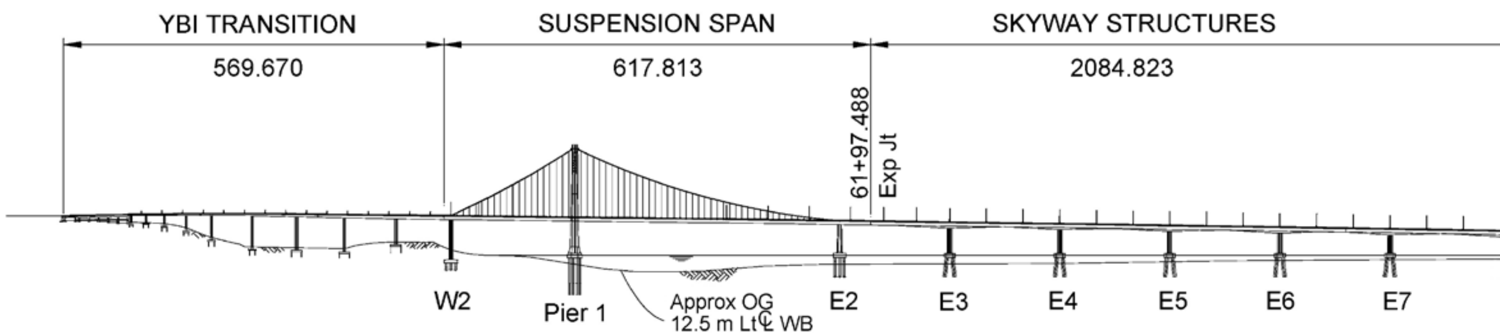


One-of-a-Kind Design

The New San Francisco-Oakland Bay Bridge Eastern Span.

The New San Francisco-Oakland Bay Bridge Self-Anchored Suspension Span

By Marwan Nader, Ph.D., P.E. and Brian Maroney, Dr. Engr., P.E.

How do you design a replacement span that is, in fact, irreplaceable? The combination of stringent seismic safety criteria, gelatinous geological conditions, and a passionate community determined to maintain a long-standing tradition of historic suspension bridges might seem like insurmountable obstacles to innovation. But through well-coordinated community meetings, sincere respect for public desires, and skillful incorporation of state-of-the-art advances in architecture and engineering, the San Francisco Bay Area will soon be home to the world's longest single span, self-anchored suspension (SAS) bridge.

Item	Value
Longest single span SAS	385 m
Longest unsupported span between piers for a SAS	385 m + 180 m = 565 m
Longest effective span for SAS	2 x 385 m = 770 m
Largest cable diameter for a SAS	0.78 m
Longest transverse distance between suspender of a suspension bridge	72 m
Suspension bridge with no connection between deck and tower	First
Four-legged pentagonal-shaped tower	First
Single tower to use the concept of fusing shear links to protect the shafts during an earthquake	First
Largest tower saddle for a suspension bridge	380 tons
Use of kevlar suspender rope in a suspension bridge	First
Longest piles supporting suspension bridge	100 m
Largest looped suspension cable in any bridge	0.78 m cable loop
Largest 3-dimensional PT cap beam	72 m x 16.5 m x 7 m (LxWxD)
Highest effective asymmetry span ratio in a SAS	1 : 4.3
4.5 m wide bicycle/pedestrian path on a SAS	First
Length of steel wire used	30,000 km
Amount of structural steel used	55,000,000 kg

Figure 1: San Francisco Oakland Bay Bridge Self–Anchored Suspension Bridge Statistics.

With a record-setting single span of 385 meters, corresponding to an effective SAS span of 770 meters, the San Francisco-Oakland Bay Bridge Self-Anchored Suspension (SFOBB-SAS) bridge is poised to set numerous world records upon its completion in 2013 (*Figure 1*). Throughout the design process, the engineering team continued to further the practice of suspension span bridge design.

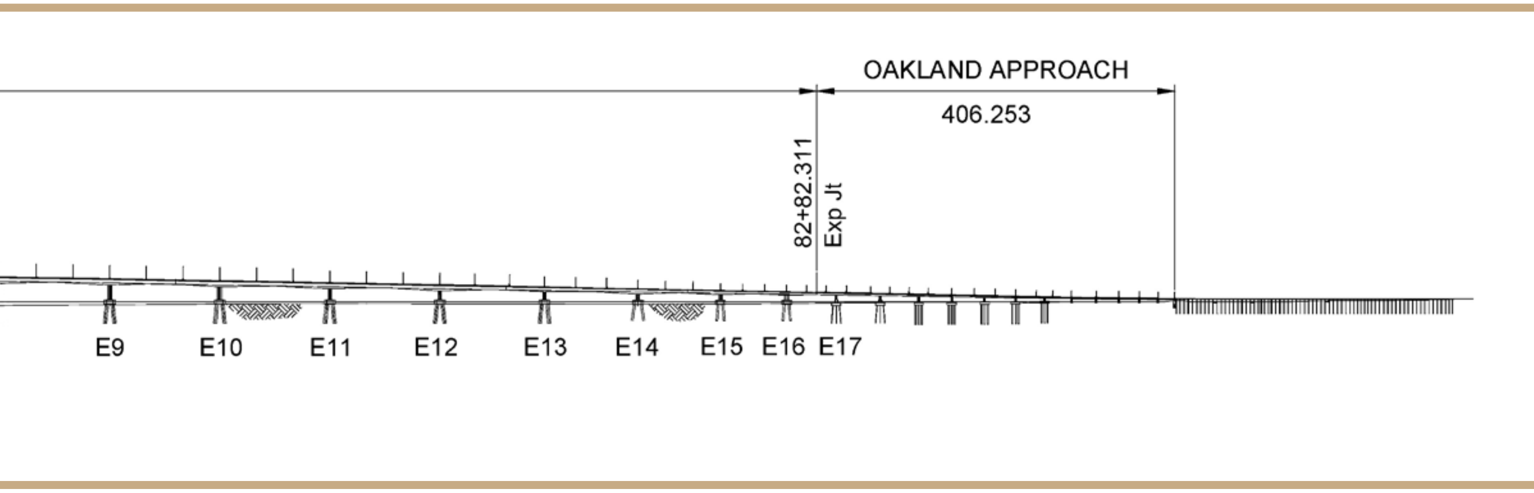
General Features of the East Span SAS

From east to west, four distinct bridge segments make up the entire 3.6 kilometer long, 25 meter wide East Span crossing: a low rise post-tensioned concrete box girder near the Oakland shore; a 2.4-kilometer segmental concrete box girder segment over most of the length of the bridge; a distinctive single-tower, SAS signature span segment over the primary marine navigation channel; and a post-tensioned concrete box girder segment that connects parallel roadways to the existing over-under geometry of the Yerba Buena Island (YBI) tunnel. Because the Bay Bridge carries a designated lifeline route, performance criteria require the new structure to be able to carry emergency traffic soon after the occurrence of up to a 1,500-year return period design earthquake.

