2792

SEISMIC STUDIES OF THE SAN FRANSISCO-OAKLAND BAY BRIDGE

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SUMMARY

Computational simulation plays a central role in the engineering analysis and design of major bridge structures and accurate simulations are essential for the development of earthquake resistant and economical structural designs. This paper describes new methodologies and computational tools which have recently been developed for simulating earthquake ground motions and the seismic response of cable supported bridges. The simulation tools are described and an example application for an important long-span suspension bridge is demonstrated. The application portion of the study has particular focus on the potential damaging effects of long period displacement pulses and permanent ground displacements which can occur when a bridge is located in the near-field of a major earthquake fault.

INTRODUCTION

Realistic and accurate simulation of the seismic response of long-span bridges presents a significant technical challenge. The generation of broad-band, spatially varying ground motion is a difficult seismological and geotechnical problem, particularly for bridges located near a causative fault where long period near-field effects may dominate the ground motion hazard for flexible structures. Accurate simulation of the transient dynamic response of large bridges also presents the structural engineer with a significant challenge. Nonlinear response simulations are computationally intensive for long-span bridges due to the shear size of the structural systems. If significant nonlinearities are prevalent in the structural system, such as geometric nonlinearities associated with large displacements, material nonlinearities due to members yielding or buckling or strong nonlinearities due to impact at expansion connections or rocking foundations, the computational requirements with general purpose finite element codes may be prohibitive.

A multidisciplinary research and development project conducted by the University of California at Berkeley and the Lawrence Livermore National Laboratory is investigating both earthquake ground motion and structural response issues for long-span bridges. The research is developing a new massively parallel linear finite difference computer program for modeling earthquake wave propagation in bedrock on a regional basis [Larsen and Schultz, 1995]. A special purpose finite element program has also been developed for simulating the nonlinear response of cable supported bridges [McCallen and Astaneh-Asl,

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1997]. This program exploits the special characteristics of cable supported bridges to arrive at an efficient and economical simulation model for nonlinear time history analyses.

These tools are being applied in a case study to an important bridge on the West Coast of the United States. The San Francisco-Oakland Bay Bridge is located in California, USA, crossing the San Francisco Bay and connecting the cities of San Francisco and Oakland (Figure 1). Currently, the bridge carries an average of more than 280,000 vehicles per day and is one of the busiest major bridges in the United States. The bridge consists of two steel suspension bridges in tandem on the Western Crossing of the bridge, and a series of cantilever and simply-supported truss spans on the Eastern Crossing. The bridge has two decks, each deck with five car lanes. During the 1989 Loma Prieta earthquake, a 15m long segment of the Eastern Crossing bridge deck collapsed, causing closure of the bridge for one month. Since the Loma Prieta earthquake, this bridge system has been the subject of a number of research and design studies supported by the California Department of Transportation. This bridge was selected for the current study because the bridge and surrounding seismic setting embody all of the important issues related to long-span bridge response. The bridge is also a key transportation link for the San Francisco Bay Area and additional insight into the seismic response adds information to the knowledge base for this critical structure.

GROUND MOTION MODELING

Ground motion synthetics for long-span bridges must include waveform information across a frequency range which encompasses the characteristic frequencies of the structure. In long-span cable bridge structures, this can represent a very broad frequency range since the long wavelength modes of the deck system can exhibit very low frequencies (e.g. 0.1-0.05 Hz) relative to the vibrational frequencies of the bridge towers (e.g. 5-8 Hz). Historically, very long period motions have not been accounted for in seismic hazard characterizations because of a lack of understanding of ground motion phenomenology and the unknown existence of long period ground motion pulses. In the last few years, with additional insight gained by a handful of near-field ground motion measurements, the importance of long period motions have become clear. Analytical and numerical studies of wave radiation patterns have confirmed the potential for large, long period ground displacement pulses and significant permanent ground displacements in the near field. Ground motion observations obtained from the 1992 Landers California earthquake in particular have provided insight into these important issues with observations of large, long period displacement pulses near the fault [Iwan and Chen, 1995]. However, the paucity of near-field strong motion measurements leaves significant uncertainty regarding the precise waveforms of near-field motions. Seismologists must rely on analytical and numerical methods in order to provide engineers with estimates of the near-field wave forms.

