

When Lighter is Better

**Bay-area
bridge features
sand-lightweight
concrete segments
with long spans
and a seismically
resistant design**

In the San Francisco Bay area, two world-class segmental concrete bridges are nearing completion. Last winter's issue of *ASPIRE*[™] featured the San Francisco-Oakland Bay Bridge Skyway (Skyway). The second is the 2.5-km (1.5-mile)*-long, 22-span Benicia-Martinez Bridge to be completed this summer. Both are built to withstand earthquakes in high-seismic zones and are considered to be lifeline structures that must remain open to emergency traffic immediately after a major earthquake.

The new Benicia-Martinez Bridge was built to relieve congestion, unlike other toll projects in the Bay Area that were retrofit for seismic needs. When the Benicia-Martinez Bridge is completed, it will carry five lanes of northbound I-680 traffic across the Carquinez Strait between Martinez and Benicia, California. Despite corridor expansions, the existing bridge creates a severe bottleneck for traffic, which the new bridge will relieve.

*The Benicia-Martinez Bridge was designed using SI units. Conversions are included for the benefit of the reader.

Because of their similar construction and time frames, the Skyway and Benicia structures invite comparison. They're both designed as segmental concrete box girder bridges built to withstand substantial earthquakes. The Skyway is renowned for the size of its precast segments, which weigh up to 800 tons apiece, compared to 40 to 60 tons for a more conventional bridge. Benicia-Martinez, though, offers its own unique aspects.

'Lifeline Standards' Used

The California Department of Transportation (Caltrans) required that the Benicia-Martinez Bridge be built to "lifeline standards" because the Green Valley Fault is situated approximately 3 miles east of the bridge. Its location controlled the seismic design.

Although both bridges are constructed primarily using the balanced cantilever method, the Skyway features a precast concrete segmental design and the Benicia-Martinez Bridge is cast-in-place with sand-lightweight concrete. The sand-lightweight concrete uses normal weight sand as fine aggregate and

profile

BENICIA-MARTINEZ BRIDGE / CARQUINEZ STRAIT, CALIFORNIA

ENGINEER: A joint venture of T.Y. Lin International, San Francisco, and CH2M-Hill, Sacramento, Calif. Caltrans designed the northern elevated approach spans.

PRIME CONTRACTOR: Kiewit Pacific Co., Martinez, Calif.

CONCRETE SUPPLIER: Kiewit Pacific Co. and RMC Lone Star for the northern elevated approaches

LIGHTWEIGHT AGGREGATE SUPPLIER: Carolina Stalite Company, Salisbury, N.C.

REINFORCING STEEL SUPPLIER: Regional Steel Corporation, Tracy, Calif.

POST-TENSIONING SUPPLIER: Schwager Davis, Inc., San Jose, Calif.