The SAS portion of the new East Span consists of dual box girders suspended from cables, which are supported on the 160-meter tower located off of the eastern shore of YBI. As the architectural center of the bridge, the SFOBB-SAS spans 565 meters between piers E2 and W2, with a 385-meters main span over the primary navigational channel and a 180-meter back span (*Figure 2*). SAS will also have a 4.5 meter wide bicycle/pedestrian path.

The longitudinal asymmetry of the bridge subjects pier W2 to a vertical uplift while the bridge is lightly supported on pier E2. Thus, the main tower supports most of the bridge dead load. The uplift at pier W2 is fully counterbalanced by the pre-stressed concrete cap beam at pier W2. This ensures that the bridge is always balanced without relying on the pier to carry any tension. In order to balance the moments in the box girder caused by the 49-meter cantilever at the east anchorage, suspenders do not support a 35-meter segment of eastern end of the main span.

The SFOBB will be the first suspension bridge constructed with no connection between the deck and the tower. In fact, the SAS bridge box girders will be "floating" at the tower, with the suspenders providing the only connection between the box girders and the tower.



This implies that while the tower supports most of the bridge dead load, the tower is not the primary element that resists the box girder's lateral seismic loads. The tower seismic response is mainly governed by its own mass and stiffness. The tower generally behaves as a propped cantilever with a spring resistance at the tower saddle. The gap between the tower and the deck is designed to be large enough to avoid impact during a Safety Evaluation Earthquake (SEE). Piers E2 and W2 are designed to provide the main lateral seismic support of the bridge.

The 0.78-meter diameter cable is anchored to the east anchorage and is looped around the west bent through deviation saddles. The suspenders are splayed to the exterior sides of the box girders and are spaced at 10 meters.

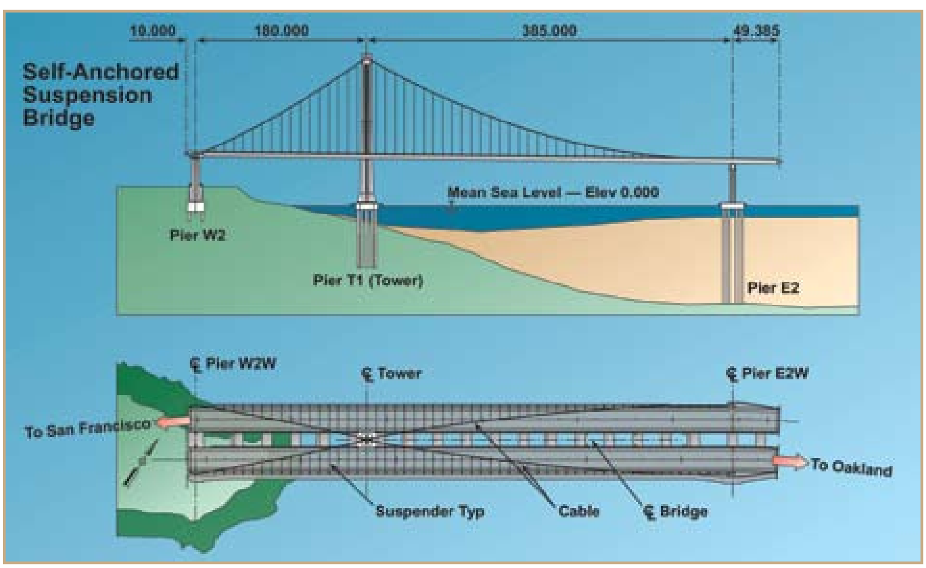


Figure 2: Elevation and Plan Views of the East Span SAS.

Orthotropic Box Girder

The roadways are carried by the SAS superstructure, which consists of dual orthotropic steel box girders. These girders are in longitudinal compression (reacting against the cable tension force) and are a part of the gravity load-resisting system. Transverse diaphragms, spaced at 5 meters, support the orthotropic deck and distribute the suspender loads to the entire box. The box girders are connected together by 10-meter wide by 5.5-meter deep crossbeams spaced at 30 m on center. With a span of 72 meters, these cross beams carry the transverse loads between the suspenders and ensure that the dual boxes act composite during wind and seismic loads (Verendeel truss action).

The bridge carries a pedestrian path on the south side of the eastbound deck. The pedestrian path eccentric load is balanced by a counter-weight on the north side, and the box girders are directly connected to Piers W2 and E2.

Pier W2

At its west end, the steel box girders frame into the W2 prestressed cap beam. The connection between the orthotropic steel box girders and concrete cap beam is subjected to the reaction forces between the cable system and the W2 pier. Additional prestress is added through post-tensioned strands connected at each steel orthotropic rib. The west piers are reinforced concrete columns which are monolithically connected to the prestressed cap beam forming the west bent. The west bent is supported on gravity footings, which are cast into rock with 10-meter long corner piles. A tie-down system, designed to keep the west piers in compression during the design seismic event, connects the west bent cap beam to the gravity footings.

Pier E2

The east bent is comprised of two reinforced concrete piers and a prestressed concrete cap beam. The prestressed cap beam is introduced to protect the bearings and shear keys that connect the box girders to the east bent. The bearings are designed to support the vertical loads (with the capacity to resist lateral loads) while the shear keys are designed to resist all the lateral loads. The bearings are made of a spherical bushing assembly capable of large rotations about the transverse axis of the bridge, thus providing an almost true pin connection. Sixteen (16) 2.5-meter diameter cast-in steel shell concrete piles support the east bent. These vertical piles are about 100 meters long, to date the longest piles supporting any suspension bridge in the world, and are founded on bedrock.

Structural Hinges

Structural hinges between the SAS and the Skyway, as well as the SAS and YBI transition structures, are designed to allow the structures to move relative to each other in the longitudinal direction. The hinges are comprised of compact steel beam pipe sections capable of elastically transferring dead loads and live loads, and structurally yielding under design level seismic loadings in order to protect major structural elements (i.e., fusing).

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Tower T1

The bridge's 160-meter single tower is perhaps its most unique design element. The main tower is composed of four shafts interconnected with shear links along its height, which act as fuses to protect the shafts during an earthquake. The tower shafts are stiffened pentagonal steel box sections which taper along the height, and are provided with diaphragms spaced at 4 meters. These tower shafts are rigidly connected at the top and bottom by tower saddle grillage and tower base grillage, respectively (*Figure 3*).

