Transactions on the Built Environment vol 3, © 1993 WIT Press, www.witpress.com, ISSN 1743-3509

# A methodology for calculating the response of structures to earthquakes on specific faults

D.B. McCallen, F.E. Heuze, P.W. Kasameyer
*Lawrence Livermore National Laboratory, Livermore CA, USA*

## ABSTRACT

We are developing a methodology chain to estimate the response of structures to large earthquakes from specific faults. The methodology consists of three distinct steps: generation of synthetic bedrock motion at the site of the structure due to a postulated large earthquake; nonlinear effective stress analysis of the soil response at the site to transform bedrock motion to surface motion; and linear/nonlinear finite element analysis of the structure based on the predicted surface motions. Progress in all steps is reported here.

## INTRODUCTION

Our computational simulation of the seismic response of a critical structure is illustrated in Figure 1. To envelope the motions that might be observed at the structure site, the seismologists develop a suite of possible earthquake rupture scenarios for each fault that can contribute significant ground motion at the site. Field instrumentation is placed in bedrock under the structure site, and over a period of time, bedrock motions due to micro-earthquakes emanating from the causative fault(s) are recorded. These recordings serve as empirical Green's functions, which characterize the motion at the structure site location due to slip of an elemental segment of the fault. By appropriate summation of the responses due to each element of the fault rupture zone for a given rupture

Transactions on the Built Environment vol 3, © 1993 WIT Press, www.witpress.com, ISSN 1743-3509


**I** Estimation of Bedrock Motion With Empirical Green's Functions *(Realistic time histories)*

**II** Site Response Based on Nonlinear Effective Stress Finite Element Analysis *(Including Liquefaction)*

**III** Structural Response Based on Nonlinear Finite Element Analysis *(Nonlinear contact, R/C failure)*

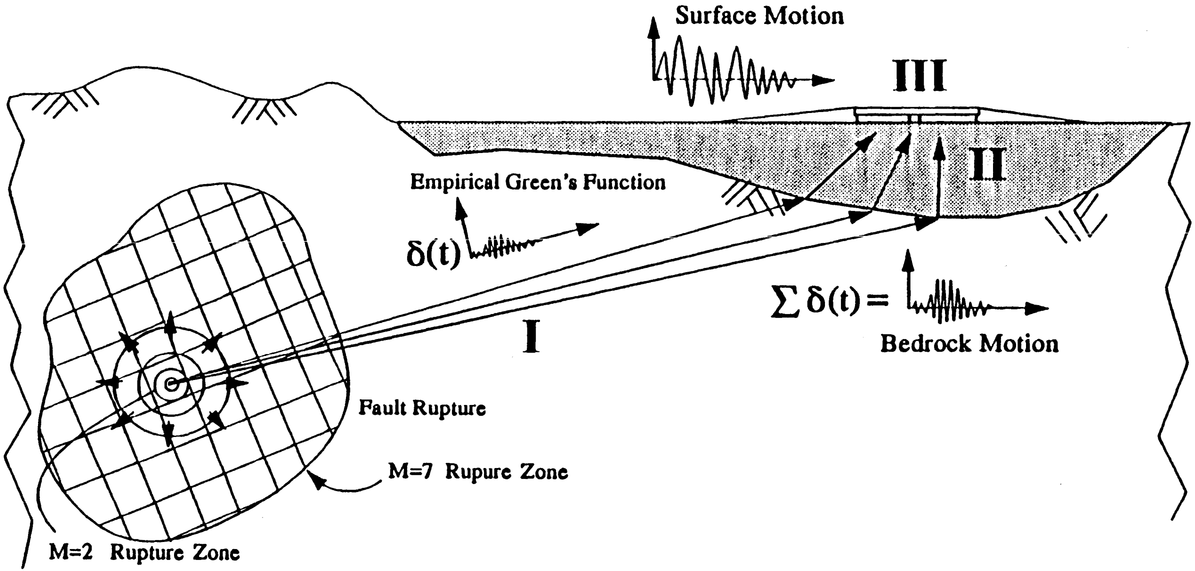


**Figure 1: Methodology for structures response to large earthquakes on specific faults.**

scenario, the bedrock motion due to slip over a large area of the fault (corresponding to a large magnitude earthquake) can be estimated. By considering a suite of several possible fault rupture models, which characterize the different manners in which the fault rupture can propagate across the total fault rupture zone, a suite of acceleration time histories is generated. That family of time histories is representative of the range of ground accelerations that could be expected at the site for a given size earthquake. Hutchings et al. [1-3] have led the development of the empirical Green's function technique and demonstrated the utility of this method using Loma Prieta earthquake data and a suite of 25 rupture models on the San Andreas fault [2].