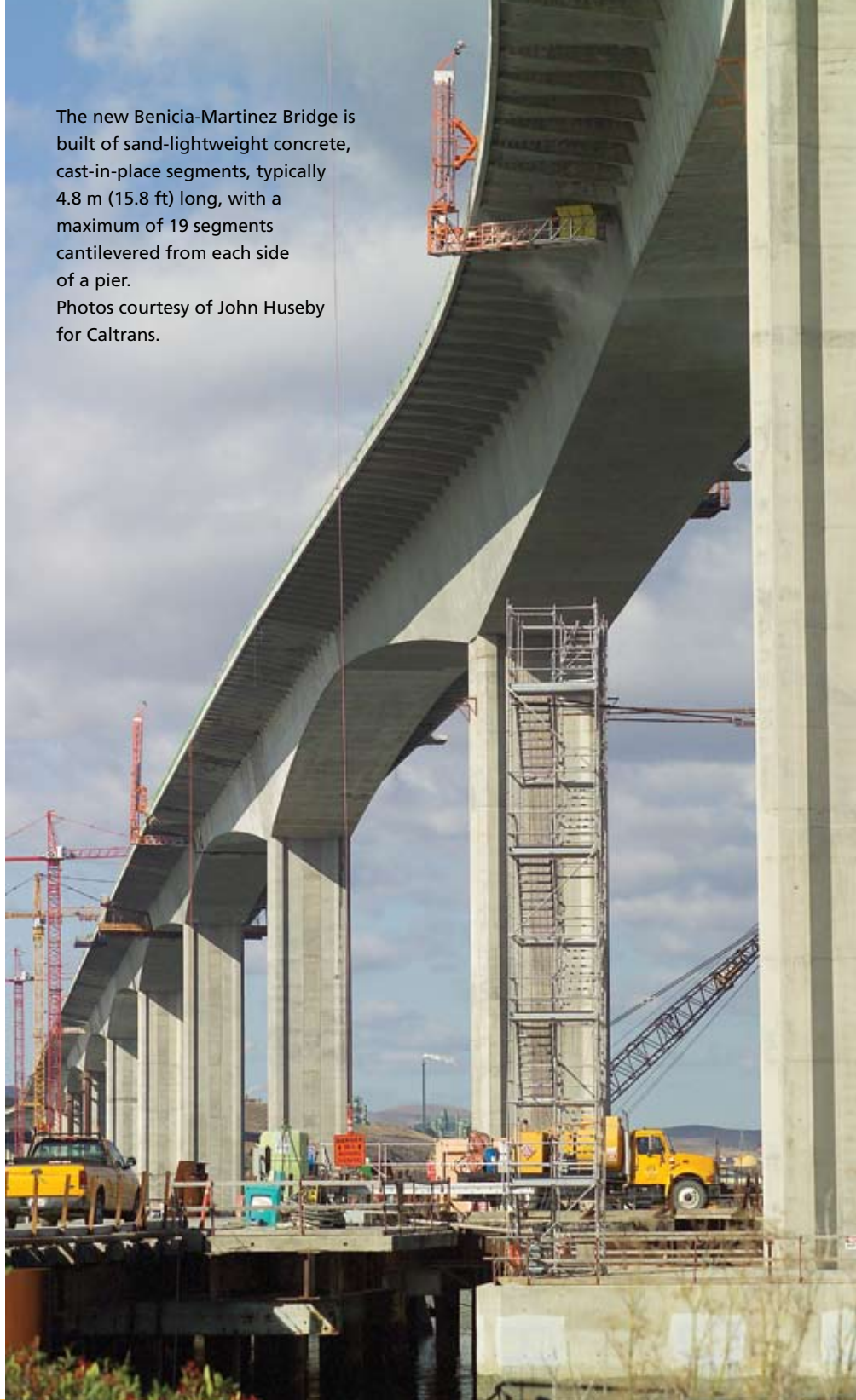
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lightweight coarse aggregate to produce concrete that is lower in density than normal weight concrete.

Span lengths on the cantilever portion of Benicia-Martinez Bridge range from 127.4 to 200.8 m (418 to 659 ft). Including the Caltrans-designed northern approach spans, the bridge encompasses 22 spans, with 16 over water. The segment cross section consists of a single-cell box girder with a total depth ranging from 11.4 m (37.4 ft) over the piers to 4.54 m (14.9 ft) at midspan. The top flange has a width of 24.0 m (78.7 ft), while the bottom flange thickness varies from 1.80 m (5.9 ft) at the pier segment to 250 mm (9.8 in.) at midspan.

Designing 200-m (656-ft)-long spans for cast-in-place segmental construction pushes the limits of the construction technique. The segments at Benicia-Martinez are 4.8-m (15.8-ft) long with a maximum of 19 segments cantilevered from each side of a pier. Add in that these long spans were designed for a high-seismic zone, and the bridge becomes the first of its kind—and a world-class structure.

The new Benicia-Martinez Bridge is built of sand-lightweight concrete, cast-in-place segments, typically 4.8 m (15.8 ft) long, with a maximum of 19 segments cantilevered from each side of a pier.
Photos courtesy of John Huseby for Caltrans.



CAST-IN-PLACE, SINGLE CELL, SEGMENTAL BOX GIRDER / CALIFORNIA DEPARTMENT OF TRANSPORTATION (CALTRANS), OWNER

FORM TRAVELER SUPPLIER: VSL

BRIDGE DESCRIPTION: The main bridge is 2266 m (7434 ft) long by 24.0 m (78.7 ft) wide at the deck and is divided into four frames with lengths of 515.8, 644, 811.4, and 290.3 m (1692, 2113, 2662, and 952 ft), plus a short length at one end.

STRUCTURAL COMPONENTS: 344 cast-in-place lightweight concrete segments, 16 piers, 99 foundation piles in water, average height of structure is about 45 m (150 ft) above water

BRIDGE CONSTRUCTION COST: \$660 million

Four types of bridges were evaluated during design: a steel-truss bridge; a steel box-girder bridge; a concrete cable-stayed bridge; and a cast-in-place balanced cantilever lightweight concrete segmental bridge. Without factoring in the 150-year lifecycle aspect, the initial cost of the cast-in-place, lightweight concrete, segmental bridge was lower than the other structure types, and it was selected.

Lightweight Concrete Adds Length

The designers and Caltrans evaluated the use of 160-m (528-ft)-long spans on the four bridge types, and that length was used to begin design work on the bridge. But the Coast Guard asked for a 200-m (656-ft)-long span for navigational purposes, and the lengths were changed during final design. The lifeline structure criterion also was included during the final design stages.