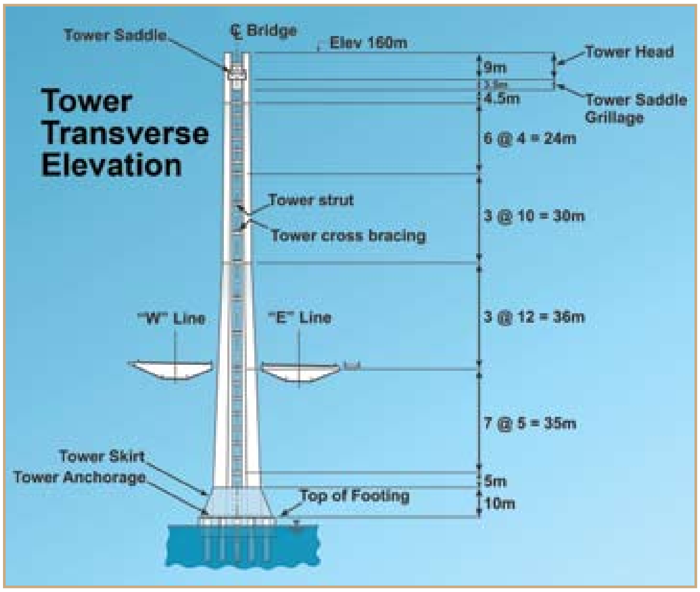

Figure 3: Single Tower with Four Shafts Interconnected with Shear Links.

The tower is fixed to a 6.5-meter deep pile cap with anchor rods and dowels. The pile cap consists of a steel moment resisting frame encased with concrete and is supported on thirteen 60-meter long, 2.5-meter diameter cast-in-steel-shell piles, which are extended and embedded into rock

The tower shear links play a significant role in resisting the seismic loads as well as to supply the tower with the proper stiffness during service load conditions. The tower shear links are designed to satisfy the following criteria:

- Supply the tower with the required stiffness for service load conditions,
- Remain almost elastic during a functional evaluation earthquake (FEE),
- Plastify during a safety evaluation earthquake (SEE); thus dissipating energy and limiting, the damage in the tower shafts (shafts are designed to remain almost elastic),
- To be replaceable after an SEE, if necessary.

In order to satisfy the above requirements, designers evaluated various configurations of the tower, including the strength and stiffness of the shear links as well as their location along the height of the tower. These static pushover studies determined the response of the tower during service loads, wind loads, FEE and SEE loads, providing an optimal layout of these links, as well as their stiffness and yield strength.

Although the tower shafts are designed to remain elastic during SEE, the shafts were designed as stiffened box sections per ATC-32. This insured that the shafts could undergo large inelastic compressive strains without locally buckling.

Figure 4 shows a full-scale test specimen tested at the University of California at San Diego at a rotation of 0.07 radians.

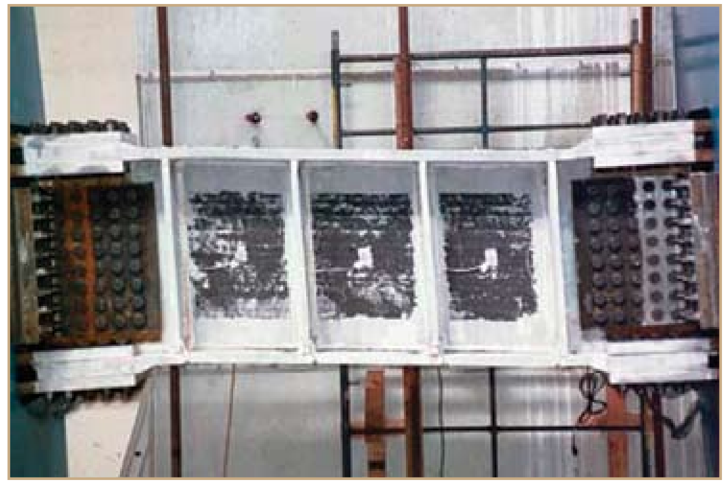

Figure 4: Full Scale Test of Shear Link Type 1 at UCSD.

Seismic Performance of SAS

Seismic analysis was performed using the ADINA general-purpose finite element program. The design team employed three forms of analysis: time history analysis (global model), pushover analysis, and local detailed analysis. Time history analysis was the primary means of analysis for several reasons. Foremost among these is that the bridge foundations are subjected to different excitations. The tower and west pier of the bridge are founded on rock, while the east pier is supported in deep soil. The ground motions at these supports are completely different in character and intensity. This was reflected in the analysis by applying different ground displacement histories at the supports. The designers used pushover analysis to evaluate ductility of critical elements and to establish failure mode sequence. Local detailed analysis was used to establish local strain/stress demands and to evaluate the modeling used for the global model.

The bridge design is based on a limited ductility design, in which plastic deformations are clearly defined and predetermined. The bridge is designed to remain largely elastic with the exception of the east and west piers, which are designed to form plastic hinges. The shear links between the tower shafts are also designed to yield in shear during the SEE earthquake. The maximum rotation demand on these links is 0.04 radians compared with an ultimate rotation of 0.09 radians. The piles were designed to sustain minimal damage (strains less than 0.01 for concrete and 0.02 for steel) when subjected to the SEE displacement demands. The tie down at the west pier was designed with a factor of safety of two.

Figure 5: T1 Foundation (W2 Pier in Background).

Project Status

The SAS Bridge is comprised of three separate construction contracts:

- Land Foundation, including the Pier W2 and foundation
- Marine Foundation, including the footings for the tower and Pier E2 as well as Pier W2
- Superstructure and Tower, including the tower, suspended structure and cable system

The Land Foundation was completed in October 2004. The Marine Foundation is under construction and will be completed in March 2008 see (*Figures 5 and 6*). The Superstructure and Tower contract was awarded in May 2007 to the American Bridge/Fluor Joint Venture and is currently under construction. The East Span SAS is expected to be complete in 2013.▪