The transmission of earthquake motion from bedrock through the soil to the soil surface can result in significant modification of the bedrock motion. Traditionally, the nonlinear behavior of the soil under strong seismic motion has been modeled with 'equivalent linear' methods [4]. But such equivalent linear models cannot describe the evolution of pore pressure and predict liquefaction; i.e. they cannot perform the "effective-stress" analysis which we deemed essential for this project. So, we are working in partnership with Princeton University whose 3-D DYNAFLOW model is capable of seismic effective stress analysis [5].

Nonlinear structural-response computations are being performed with nonlinear finite element software developed at LLNL. The implicit, nonlinear, finite deformation program NIKE3D [6] principally is being used to model the structures. NIKE3D has a number of nonlinear constitutive models and advanced contact-surface capabilities for modeling gap opening and closing.

The seismic analysis procedures and capabilities under development are being applied to two transportation structures in California. The first structure is the Dumbarton Bridge, which is the southern-most crossing of the San Francisco Bay. The second is the Painter Street Bridge at Rio Dell, in northern California. This paper focuses on the Painter Street Bridge, which has been heavily instrumented by the California Department of Mines and Geology (CDMG). The high rate of occurrence of earthquakes in that seismically active region of northern California has allowed the measurement of response of this bridge to a number of significant earthquakes. In April 1992, three earthquakes with magnitudes up to 7.0 occurred within close proximity to Rio Dell and the Painter Street Bridge location (Figure 2); they are called the Petrolia earthquake and aftershocks. During the largest of these shocks, the Painter Street Bridge was shaken violently, with lateral deck accelerations up to 1.23 times gravity. These accelerations are among the largest ever measured on a structure during an earthquake. Prior to the April earthquakes, McCallen, et al. [7] had constructed a detailed finite element model of the Painter Street bridge/abutment system (Figure 3) and had performed detailed parameter studies on the dynamic response of the system. Since an extensive modeling effort had already been initiated on this bridge, the latest set of quakes was a fortuitous event, that offered a new opportunity for validating our methodology in a location of strong ground motion.

## PROGRESS

As a result of the Petrolia quakes, the LLNL efforts at the Painter Street site have been scaled up significantly. At our request, the California Department of Transportation drilled four new boreholes, two in the abutments and two at road level (Figure 3). The soil-rock interface was about 24 m below road elevation. Core samples of soils were tested in cyclic triaxial compression at the University of California, Berkeley. One of the road-level holes was used for up-hole S-wave surveying. A seismometer was emplaced 6 m into bedrock in the other road-level hole. Another seismometer was emplaced 1 m into the ground, near the collar of that hole. The package at bedrock depth is currently being used by seismologists to measure empirical Green's functions for micro-earthquakes emanating from nearby faults, including those causative of the Petrolia shocks. To date, Painter Street site bedrock responses have been measured for eight micro-earthquakes emanating from the fault locations indicated in Figure 4. Based on the empirical Green's functions obtained from these measurements,

Transactions on the Built Environment vol 3, © 1993 WIT Press, www.witpress.com, ISSN 1743-3509