The ground motion estimates completed for this study were generated using forward computations with physics based models. To capture the required broad band motion two approaches were employed. The high frequency components of motion were determined based on a Green's function approach in which small micro earthquakes occurring along the Hayward fault were measured over a period of time with sensitive seismic sensors in bedrock (Figure 2a) at the Bay Bridge site. The small earthquakes serve as empirical Green's functions which incorporate information about the complex path and site response characteristics as seismic waves emanate from a "patch" on the fault to the site of the structure in question. By appropriately summing up the sources for the entire fault region through a convolution process, the site motion for a large earthquake can be estimated [Hutchings, 1988, Hutchings, 1991]. The small micro earthquakes which are recorded to construct the empirical Green's functions are deficient in long period information because the small events do not generate significant energy at long wavelengths. Research studies have indicated that the Green's functions can resolve motions down to approximately 1 Hz frequency, with lower frequency motions being in the signal noise.

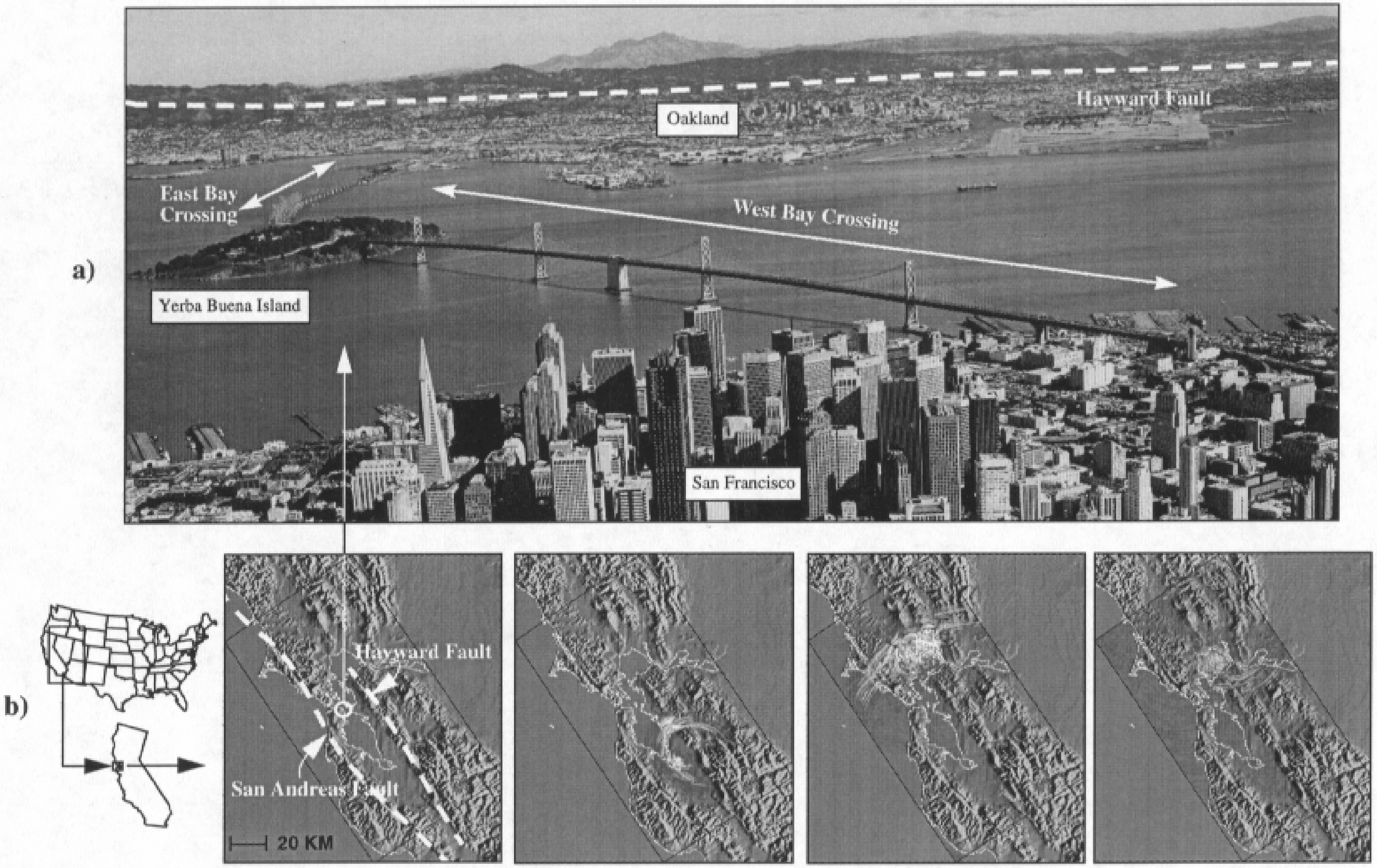

Figure 1. The San Francisco-Oakland Bay Bridge and local faulting. a) Eastern and western crossings; b) fault locations and computed regional wave propagation for a M=7 Hayward Fault earthquake.

To develop understanding of the long period motions which could occur at the bridge site, and to augment the high frequency motions from the Green's function method, a massively parallel finite difference model was constructed for the Bay Area region. This model consisted of 50 million regular finite differences zones of 1/4 Km dimensions. The existing geologic database does not provide sufficient spatial detail on the in homogeneities in the earth to warrant any finer discretization of the geology. This lack of geology definition on a fine scale results in a frequency limitation in the simulation as higher frequency wave components of motion are scattered by the inhomogeneities which cannot be characterized in the model. As a result, the numerical simulations provide information at frequencies of approximately 1 Hz and lower. The complete synthetic broad-band characterization of site ground motions is obtained by a frequency domain merging of the high frequency motions obtained from the empirical Green's functions method with the low frequency motions obtained from the massively parallel simulations.