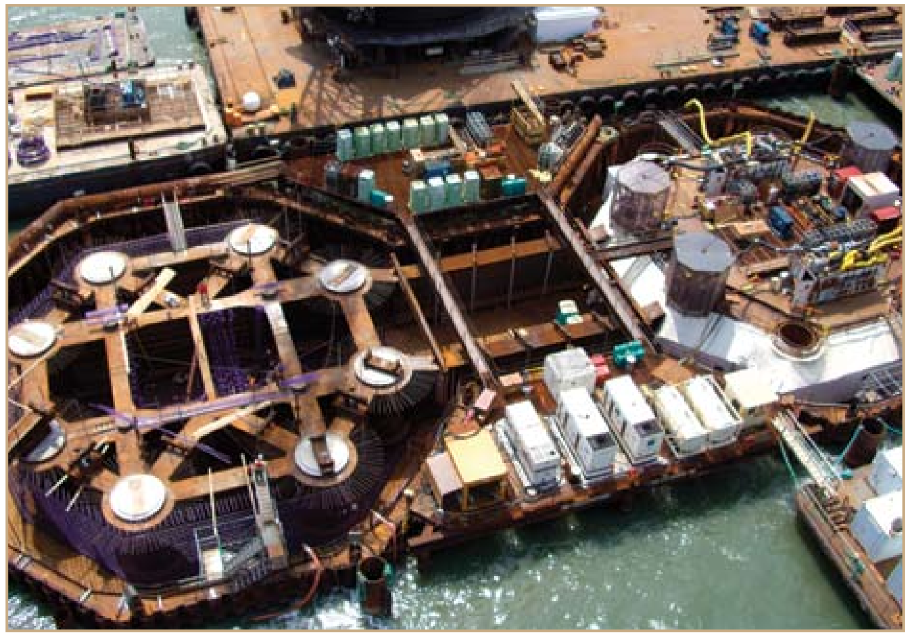

Figure 6: E2 Foundation.

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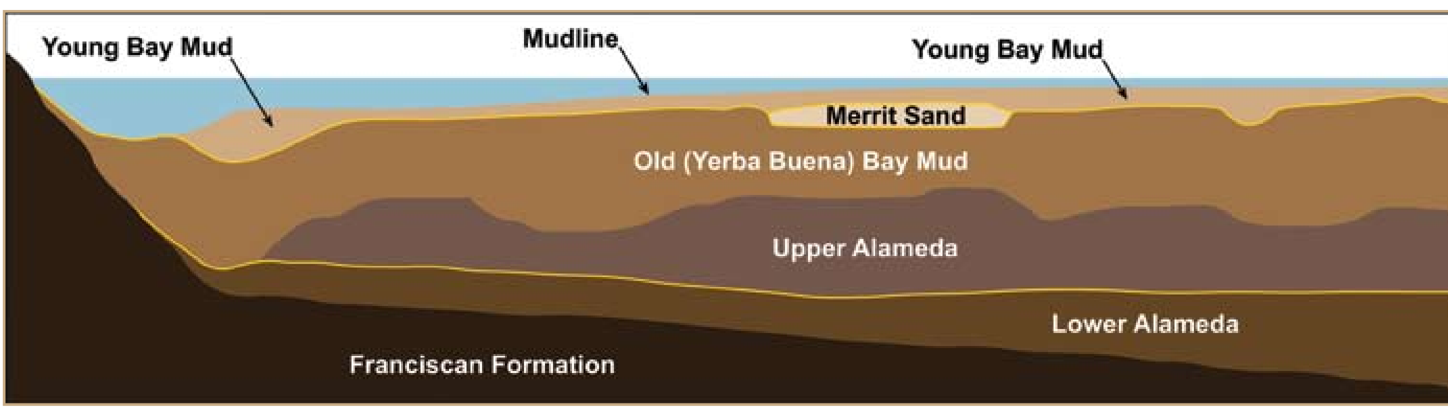
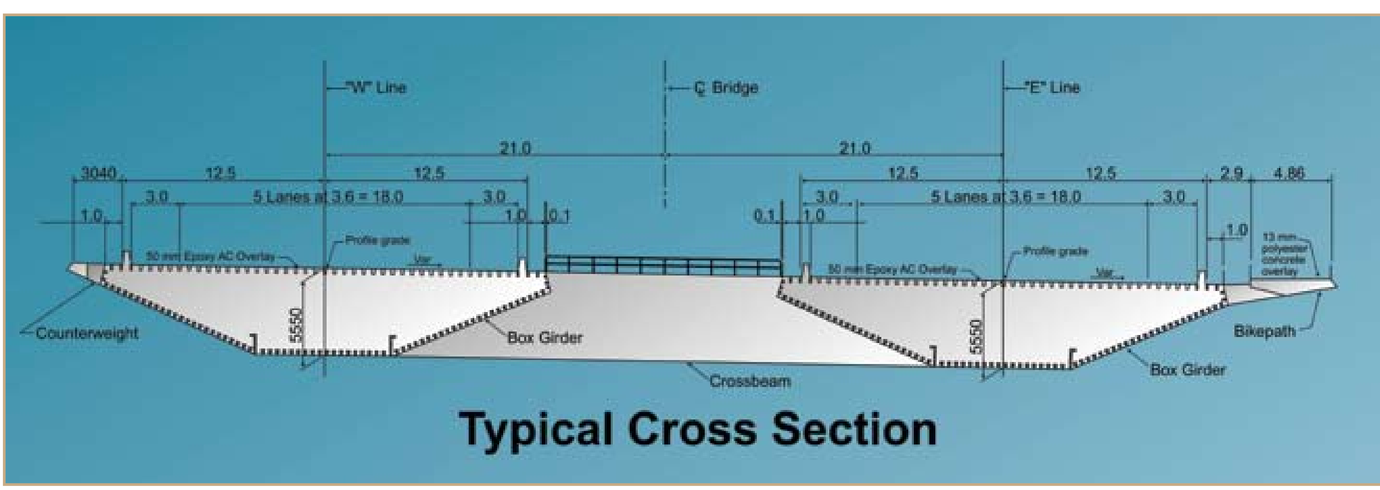
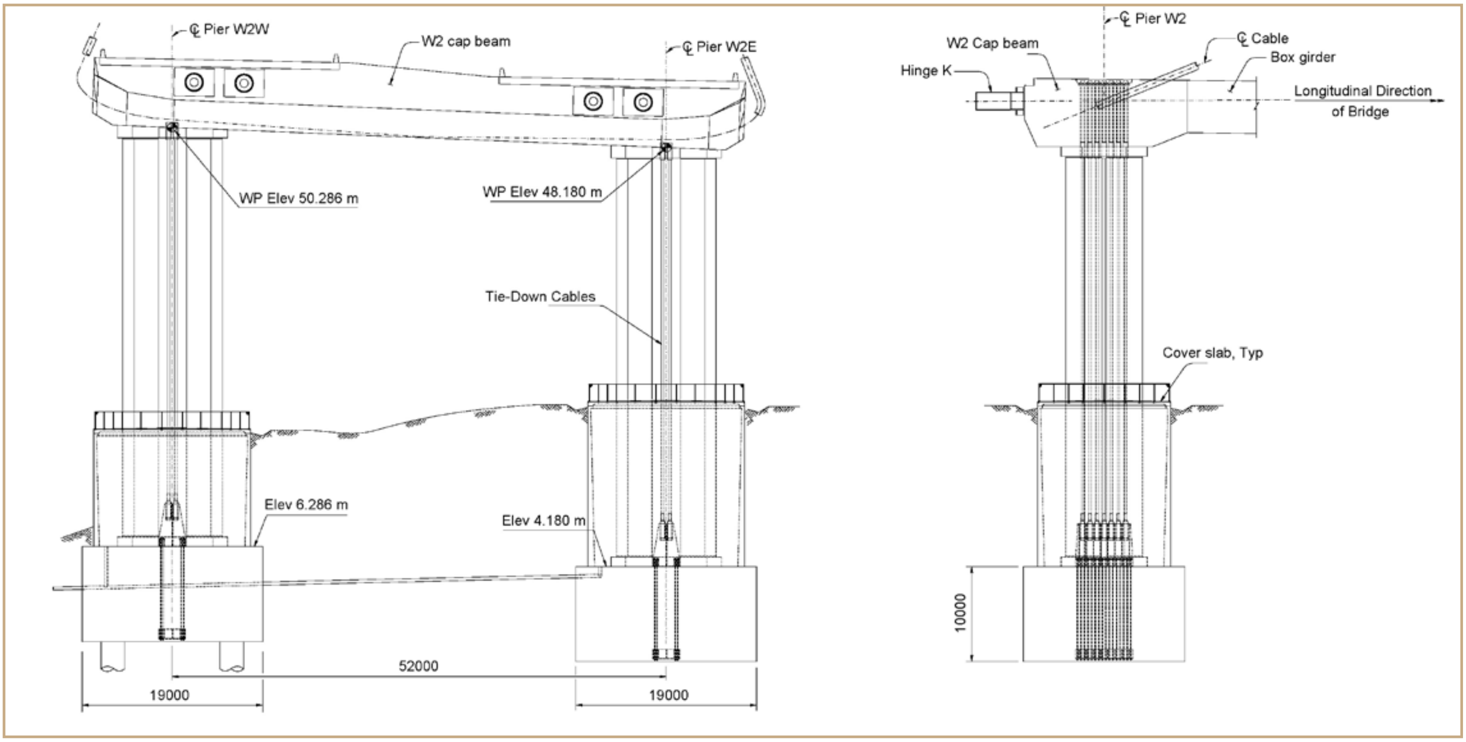


