ASSESSING BRIDGE PERFORMANCE – WHEN, WHAT, HOW

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Abstract

This paper outlines the value of assessing bridge performance of major bridges that incorporate innovative design procedures, structure types, construction methods, and new materials. Such innovative procedures, methods and materials help enhance long-term durability, increase expected bridge life, and help decrease the cost and impact of construction. When to consider a health monitoring system, what should be measured, and how various aspects of a structure are measured are described using the new Benicia Martinez Bridge in California as a case study. A brief overview of the instrumentation plan for this bridge is presented. The information collected will be used to periodically evaluate the performance of the bridge and to validate/enhance current design practice.

1.0 Introduction

With new innovative materials, new methods of construction, and complex analysis methods, bridge designers continue to challenge standard practices with longer spans and more sophisticated designs. When incorporating new state-of-the art/state-of-the-practice developments into the design of bridges, particularly large important bridges, designers should consider establishing a way to assess the actual long term performance. Although all the analyses may indicate successful performance, in some cases, it is prudent to monitor specific aspects of performance and hence validate design assumptions. This assessment of performance is also called "health monitoring."

Health monitoring can be used to assess the deterioration of a bridge due to service conditions over its service life, or to assess bridge performance subsequent to unforeseen loading conditions. Health monitoring can help bridge owners to: plan and design effective retrofit strategies; program long term maintenance; reduce life cycle costs through preventive maintenance; and, evaluate bridge integrity immediately after rare events such as floods, earthquakes, vehicle/vessel collisions, etc. Health monitoring can lead to a better understanding of bridge behavior, better analysis and design approaches and improved construction methods. When to employ some means of continuously and systematically assessing performance of particular bridge structures needs to consider several factors. Once it is deemed important to establish a health monitoring system, careful consideration must be given to exactly what should be monitored, how the data will

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be collected and how the data will be used.

2.0 When To Consider Health Monitoring

For typical overcrossing, undercrossing and interchange bridges, regular bi-annual inspections by trained engineers is usually adequate to assess the health of these "ordinary" structures. But on "non-typical" structures with high replacement costs and significant impacts if damaged, regular physical inspections are not enough. Large toll bridges, bridges deemed critical and important to the public, and other structures that incorporate unique design features or specialized construction methods or materials, such as segmental construction or lightweight concrete need to be monitored. Cable-stayed bridges, suspension bridges, scour-critical bridges, and critical structures in high seismic areas are examples of structures where additional health monitoring may make sense.

One example of such a structure is the new high level Benicia Martinez bridge, (Fig. 1) across the Carquinez Strait that connects the cities of Benicia and Martinez in California. In addition to relieving the current traffic congestion, this structure has significant seismic importance, as it is part of the State of California lifeline route system. This structure is designed using Caltrans' "Important Bridge" seismic design criteria and needs to be serviceable within hours of a major seismic event. A significant portion of this structure is designed to be constructed segmentally using sand lightweight concrete and has maximum spans of approximately 200 meters. The 25 meter wide superstructure is being designed as a single cell box with large overhangs accommodating light rail loading. Several factors that were instrumental in initiating the health monitoring of this $600 million bridge include: a) high seismic demands, b) long spans subject to excessive deflections, c) use of sand lightweight concrete with lower modulus of elasticity, and, d) a cast-in-place balanced cantilever segmental construction method that results in significant creep and shrinkage. Listed below is a more detailed summary of these and other factors considered:

2.1 Seismic Importance

The site for the new Benicia Martinez bridge is located 3 miles west of the potentially active Green valley (M=6.75) fault. The new Benicia Martinez Bridge is on a "Seismic Lifeline Route". The bridge is designed to remain operable shortly after a major seismic event. The unique topography of this site, with the rockline dipping at steep 70-degree angles at both ends of the bridge, has required varying column lengths along the length of the bridge. The seismic design has been a challenge. Replacement of this structure would take several years of significant effort and considerable cost. It is of paramount importance to monitor the seismic behavior of this structure during a seismic event to help quickly assess the bridge's condition and evaluate short and long-term safety concerns and recovery strategies.

