San Francisco-Oakland Bay Bridge: OPA Winner

The 2015 Outstanding Project Award (OPA), which recognizes the superior work of DFI members, was awarded for the San Francisco-Oakland Bay Bridge New East Span. The award was presented to representatives from Caltrans and the T.Y. Lin International/Moffatt & Nichol Joint Venture at the DFI 40th Annual Conference on Deep Foundations in Oakland, Calif. A committee selected this project based on size, scope and challenges of the project; degree of innovation and ingenuity exercised; and the uniqueness of the solution to the difficulties of the job.

A bridge across the bay between San Francisco and Oakland was proposed as early as 1872, but it took until November 12, 1936, until it became a reality. The bridge spans to the west of Yerba Buena Island were conventional suspension spans, while the east spans used a steel cantilever truss design and simple steel truss spans. This double-deck bridge served the Bay Area well until 1989. In that year, the magnitude 7.1 Loma Prieta earthquake damaged the East Span of the San Francisco-Oakland Bay Bridge. The resulting interruption to service across the bay demonstrated the vital role this bridge plays in the economic and life safety activities of the Bay Area.

The project owner, California Department of Transportation (Caltrans), determined that the safest, most cost-effective solution was a total bridge replacement. The Engineer-of-Record, T.Y. Lin International/ Moffatt & Nichol Joint Venture, working closely with Caltrans, the Metropolitan Transportation Commission (MTC) and the California Transportation Commission (CTC), was charged with developing a comprehensive design strategy that met the project’s stringent criteria for seismic safety. These criteria included the new bridge’s designation as a regional Lifeline Structure that must open to emergency traffic shortly after the occurrence of a 1,500-year return period earthquake.

The Bridge and Its Foundations

The 3.5 km (2.2 mi) long San Francisco-Oakland Bay Bridge New East Span (East Span), which was completed and opened to traffic on September 2, 2013, carries 300,000 vehicles each day and consists of four interrelated components. These are: the 624 m (2,047 ft) long Self-Anchored Suspension Span (SAS); the 1.9km (1.2 mi) long Skyway that ascends to the SAS from the Oakland shoreline; the 1,289 m (4,229 ft) long Oakland Touchdown (OTD) connecting the Skyway to California’s Interstate 80; and the 470 m

East Span general arrangement
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The foundations and superstructures of the four components of the bridge are interconnected, and so respond in an interactive way. The foundations are designed to experience limited inelastic behavior during even the SEE so as to not require any post-event repair. They are designed to be ductile, so if seismic events or vessel impact do occur, yielding may result, but not fracturing or collapse. Above the foundations, the bridge and its support piers are designed to behave in a safe and ductile manner during these design events, but some limited repairs are anticipated after extreme events.

Foundation Design Considerations
Local soil conditions strongly affected the choice of foundation types. Where bedrock was at or close to the surface, spread footings with drilled piles or rock socket tie-downs were used. Where there was significant soil depth, driven piles were utilized. Because foundation cost was a high proportion of the total cost, emphasis was placed on developing designs and specification provisions that would reduce costs.

Caltrans adopted an aggressive program to provide an early geotechnical characterization of the site and design earthquake motions. Fugro-EMI provided geotechnical site investigation, site characterization and geotechnical engineering services. This enabled the designers to develop marine foundation designs that changed little from the conceptual phase to final design. However, on YBI, because of late access for soils investigation, designs were progressed using assumed soils and then updated as properties became available. The geology along the bridge profile consists of soft Young Bay Mud overlying local sand layers, stiffer Old Bay Mud, Upper and Lower Alameda Formations (layers of stiff clay, silt, dense sand and gravel) overlying Franciscan Bedrock.