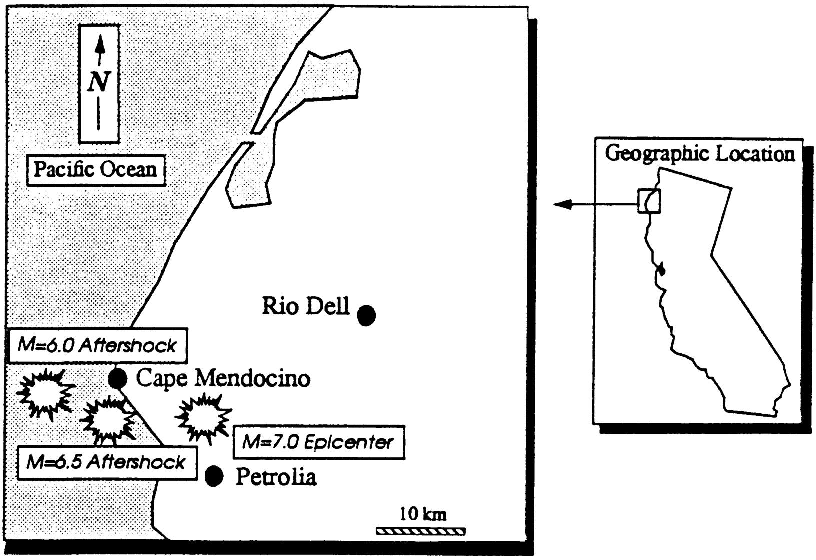


**Figure 2: The Painter Street Bridge in Rio Dell, CA, and location of the Petrolia Earthquakes of April 1992.**

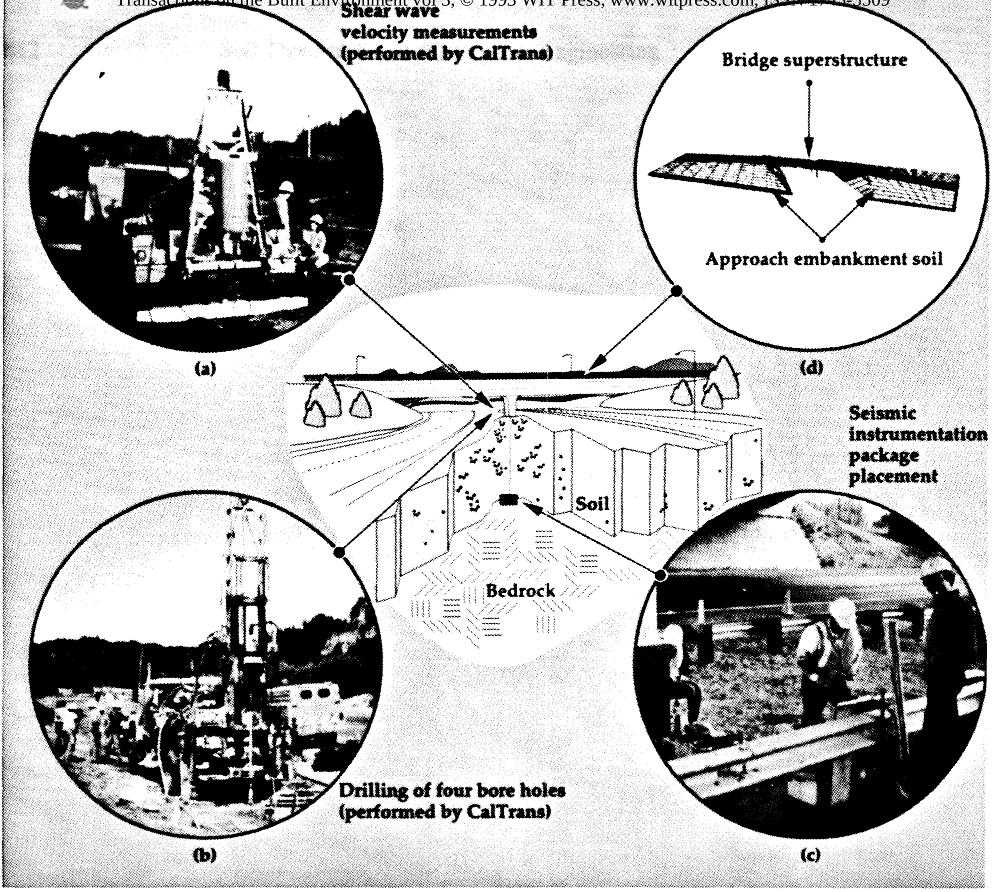


Figure 3: Schematic of activities at the Painter Street Bridge.

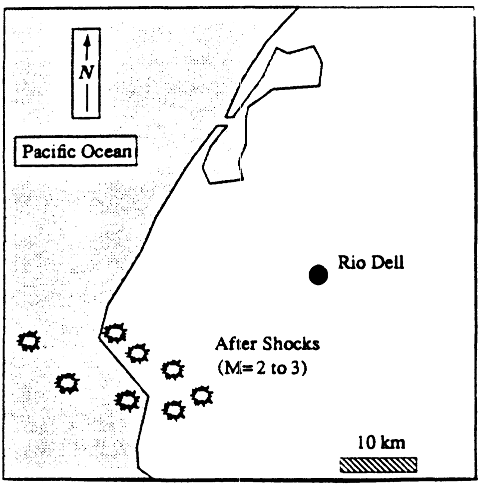


Figure 4: Location of aftershocks used for acquiring empirical Green's functions at Painter Street.

synthetic bedrock-ground-motion time histories have recently been generated for a number of earthquakes of magnitude M = 7.0. Samples of Painter Street site synthetic time histories, each based on a different fault rupture propagation model, are shown in Figure 5.

In parallel to the seismological work, finite element modeling of the Painter Street bridge/abutment system has progressed into the nonlinear regime. For dynamic analyses, the superstructure, pile foundation, and approach embankment soil masses have been modeled as shown in Figure 6. Nonlinear hysteretic behavior of the soil embankments has been experimentally identified as a very important factor in the dynamic response of such a bridge system [8, 9]. The primary objective of constructing a detailed, three-dimensional model of the bridge/soil system was to allow incorporation of the effects of nonlinear soil stiffness and soil mass. This is in contrast to finite element models which are used in traditional design and analysis for this type of bridge; such models neglect the soil mass, and the soil stiffness typically is represented by linear elastic, amplitude-independent springs. For the Painter Street non linear analyses, the detailed finite element model is truncated at approximately the original ground surface elevation, and the surface free field motion is applied directly to the base of the model at that elevation (Fig. 3). This approach neglects potential soil-structure interaction effects between the piles and soil below this level, and prevents radiation of energy vertically back into the soil. However, interaction between the soil and piles typically occurs in the top portion of the piles, and energy loss through radiation will be small relative to the energy dissipated by the nonlinear hysteretic behavior of the soil embankments.