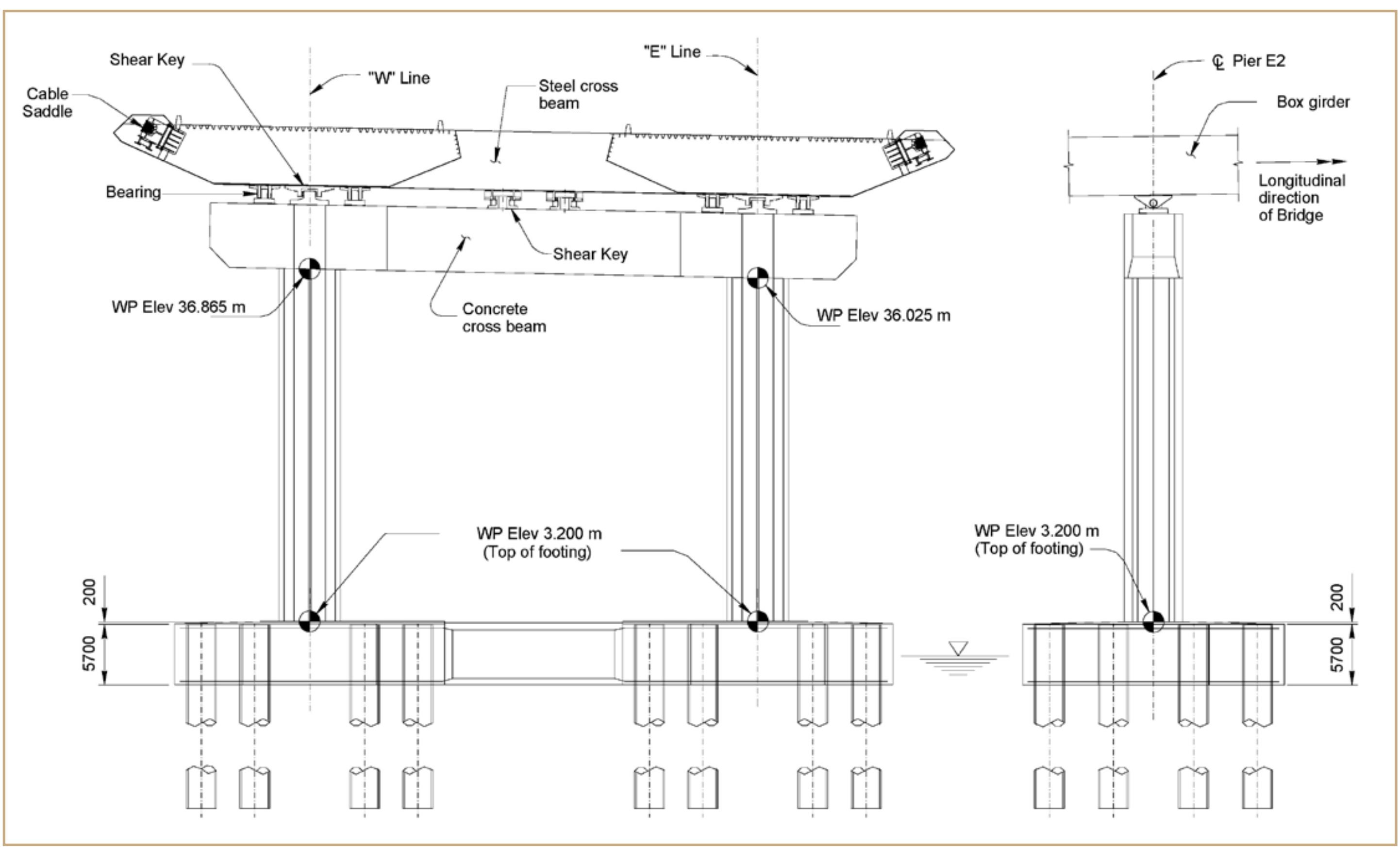
San Francisco - Oakland Soil



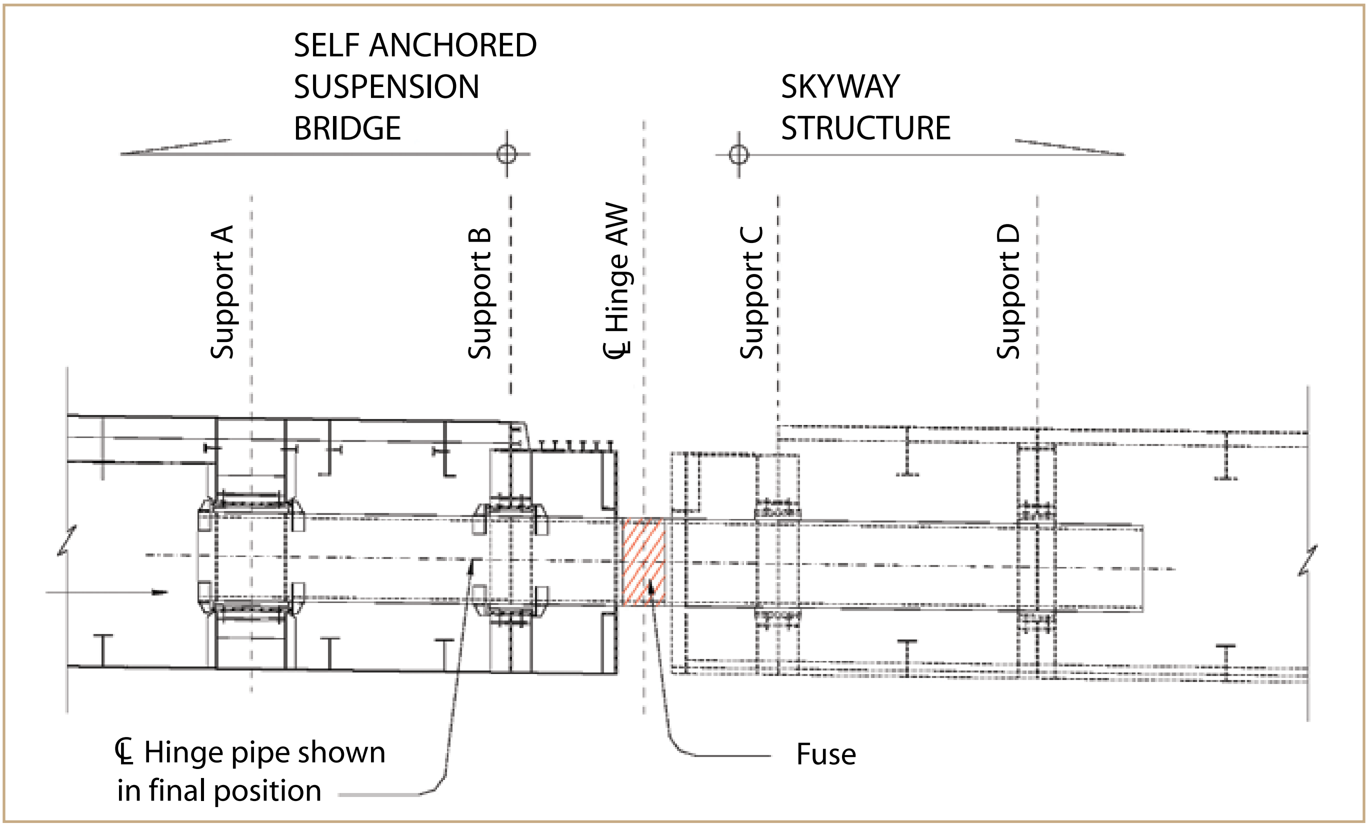