Principal design criteria for the foundations required the foundations to resist gravity and operational loads with appropriate factors of safety; to remain essentially elastic during the SEE, and to limit the post-earthquake horizontal displacements of the footings to 150 mm (5.9 in). Cost-based optimization of the Skyway spans
was performed and two aspects of normal practice were refined for the design of the large diameter deep-driven piles. These are test-based pile capacity/penetration and displacement-based SEE design. The measured resistance to driving large piles through clay-dominated formations is not a good indicator of the ultimate capacities of these piles after the dissipation of pore water pressure. This has long been recognized in the design of large piles, where the capacities of the piles have been based on tested soil properties. The measured resistance to driving is commonly in the range of 30% to 50% of the ultimate skin friction capacity. These piles drive unplugged and significant end bearing is available after setting concrete plugs in the piles. This further reduces the value of using resistance to driving as a measure of ultimate pile capacity. Target penetration was, therefore, used as the primary basis of pile driving acceptance. This approach is appropriate where predictable foundation behaviors are known, as in the Lower Alameda formation on the site. It also eliminates uncertainties that are reflected in higher bid prices.

Using traditional procedures, piles are designed as either skin-friction or end-bearing piles. The design of the piles for load combinations of gravity, construction, and deck shrinkage actions was based on the skin-friction capacity and force-based factors of safety. However, the use of force-based criteria was not appropriate for these piles for the SEE because the ultimate capacity of the piles includes high-end bearing in the Lower Alameda Formation in addition to the skin-friction capacity. The post-earthquake settlement of the footings was determined, using the SEE depth-varying ground motion records. In addition, analysis of the effects of wide variations of end bearing confirmed the soundness of this approach and significant cost savings were realized.

Earthquake Response

The seismic design of the foundation was affected by marine footing mass, kinematic pile response, and vertical and battered piles. The dynamic response of the over-water sections of the bridge to earthquakes shows that while the deck sway modes primarily cause axial loads in the piles, the footing sway modes cause most of the pile bending. Bending is significant in the SEE, so there is a strong incentive to minimize the footing mass. Concrete-encased steel footing frames were used rather than reinforced and post-tensioned concrete footings, which would have been much more massive. In order to minimize the footing size, the Skyway foundations utilized slightly battered piles. These are spaced more closely at the footing but provide the spacing needed at depth to avoid detrimental group effects. In addition, it was found that battered piles were needed to meet the post-SEE footing displacement limits.

The time-varying and depth-varying motions of the soil during seismic events cause bending in the long large-diameter piles. This kinematic response was incorporated in the total dynamic response of the soil-pile-structure system under SEE shaking. The design of the piles for this real phenomenon increases the reliability of the foundations over previously-used design methods, particularly at depth.

The east piers of the SAS have vertical piles, while the Skyway has battered piles. This is because the east piers have relatively little dead load and are controlled by pile tension, whereas the Skyway has significant dead load, which reduces tension forces. Also, the soil at the east piers includes a thicker sand layer, which reduces the tension capacity of the piles.

Vertical piles also reduce cyclic axial loads in earthquakes, minimizing the total tension on the piles, with a small increase in pile bending. It is generally preferable to use vertical piles in earthquake designs because vertical piles can also provide a more ductile response during an earthquake than highly-battered piles. In addition, they are easier to install and have lower axial loads. In the design of the Skyway, slightly battered piles were found to be the most cost-effective way of meeting all of the design criteria, particularly the post-earthquake displacement limits.
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The key construction considerations used during the design of the East Span foundation systems included: ease of construction, cost and service reliability. Design decisions were made to provide the contractors with significant flexibility. General and foundation contractors were selected for the separate project component contracts.

The Skyway contractor was Kiewit/FCI/Manson, a joint venture that also constructed the SAS tower and east piers foundations. The SAS bridge contractor was American Bridge/Fluor Enterprises, a joint venture that constructed the temporary tower foundations and the tower footing fenders. The west end of the YBITS and east end of the OTD used more traditional foundations, with shorter spans and smaller piles for more standard soil conditions. Contractors included MCM Construction (OTD1), Flatiron West (OTD2), MCM Construction (YBITS1), and California Engineering Contractors/Silverado Contractors Joint Venture (YBITS2).

Much of the East Span’s route is over water that is too shallow to permit crane vessels to work. Dredging of the bay to increase the draft to permit vessels to enter and work in the regions of the new bridge was a necessity. Caltrans obtained permits that allowed for this dredging, with great care taken regarding the environmental sensitivity of the local ecology.

