including those that were unique and creative.

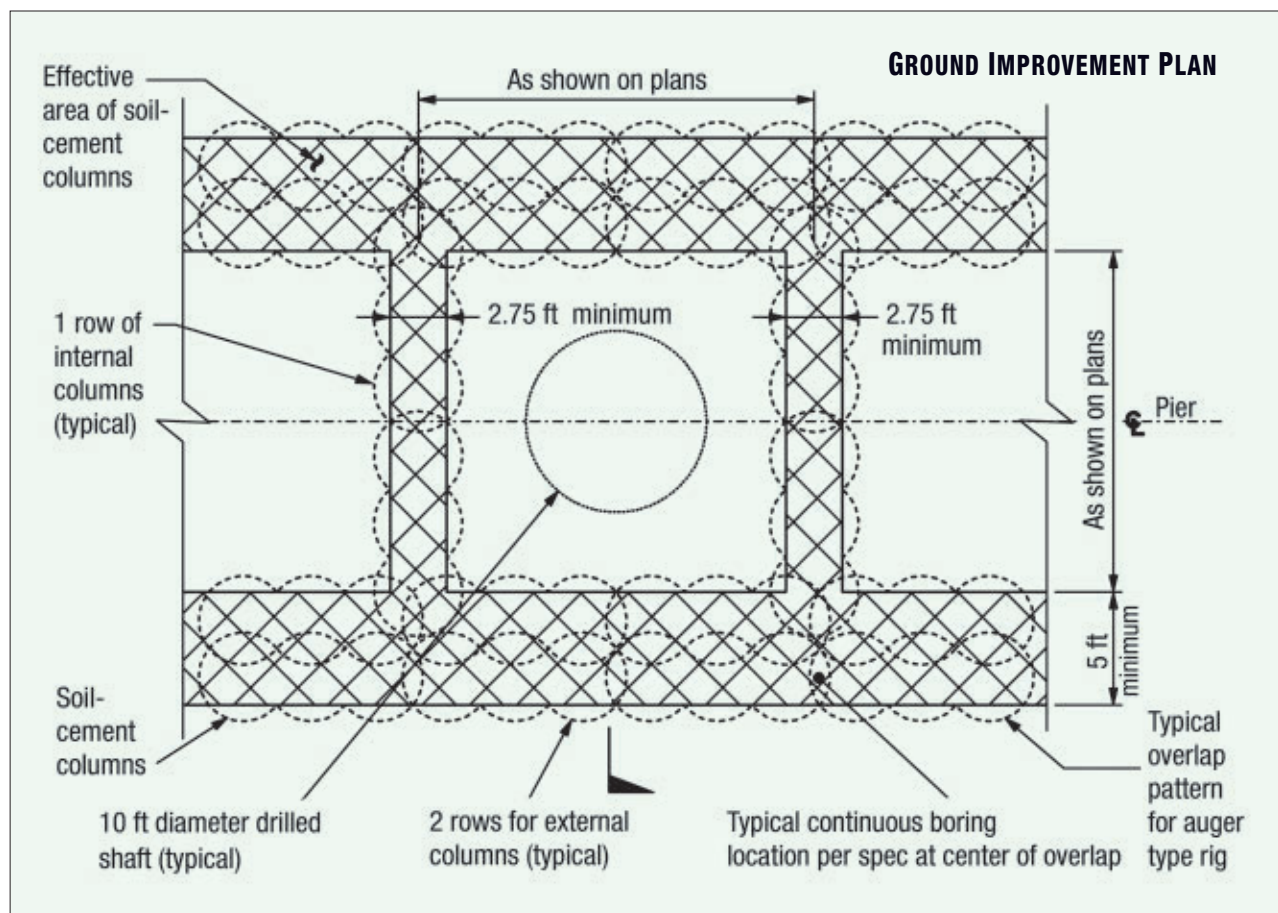
After an earthquake that causes liquefaction has ended, the pore pressures dissipate, allowing the soil grains to come back into contact with one another and the soil to regain strength. Through this process, the soil also settles. The predicted liquefaction-related settlement at the site was 6 to 18 in. at the ground surface. Because of friction along the sides of the pile or shaft, settlement of soil around a deep foundation imposes a downward force. (This is referred to as downdrag.) Less than $\frac{1}{2}$ in. of differential movement between the side of the pile or shaft and the soil can cause these downdrag forces to occur. Nonlinear effective stress analyses indicated that this amount of movement or more would occur at depths of as much as 120 ft. The geotechnical engineers from Shannon & Wilson estimated that the unfactored (ultimate) downdrag force on the 10 ft diameter drilled shafts would be as much as 1,200 tons and on the 5 ft diameter pipe piles would be as much as 500 tons. As a result, the WSDOT bridge engineers decided to extend the foundations 20 to 30 ft into the very dense glacial soils to achieve the needed resistance. Two 10 ft diameter drilled shafts were used at each bent for the northern nine bridge spans. These shafts reached depths of 150 ft below the ground surface. For the southern three bridge spans, 5 ft diameter pipe piles were used in pile groups of eight (two rows of four) to support each bent. The open-end piles reached depths of 260 ft below the ground surface.