The specific manner in which the fault rupture evolves during an earthquake has a large effect on the ground motions at a specific site. Since the precise manner in which the fault ruptures is not known a-priori, a number of potential fault rupture scenarios must be investigated when developing the hazard for a particular site. Recent research indicates that on the order of 25 to 30 rupture scenarios should be examined in order to capture the variability of the fault rupture process. Figure 2 shows example synthetic ground motions at the Bay Bridge site for one particular rupture scenario for a M=7 Hayward fault earthquake. This particular rupture scenario, which corresponds to a bi-lateral rupture propagation on the Hayward fault with rupture initiating adjacent to the Bay Bridge, results in a particularly large ground displacement pulse at the bridge site.

STRUCTURAL MODELING

The San Francisco - Oakland Bay Bridge was completed and opened to traffic in 1936. The bridge consists of two segments. The West Bay Crossing, which is the subject of this study, connects the city of San Francisco with Yerba Buena Island, and the East Bay Crossing, which connects Yerba Buena Island with the city of Oakland (Figure 1). The West Bay Crossing consists of twin suspension bridges in tandem connected to a central anchorage pier. The central anchorage pier was specially designed to resist the unbalanced live load of the suspension cables of the two suspension bridges. The foundation system chosen for the bridge was open caissons. The caissons, which include the central anchorage caisson and the caissons which support each tower, were placed directly on bedrock and rely entirely on self weight to maintain contact with the bedrock. There is no positive anchorage system to resist uplift of the caissons. The San Francisco anchorage consists of a concrete block supported on bedrock and the Yerba Buena anchorage consists of a cable bent and eye-bar chains buried in two reinforced concrete filled tunnels. The steel towers are attached to the piers by 40 anchor bolts connected to steel girders deep in the concrete piers. The suspension bridge towers consists of two multi-cell legs braced to each other with diagonal elements and struts. The tower legs are silicon high strength steel while the diagonals and struts are mild carbon steel. Each of the main cables are attached to the tower tops with a single cast steel saddle. The main cables consist of 37 strands with each strand having 472 wires, each wire having a diameter of 5 mm. The deck stiffening trusses are Warren type trusses with the individual truss members constructed with laced steel members. The ends of the stiffening trusses are supported on rocker posts. The rocker posts provide transverse restraint but permit longitudinal movement of the stiffening trusses to accommodate thermal expansion and contraction. Expansion joint connections limit longitudinal motion of the trusses to approximately 36 cm outward and 25 cm inward.