Typical Cross Section



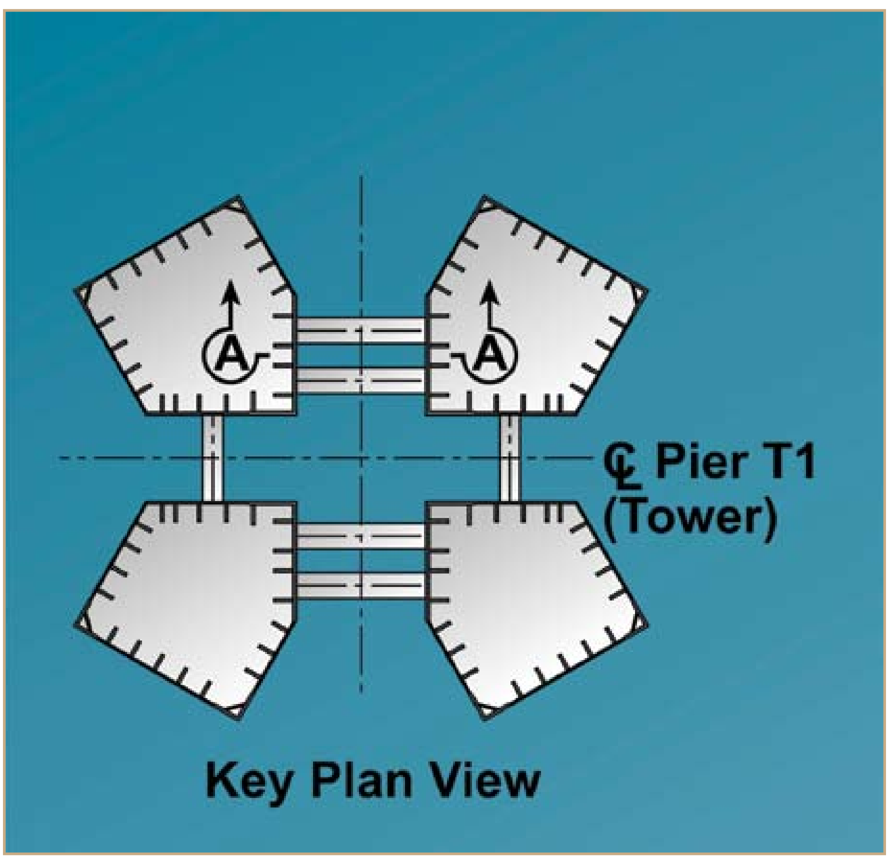
Elevation of the West Bent.