2.2 Sand lightweight concrete

The new bridge is designed with long spans to minimize the number of columns in the bay. This reduces the substructure cost, which comprises a significant fraction of the total outlay. However the long spans increase the seismic demands on each supporting pier. In an effort to reduce the seismic demands and the sizes of substructure elements, sand lightweight concrete (LWC) has been selected as the material of choice for the superstructure as it gives a 20% weight reduction.

Historical data from structures constructed with LWC indicate problems and the need for proper use of LWC parameters. The modulus of elasticity for LWC is significantly lower than normal weight concrete. This increases the concern for long-term deflections due to the long spans on this structure. For this structure lightweight aggregates from different vendors have been subject to short-term tests to prequalify aggregates to meet minimum modulus requirements. Short-term tests using several lightweight aggregates have indicated the need for high strength concrete mixes to obtain the design values for the modulus of elasticity. With a limited national database on long span LWC structures to compare and learn from, it is essential to instrument and monitor the short and long term behavior of this bridge.

2.3 Creep and Shrinkage

It is well recognized that creep and shrinkage play a vital role in the redistribution of internal forces like bending moment, shear, and prestressing. The actual characterization of system change due to creep and shrinkage in bridge structures has been limited, especially in the LWC long span bridges. Lightweight aggregates have significant creep and shrinkage characteristics. Several assumptions and analytical models have been used to predict the creep and shrinkage behavior of this bridge. Monitoring actual behavior of the structure can validate these analytical assumptions. Health monitoring can aid in tracking these complex time dependency effects.

2.4 Type of Construction

The new Benicia Martinez bay crossing is over 2.5 kilometers long. The bridge stands over 30m above the mean water level and spans across a busy navigational channel. Therefore, the cast in place balanced cantilever segmental erection technique has been chosen as the method of construction. This type of construction involves sequential stressing of segments across each span. The concrete is stressed at the relatively young age approximately 2-4 days from the time of casting. The modulus of elasticity of concrete is very low at this time resulting in significant creep. In addition, as the balanced cantilever operation progresses, stressing operations of subsequent segments result in a complex creep phenomenon.

2.5 Unique Features

The 200m longest span of this bridge puts it among the top few long-span structures built using this method of construction. The 25m wide superstructure is designed as a single cell box with 6m overhangs on either side. The superstructure is designed to carry 5 lanes of highway traffic plus a light rail load on the overhang. The maximum depth of the superstructure is about 11.5m. The superstructure is transversely prestressed with supporting ribs and an edge beam. Hollow columns with confined corner elements have been designed at several piers. All of the above nonstandard features further substantiate the need for health monitoring of this structure.

2.6 Near Midspan Hinges

A result of the balanced cantilever construction is the provision for near midspan span hinges. Deep steel box beams have been used at these hinges to transfer large static and dynamic loads. The hinges have posed significant design issues with respect to the transfer of forces. These deflection and load concerns add to the need for monitoring the behavior of this structure.

3.0 Health Monitoring – What to Monitor

Once a bridge owner determines the necessity for more definite methods to assess performance of a particular structure over the life of that structure, the focus must then be placed on exactly what needs to be monitored. The goals of a particular health monitoring program must be clear.