In this research, a special purpose nonlinear finite element program, SUSPNDRS, has been developed for the transient nonlinear analysis of cable bridge structures. The program employs special element technologies which were developed to significantly reduce the number of degrees of freedom required to accurately characterize a cable bridge system. The program includes capabilities for both geometric and

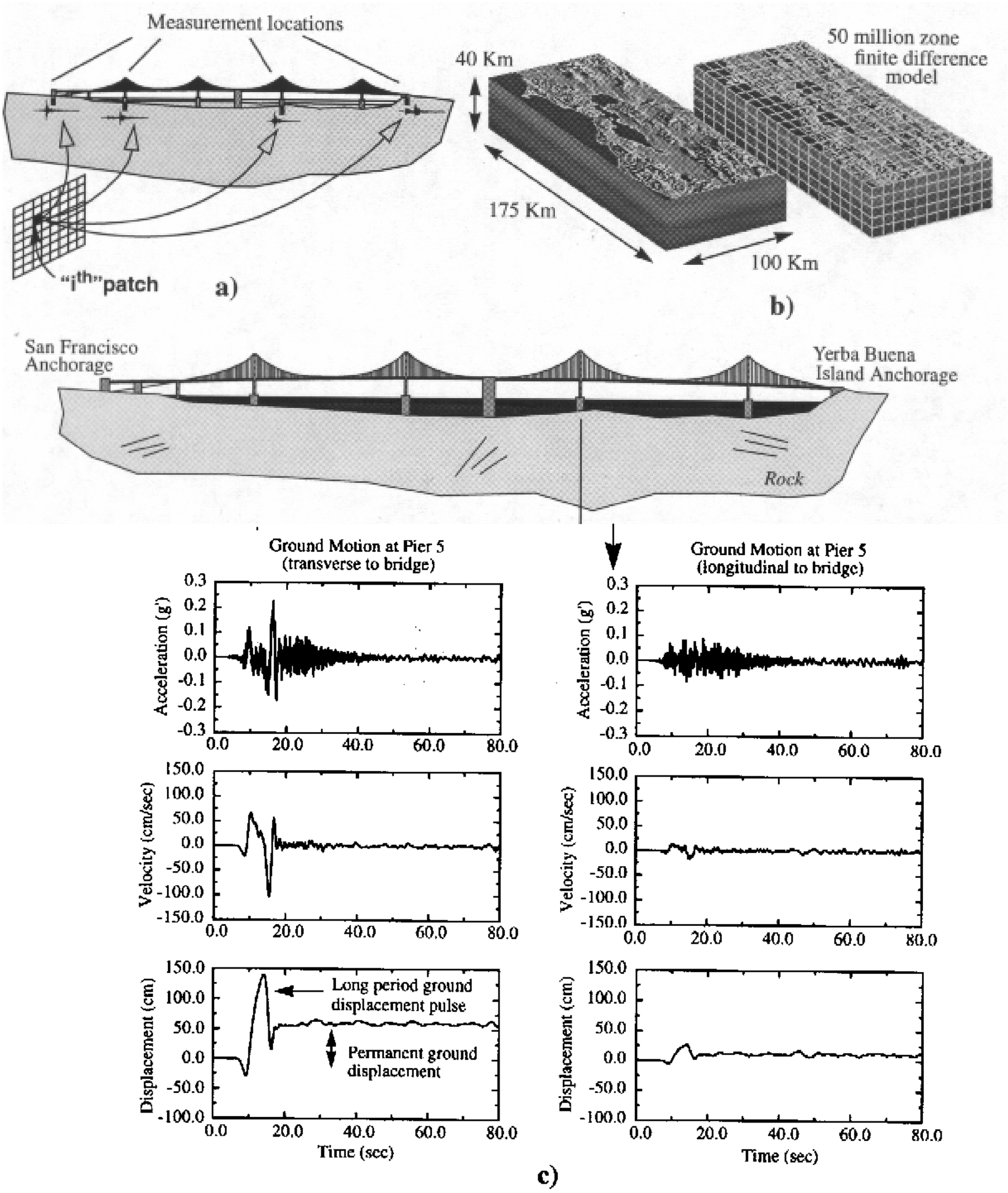

Figure 2. Broad-band synthetic ground motion generation. a) Measured small micro earthquake motions at the bridge site serve as empirical Green's functions for high frequency motions; b) regional massively parallel finite difference model for low frequency motions; c) bedrock motions for one idealized fault rupture scenario for a M=7 Hayward Fault earthquake.

material nonlinearities. The program accounts for finite displacements in the bridge system and employs an updated Lagrangian framework for each structural element in which a local element coordinate system tracks with the element through space and time to remove gross rigid body displacements. The five major components of the bridge model are illustrated in Figure 3, and the details of the bridge model element technologies are provided in the referenced report [McCallen and Astaneh-Asl, 1997].

