CROSSING THE NARROWS

The new Tacoma Narrows Bridge, in Washington State, is one of the first in America to use the design/build delivery method and the first in the world to complete, side-by-side bridge models in a wind tunnel. By Thomas Spoth, P.E., M.ASCE, and Tim Moore, P.E., S.E.

It is likely that every American engineer can recall the film of the suspension bridge to cross the Tacoma Narrows, which separates’ southern part of the Olympic Peninsula. That structure opened to

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stunning collapse, the event shook the engineering community and the profession’s understanding of wind-induced forces in an elegant type of popularity at the time: the suspension bridge.

The event spawned investigations, studies, debate, and rancor among engineers—a much better understanding of how the flexibility of such structures—both vertically and horizontally—can give rise to extreme oscillations. Subsequent generations of suspension bridges have benefited from far more rigorous understanding of the relationship between span widths and lengths in these crossings.

Perhaps no bridge owner has been more cognizant of these changes and more prepared to prevent similar disasters than the Washington State Department of Transportation. In 1950, it opened a suspension bridge replacement for that first bridge in 1950. It was the bridge’s deepwater caissons and above its submerged debris field. Last year, completion of a new Tacoma Narrows Bridge, which will alleviate traffic congestion.

In this recently completed project, the WSDOT benefited not only from the gained in the decades since the original bridge’s collapse but also from a relitigation of the possibility of problematic oscillations induced by even slight changes in the relationship between span widths and lengths in these crossings.

The need for additional traffic capacity across the Tacoma Narrows was recognized in 1993 several proposals were issued under a special provision of a Washington State Department of Transportation public-private proposals to develop transportation infrastructure projects in the state. (See “New Tacoma Narrows Bridge Offit Engineering, September 2007, pages 16–18.)

On September 25, 2002, the WSDOT issued a notice to proceed, directing TNC—a 50:50 joint venture of Bechtel Infrastructure Corporation, of San Francisco, California—to design and construct the new suspension bridge. TNC retained Parsons/Hewlett-Packard Transportation Group—part of Parsons, of Pasadena, California—to design the bridge and provide other services.

The new suspension bridge has a main span of 854 m and carries Route 16, the direction from Gig Harbor toward Tacoma. The new bridge is one of the most structurally innovative in North America to be constructed under a design/build contract, and it is a model of cost-effective manner, something that might not have been possible otherwise. The bridge testifies not only to the effectiveness of modern engineering and the advantages conferred by cooperative planning and teamwork.

Early in the concept stage, a cable-stayed bridge was considered, but it was determined that the structure would not have the same aesthetic appeal as a suspension span, especially in light of the new bridge’s proximity to the 1950 bridge. The basic configuration of the suspension bridge was then served as the basis upon which the design/build approach was developed.
The bridge was originally designed to have one lane for high-occupancy vehicles for the other traffic, all traffic traveling eastward; the 1950 bridge would accommodate traffic entering from Gig Harbor and exiting at Tacoma. Eventually public participation in the final design details led to the inclusion of design features that will facilitate the construction of a lower level with shoulders and maintenance access lanes or, as mentioned above, major structural elements of the bridge, including the towers and foundation superstructure framing, were designed to physically accommodate the sector system would have to be added to fully support the lower level should the analyses, including seismic and aerodynamic studies, were conducted to support elements for these potential future loads.

Early in the project the design/build team tackled the challenge of determining the foundation type for the two main towers of the new bridge. Two prominent details: large-diameter drilled shafts and deepwater gravity caissons. Because of site conditions—including very deep water, swift tidal flows, geotechnical issues for boulders to conflict with foundation locations, and the overall design and construction teams advanced two competing initial designs and then evaluated possible foundation design and construction scenario. This approach enabled each of the design teams to evaluate the design of both the new structures.

The soil conditions at the caisson locations result from glacial deposits of silt.
depth to bedrock is estimated to be roughly 550 m. The soils in the upper 5 moderately dense to dense, while the materials encountered at greater depth they were glacially overridden by about 1,000 m of ice. These very dense geocompetent bearing stratum for the caissons and made it possible for the caissons proceed efficiently using conventional clamming equipment.

Each of the two caissons consists of a 5.5 m tall steel armored cutting edge, provided buoyancy during construction, a submerged reinforced-concrete caisson stories high encompassing integral dredge wells, and a 4.6 m thick caisson pedestal of the tower base. In plan, the footprint of each caisson is 24.3 by 35.8 m.