The small-amplitude shear moduli for the approach embankments and original grade soils were estimated from our P and S-wave surface refraction measurements [10]. To represent the nonlinearity of the soil in the bridge/abutment finite element model, the small-strain shear moduli obtained from these measurements were used with standard soil modulus degradation and damping curves [11]. To represent the standardized modulus degradation and damping curves in the NIKE3D finite element code,

Transactions on the Built Environment vol 3, © 1993 WIT Press, www.witpress.com, ISSN 1743-3509



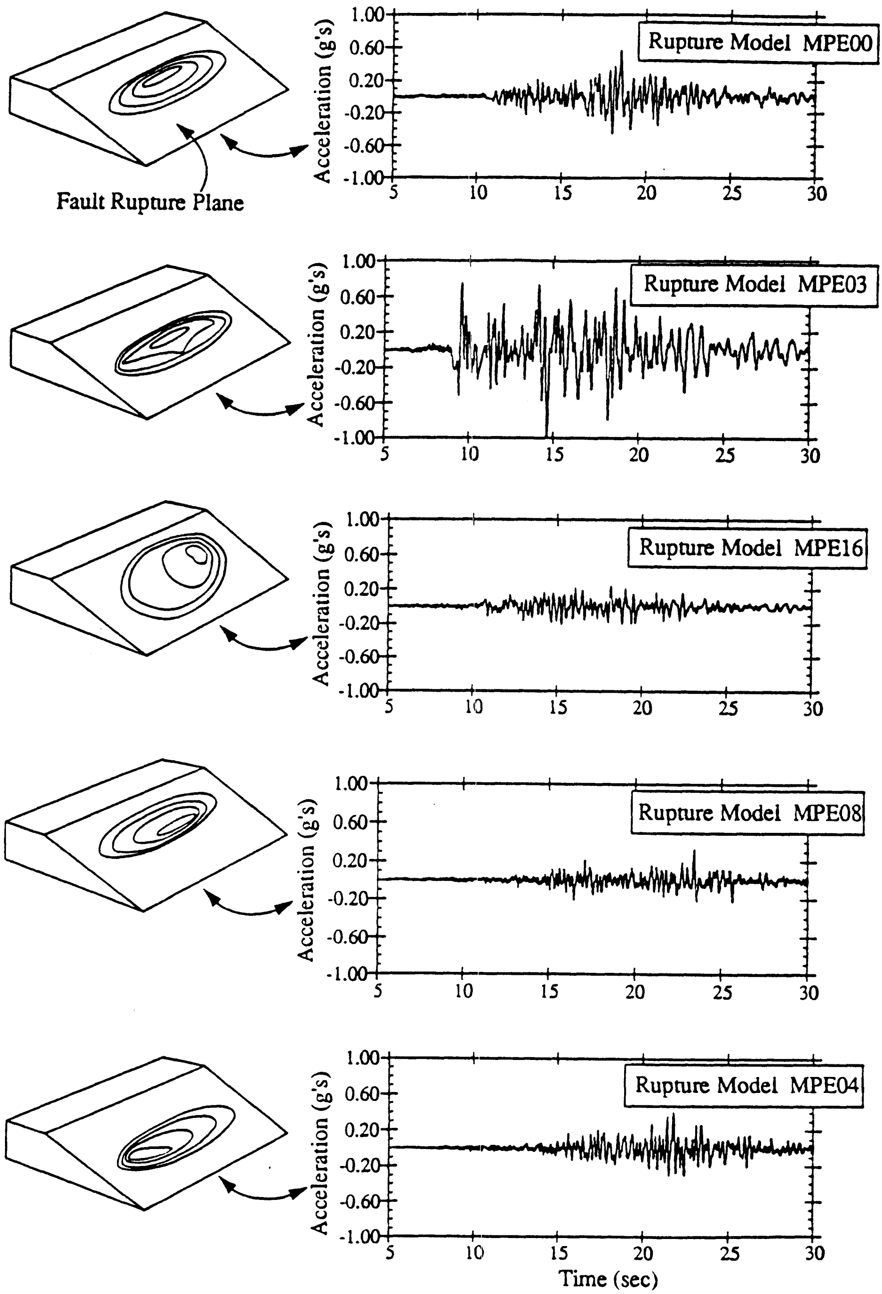


**Figure 5: Five fault rupture scenarios, and resulting bedrock motion under the Painter Street Bridge. (M = 7.0)**

Transactions on the Built Environment vol 3, © 1993 WIT Press, www.witpress.com, ISSN 1743-3509