The installation of deeply driven piles for the southern three bridge spans created another challenge: driving piles causes vibrations. Ground vibrations can damage adjacent utilities and structures, the damage deriving either from the vibration itself or from vibration-induced settlement of the ground. The project site is surrounded by structures, buildings, roadways, railroads, and utilities, and the new southbound bridge had to be constructed adjacent to the existing viaduct as the latter carried live traffic. The engineers determined that when the pile driving would be performed within 50 ft of a structure and penetration of more than 10 ft into very dense glacial soils was needed, the potential vibrations during pile driving could damage the



Expanded polystyrene (EPS) geofoam was used as a lightweight fill. The EPS blocks can be easily cut and shaped to fit any embankment configuration and can be placed at rates of up to 1,000 cu yd per day, much faster than a gravel borrow embankment supported by a mechanically stabilized earth wall. After the EPS blocks are placed, they are covered with plastic to protect them from fuel or oil spills, and a roadway pavement section is then constructed over the EPS embankment.





structure, depending on the structure's location, foundation type, and condition.

To safeguard the public, Shannon & Wilson's geotechnical engineers worked with WSDOT structural engineers to develop an innovative composite pile system. First, a 5 ft diameter pile was driven so that it would penetrate about 2 to 5 ft into glacial deposits. Then the soil was removed from the upper 100 ft of this pile, and a 3 ft diameter inner pile was driven through the larger pile so that the smaller pile would penetrate 20 to 40 ft into the glacial soils to achieve the required design resistance. The 3 ft diameter pile, which had to penetrate deeper into the glacial soils, was therefore isolated from the soils outside of the 5 ft diameter pile during driving. This approach reduced vibration and settlement of the existing viaduct. Vibration and settlement monitoring was performed during test pile installation to confirm that settlements and vibrations were within acceptable limits. During pile driving, no viaduct closures were required, and no settlement or damage to the viaduct occurred.

The next major hurdle to overcome was dealing with lateral forces caused by the liquefied soil on the foundations. When soils liquefy, they also tend to flow downhill (a phenomenon called lateral spreading). Although this site was relatively flat, the liquefied soil would head toward the nearest slope, which was the U.S. Coast Guard slip in Elliott Bay. Numerical computer analyses indicated that the ground could move laterally toward the west by as much as 1 to 4 ft when the design earthquake hit. On their way west, the liquefied soils would push on the bridge foundations, imposing

lateral forces that would be too high for the structural design to accommodate. Trying to improve the ground to stop the liquefaction was not economical. Making the piles larger or deeper could not be done because they were already maximized in these respects. In the end, a method of shielding the foundations against the lateral spreading forces was selected.

Shannon & Wilson engineers performed dynamic soil-structure interaction computer analyses to evaluate ground improvement configurations that could isolate the bridge foundations from the lateral spreading loads. The analyses indicated that the deep soil mixing (DSM) method of ground improvement (using soil mixed with cement) would be effective in preventing excessive loading on the foundations. The DSM process would be carried out in cells surrounding the foundations. This unique use of ground improvement was innovative and had not previously been performed for a WSDOT project. The ground improvement cells were to extend to a depth of 50 to 100 ft around eight foundation groups that were within the lateral spreading zone.

The ground improvement was carried out in two phases using both DSM and jet grouting. DSM is performed by lowering a mixing paddle assembly into the ground that simultaneously disturbs the soil and mixes it with cement grout. The assembly is then removed in slow steps as more grout is added and mixed with the soil. The result is a soil-cement column with an ultimate compressive strength of at least 300 psi. To build the complete cell around the bridge foundations, overlapping 2.75 ft diameter columns were installed to achieve a 5 ft wide cell wall. To provide stiffness (Continued on Page 94)

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(Continued from Page 83) to the system, 2.5 ft wide interior cross-walls also were constructed.