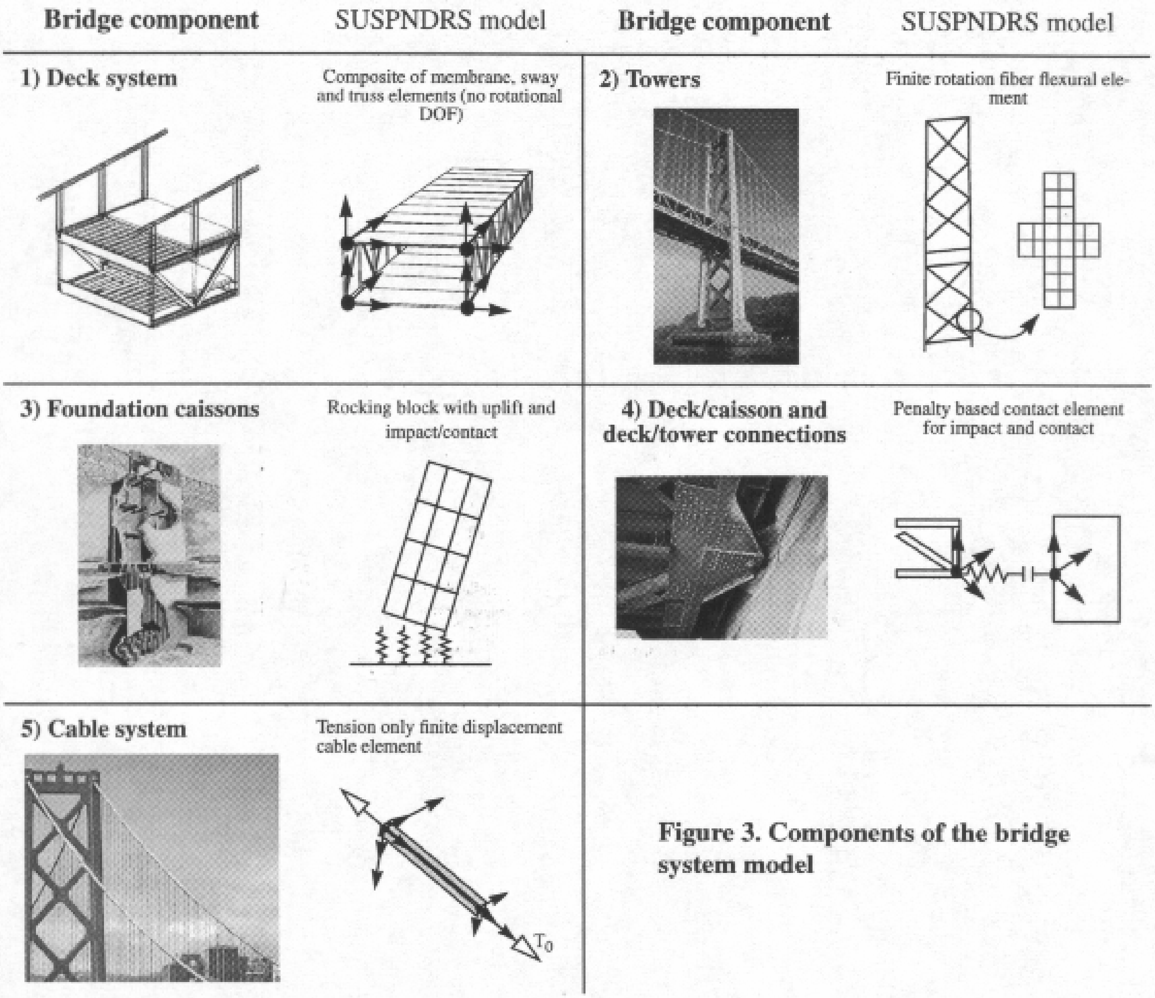

Figure 3. Components of the bridge system model

One of the objectives of the simulation model development was the construction of a transient solution framework which could handle a multiplicity of strong nonlinearities, including the abrupt and strong nonlinearities associated with impact and contact in the bridge system. The solution algorithm which was developed consists of a hybrid implicit-explicit algorithm whereby the initial static state of the bridge under gravity load is determined based on an implicit solution with Newton equilibrium iterations. A static load initialization procedure has been developed which allows the SUSPNDRS program to compute the correct static geometry and element forces starting with any arbitrary initial geometry definition of the bridge cables and deck [McCallen and Astaneh-Asl, 1997]. Once the appropriate gravity configuration is achieved, transient earthquake analysis is carried out with an explicit, central difference based time integration scheme. The explicit scheme is particularly powerful, and has significant advantages over implicit time integration schemes traditionally used in earthquake computations, when modeling the impact and contact associated with caisson rocking or deck-to-tower or deck-to-caisson impacts. Rigorous modeling of contact phenomenon can lead to significantly increased computational effort, or complete lack of appropriate convergence in implicit integration schemes, whereas the efficiency of explicit schemes is not adversely effected by contact.

In the explicit scheme, the bridge equations of motion are formulated in terms of absolute displacements rather than the displacements relative to the ground and the specification of multiple support input motions is trivially simple.

SIMULATED EARTHQUAKE RESPONSE