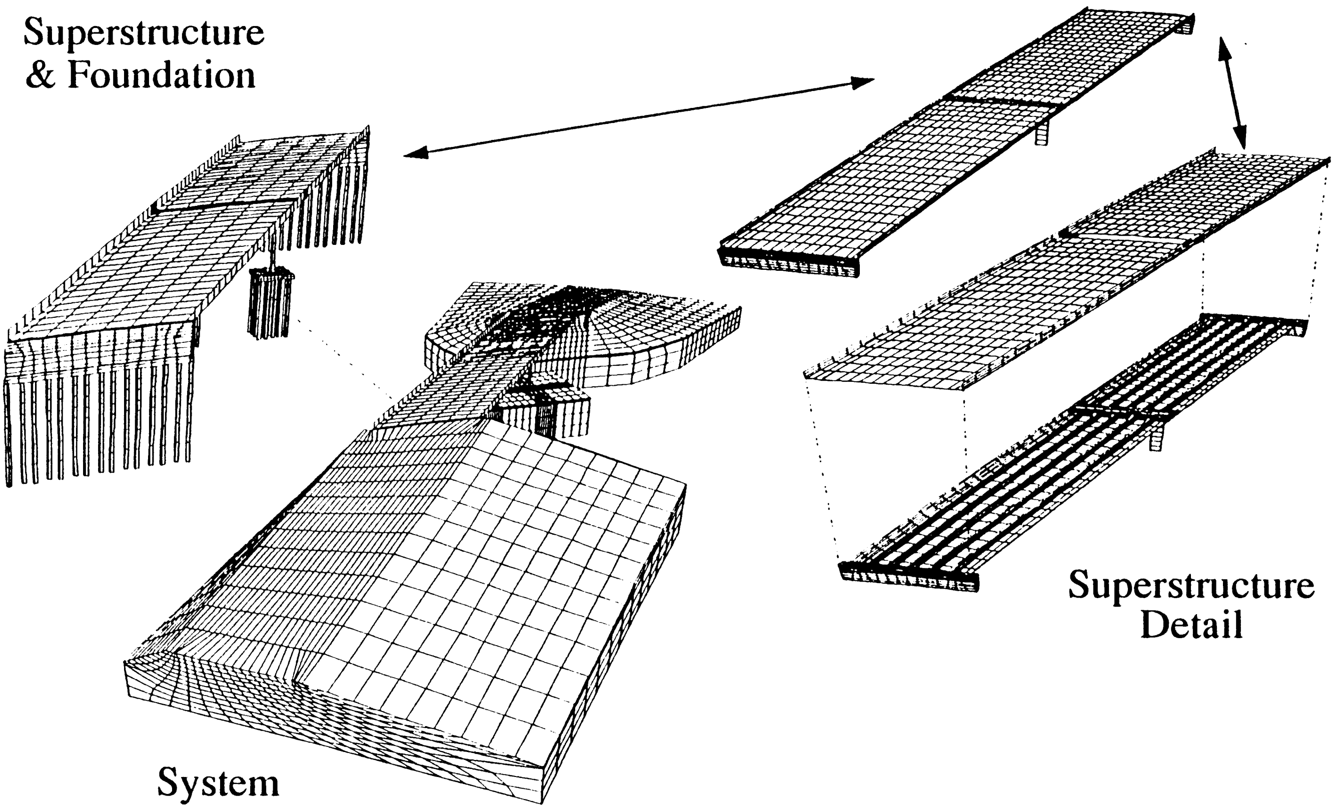


**Figure 6: Detailed finite element model of the Painter Street Bridge, its abutments and foundations.**

a simple Ramberg–Osgood constitutive model was used to model the soil. The material parameters were set such that the Ramberg–Osgood hysteresis loop would yield modulus degradation and damping curves very similar to Seed's standardized curves [11]. The procedure for determining the Ramberg–Osgood parameters to approximate given modulus degradation and damping curves was developed by Ueng and Chen [12]. The modulus and damping curves obtained from the Ramberg–Osgood constitutive model fit with Ueng and Chen's technique are shown in Figure 7 along with the original curves of Seed. The shear stress-strain behavior generated with the fitted Ramberg–Osgood model in the NIKE3D finite element program also is shown in Figure 7.

A number of time history analyses have been carried out with the detailed bridge abutment model shown in Figure 3, as well as with simple reduced-order stick models of the bridge [13]. The bridge instrumentation records for the April 1992 Petrolia earthquakes have not yet been completely processed by the CDMG; thus, the measured free field motions were not available to apply to our model prior to this report. However, free field and bridge-response data for a magnitude 5.5 earthquake of November 1986 were available and were used to examine the accuracy of the finite element models of the bridge system.