For the Benicia Martinez bridge it was established during the design phase that ongoing monitoring and instrumentation would be useful both in understanding and assessing the condition of the bridge throughout its life and in evaluating the unique features of this bridge for future bridge designs in California and elsewhere. While the safety of the bridge under quasi-static loading is well established by design methods, the service performance over time and the details of the response of the structure to seismic forces are less precisely known. Listed below are some of the goals of the health monitoring instrumentation program for this bridge:

a. Monitor and assess bridge deflections, rotations and concrete strains of the mainspan superstructure over time. Assessment will be made by calibrating and modifying the design computer model for the bridge for the actual material properties, temperature distribution, tendon forces, deflections, strains and environmental conditions. This "best fit model" will then be studied to understand how creep, shrinkage and consequent moment distribution have affected the bridge response. This understanding will be used to make the best possible rational assessment of the present condition and to forecast the future condition of the bridge.
b. Monitor the seismic behavior of the structure during a seismic event with the help of downfield and freefield sensors installed in the ground and at several locations on the bridge.
c. Monitor and assess the post-tensioning in the bridge over its service life. This is accomplished by monitoring the relaxation of representative tendons and by installation of sensors to "listen" for wire breaks in post-tensioning.
d. Monitor and assess temperature distribution and history of different bridge elements both during construction and during service. Temperature gradient is significant and often a governing load for bridges of this type. The temperature gradient data collected is important as the dimensions of the subject box girder are outside the range of most of the bridges where data has been collected.
e. Collect supplementary information for assessment including concrete material data, ambient temperature and relative humidity in and around the box girder.

4.0 <u>How to Monitor - Instrumentation and Data Collection</u>

After establishing what needs to be monitored for a particular structure, the details of how to collect the information need to be developed. Several illustrations from the new Benicia Martinez Bridge are attached to describe the health monitoring system planned for this bridge. Figure 2 indicates the instrumentation locations for most of the health monitoring with the exception of the modal analysis and seismic sensors. Figure 3 indicates the locations of the different instruments and sensors with respect to the superstructure depth. Table 1 indicates the total number of each type of sensor at each of these locations. Figure 4 indicates the complete layout of the modal analysis sensors. Figure 5 denotes a typical seismic monitoring layout of a frame.

4.1 Deflection

Long-term deflections in Span 7 will be measured using a base-line system attached to the underside of the deck as close as possible to the longitudinal centerline of the box girder. The system consists of a No. 8 stainless steel piano wire as a reference line, two end brackets at the live and dead ends, base plates, and a caliper. The live end and dead end brackets are anchored to the underside of the deck with expansion anchor bolts as close as possible to the diaphragms at Piers 7 and 8. The piano wire is anchored to the bracket at the dead end and passes over a pulley at the live end. The wire is stressed to approximately 80 percent of its breaking strength using dead weights at the live end. Deflections are measured manually at midspan and at one fifth point. At each deflection location, a true horizontal reference steel plate is attached to the concrete using expansion anchor bolts. The distance between each base plate and the piano wire is measured using a digital caliper with a magnetic base. The base-line system will be installed immediately after the midspan closure of Span 7 is complete. In order to relate the base-line deflection readings to a prior survey performed during construction, a tie-in optical survey will be performed simultaneously with at least one set of base-line system readings. This simple system set up inside the bridge is safe and could be monitored by untrained personnel.

As an alternate to the piano wire system requiring manual readings, a system of interconnected liquid levels, monitored with precision vibrating wire level sensors, and capable of automatically reporting accurate differential deflections to the automatic data acquisition system (ADAS) may eventually be used.

4.2 Change in Length

Longitudinal length changes in Spans 7 and 8 will be measured using extensometers. Each extensometer consists of a 6-mm diameter graphite rod with a low coefficient of thermal expansion inserted into an 18-mm diameter PVC pipe that is attached to the underside of the top slab. The graphite rod is fixed to the concrete deck close to one diaphragm. The other end is attached to a linear variable displacement transducer (LVDT) attached to the concrete deck near the other diaphragm. The system will be installed along the longitudinal centerline of the box girder immediately after the midspan closures are complete. The LVDT's are connected to the ADAS.

4.3 Strain

Strains are measured using vibrating wire strain gages (VWSG). Vibrating wire strain gages will be equipped with thermisters for measurement of temperature at the gage location. VWSG's are supported prior to concrete placement such that they are held in position during concrete placement but not restrained from any longitudinal length change. Gages will be connected to the ADAS prior to concrete placement.

