STATUS OF THE BRIDGE AND DOWNHOLE SEISMIC INSTRUMENTATION INSTALLED THROUGH THE CALTRANS / CDMG PROJECT

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Abstract

Having instruments in place to simultaneously record the movements of the ground and of bridge structures during seismic events is imperative to advancing our understanding of how these structures respond to earthquake motions. The California Department of Transportation (Caltrans) has been working with the California Division of Mines and Geology (CDMG) for several years placing strong motion sensors at bridge and downhole sites to record earthquake induced motion. There are 65 bridges instrumented as of December 2001 and some large installation projects are currently underway for the San Francisco bay area's toll bridges. In addition, this instrumentation project has nine downhole (subsurface) arrays throughout the state with more downhole arrays to come on line soon. These downhole arrays have sensors as deep as 800 feet and are all located adjacent to instrumented bridge structures. This paper will discuss the current status of the bridge and downhole seismic instrumentation projects and how the recorded data will be used for design purposes.

Introduction

The process of recording the motions of large structures during major earthquakes is a complex affair. If we knew where the next big earthquake would be located and we also knew which particular structures would be most affected by that quake, the job would be relatively simple. Placing sensors on the structures that will be close to the next big earthquake's epicenter is the goal of this project. In California there are many locations where a large earthquake could occur and there are many candidate bridge structures to choose from. Each earthquake is not the same and will produce a signature waveform that will excite each structure differently. Since we don't know where the next magnitude 7.0 plus event will occur, we can only instrument bridge structures where the historic seismic activity is most prevalent. In these regions, a variety of bridges are being instrumented for strong motion to gain some understanding of how large earthquakes excite different bridge types. Most locations selected are near major faults or are in potentially high seismic zones. The object of the project is to monitor both small and massive bridge structures. The majority of bridges in California are small two and three span structures. Some of these structures need to be monitored, on the other hand, the great bridges, such as our toll bridges, represent a huge investment to the public and are crucial to the state transportation system. Hundreds of vehicles could be traveling on any one of these toll structures at a given time. The instrumentation of a toll structure is in and of itself a large monitoring project, but it is important to know how all of the different bridges, large and small, react to earthquakes.

In California, the two largest cities, Los Angeles and San Francisco, are located in potentially high seismic regions. These cities have many bridges. In the case of Los Angeles, these bridges are also spread out over a large area. On the other hand, the San Francisco bay area has the majority of our large toll structures. These sizeable structures create an opportunity to have unique structural vibration studies but require a numerous amount of sensors to gain a good understanding of their global responses to earthquake induced motions.

The Golden State has many major faults such as the San Andreas Fault. Anywhere along the San Andreas Fault we can expect a major earthquake, but of course, in some segments there simply are no