The 1986 free-field acceleration time histories were used as input motion to the base of the bridge system models. The model response predictions were compared to the actual bridge response data measured by the CDMG bridge instrumentation array. Since the details of all of the response predictions are given elsewhere [13], only an illustrative example of the response predictions is provided here. The detailed model response predictions for the absolute displacement at channel 7 (transverse motion at mid-span) are shown in Figure 8. Figure 8a shows the response of the detailed model when a linear elastic soil model is used, and mass- and stiffness-proportional Rayleigh damping is used to provide approximately 5% damping in the first transverse and longitudinal modes of the bridge system. For the linear analysis, soil properties were set equal to the small-strain soil properties [10]. Two

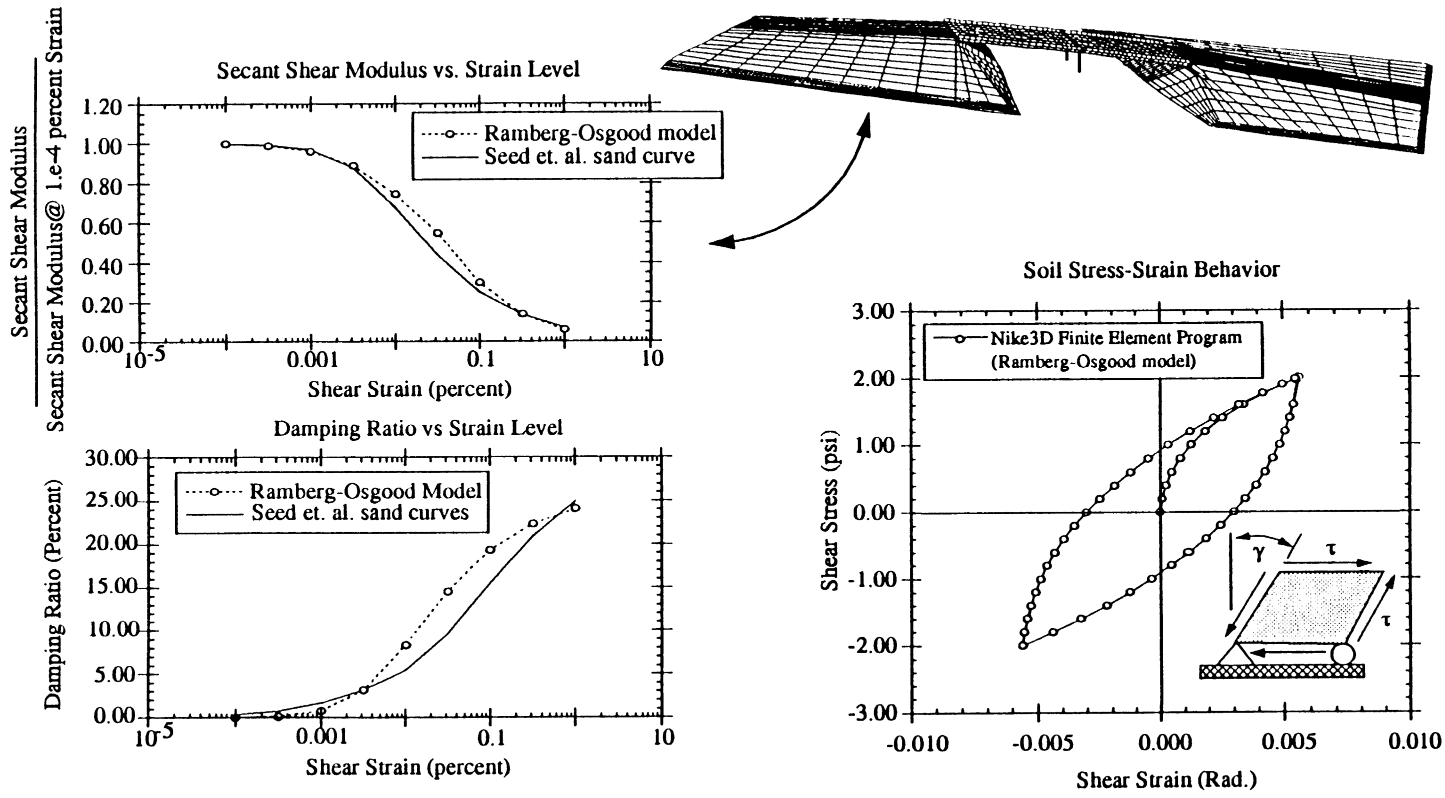


**Figure 7: Non-linear model of bridge abutment for initial 3-D dynamic analysis.**

Transactions on the Built Environment vol 3, © 1993 WIT Press, www.witpress.com, ISSN 1743-3509