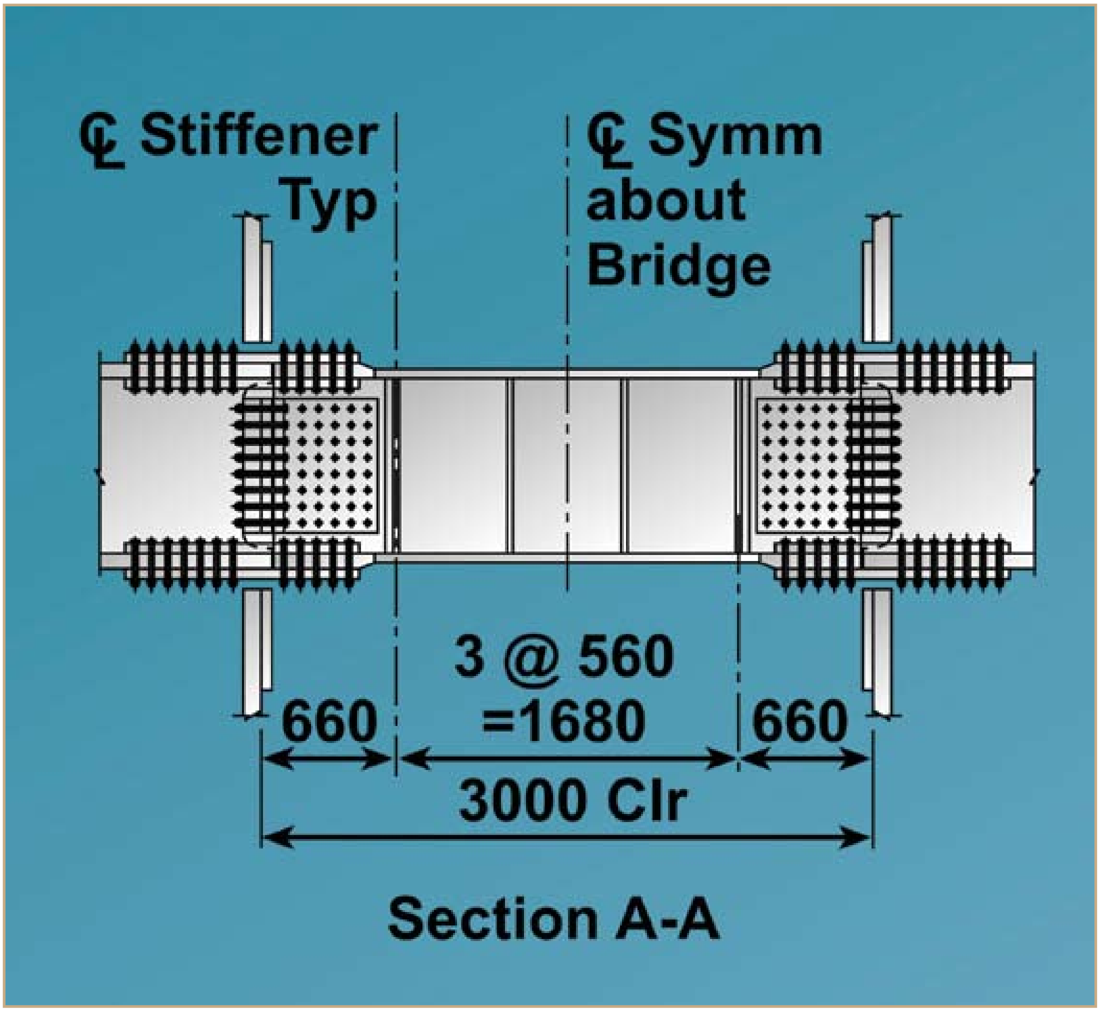
Elevation of the East Bent.



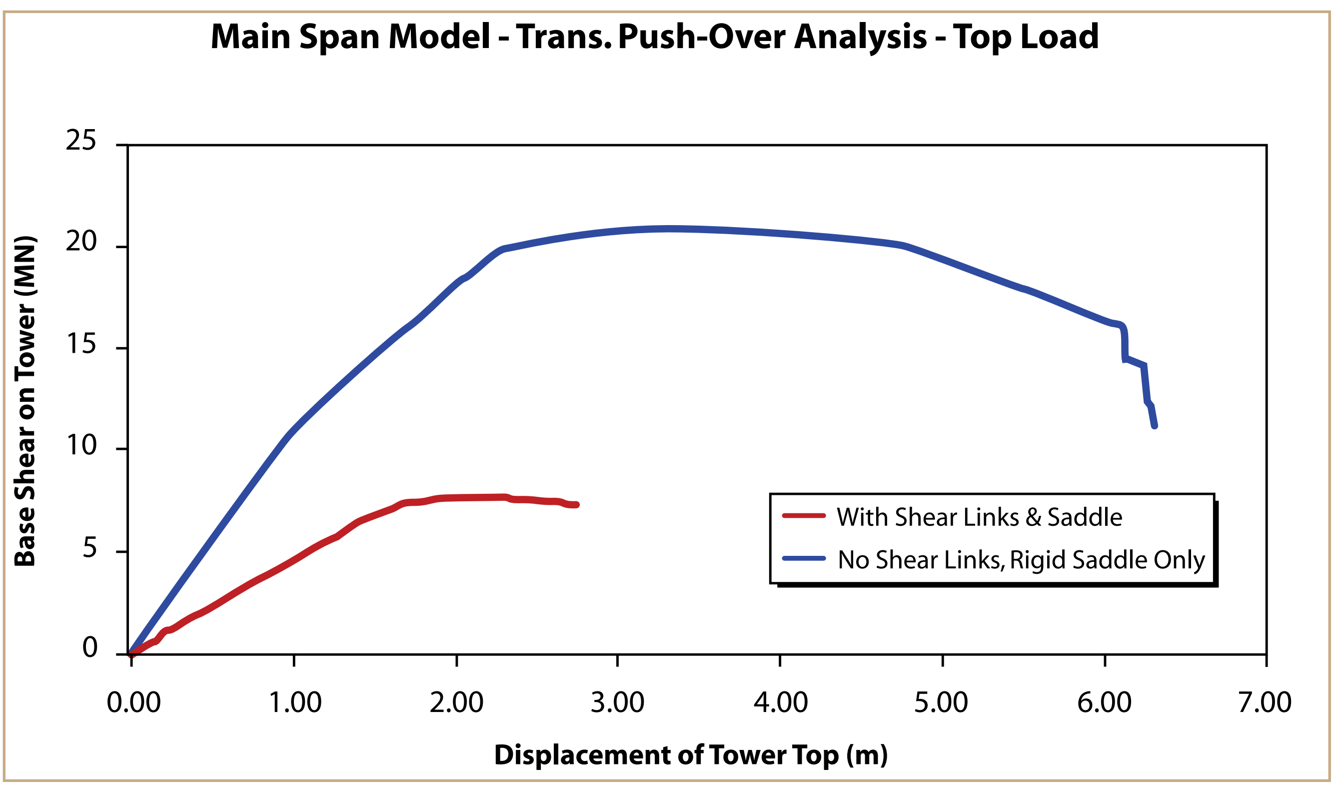
Skyway to Hinge.