4.4 Rotation

Rotations are measured using tiltmeters. Two tiltmeters are installed, one in a horizontal and one in a vertical position on the sloping walls of the box girder. Tiltmeters at Locations B and D (see Fig. 2) will be installed and connected to the ADAS prior to completion of closure pour in Span 7. The tiltmeter at Location E will be installed immediately after the footing is cast and connected to the ADAS prior to completion of closure pour in span 7.

4.5 Concrete Temperature

Concrete temperatures are measured using Copper-Constantan Type 'T' thermocouples with a temperature range of -46°C to 121°C. Thermocouples are installed and connected to the ADAS prior to concrete placement and will be held rigidly in place during concrete placement to prevent movement from their intended locations. Heat of hydration due to mass concrete at deep bent cap and footing locations are a major concern on this bridge.

4.6 Ambient Temperature

Air temperatures are measured using Copper-Constantan Type 'T' thermocouples with a temperature range of -46°C to 121°C. Thermocouples are installed and connected to the ADAS prior to concrete placement and will be held rigidly in place during concrete placement to prevent movement from their intended locations.

4.7 Relative Humidity

Relative humidity is measured at two locations. One meter is located inside the box girder of Span 7 and the other meter is placed outside the box girder near Pier 7 to measure external humidity. They will be protected from the direct influence of the sun and rain by their location in the permanent shadow of the box girder. The humidity meters will be installed and connected to the ADAS immediately after construction of the pier segment at Pier 7.

4.8 Prestressing Force

Forces in two span-tendons of the seventh span are to be measured with center hole load cells having a capacity of 3000 KN. The load cells are installed around the strand prior to post-tensioning and are located between the anchor plates for the wedges and the concrete build-out for the anchor plate bearing. Load cells with a maximum non-linearity of one percent over their load range are connected to the ADAS prior to stressing the instrumented tendons. Tendons with the load cells are not grouted.

4.9 Hinge Force

Load Cells for the measurement of hinge forces are incorporated in the Hinge C and D bearings. At Hinge D in Span 8, four bearings per pair of steel box beams, for a total of 8 cells will be connected to the data collection system.

4.10 Wire Break Detection

Condition of the post-tensioning tendons is continuously monitored to detect and record failures of individual wires. Wire breaks are detected using surface mounted broad band accelerometers. A total of 90 sensors will be mounted on the underside of the deck span after removal of the formwork. Sensors will be connected to the SoundPrint® data acquisition system provided by Pure Technologies Ltd.

4.11 Corrosion, Epoxy Coated Reinforcement

The potential for corrosion of reinforcement is measured using rebar probe assemblies with reference electrodes. Eight probes with reference electrodes are placed at Piers 7 and 8 for a total of 16 pairs. At each pier, four pairs are placed in the footing at mean sea level and four pairs in the pier shaft not more than 1 m above the top of the footing. Sensors are attached to the layer of reinforcement closest to the surface.

4.12 Corrosion, Steel Pile Casings

The potential for corrosion of the steel pile casings is measured using immersion reference electrodes. Four sensors are placed on four different steel pile casings at each of Piers 7 and 8 for a total of eight sensors. The sensors are installed on the outside of the casing within 1 m of the underside of the footing, then connected to the ADAS.

4.13 Survey Monuments

Three permanent corrosion resistant monuments are to be installed on top of each footing for assessment of horizontal and vertical movements and rotations. The monuments will be installed with their elevations and positions determined before construction of the pier shafts.

4.14 Seismic sensors

The California Department of Transportation in association with the California Department of Mines and Geology is instrumenting the complete length of this bridge with extensive free field and down hole sensors. Numerous seismic recording accelerometers will be placed at strategic locations on and off the bridge including a) pier tables, b) along the height of columns, c) footings, d) along the depth of the piles, e) at different depths in the soil. Displacement sensors will also be placed at several locations on the bridge to monitor the displacement history during a seismic event. Displacement and acceleration characteristics of the bridge during a seismic event will be recorded using data recorders and accessible from remote locations. Battery backup power will allow for readings through power outages.