The new bridge caissons are a mere 20 m from the foundations of the 1950 bridge showed that while the scour hole was to go to reach its full potential. Site investigations using underwater video revealed that a layer of gravel had formed on the seabed and was resisting new caissons required a level bed on which to land, it was necessary to excavate seabed, which would expose the entire area, including the existing bridge, to during periods of low tidal flows, the seabed was leveled and a thick layer of the areas around both the new and the existing bridge foundations.

The caissons for the new bridge were constructed over the water, in position concrete in lifts, slowly sinking the caisson to the mud line, and then excavating in the caisson to allow the caisson to penetrate the soils to the required embankment elevation was reached, the lower 7.5 m of the caisson was filled with a seal. During the sinking operations, each caisson was held in place by a radial force provided for every lift of the caisson concrete. The positioning of the caisson Positioning System (GPS) receivers and land surveys, the tolerances being l

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The steel cutting edge was prefabricated in a dry dock operated by Todd Shipyards, a shipbuilder based in Seattle, and towed to Tacoma, where an additional 12.4 m was constructed on top of it. Each caisson was later towed to the bridge site, moored to an extensive anchoring system to hold it in place while construct

The schedule-driven requirement to establish the final caisson tip elevation caissons was directly related to the hydraulic and scour studies. The design that a determination of the final caisson tip elevation was critical to advancing the design, to planning and scheduling the construction activities, and to procuring construction materials and equipment. Through the design/build environment were simultaneously launched to arrive at the correct solution for the caisson formation of groups in which representatives of the owner, the designer, and the construction issues, established the depth of scour, studied the depth and the structure’s robustness with respect to ship impacts and seismic construction means and methods were to be employed, and planned all activities associated with the caissons.

To reduce costs, maintain the schedule, and impart aesthetic appeal, the bridge towers would be of high-strength concrete with steel and precast concrete. To the best of our knowledge, this is only the second time that a major suspension bridge in the world has used reinforced-concrete towers in a zone of high seismic activity. The new bridge over California’s Carquinez Strait, which opened in 2003. (See “Suspension Bridges,” Engineering News-Record, June 2000, pages 60–65.)

ELEVATION
The towers are 154 m tall and each leg is rectangular in cross section with a seismic performance and overall ductility of the legs were achieved by steel highly confined concrete for each tower leg wall. Moreover, each corner of steel corner reinforcement, which provides a level of confinement equivalent cross strut that connects the legs of each tower has also been posttensioned performance.

In conformity with project standards that were jointly developed by the owner contractor, the aesthetic treatment of the tower legs included a pigmented color. Furthermore, the cross struts were formed with X-shaped recesses to complement that of the existing steel bridge. To increase the bridge’s long frequency of required maintenance, the project’s standards called for a high microsilica concrete as well as an epoxy coating for the bar reinforcement protection against corrosion.

Each of the two main suspension cables of the new bridge comprises 8,816 resulting in an overall cable diameter of 521 mm. These cables are anchored embedded deep within the anchor blocks of the gravity anchorages. The granular soil consisting of very dense sand and gravel located at both ends of the bridge resists the pull of the main cables. The anchorage excavations are retained shotcrete that made it possible for the mass concrete of each anchorage to be shotcrete that had been applied to the soil, eliminating the need for addition.

Each anchorage encompasses 15,700 m³ of cast-in-place reinforced concrete.

The design team faced a unique challenge in ensuring that the bridge would a seismic event but also during a landslide induced by such an event along the Narrows. To guard against this threat to the completed bridge, a 6 m deep knickpoint over the bottom of the gravity anchor block, thus securing the anchorage deep within the hillside. To further guarantee the safety of the anchorages under service and design, the design team retained Shannon & Wilson, Inc., a geotechnical engineering firm based in Portland, Oregon, to perform detailed geotechnical studies that included a three-dimensional soil-structure interaction model advanced computer modeling techniques. The detailed computer model included the initial anchorage settlement, the predicted displacements induced by seismic, and the ability of the bridge to accommodate a future lower-level design.

Since construction of the anchorages was a vitally important project milestone, the owner contractor began excavation before the final details of the cable anchorages were completed. To achieve this objective, TNC and Parsons/HNTB collaborated to advance the project standards relating to the excavation limits. This early release of the overall anchorage construction to commence on time; the final design details were issued at a later date.

The main cables were constructed of high-strength galvanized steel wire of the air on-site to form 19 strands per cable. Each strand is composed of 464 wires per cable. The strands were compacted into a single circular cable. With
chambers, the individual wires are looped around semicircular steel strand rods embedded deep within the anchor blocks.