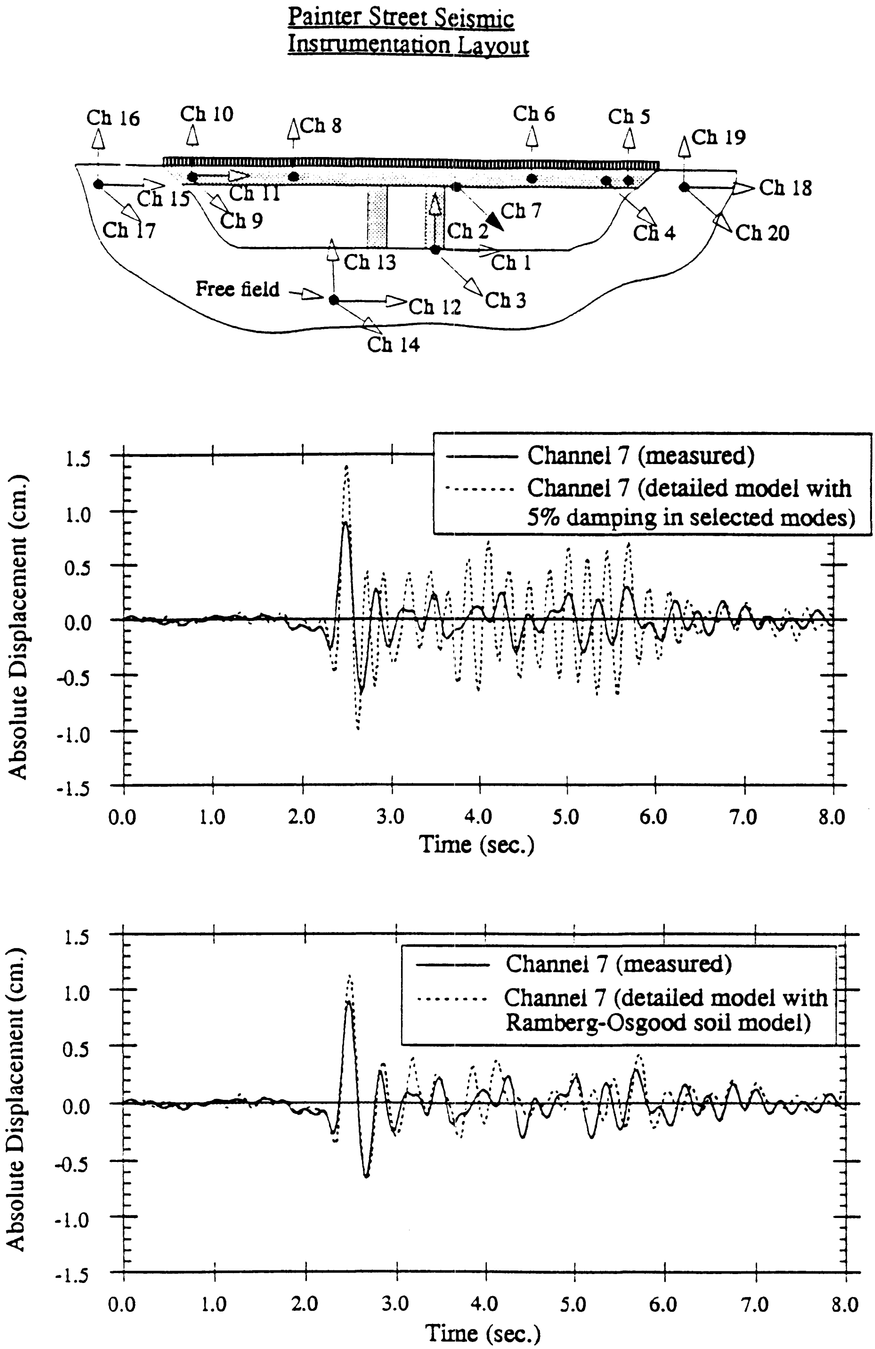


**Figure 8: Comparison of Painter Street Bridge response for M = 5.5 event, using linear and non-linear soil models.**

observations can be made: (1) the frequency content of the bridge model is significantly too high when the small-strain soil properties are used; and (2) the amplitude of the response prediction is too large relative to the measured response. The bridge response prediction using the detailed model with the nonlinear Ramberg–Osgood soil model is shown in Figure 8b. This model also used mass-proportional Rayleigh damping, in which the damping in the first transverse mode was set to 10%. The nonlinear model exhibits significant improvement over the linear model. The nonlinear model displays appropriate softening and energy dissipation in the system, such that the frequency content and amplitude are more representative of the actual structural response.

## FUTURE WORK

Significant progress has been made in the study of the Painter Street overcrossing site. Construction of the seismological model and the structural model have been completed, and calculations have been generated with both models. Additional field measurements of Green's functions from future micro-earthquakes will continue to enhance the site seismological model, and newly obtained laboratory data will improve the soil characterization in the finite element model of the bridge/abutments. The site-soil characterization will also allow site-response analysis to transform bedrock motion to soil surface motion. Specific tasks which we intend to perform during the next year include:

(1) Use of the nonlinear model of the bridge/abutment system to predict the response of the bridge to the measured free field motion from the April 1992 Petrolia earthquake. The predicted response will be compared to the actual bridge response measured by CDMG. This earthquake should have resulted in significant nonlinear behavior of the bridge/abutment system, and this analysis will allow us to further verify the ability of the nonlinear model to accurately predict bridge/abutment response.