4.15 Modal Analysis

Sensors will be installed in the longest frame at quarter span locations along the span and at quarter points along the column height. A baseline modal system will be established using prescribed dynamic testing prior to subjecting the bridge to live loading. Modal parameters such as the resonant frequencies and mode shapes will be constantly measured and compared to the baseline parameters. Established damage detection methodologies will then be used to identify damage areas in the structure and establish the severity of damage. The results from the analysis could subsequently be used to determine load capacity, rating and useful life.

5.0 Data Acquisition System and Installation Schedule

A data acquisition system capable of collecting all the above data will be used on the Benicia Martinez Bridge. The data collected using an automatic data acquisition system will be used to monitor and assess the performance of the structure and to enhance current design practices. Table 2 indicates the installation schedule for the different sensors outlined in Section 4. A joint effort involving Caltrans, a University of California research team, the California Department of Mines and Geology, the design team, and the contractor will ensure proper installation, data collection and interpretation.

6.0 Material testing

In addition to the material testing for quality control, the tests indicated in Table 3 will be performed on the materials used in Regions A through D. The data collected from these tests will be used to validate the design parameters.

7.0 Cost of Health Monitoring System for the Benicia Martinez Bridge

The cost for the instrumentation of health and seismic monitoring of the new Benicia Martinez Bridge is approximately $ 2,000,000. The California Department of Mines and

Geology will furnish the seismic monitoring equipment valued at approximately $375,000. In addition to the instrumentation, the State of California anticipates spending about $600,000 for data collection and monitoring over the next five years. The monitoring cost is expected to significantly drop thereafter. The cost to health monitor this structure is a fraction of the total construction cost in exchange for valuable data on complex structure behavior.

8.0 Conclusions

New technologies and advances in data acquisition systems have helped make assessing very specific aspects of bridge performance possible. But what can be assessed comes at a price and is not appropriate for all structures. When newly designed important bridges include what could be considered "extra-ordinary" design features, sophisticated analyses, unusual construction methods, and/or high performance materials, health monitoring systems can be economically effective at verifying assumptions and detecting and assessing unexpected behavior. Any health monitoring program must be planned in detail and include clear understanding of how collected data will be processed, analyzed and acted upon. When completed, the health monitoring system installed in the new Benicia Martinez structure will allow for the measurement and collection of a vast amount of data to help assess the short and long-term performance of that structure. This data will help maintain the structure to provide a safe and efficient bay crossing for the traveling public. It will also serve as a useful database of performance information for bridge design engineers around the world. This proactive approach to improving the quality of structure design is a well-justified step in responsible engineering.