The large ground displacement pulse in the synthetic earthquake records (Figure 2) has a total time duration on the order of five seconds. For stiff structures, which exhibit natural periods of vibration significantly shorter than five seconds, the structure would have minimal dynamic response to this long duration pulse and would move essentially as a rigid body with the ground motion. For long period flexible structures, on the other hand, this long period pulse can significantly excite the lower frequency modes of vibration, providing a significant dynamic impulse to the structure. The fundamental vibrational mode of one of the Bay Bridge suspension segments consists of transverse vibration of the main span. Based on field measurements completed in 1936, and natural mode computations from the current study, the fundamental mode has a period of approximately 9 to 10 seconds. Thus the ground motion pulse duration is almost exactly one-half the natural period of the bridge. The result is that the ground displacement pulse imparts tremendous energy to the Bay Bridge system at the start of the earthquake motions. Animation of the bridge response indicates that the towers of the bridge move with the ground, while the mainspan deck can't respond fast enough due to its large mass and flexibility and it essentially lags behind the towers. As the deck finally starts to move to catch up with the displaced towers, the tower motion has reversed direction and started to move with the ground displacement pulse in the opposite direction (Figure 4). The result is that the main span deck is essentially flung between the towers in sling shot fashion, with a large transverse displacement and corresponding high stresses in the deck system.

CONCLUSIONS

Two new computational tools have been developed for simulating earthquake ground motions and the response of long-span cable bridges. These tools are shedding light on the nature of near-field ground motions, including long period and permanent displacements which can occur in the near-field, and the damaging effects these motions can have on flexible, long period structures.

