ECAS2002 International Symposium on Structural and Earthquake Engineering, October 14, 2002, Middle East Technical University, Ankara, Turkey

The Effects of Local Soil Conditions and Wave Velocities to the Stochastic Response of Cable-Stayed Bridges

K. Soyluk, A. A. Dumanoglu
Karadeniz Technical University, Department of Civil Engineering, Trabzon, Turkey

ABSTRACT: In this paper, a comprehensive investigation of the stochastic response of a cable-stayed bridge subjected to spatially varying ground motions is performed for variable wave velocities and local soil profiles. While the ground motion is described by power spectral density function, the spatially variability of ground motions between the support points is taken into account with the incoherence, wave-passage and site-response effects. In the analysis mean of maximum response values of the ground motions with variable wave velocities are compared with those of the constant wave velocities. It is observed that the variation of the wave velocities depending on the local soil conditions, has important effects on the dynamic behaviour of the bridge.

Keywords: Spatially varying ground motions, cable-stayed bridge, dynamic displacement, pseudo-static displacement, mean of maximum response values

ÖZET: Bu çalışmada zemin şartlarındaki değişime bağlı olarak yer hareketi yayılma hızındaki değişim dikkate alınmak suretiyle kablolu bir köprünün stokastik davranışı incelenmektedir. Yer hareketi spektral yoğunluk fonksiyonu ile tanımlanırken, yer hareketinin değişimi korelasyon etkisi, dalga yayılma etkisi ve zemin şartlarındaki değişim ile dikkate alınmaktadır. Yer hareketi yayılma hızının zemin cinsine bağlı olarak değişiminin dikkate alınması ile elde edilen tepki değerleri, dalga yayılma hızının sabit olması durumunda bulunan değerlerle karşılaştırılmaktadır. Çalışma sonucunda, yer hareketi yayılma hızının zemin cinsine göre değişimimin dikkate alınmasının yapının dinamik davranışı üzerinde önemli etkisinin olduğu gözlenmektedir.

Introduction

It is obvious that earthquake motions will be subjected to significant variations because of travelling with finite velocity, coherency loss due to reflections and refractions and the difference of local soil conditions at the supports. This variation will cause to internal forces because of the pseudo-static displacements which normally do not produce internal forces for uniform ground motions. Therefore, when analysing structures, the spatial variability of the earthquake motions should be considered. The effect of spatial variation of ground motion on the response of deck arch, suspension and cable-stayed bridges are investigated in recent years (Sweidan 1990, Hawwari 1992, Allam and Datta 1999, Allam and Datta 2000, Soyluk and Dumanoglu 2000, Dumanoglu and Soyluk 2000, Soyluk 2002). In these studies it was observed that the spatial variation of ground motion has important effects on long-span bridges.

In this study, stochastic response of a cable-stayed bridge subjected to spatially varying ground motions is performed for variable wave velocities and local soil profiles. While the ground motion is described by power spectral density function, the spatial variability of ground motions between the support points is taken into account with the incoherence, wave-passage and site-response effects.

Spatially Varying Ground Motion

The variability of the ground motion is characterised with the coherency function as follows (Der Kiureghian et al. 1997)

$$\gamma_{lm}(w) = \frac{S_{\ddot{u}_{gl}\ddot{u}_{gm}}(w)}{\sqrt{S_{\ddot{u}_{gl}\ddot{u}_{gl}}(w) * S_{\ddot{u}_{gm}\ddot{u}_{gm}}(w)}} \tag{1}$$

where $S_{\ddot{u}_{gl}\ddot{u}_{gl}}(w)$, $S_{\ddot{u}_{gm}\ddot{u}_{gm}}(w)$ and $S_{\ddot{u}_{gl}\ddot{u}_{gm}}(w)$ indicate the auto-power spectral densities of the accelerations and their cross-power spectral density, respectively. For the coherency function the model proposed by (Der Kiureghian et al. 1997) is used

$$\gamma_{lm}(w) = \gamma_{lm}(w)^{i} \exp\left[i\left(\theta_{lm}(w)^{w} + \theta_{lm}(w)^{s}\right)\right] \tag{2}$$

where $\gamma_{lm}(w)^i$, $\gamma_{lm}(w)^w$ and $\gamma_{lm}(w)^s$ characterise the incoherence, the wave-passage and the site-response effects, respectively. For the incoherence effect, the extensively used model proposed by (Harichandran and Vanmarcke, 1986) is considered