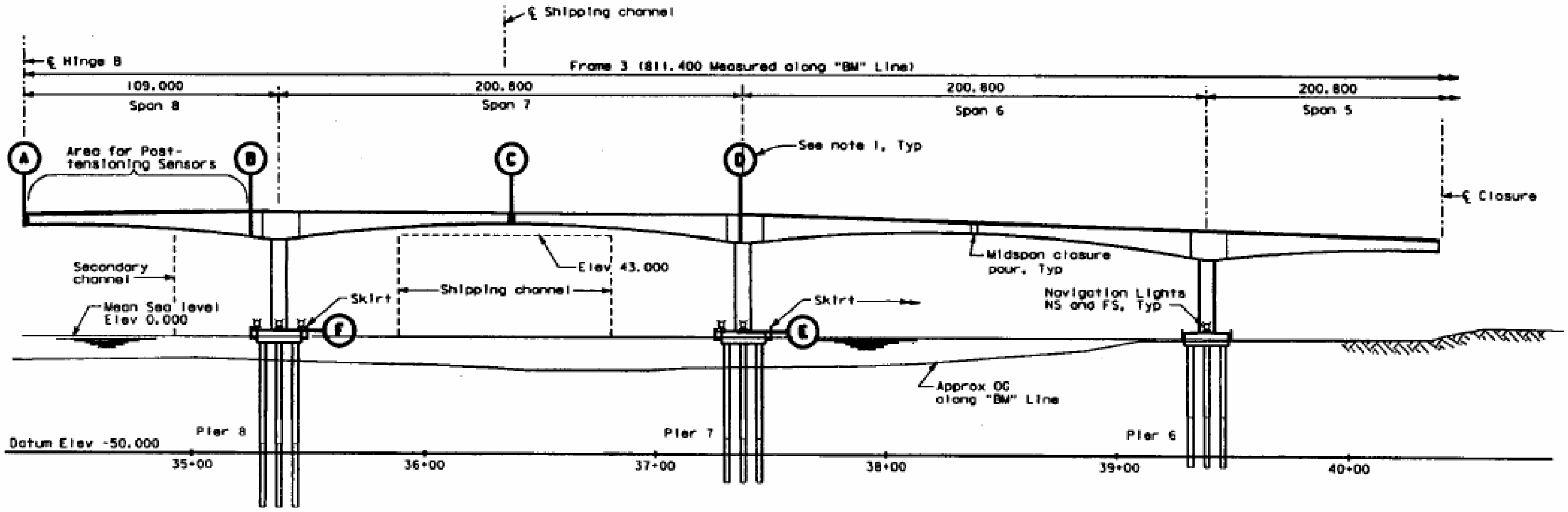

Fig. 2 Instrumentation Locations.