(2) To test the predictive capability of the empirical Green's

function approach, generate the suite of 25 time histories that would be used to model a M=7.0 event on the fault causative of the Petrolia earthquake.

(3) The bedrock-motion time histories will be transformed to surface motion with a soil response analysis, and the suite of surface time histories will be compared to the actual free field motion measured at the site by CDMG.

(4) The suite of predicted free field responses will be run through the structural model, and response statistics will be compared to the actual response from the April 1992, M = 7.0, earthquake.

The ultimate goal of our project is to allow accurate site-specific estimates of structural response for a specified earthquake on a specified fault. For practical applications of this methodology, it will be essential to decide how the structural engineer may best use the information provided by the suite of time histories developed by the seismological portion of the study. It will generally be impractical to perform 25 time history analyses (or more if multiple faults/multiple rupture zones are considered) for a large structural model. It is necessary to consolidate the information obtained from the time histories into a simplified form (e.g., a representative response spectrum and corresponding single time history) to achieve practical application.

The Painter Street site study will allow a critical evaluation of the accuracy of the method that is being developed, and a demonstration of our technology in all segments of the methodology chain. It will also provide an opportunity for interaction between structural analysts and seismologists, so that appropriate procedures for using the earthquake ground motion in structural response calculations can be developed.

The Dumbarton bridge, a much larger structure founded on piles and soft soils, will be the object of our second application of the entire methodology. It will exercise the effective stress models for earthquakes up to M = 7.5 on the Hayward Fault and M = 8.0 on the San Andreas Fault.

## REFERENCES

1. L. Hutchings, "Modeling Earthquake Ground Motion with an Earthquake Simulation Program (EMPSYN) that Utilizes Empirical Green's Functions", Lawrence Livermore National Laboratory, Livermore, California, *UCRL-ID-105890*, (1992).

2. L. Hutchings, "Prediction of Strong Ground Motion for the 1989 Loma Prieta Earthquake, Using Empirical Green's Functions", *Bull. Seismological Society of America*, vol. 81, no. 5, pp 1813–1837, (1991).

3. L. Hutchings, "Empirical Green's Functions from Small Earthquakes: A Waveform Study of Locally Recorded Aftershocks of the 1971 San Fernando Earthquake", *J. Geophysical Research*, vol. 95, no. B2, pp 1187–1214, (1990).

4. P.B. Schnabel, H.B. Seed, and J. Lysmer, "SHAKE—A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites", Earthquake Engineering Research Center, University of California, Berkeley, California, *Report EERC-72-12*, (1972).

5. J.H. Prevost, "DYNAFLOW, User's Manual", Department of Civil Engineering, Princeton University, (1992).

6. B.N. Maker, R.M. Ferencz, and J.O. Hallquist, "NIKE3D: A Nonlinear, Implicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics", Lawrence Livermore National Laboratory, Livermore, California, *UCRL-MA-105268*, (1992).

7. D.B. McCallen, K.M. Romstad, and G.L. Goudreau, "Dynamic Response of a Reinforced Concrete Box-Girder Bridge," Lawrence Livermore National Laboratory, Livermore, California, *UCRL-53868-91*, pp 2-12 (1992).

8. J.C. Wilson, and B.S. Tan, "Bridge Abutments: Assessing Their Influence on Earthquake Response of Meloland Road Overpass", *ASCE J. Engineering Mechanics*, vol. 226, no. 8, pp 1838–1856, (1990).

9. S.D. Werner, J.L. Beck, and M.B. Levine, "Seismic Response Evaluation of Meloland Road Overpass Using 1979 Imperial Valley Earthquake Records", *Earthquake Engineering and Structural Dynamics*, vol. 15, pp 249–274, (1987).
10. F.E. Heuze and R.P. Swift, "Seismic Refraction Studies at the Painter Street Bridge Site, Rio Dell, California", Lawrence Livermore National Laboratory, Livermore, California, *UCRL-ID-108595*, (1992).
11. H.B. Seed, R.T. Wong, I.M. Idriss, and K. Tokimatsu, "Moduli and Damping Factors for Dynamic Analysis of Cohesionless Soils", Earthquake Engineering Research Center, University of California, Berkeley, California, *Report EERC-84/14*, (1984).
12. T.S. Ueng, and J.C. Chen, "Computational Procedure for Determining Parameters in Ramberg–Osgood Elastoplastic Model Based on Modulus and Damping Versus Strain", Lawrence Livermore National Laboratory, Livermore, California, *UCRL-ID-111487* (1992).
13. D.B. McCallen and K.M. Romstad, "Dynamic Response of a Reinforced Concrete, Box-Girder Bridge", Lawrence Livermore National Laboratory, Livermore, California, *UCRL-ID-110640*, (1992).


## ACKNOWLEDGMENTS

This work performed by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48 with the U. S. Department of Energy. We thank S. Uhlhorn for her fine typing.