$$\gamma_{lm}(w)^{i} = A\, e^{\frac{-2d_{lm}}{\alpha\theta(w)}(1-A+\alpha A)} + (1-A)\, e^{\frac{-2d_{lm}}{\theta(w)}(1-A+\alpha A)} \tag{3}$$

$$\theta(w) = k\left[1 + \left(\frac{w}{2\pi f_0}\right)^{b}\right]^{-\frac{1}{2}} \tag{4}$$

where d_{lm} is the distance between support points l and m. A, α, k, f_0 and b are model parameters and in this study the values obtained by (Harichandran et al. 1996) are used (A=0.636, α=0.0186, k=31200, f_0 =1.51 Hz and b=2.95). The wave-passage effect resulting from the difference in the arrival times of waves at support points is defined as (Der Kiureghian and Neuenhofer, 1991)

$$\theta_{lm}(w)^{w} = -\frac{w d_{lm}^{L}}{v_{app}} \tag{5}$$

where v_{app} is the apparent wave velocity and d_{lm}^{L} is the projection of d_{lm} on the ground surface along the direction of propagation of seismic waves. The site-response effect due to the differences in the local soil conditions is defined as (Der Kiureghian et al. 1997)

$$\theta_{lm}(w)^{s} = \tan^{-1}\frac{\mathrm{Im}[H_l(w)H_m(-w)]}{\mathrm{Re}[H_l(w)H_m(-w)]} \tag{6}$$

where $H_l(w)$ is the local soil frequency response function representing the filtration through soil layers. The power spectral density function of the ground acceleration ($\ddot{u}_{g_l}$) characterising the earthquake process is assumed to be of the following form modified by (Clough and Penzien, 1993)

$$S_{\ddot{u}_{g_l}\ddot{u}_{g_l}}(w) = So\,|H_l(w)|^2 |H_f(w)|^2 \tag{7}$$

where

$$|H_l(w)|^2 = \frac{w_l^4 + 4\xi_l^2 w_l^2 w^2}{(w_l^2 - w^2)^2 + 4\xi_l^2 w_l^2 w^2} \tag{8}$$

$$|H_f(w)|^2 = \frac{w^4}{(w_f^2 - w^2)^2 + 4\xi_f^2 w_f^2 w^2} \tag{9}$$

are the frequency response functions of the first and second filters representing dynamic characteristics of the layers of soil medium above the rock bed, S_0 is the amplitude of the white-noise bedrock acceleration, w_l and ξ_l are the resonant frequency and damping ratio of the first filter, and w_f and ξ_f are those of the second filter.

In this study, it is assumed that the island abutment is founded on firm soil (F), the island pier is founded on medium soil (M) and the supports at the mainland site are founded on soft soil (S) type. The spectral density functions representing the ground motions at the support points are shaped according to the soil type at the supports, as shown in Fig. 1. The filter parameters for these soil types proposed by (Der Kiureghian and Neuenhofer, 1991) are utilised as shown in Table 1. The calculated values of the intensity parameters for each soil type are: S_0(firm)=0.00177 m^2/s^3, S_0(medium)=0.00263 m^2/s^3, S_0(soft)=0.00369 m^2/s^3.

Soil Type	w_g (rad/s)	ξ_g	w_f (rad/s)	ξ_f
Firm	15.0	0.6	1.5	0.6
Medium	10.0	0.4	1.0	0.6
Soft	5.0	0.2	0.5	0.6

Table 1. Power spectral density parameters for model soil types

Random Vibration Theory

The variance of the i[th] dynamic response in the case of spatially varying ground motion can be written as (Hawwari, 1992)

$$\sigma^2{}_{z_i}^{d} = \sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{r}\sum_{m=1}^{r}\psi_{ij}\psi_{ik}\Gamma_{lj}\Gamma_{mk}\int_{-\infty}^{\infty}H_j(-w)H_k(w)S_{\ddot{u}_{g_l}\ddot{u}_{g_m}}(w)dw \tag{10}$$

where $[\psi]$ is the eigenvectors, $[\Gamma]$ is the modal participation factor, $S_{\ddot{u}_{g_l}\ddot{u}_{g_m}}(w)$ is the cross spectral density function of accelerations between supports l and m, H(w) is the frequency response function, n is the number of free degrees-of-freedom and r is the number of restrained degrees-of-freedom. The variance of the i^{th} pseudo-static response can be written as

$$\sigma^2{}_{z_i}^{qs}(w) = \sum_{l=1}^{r}\sum_{m=1}^{r}A_{il}A_{im}\int_{-\infty}^{\infty}\frac{1}{w^4}S_{\ddot{u}_{g_l}\ddot{u}_{g_m}}(w)dw \tag{11}$$