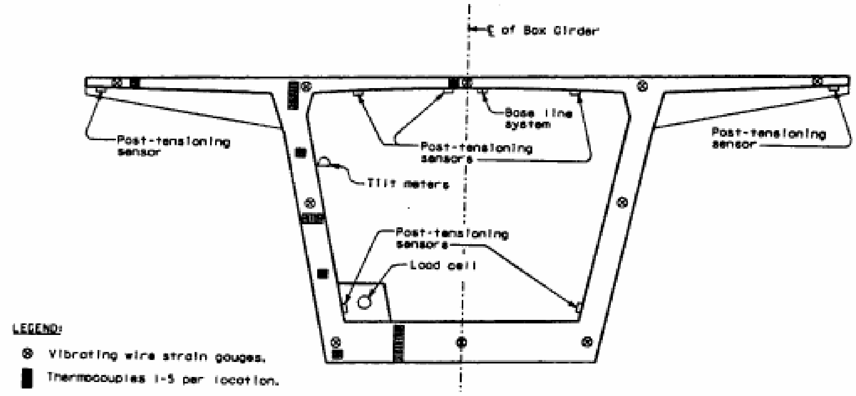

Fig. 3 Location of instruments in a cross section

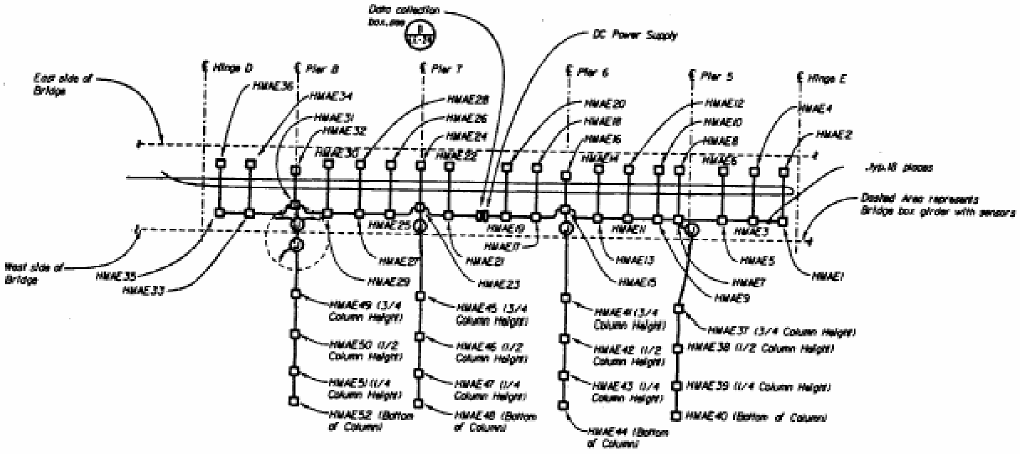

Fig. 4 Layout of Modal analysis sensors

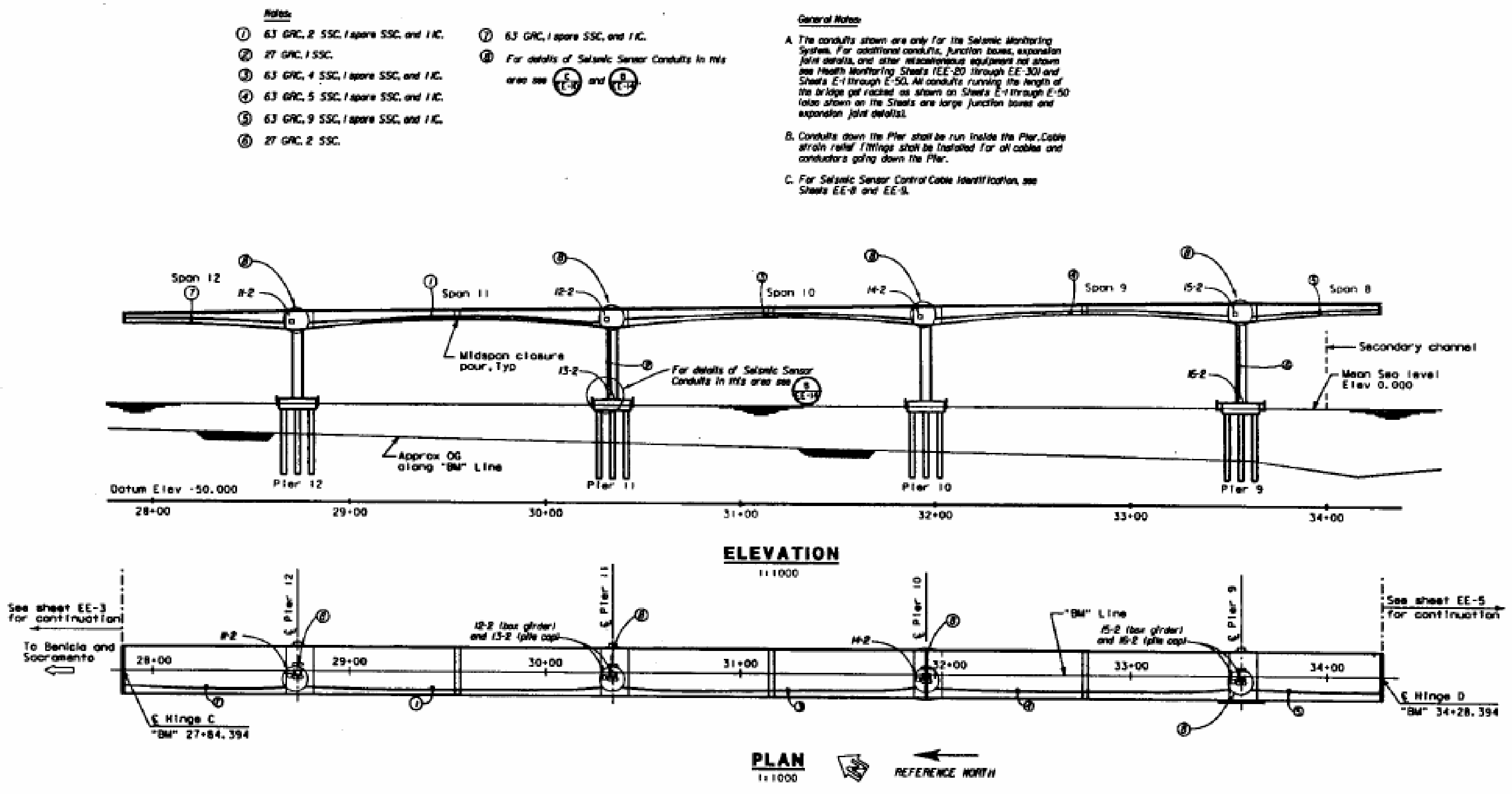

Fig. 5 Typical Seismic Monitoring layout.