The cable wires are further protected from corrosion by a multilayered system of urethane-based waterproofing paste, zinc-coated steel wire wrapping, and a layer of elastic polymers.

Cast steel saddles cradle the main cable wires passing over the tower tops. Trough surfaces are machined along a vertical radius to form troughs supporting the splay saddles with multiple curved surfaces. The splay saddles carry the main cables into the anchor strands toward the correct strand shoes. The splay saddles rest on seven reinforcing rods into a steel base plate.

During the construction of the anchor blocks, steel tubes and anchor frames were used to receive high-strength steel anchor rods, which in turn receive the strand shoes and transfer the force back to the anchor block. Prior to the spinning of the main cable strands, the tubes, and their ends were secured in order to anchor the strand shoes. After the tubes were erected, the space between the anchor rods and the interior walls of the tubes were protected by a multilayered system of waterproofing paste, zinc-coated steel wire wrapping, and a layer of elastic polymers.
Cast steel cable bands secure the main cables in their compacted shape and ropes that support the deck. Slip tests were performed to quantify the repres bands relative to the clamping tension and ensure adequate performance in typically take the form of zinc-coated structural wire rope 41.3 mm in diam consists of either two or four lengths of rope, each yielding four rope termi suspenders consist of two lengths of rope that are looped over the cable ban suspenders consist of four lengths of rope anchored to cable band lugs using input from the public not only was instrumental in defining the need for l the owner decide that the new bridge should complement, rather than rep These criteria led the design/build team to a unique solution that includes stiffening truss with an integral orthotropic steel deck, a feature that makes design produced an efficient structural system and accommodated off-site fi some more than 36 m in length. The entire 1,646 m of continuous structure delivered in 46 segments. The segments were delivered to the project site as SWAN-class vessels (semisubmersible vessels that can accommodate loads Once on-site, the segments were lifted into place and joined to form the con new bridge. The design typically used conventional steel of grade 50, permi detailing that facilitated fabrication. However, in areas of high structural de of high-performance steel of grade 70.

Some structural modifications of the bridge segments were made to take int conditions during ocean transport. Temporary attachments to the permanent to help the steel segments make the trip from Koje, South Korea, where the; Rather than adding new members to the existing design, the fabrication and collaborated to strengthen certain elements of the permanent structure to ac operations.

The Tacoma Narrows bridges are located in a unique hydraulic setting, one fluctuations exceed 5 m across a 40,000 ha area of the Puget Sound. This h current flow rates of 120,000 m³/s and flow velocities reaching 3.7 m/s. In s hydraulics are complicated by the new bridge foundations, which are locate existing foundations just 20 m away, and by the fact that the caisson alignm skewed with respect to the direction of the tidal flow by more than 15 deg for all of the bridge foundations, the team was required to ensure channel st depths were determined by obtaining measurements at the site, including ve channel bed material analyses, and a bathymetric survey; by developing a d computer simulation for Puget Sound as a whole; and by physical modeling at Colorado State University.

Tide levels were estimated by using field data and harmonic analysis, but th on frequency. To obtain the frequency-based tidal variations required for a from a gauge in Seattle going back 100 years were used. The computer moc using an underwater acoustic current Doppler profiler, a type of sonar that r range of depths. The profiler was installed at the site to correlate actual vel tide data with the computer analysis.

Only a handful of side-by-side suspension bridges exist in the world, and n Tacoma Narrows bridges. Nor are the members of the other pairs in such cl only 55 m center to center. For this reason, as well as for the obvious reason bridge’s collapse, rigorous wind tunnel testing of both the 1950 and the 200 rwdi, a wind engineering and environmental consulting firm based in Guelp
stability and the dynamic wind interaction between the structures. Because of this problem, side-by-side full-bridge aeroelastic models, each 7.22 m in length, of-the-art laser cutting and stereo lithography techniques to capture every detail. For the first time ever, two complete side-by-side suspension bridge models provided the needed assurance that the two bridges would not suffer from interference effects and that a safe and economical design could be released.

Because of the complexity of this unique wind loading situation, it was necessary not only for bridge performance but also for the scope of available technology to validate the design. The design/build environment made it possible to establish a team representing the owner, the designer, the builder, specialty subconsultants, and participate in testing at one of the largest wind tunnels in the world—the 9.1 m diameter tunnel operated by Canada’s National Research Council—to oversee the tests.

The project area is in a region of high seismic potential, one that can see shallow crustal earthquakes. The project design criteria included a performance approach that considered both a safety evaluation earthquake (SEE) and an economic evaluation earthquake (FEE). The FEE and SEE correspond to ground motion return periods of respectively 100 years and 2,500 years.