where A_{il} and A_{im} are equal to static displacements for unit displacements assigned to each support points. The covariance between the i^{th} pseudo-static and dynamic response components may be expressed as

$$\begin{aligned}\mathrm{Cov}(z_i^{qs}, z_i^{d}) &= \mathrm{Re}\left[\int_{-\infty}^{\infty}S_{z_i^{qs} z_i^{d}}(w)dw\right] \\ &= \sum_{j=1}^{n}\sum_{l=1}^{r}\sum_{m=1}^{r}\psi_{ij}A_{il}\Gamma_{mj}\left(-\int_{-\infty}^{\infty}\frac{1}{w^2}H_j(w)S_{\ddot{u}_{g_l}\ddot{u}_{g_m}}(w)dw\right)\end{aligned} \tag{12}$$

Mean of Maximum Value

Depending on the peak response and standard deviation (σ_z) of z(t) the mean of maximum value, μ, in the stochastic analysis can be expressed as (Wung and Der Kiureghian, 1989)

$$\mu = p\sigma_z \tag{13}$$

where p is the peak factor, which is a function of the time of the motion and the mean zero crossing rate.

Mathematical Model of the Bridge

In this study, the Jindo Bridge built in South Korea is chosen as a numerical example. Jindo bridge has three spans; the main span of 344 m and two side spans of 70 m. To investigate the stochastic response of the Jindo bridge two dimensional mathematical model is used for calculations (Fig. 1). The chosen finite element model is represented by 420 degrees of freedom. The stiffening girder and towers are represented by 139 beam elements. The cable stays are modelled with 28 truss elements and the nonlinearity of the inclined cable stays is considered with equivalent modulus of elasticity.

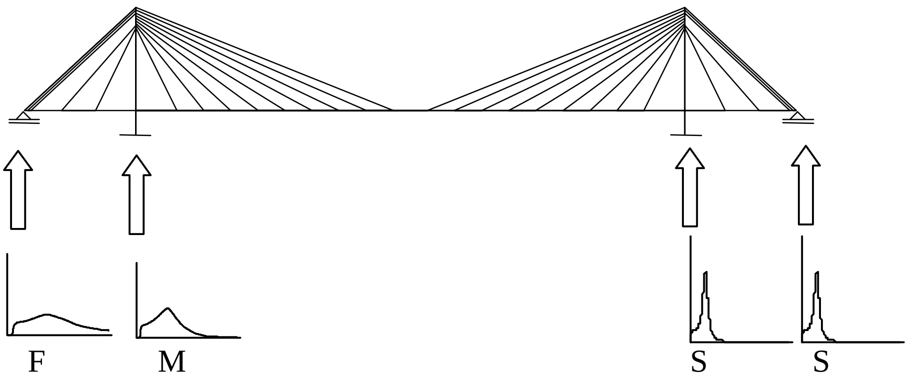

Figure 1. Cable-stayed bridge subjected to vertical ground motion

Numerical Results

In this study stochastic analysis of a cable-stayed bridge is performed for spatially varying ground motions by taking into account the incoherence, wave-passage and site-response effects. Mean of maximum pseudo-static and dynamic response values obtained for variable and constantly travelling wave velocity cases are compared with each other. For the apparent wave velocity the following three cases are taken into account depending on the local soil profiles.

Case 1: v_{app}=1000 m/s (constant wave velocity case)
Case 2: v_{app}=1800 m/s (firm soil), v_{app}=600 m/s (medium soil), v_{app}=200 m/s (soft soil)
Case 3: v_{app}= 800 m/s (firm soil), v_{app}=400 m/s (medium soil), v_{app}=200 m/s (soft soil)

Mean of maximum values of pseudo-static component of vertical deck and horizontal Jindo island tower displacements are compared for variable and constantly travelling wave velocity cases in Figs. 2-3. Because the pseudo-static displacements are close to each other for both constant and variable wave velocity cases, it can be outlined that the variation of the wave velocity depending on the local soil conditions has insignificant effect on the pseudo-static displacements. It can be observed that the variation of the wave velocity has important effect on the dynamic deck displacements and horizontal Jindo island tower displacements as compared with those of the constantly travelling wave velocity case (Figs. 4-5). The dynamic displacements obtained for two variable wave velocity cases (Case 2 and Case 3) induce very close displacement values. At the bridge deck where maximum dynamic displacement take place, the displacement value obtained for Case 2 cause the response by % 23 increase when compared to the response due to constantly travelling wave velocity case (Case 1). Similar ratio is also obtained for Case3. At the island tower top, the displacement value obtained for Case 2 cause the response by % 33 increase when compared to those of the constantly travelling wave velocity case (Case 1). The ratio obtained for Case 3 is %30. It is obvious that the total displacements which are obtained by summing the pseudo-static, dynamic and covariance response components will cause larger response values for varying wave velocity cases compared to those of the constantly travelling wave velocity case. Although not shown in this paper the results obtained for member forces show similar tendency as those of the displacements. However, the increase ratio obtained for member forces in the case of varying wave velocity cases are larger than those of the displacements.