Type of Measurement		Deflection	Length Change	Strain	Rotation	Temper -ature	Humidity	Prestress Force	Hinge Force	Wire Break	Corrosion
Sensor Type		Base-line System	Extenso-meters	Vibrating Wire Strain Gages	Tilt-meters	Thermo couples	Relative Humidity Meters	Load Cells	Load Cells		Reference Cells
Location	Key										
Near Hinge, Span 8	A		1 (Span 8)	10					8	90	
Near Pier 8, Span 8 (sand lightweight concrete)	B	1 (Span 7)		10	1						
Midspan, Span 7	C		1 (Span 7)	10		20		2			
Pier Table Span 7 Pier 7	D			10	1	20	2				
Footing, Pier 7	E				1	10					12
Footing Pier 8	F										12
Total		1	2	40	3	50	2	2	8	90	24

NOTES:

1. Not all instrument are installed at each location.

Table 1 General location of the Health Monitoring Instrumentation.

Measurement Type	Sensor	Installation
Deflection	Base-line system	After midspan closure of Span 7
Length Change	LVDT	After midspan closures of Span 7 and Span 8
Strain	VWSG	Before concrete placement
Rotation at Locations B and D	Tiltmeter	Before midspan closure of Span 7
Rotation at Location E	Tiltmeter	After footing concrete is placed
Concrete Temperature	Thermocouple	Before concrete placement
Air Temperature	Thermocouple	Before concrete placement
Relative Humidity	Humidity meters	After casting pier segment at Pier 7
Prestressing Force	Load Cell	During tendon installation
Hinge Force	Load Cell	During hinge installation
Wire Break Detection	Broadband accelerometers	After midspan closure of Span 7
Corrosion - Reinforcement	Reference cells	Before concrete placement
Corrosion - Steel Pile Casings	Reference cells	After footing concrete is placed
Survey Monuments	N/A	After footing concrete is placed

Table 2 Installation Schedule

Material Property	Number of tests at Each Age, Days						Total Specimens
	3	7	28	56	91	180	
Compressive Strength 18 cylinders from each of 4 locations	12	12	12	12	12	12	72
Modulus of Elasticity 18 cylinders from each of 4 locations	12	12	12	12	12	12	72$^{\text{(NOTE 1)}}$
Coefficient of Thermal Expansion 3 cylinders from each of 4 locations	12	N/A	12	N/A	N/A	12	12
Creep and Shrinkage 12 cylinders from each of 4 locations							
Creep	8	N/A	8	N/A	N/A	8	24
Shrinkage	8	N/A	8	N/A	N/A	8	24

NOTES:

1. Same specimens as compressive strength.
2. Total number of cylinders is 33 per instrumentation locations. Locations are A, B, C, and D as identified in Fig. 2.

Table 3 Concrete Materials Testing Program

Acknowledgements

The authors acknowledge the efforts of Mr. Scott Hunter with TY Lin International for proposing portions of the health monitoring system across the shipping channel, Mr. Pat Hipley with the California Department of Transportation (Caltrans) and the California Department of Mines and Geology for architecture of the seismic monitoring, Mr. Charles Sikorsky with Caltrans for devising the modal analysis instrumentation, Mr. James Lacy with Caltrans for devising the electrical connectivity of this complex system, and Mr. Ron Bromenschenkel with Caltrans for his efforts during the development of this program.

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