The ground motions were based on a probabilistic seismic hazard analysis that considered sources from the Cascadia Subduction Zone, shallow crustal sources, and those within the subducted Juan de Fuca Plate lying beneath the region. For the S Bridge, the design considered primarily “minimal damage” with some “repairable damage” components and limited permanent displacement or drift of the bridge. The requirement in the case of the FEE called for no damage, requiring essential structural repair. It was also required that the earthquake performance of the bridge was assumed assuming both the current level of the seafloor and the level that would be estimated depth of future scouring were reached.

Compliance with the performance-based design criteria was verified through history analysis that included extensive soil-structure interaction modeling. The analysis verified that the bridges had adequate stiffness to modeling the caissons and towers because these elements represent a significant overall mass participation involved in a seismic event. The analysis verified that the towers had adequate rocking tendencies during peak seismic ground motions was an effective means of combining the forces in the caissons, the towers, and the superstructure during earthquake loading.

By successfully implementing state-of-the-art seismic analysis methods, the performance-based seismic goals are readily achievable through computer-aided design, specifying performance-based goals through design criteria pertaining express alternative levels of seismic performance versus cost were developed. For the Bridge, limits on the residual drift of the towers typically controlled the performance. Although the towers had nominal strain limits were in some cases less than 70 percent of the criteria limits. A not typically specified in bridge design codes, efforts to develop performance from additional studies on the link between strain and drift performance.

The new Tacoma Narrows Bridge is exceptional in that it was designed for. Because this presents unique challenges in the area of maintenance, the desi
extensive maintenance access features into the final design. These include a traveler, tower elevators, stairway and fixed-ladder access with permanent l and grab bars, and an entirely new maintenance facility and workshop.

One particular challenge in this regard was to meet those requirements while weight and use of material. Innovations adopted to achieve these otherwise into the integrated task force environment. As a result, the lower-level lateral br maintenance walkways. The bottoms of the truss chords are configured with wheels of maintenance travelers without the need for a sem of traveler rail. What is more, the configuration of the truss and tower ent the entire span, a significant advantage in future maintenance efforts.

From the beginning of the design phase, construction considerations were made to make fabrication and erection more efficient. The format is ideal for projects of this type—complex, multidisciplinary undertakes that are large in scope and international with regard to the project one entity—the design/build team—retain responsibility and control of the project’s goals and satisfy the owner’s expectations.

Long after the design packages were issued for construction, engineering te contributions, serving side by side with the contractor’s construction staff. In the process, placing its fabrication specialists and welding inspectors in a right of refusal at any time if it determined that fabricated components did not meet project requirements.

The design/builder was able to dispatch teams of engineers, fabrication spe assurance auditors to Koje to work with the fabricators and steel suppliers a fabrication and transportation procedures matched the project requirements. fruitful, and the fabrication met all of the quality requirements as well as the

Regardless of how successful communication was during the design, new issues throughout the construction phase. These often led to improved efficiency for fabrication process. Moreover, field conditions sometimes varied from what was expected, and was required. As a result, a key component of the work included the timely requests and requests for information. These required ongoing design team reasons, since design documents were maintained to serve as the as-built re engineers who served with the design team throughout the design process n approach even more effective.

Parsons
The congestion that was plaguing the existing bridge has been eliminated by crossing, a toll bridge using electronic toll tags. The public has been enthusiastic savings in their daily commutes. The WSDOT considers the project success perspectives, among them that it closely adhered to its schedule, met exactitude was completed for less money than was budgeted. Of particular importance lower cost and its effect on tolls. At the start of the project, the combined W construction budget for the new bridge plus main-line and interchange construction was put at $760 million. Once the upgrading work on the existing over to the WSDOT, it is projected that the overall project construction cost to the public of $38 million. Second only to an impeccable safety record, th one of the greatest outcomes of the project’s approach, which was captured one team.’’

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Project Credits
Owner and oversight: Washington State Department of Transportation
Design/builder: Tacoma Narrows Constructors (TNC), a joint venture of B Corporation, San Francisco, and Kiewit Pacific Company, Omaha, Nebraska
Design engineers, engineering support during construction, and quality joint venture of Parsons Transportation Group, Pasadena, California, and H
Wind performance technical consultant: RWDI, Guelph, Ontario
Fabrication and erection engineering: Nippon Steel/Kawada Bridge, a jo
Geotechnical consulting engineers: Shannon & Wilson, Inc., Seattle
Specialty consultants: Earth Mechanics, Inc., Fountain Valley, California
Consulting Engineers: STD&A, San Diego