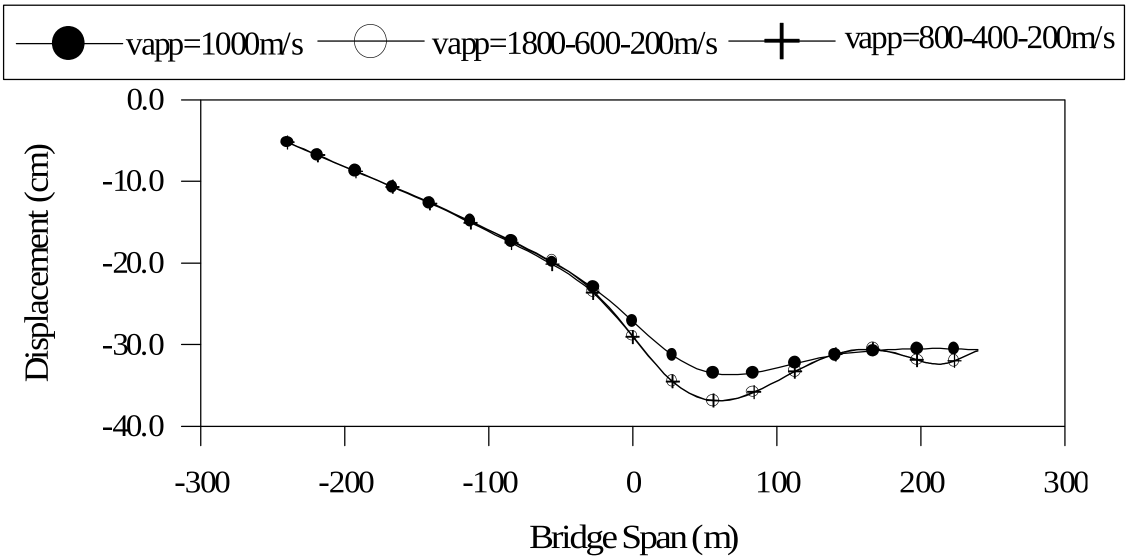

Figure 2. Mean of maximum vertical pseudo-static deck displacements

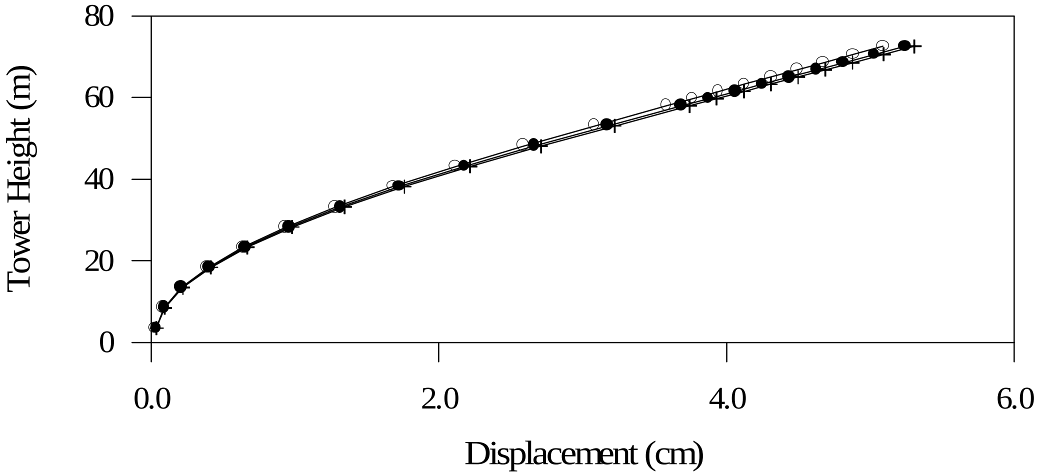

Figure 3. Mean of maximum horizontal pseudo-static displacements at the island tower