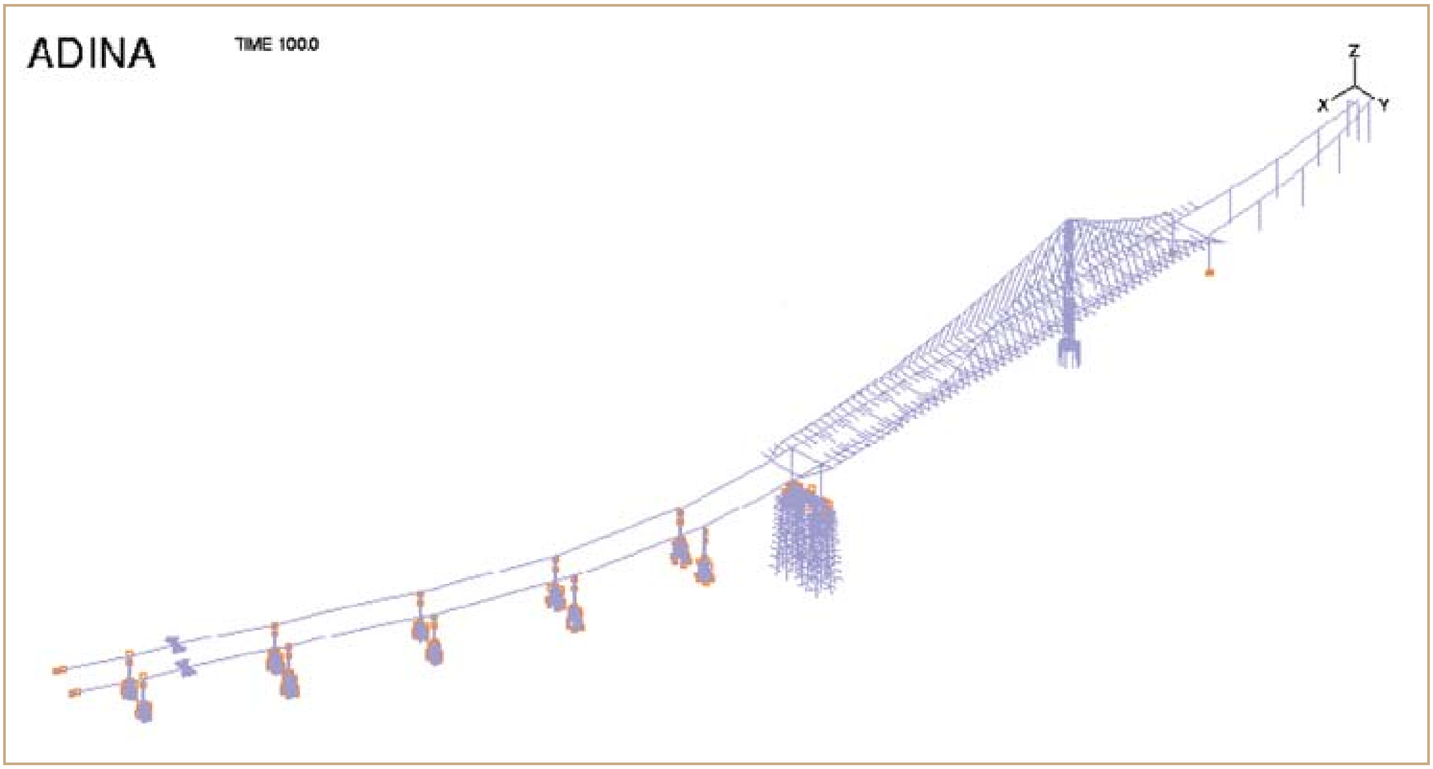
Typical Tower Cross Section - Key Plan View.



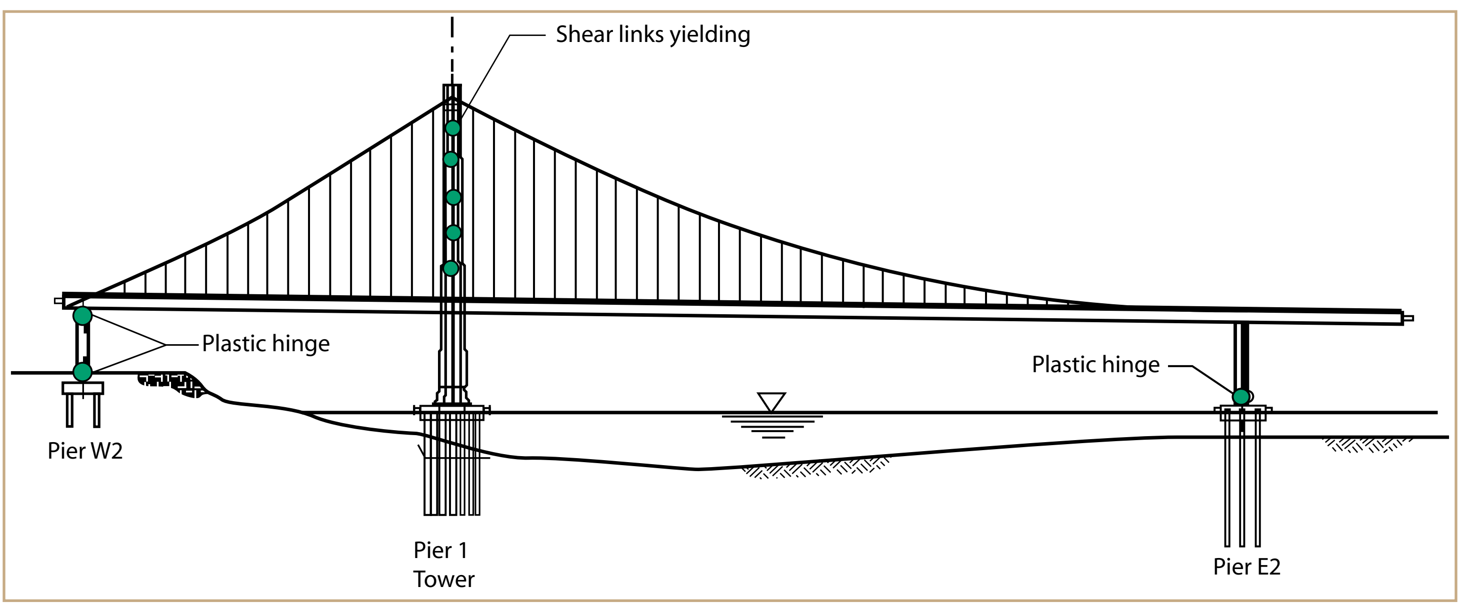
Typical Tower Shear.



Typical Pushover Analysis.



Adina Model.



Seismic Response.