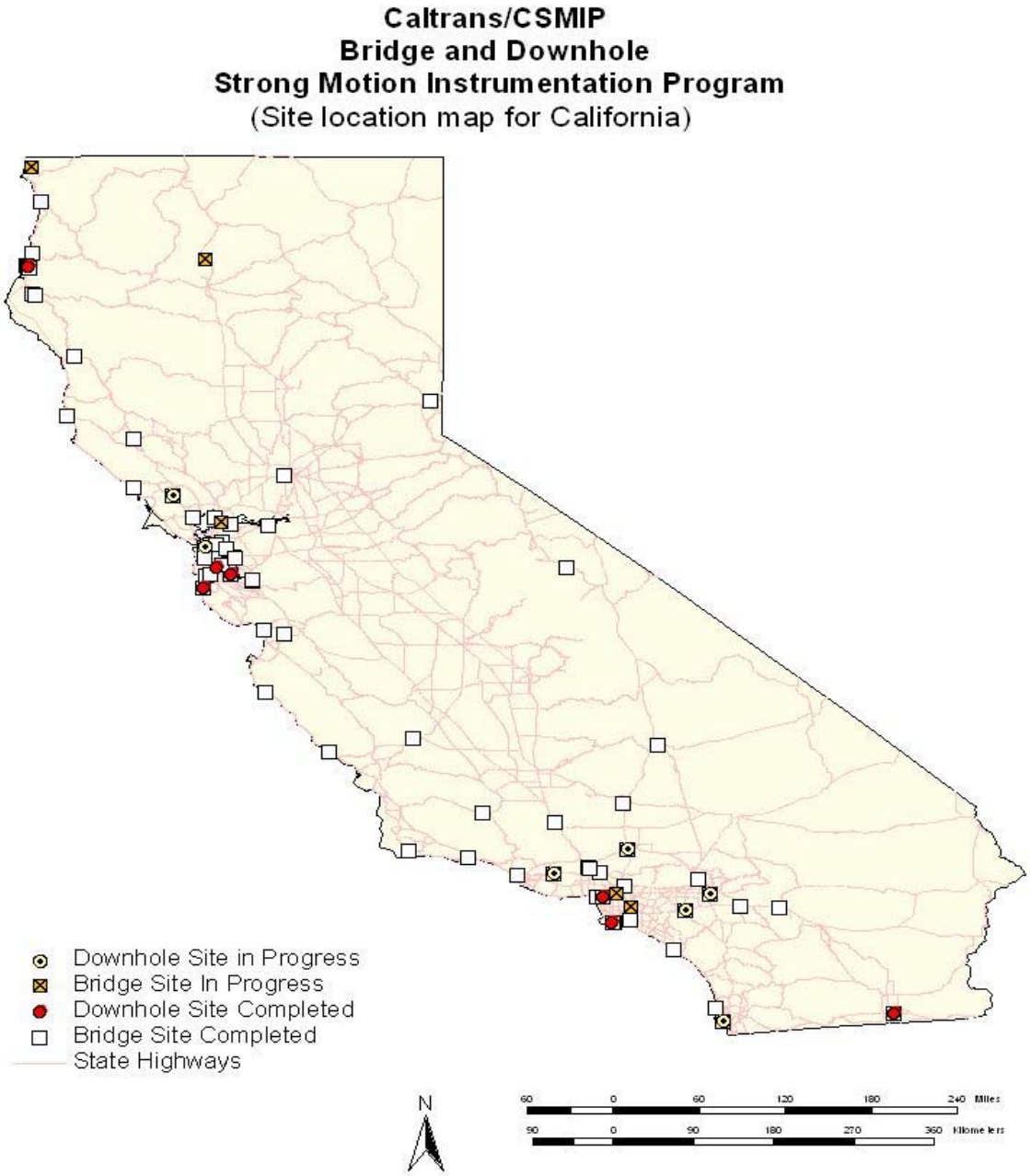

Figure 1. Site location map for strong motion instruments

bridges. In reality, for only a short distance above and below the San Francisco bay area will the San Andreas Fault pose a near fault threat to any of the large population centers. Therefore, a combination of historic earthquake activity and choosing locations in relation to large population centers represent part of the criteria used to determine which structures are candidates for sensors. Los Angeles and San Francisco have the bulk of the sites, but it would not seem prudent to concentrate all of the instruments in two regions of the state. Many structures are instrumented on the far north coast, which is highly seismic but lightly populated. The Juan de Fuca plate is still subducting under North America and this creates a potential for great earthquakes. These earthquakes could be very damaging if their epicenters were to occur near shore. High seismicity is the weighing factor for choosing structures on the northern California coast.

In California there are many ways to induce seismic waves and these range from subduction faults, strike-slip faults, thrust faults and volcanoes. Will these different mechanisms produce the same waveform? Are some earthquakes more damaging to long period structures as opposed to stiff short period structures? Do large vertical motions create an issue for seismic design and will near fault effects need to be considered? How do various bridge configurations react to different types of earthquakes? This host of concerns is another factor for spreading out the arrays. Many of the strong motion stations for bridges in California are in and around the major cities but some are located in more rural, highly seismic zones to fill in the gaps along major faults.