The key to achieving the extra span length and satisfying lifeline structure criteria was the use of lightweight concrete. The lighter the segments that can be cast, the less massive is the structure that pushes the piers in a seismic event. But finding the right mix design during construction required countless tests and evaluations of more than 30 concrete mixtures. Caltrans, designers, and the contractor investigated a variety of aggregates, admixtures, cement contents, and water-cementitious materials ratios.

125 pcf Density

As finally designed, the specified concrete has a density of 125 pcf, or about 15 percent less than conventional structural concrete. Designers considered using lightweight sand, which could have produced a concrete density of 110 pcf, but it would not meet all the necessary material property requirements. Using normal weight sand produced concrete with a density in the range of 120 to 125 pcf, which would result in much improved concrete qualities, including higher strength, higher modulus of elasticity, lower creep, and less shrinkage.

With all of the elaborate testing efforts, the design and construction team discovered that to meet the modulus of elasticity requirements, the concrete needed a high cementitious materials content. That gave it a compressive strength of between 10,000 and 11,000 psi, where only 6500 psi was needed by design.

Special aggregates were used to achieve the desired properties. The fine aggregate (Sechelt sand) was imported from Canada and the coarse lightweight aggregate (Stalite) came from North Carolina.

Ice in the Concrete

Due to the high cementitious materials content, the concrete produced a high heat of hydration. Yet the specifications limited the maximum concrete temperature during curing to 71°C (160°F) to avoid delayed ettringite formation. To achieve this, the contractor used ice in the concrete instead of water and cooled the concrete with liquid nitrogen. A long wand with a nozzle was used to inject liquid nitrogen, for a few minutes, into the concrete in the trucks. The combination of ice and nitrogen lowered the initial temperature of the concrete to 40 to 50°F.

A system of plastic tubes in the segments carried water to cool the concrete during the curing process. Radiator-like tubes ran through the bottom slab, the webs, portions of the top slab, and the connection of the web to the top slab.

Marine placement of lightweight concrete posed additional challenges. The contractor provided an on-site batching plant on the south shore of the Carquinez Strait. Mixing trucks traveled from the batch plant to a barge and drove on board. The barge, which could carry four loaded trucks each time, transported the concrete to the desired pier cantilever location.

'The key to achieving the extra span length and satisfying lifeline structure criteria was the use of lightweight concrete.'



High cementitious materials content created high heat of hydration, so the contractor used liquid nitrogen with a wand to cool the concrete inside the trucks. Photos courtesy of T.Y. Lin International.



Barges carried concrete trucks to a concrete pumping barge located near the segments being cast. The pump could deliver concrete as high as 55 m (180 ft).

Including the northern approach spans, the 2.5-km (1.5-mile)-long bridge has 22 spans with lengths up to 201 m (659 ft).
Photo courtesy of John Huseby for Caltrans.

Concrete Mix Proportions*

| Material | pcy |
|-----------------------|------|
| Cement | 833 |
| Fly Ash | 49 |
| Metakaolin | 98 |
| Water | 304 |
| Sand | 1233 |
| Lightweight Aggregate | 858 |
| w/cm ratio | 0.31 |

*In addition, a shrinkage-reducing admixture, hydration-stabilizing admixture, and high-range water-reducing admixture were included.

Lightweight Concrete Properties

| Property | Specified Value | Average Measured Values* |
|-----------------------------------------------|-----------------|--------------------------|
| Unit Weight, pcf | 125±2 | 125.2 |
| Compressive Strength, psi | 6500 at 28 days | 10,500 at 35 days |
| Modulus of Elasticity at 28 days, ksi | 3400 min. | 3800 |
| Shrinkage after 180 days, % | 0.05 max. | 0.042 |
| Specific Creep after 365 days, millionths/psi | 0.48 max. | 0.22 |
| Splitting Tensile Strength at 28 days, psi | 450 min. | — |

*From production concrete.

For some placements, the barges were secured to the side of another barge with a concrete pump that pumped the concrete vertically to a height of more than 55 m (180 ft). On board the pump barge, the concrete was remixed before being pumped vertically to the placement location.

For other placements, the barges were secured to the side of a footing, where a tower crane raised buckets of concrete to a remixer on the bridge deck from which the concrete was then pumped horizontally up to 100 m (330 ft) to the intended segment. The trial-batch program produced only a few possible mix candidates that satisfied the specified concrete properties, the high early strength, and the flow characteristics to allow wet concrete to be pumped and placed at the segments. High early strength characteristics helped to reduce the segment cycle times and facilitate faster completion of the project.

The structure made use of midspan hinges between the three-span continuous frames, a unique application especially in a high-seismic zone. These elements provide continuity for post-construction loads (live loading and force redistribution) as well as to lock the cantilevers laterally and vertically together for temperature movements and a seismic event. The hinges are comprised of built-up steel box-girder elements installed inside the box-girder superstructure. During an earthquake, the steel girders transmit transverse and vertical forces across the span, yet they still allow independent longitudinal sliding between each adjoining frame.