The construction of the marine foundations for the tower and the east piers of the SAS and the water-level Skyway piers used temporary footing supports and, when required, cofferdams. The vertical piles of the tower and the east piers enabled preinstallation of the steel piles so that the footing frames could be lowered down over these piles. For the tower, temporary casings were first installed to allow the drilling of the rock sockets through the surface soil and rock materials down to an elevation of -30 m (-98.4 ft) for the permanent steel casings of the first stage piles, which were set in the rock with cement grout. The lower, second stage CIDH piles were constructed after drilling their vertical rock sockets, using the permanent casings as drilling casings. After the piles were connected to the foundation frame by welding and filling the pile-sleeve annuli with cement grout, the footing’s encasement and infill concrete were placed in preparation for the later installation of the precast fenders and tower base plate.

The Skyway foundation piles required a separate temporary pile guide frame, supported on independent piles, to guide the piles through the footings during driving. The guide frames included retractable hydraulic guides to enable the free-riding hydraulic hammers to pass as they approached their target elevations. These piles, which required field splice welding, did not touch the footing frame during driving. Several of the westernmost footings of the Skyway were located at the waterline. The remainder, the buried Skyway footings, required partially dewatered cofferdams. Here, after excavation, a gravel bedding was placed to support the footing frames during pile driving and footing construction and a small amount of gravel was used to lock the footings in place.

The YBITS are on land, and while their foundation construction was complex, it was also conventional. The SAS backspan piers on YBI are founded on rock and the deep rock excavation (controlled blasting) was significant in their construction. Mass concrete design required surface and internal tie reinforcement, as well as other measures to control thermal cracking of the footing. Rock sockets were used at the northern westbound footing and tall retaining walls were required around the piers to permit free pier movement during earthquakes.
Pile Size and Installation Equipment

The 2.5 m (8.2 ft) diameter piles used in the marine sections of the bridge were designed to be driven to the Lower Alameda Formation. A free-riding 1700 kJ hammer (no sliding leads) was specified for the deep-driven piles to ensure pile driveability. A uniform 2.5 m (8.2 ft) diameter was adopted for the SAS and Skyway piles to enable standardization of handling and installation equipment and adequate redundancy.

The design of the foundations was necessarily based on assumed methods of construction, prior to the award of the construction contracts. In general, the designs provided flexibility to the contractors for refinements when construction methods were known. Among the options that were considered were: pile installation in one piece versus making field splices, pile installation through the footing frames versus preinstalling the piles, and lowering the footing onto the piles. The possibility of one-piece piles did not affect pile design, but it did require limitations on the locations of field splice welding. To enable the preinstallation of one-piece battered Skyway piles, the footing frames were designed with oversized sleeves. After award, the Skyway contractor opted to install the piles through the footing frames, thus reducing the size and fabrication cost of the frames.

Construction pile loads were considered during the design phase. Additional pile loads are inherently caused by the out-of-balance moments associated with the precast segmental “balanced cantilever” Skyway deck erection technique. These additional pile loads are experienced before full set up pile capacity has been realized. Caltrans' Pile Installation Demonstration Program, performed more than one year prior to bidding, enabled the calibration of the pile friction set-up rate, as well as minimizing uncertainties associated with pile driving energy requirements. Removing these uncertainties helped to reduce construction bids.

Looking to the Future

In an effort to protect native marine mammal and fish species, the Pile Installation Demonstration Program permitted the East Span project to be contracted not only with minimum uncertainties in pile driving hammer energy, but also while enabling methods to be developed that minimized underwater noise levels and their implications. The findings of these studies have contributed to the industry's technical knowledge in a culture of concern for marine fauna during such large-scale marine construction.

The SAS Tower piles and selected Skyway piles contain seismic monitoring equipment, which will enable the California Division of Mines and Geology to collect valuable information and record ground motions during an earthquake. This will assist in the reliability of the design of future infrastructure in California and elsewhere.

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Placement of tower pile footing