Design Needs

The Spectral Response method of seismic bridge analysis is still generally used for most of Caltrans bridge design. These response curves (ARS curves) vary by soil type, distance to the fault, and the degree of expected seismicity in a particular region and are used to estimate how large a force (related to gravity, “g”) to apply to the structure. Basically, we are trying to decide what percentage of the bridge’s weight should be applied horizontally to the structure in both directions to determine how far the structure will deflect due to this loading. The closer the structure is to a known fault and the closer the bridge’s natural period of vibration matches the soil’s vibration (resonance), the greater the loading will be. The natural period of vibration of the bridge system is determined by computer programs or by hand calculations. The expected “g” force for the system’s natural period of vibration is acquired from the spectral response curves. This deflection (demand) is compared to the amount the member can deflect (capacity) to make a decision as to the seismic safety of the structure. Computer programs are used to determine if the vulnerable members (usually the columns) have enough ductility to safely deflect under the design force. For a given column configuration these programs give the distance the columns can bend before there is rebar yielding, and calculate the ultimate deflection the columns can withstand. This is referred to as “Push-Over” analysis. These ultimate capacity analysis methods were developed and verified through extensive testing at the universities on full size and scale models of concrete and steel columns, beams, footing, etc.

Linear elastic bridge computer models are also used to estimate the severity of the bridge shaking (displacements) caused by an earthquake through modal analysis. The computer model develops nodes, groups the mass to these nodes, and creates a framing system. Finite element matrix solutions determine the ultimate deflected shape by summing the spectral response for the relevant modes. These results are compared to the “push-over” models discussed previously to try to capture any anomalies that may occur due to any unusual structural framing.

This is a simple overview of the current analysis but many other failure mechanisms need to be considered, such as unseating at the supports, shear failures, liquefaction, etc., for a study of the bridge seismic resistance to be complete. If a structure is deemed “important”, a three dimensional non-linear time-history model may be developed as a more sophisticated tool to compare demands to capacities.

For most structures, the performance goal is to prevent collapse so that no one’s life will be threatened by a falling structure. We accept that some structures may have to be replaced after major events, but life safety is paramount. It is simply too cost prohibitive to bring the 13,000 state bridges up to a “no damage” scenario. We will accept the risk for replacement of a few structures in these rare events versus the massive capitol investment of upgrading all of our bridges.

What the strong motion sensors tell us are, whether the motion of that structure, induced by the ground input at that site, is what we expect and are designing for. Until there are actual readings during large earthquakes to compare the data to our theories of structural dynamics, we are only speculating as

to what this movement will be. Some sensors are placed on the ground away from any structural influences (freefield sensors) to measure the ground motion that will be used as the input data. Enough sensors are placed on the structure to have sufficient readings to determine the displacements and mode shapes. This usually requires monitoring the foundations and the superstructure simultaneously. For example, if the relative displacement of a column can be recorded, this can be compared to the damage that the column may have experienced to see if it is what the designer expected. Much can be learned from this data.

Another important aspect of structural dynamics that can be gained from the strong motion readings is how fast these structures come to rest after forced vibration (damping). How well a bridge structure damps out the movements caused by an earthquake is of great wealth.

For large toll bridges, fragility models can be developed for various members (such as the towers) that provide the relative movement that can occur before the safety of the structure is compromised. As an example, if a tower deflects two inches, it may be well inside the elastic range of that system, but if it deflects 36 inches, it may require a bridge closure. These new seismic monitoring systems will quickly make the data available to be used for the evaluation of these critical structures after an earthquake.

The Project

To verify that our seismic response analysis and model assumptions are valid, the California Division of Mines and Geology (CDMG) and the California Department of Transportation (Caltrans) have embarked on a bridge strong motion instrumentation project. Currently, 65 bridge sites throughout the state are instrumented under this project (see Figure 1). The bridge types range from two span structures with diaphragm abutments, to large sweeping single column ramp structures, to massive toll crossings. A typical bridge sensor installation and a sensor layout sketch are shown in Figures 2 and 3. Having a variety of instrumented structures will give us an understanding of how different structural configurations react to seismic input.

The sensors are placed on a bridge to record displacements in both the longitudinal and the transverse directions and if possible determine the mode shapes of the superstructures. At some sites, vertical sensors are placed at three corners of spread footings to record the rocking motion of those footings. Also, for some new designs, conduits are tied to the pile reinforcement cages and are lowered into the ground and cast in place with concrete. Downhole instruments are then placed into the piles at depth to record the underground pile movements. At the 5/14 Interchange in Los Angeles one bent (a single column pile extension pier) has sensors at 100' depth (bottom of pile), 33’ depth (the plastic hinge zone), ground level, and at the roadway elevation 100’ above the ground. This will give us motion readings from the top to the bottom of that bridge support system during an earthquake. Some toll structures will also incorporate sensors into the piles as part of their retrofitting effort.