Substructure Construction

The main-span foundation consists of large prestressed concrete footings, each supported on a pile group of eight or nine cast-in-steel shell (CISS) piles with rock socket extensions. The piles consist

of two distinct sections, an upper 2.5-m (8.25-ft)-diameter CISS pile with a permanent steel casing, and a lower 2.2-m (7.25-ft)-diameter cast-in-drilled hole (CIDH) rock socket. Together, the two sections extend up to 80 m (262 ft) into bay mud and rock.

The area's geology and topography presented challenges to pile design and construction. In a confined state, the foundation rock had substantial compressive strength, but in an unconfined state, the material would crumble in your hand. The upper sections of the piles were placed by driving permanent steel casings through mud down to the rock. The contractor then used a Menck MHU 4.5 MN (500 ton) hydraulic hammer, the second largest in the world, to perform the driving operation. All mud and soils were excavated from within the steel shell and the lower rock socket construction

Driving the pile casings set off sound vibrations underwater that led to fish being killed. The contractor devised a bubble-curtain apparatus to place around the casing that produced a curtain of air bubbles to attenuate the sound underwater and protect the fish.



commenced through the cleaned out upper section.

To build the CIDH rock sockets, the contractor initially applied a reverse-circulation drilling method. That approach relies on polymer slurry to support the rock socket holes during drilling. But unexpected caving occurred inside the rock sockets, and it was abandoned. The integrity of the rock sockets was critical, because that portion of the piles provides the maximum friction and bearing capacity. The sockets extended up to 30 m (100 ft) into the rock.

To prevent the rock from crumbling and caving, the construction team identified a subcontractor, Malcolm Drilling, which used a fully-cased rotator drilling operation that rotated a temporary casing to the prescribed rock socket tip elevation. The rock was then removed from inside the casing, the bottom of the hole was thoroughly cleaned out, and reinforcement cages were installed. As concrete was tremied into place around the reinforcement, the contractor withdrew the temporary casing, leaving the concrete in direct contact with the rock.

This rotator method had never been used over water. To permit its use, the contractor built five special work platforms over the existing CISS pile casings. Three platforms were used to

build shallow-water piers. Two platforms, with rotators aboard, were used to build the nine deep-water foundations. The platforms each weigh 1800 tons, have nine holes in them for pile installation, and are designed to support the rotator, the digging crane, and other gear. After the rock sockets were completed, the steel-cased upper sections were infilled with reinforcement and concrete.

In addition to the geological demands placed on the substructure construction, the steep rock planes sloped upward from the center of the channel toward land at about a 70-degree angle. This topography demanded deeper, taller columns in the bridge's center section and shorter columns on the landward sides. Generally speaking, tall columns are more flexible, and shorter columns are stiffer. Yet design principles required that all columns have the same stiffness in the event of an earthquake.

One solution was to install steel isolation casings in the mud and rock around the shorter columns. By placing an air gap between the shorter columns and the external casing, those columns can display unrestricted, flexible behavior during a seismic event. Another solution was to simply reduce the cross-sectional area of the shorter columns.

Protecting the Environment

Immediately after the start of CISS pile-driving operations, the remains of several Delta Smelt, Sacramento Split

Tail, and Salmon fish washed up on the shore. The project team quickly determined that the pile-driving noise was harming the fish. Pile driving was immediately discontinued, and the problem threatened to stop the project.

To overcome this obstacle, the contractor worked with Caltrans and other designers to create a bubble-curtain apparatus consisting of a steel framework with pipes, which could be placed around a pile. The apparatus was constructed using four separate quarter-circle sections to facilitate installation down through the pile casing template. Each quarter section of the apparatus consisted of finely perforated circumferential pipe at 5-ft spacing, all connected to a main vertical pipe and supported on a steel frame.

During pile driving, four quarter-circle bubble curtain devices were installed around the steel casing. Air from a compressor was pumped down the vertical pipes into the circumferential pipe to produce a bubble curtain around the pile casing. The bubble curtain provided excellent sound insulation and successfully reduced the sound by 25 to 30 decibels. The result: the fish were protected and construction could proceed.

It required considerable teamwork among the designer, the contractor, and the owner to bring this bridge to a successful conclusion. Issues including concrete mixture design, high heat of hydration, and difficulties with CIDH piles were solved in the design and construction of the Benicia- Martinez Bridge. The innovative techniques discovered and applied in this bridge could also be applied to similar projects in the industry.

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PROJECT

BENICIA-MARTINEZ BRIDGE / CARQUINEZ STRAIT, CALIFORNIA