For the design to work for the final bridge configuration, each cell around a southbound bridge foundation had to be structurally connected to its counterpart around the northbound bridge foundation (which was to be constructed more than one year later). Since the DSM method cannot drill through an area that has already been improved, there was a gap between the two sides that needed to be filled. The solution selected was to use jet grouting, which is performed by pushing, drilling, or jetting a grout pipe into the ground and then forcing water, air, or a combination of the two through the pipe to erode the soil. As the soil is eroded, cement grout is injected to mix with and replace the eroded soil. The result is a column of grout that can be even stronger than the columns created by DSM. As an added benefit, the erosion of the soil could be performed directly against the previously constructed DSM columns to create a tight connection between the two sides.

The foundation challenges for the bridge were successfully met with structural and geotechnical innovations. The remaining seismic challenge for the project was providing approach embankments that would be stable during and after the design seismic event. The approach embankments at the south ends of the bridges needed to be up to 28 ft high to connect to the bridge abutments. Because of the existing railroad tracks and roadways, the embankments had to have vertical sides, which, as mentioned previously, were to be constructed using MSE walls. These had to be constructed in three phases so that traffic flow could be maintained. Another complication was that the approach embankments at the north ends of the bridges would pass over two major sewer pipe alignments that could not easily be relocated.

Slope stability analyses indicated that the 28 ft high embankments were stable under static loading conditions. However, the analyses indicated that any embankment higher than about 15 ft could fail when the soil liquefied near the end

of strong ground shaking. Improving the ground under and around the embankments would be difficult because of the presence of the existing viaduct, utilities, railroads, and other structures. Other issues included potential loading of existing utilities under the embankments and an estimated 6 to 12 in. of settlement that could occur during each successive embankment stage. After many ideas were considered, the use of lightweight fill to construct portions of the embankments became a very attractive option. Lightweight fill would not only reduce the load on the ground but also mitigate the stability, settlement, and utility loading problems.

Expanded polystyrene (EPS) geofoam was selected as the lightweight fill because it weighs less than 2 lb per cubic foot. EPS is a type of plastic foam and is typically formed in large blocks at the factory and brought to the construction site for stacking. EPS blocks can be easily cut and shaped to fit any embankment configuration and can be placed at rates of up to 1,000 cu yd per day, much faster than a gravel borrow embankment supported by an MSE wall. After the EPS blocks are placed, they are covered with plastic to protect them from degradation as a result of fuel or oil spills, and then a roadway pavement section is constructed over the EPS embankment. Next, fascia walls are constructed in front of the EPS to impart aesthetic appeal and provide additional protection. Because EPS geofoam is roughly $1/50$ to $1/100$ the weight of gravel borrow fill, the load applied to the subgrade below the embankment is much smaller than if gravel borrow were used for the full embankment height. EPS was also advantageous in that existing soil could be excavated and replaced with EPS to create a condition whereby no net increase in load would be applied to subsurface soils and buried utilities. This weight-compensating approach was used for the northern embankments that extended over the existing sewer pipes.

Although material cost for an EPS embankment is more than that for conventional MSE-supported gravel borrow embankments, EPS can be installed faster. The use of EPS also eliminated

the need for ground improvement beneath embankments and for preloading to mitigate settlement. Because very little settlement occurred during the embankment construction, pavement and utilities did not need to be replaced. The use of EPS therefore shortened the project schedule while lowering cost and risk.

The geotechnical challenges of the H2K project were successfully surmounted through innovative design and construction approaches. As a result of close coordination on the part of Shannon & Wilson, the WSDOT, and Parsons Brinckerhoff and the cooperative spirit evinced by the general contractor—the Seattle office of Skanska USA Civil—the project was successfully completed in October 2012 within budget and one year ahead of schedule. The bridges are currently functioning to maintain traffic on Route 99 through the construction zone for the Route 99 bored tunnel project. After the viaduct along the waterfront is removed, in 2016, the H2K bridges will be connected to the bored tunnel to fully restore a vital north-south transportation lifeline through downtown Seattle. **CE**

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PROJECT CREDITS **Owner, structural engineering, and construction management:** Washington State Department of Transportation **Geotechnical engineer:** Shannon & Wilson, Inc., Seattle **Civil engineer:** Parsons Brinckerhoff, New York City **General contractor:** Skanska USA Civil, Seattle