To supplement the accelerometers and in case the accelerometers do not come to rest in their initial positions, absolute displacement instruments are used. These devices utilize high frequency radio waves to record the opening and closing of bridge expansion joints over time. The instrument is placed on one frame and projects a beam to a target on the adjacent frame and records the change in distance as the joint deflects. For example, a joint opening may start at 6 inches before the quake but may well end up at 9 inches after a colossal quake and these instruments will tell us that.

Much of the effort of the strong motion instrumentation project in the past few years has been towards instrumenting toll structures as part of the seismic retrofitting work. Eight of the ten Caltrans toll bridges have been or are currently being retrofit for earthquake motions. Some of the toll structures are being completely replaced to bring those crossings up to our current seismic standards. For all these contracts, seismic instrumentation system installation work has been included in the plans, and contractors are performing much of the system installation (installing conduit, pulling wire, placing enclosures, etc.) according to details and specifications developed by CDMG and Caltrans. Near the point of completion of the contract work, CDMG will install the sensors and recorders and take over the maintenance of the systems. Systems have also been designed and incorporated into the three new toll crossings being built in the San Francisco bay area. These bridges are; the new Bay Bridge, the new Carquinez Strait bridge, and the new Benicia/Martinez bridge. Some toll crossings are up to seven miles long and require a lot of work to complete. Vast amounts of accelerometers are needed to get meaningful data for such structures. For all of these toll bridges, almost 1000 channels will need to be maintained after the installations are completed. This is a daunting task that will require the assistance of

Figure 2. Hopland Overhead showing the sensor enclosures.

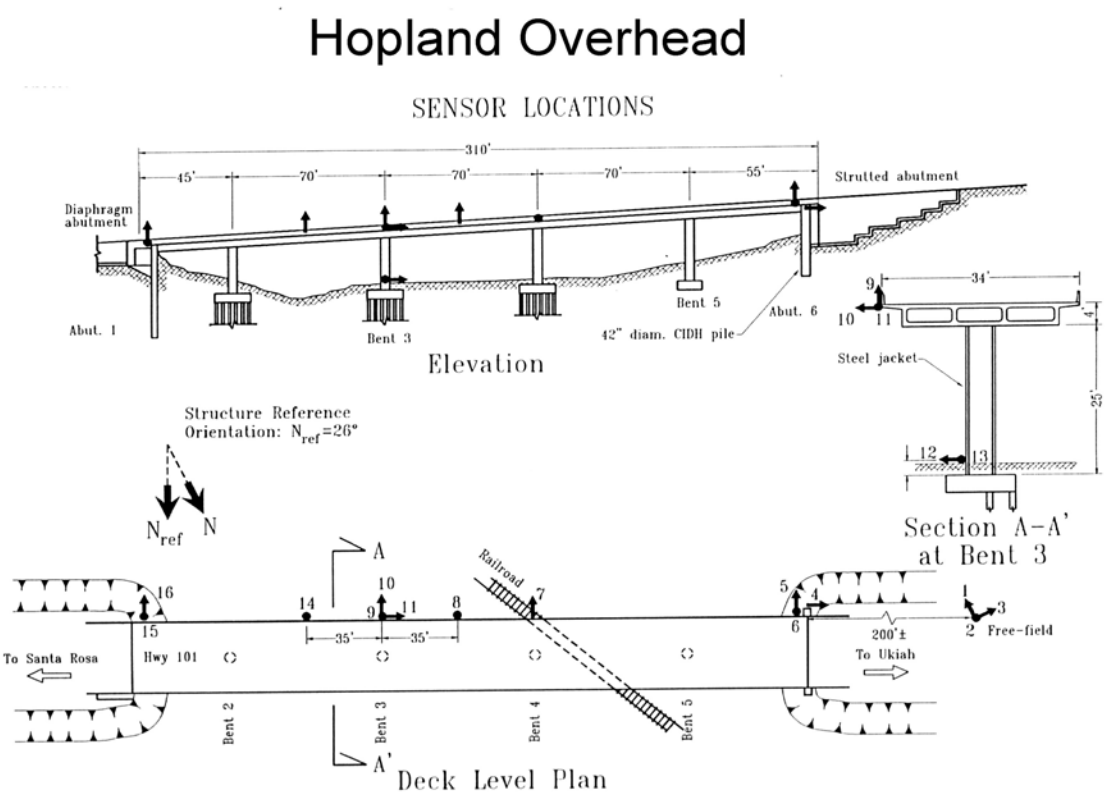

Figure 3. Hopland Overhead sensor locations.