ACKNOWLEDGMENTS

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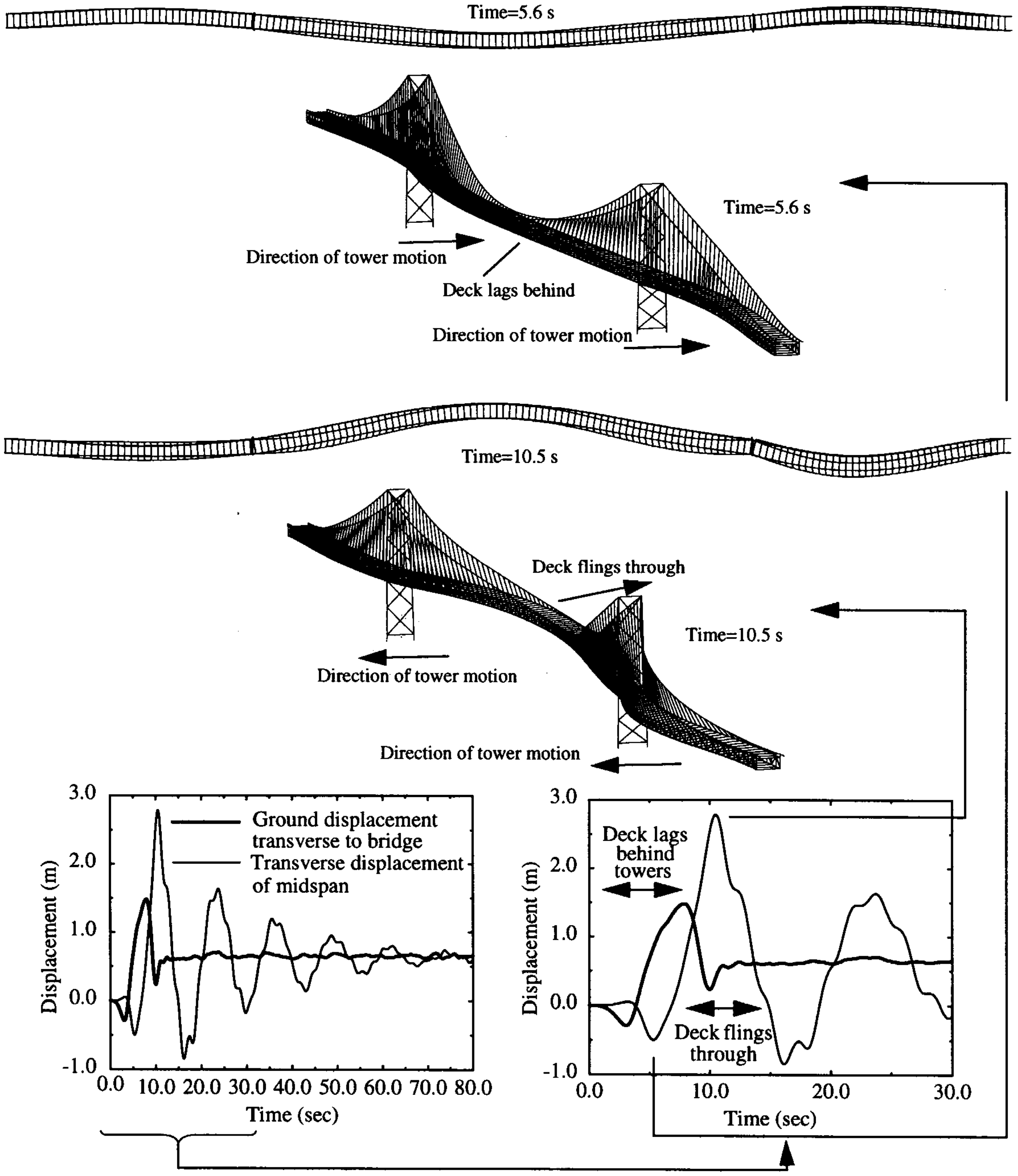

Figure 4. Displacements of bridge system due to near-field motions containing a large displacement pulse.

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