local bridge crews to be successful. The cost for strong motion sensor installation for toll bridges is usually less than 1% of the cost of the seismic retrofit. These great structures represent billions of dollars worth of investment to California's taxpayers and having seismic response data available will be invaluable.

Downhole Arrays

Caltrans has been testing bridge components for earthquake motions as a means of estimating the capacity of various bridge members for many years. Much of the work has been performed at U.C. San Diego, U.C. Berkeley and at other universities with funding from Caltrans and the Federal Highway Administration. What we haven't looked at much is what is going on deep in the ground during earthquakes. As part of this strong motion instrumentation program, downhole (subsurface) arrays are being placed near our instrumented bridges to observe the soil movement as well as the structural response. Caltrans drilling crews bore the holes and install the conduits for the downhole instruments and Caltrans Geology and Geophysics personnel log the holes (lithology, P-S suspension, E-logs, etc.) for future studies. This data is also used to determine the exact level at which to place the instrument packages. Trying to gather real data as to how various soil types respond to the underlying rock motion will advance our knowledge regarding what motions to expect at our structures. Subsurface earthquake data is needed as much as structural component testing is needed. Stiff and soft soil sites can be thought of as soil columns that react uniquely to rock motions. Whether the bridge foundation sits on rock or has 150-foot long piles driven into soft soil makes a big difference in terms of how the structure will react to earthquakes. We are also seeing that the same sites react very differently to different earthquakes. Dynamic soil modeling programs such as SHAKE and RASCAL, can utilize this data to create better models and predictions. More accurate soil models will be the building block for more realistic seismic bridge design.

Other Uses for Strong Motion Sensors

An example of another use for strong motion data is in the city of Eureka where the Humboldt Bay bridges (3 total) are augmented with seismic gates. The seismic retrofit design for these structures is still underway and the gates are an interim measure that will be in place until the retrofit construction is completed. These gates are similar to railroad crossing gates and will close the bridge in the event of strong ground shaking. The closure of the structures will prevent public use of these bridges until a thorough inspection can be completed. When the gates are activated, local traffic control personnel and the bridge maintenance crews are notified immediately. There also are permanent seismic gate systems located near the town of Leggett in which two large concrete arch bridges are instrumented in this very rural location.

In the early 90's, CDMG developed an automated alpha-numeric paging system that was used to alert Caltrans emergency response personnel to seismic events in near real time. If the shaking at an instrumented site reached a set threshold, the system would download the data via a phone line, process the data, and send a page out to selected individuals. The message would include wording as to the estimated intensity of the shaking (light, moderate, strong, severe), and would give spectral response data points (example: 1.0 g @ 1 sec.) for engineering use. This early warning system evolved into the Tri-net system that is similar in scope but is a cooperative effort between CDMG, USGS, and Caltech. Recently, this group is including the resources of U. C. Berkeley to have better coverage of northern California. This system will not record all the earthquakes in California but should cover the major cities. These groups are also developing a system to plot "shake maps" showing isobars for the intensity of ground shaking for quick use by emergency response organizations like FEMA, Caltrans, fire, police, etc. The seismic systems installed as part of this program will be made available for use in this endeavor.

Summary

Caltrans and CDMG are committed to developing and maintaining seismic motion detection systems for California's bridges. These readings will be used to further our understanding of how bridges react to large earthquakes and will be utilized to verify design assumptions and to update seismic codes. It is imperative that these systems are in place when a large earthquake occurs in California and that we

record the structural response of these bridge structures and ground sites. This data represents an invaluable tool to the development of our theories of system dynamics during earthquakes and will be an important tool for assessments of the stability of large structures after a major event.