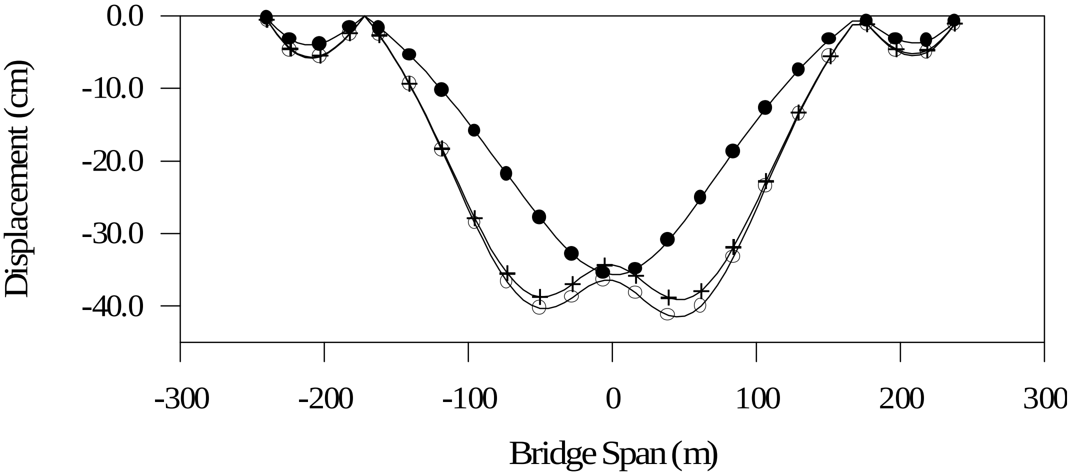

Figure 4. Mean of maximum vertical dynamic deck displacements

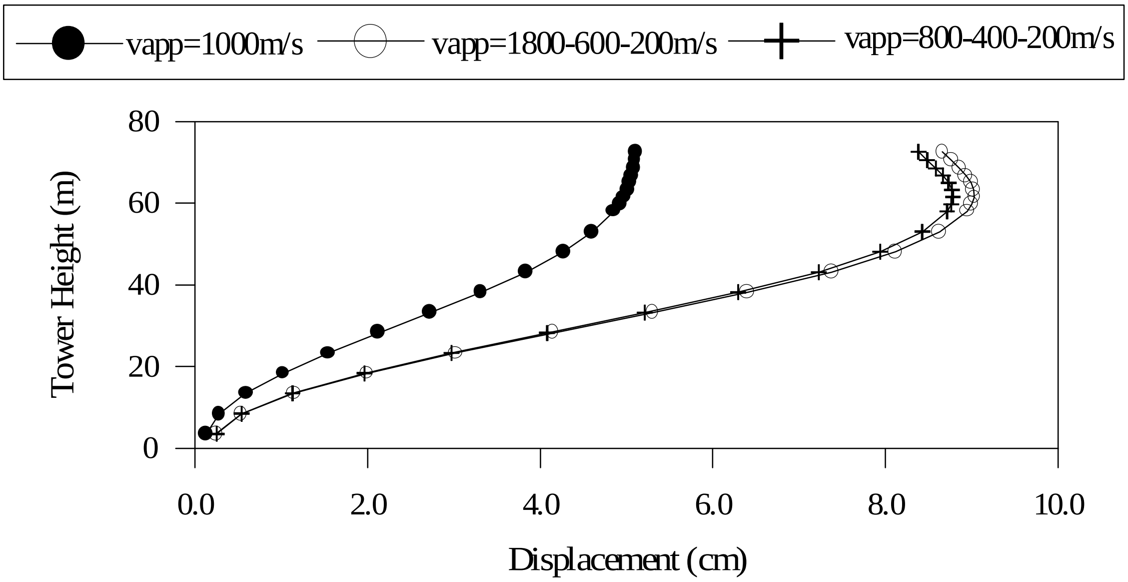

Figure 5. Mean of maximum horizontal dynamic displacements at the island tower

Conclusions

In this paper, stochastic response of a cable-stayed bridge subjected to spatially varying ground motions is conducted for variable wave velocities and local soil profiles. For the spatially varying ground motions the incoherence, wave-passage and site-response effects are considered. Mean of maximum pseudo-static and dynamic response values obtained for variable and constantly travelling wave velocity cases are compared with each other.

It can be observed that response values obtained from the spatially varying ground motion model for varying wave velocity case, are generally higher than those of the constantly travelling wave velocity case. Although the variation of the wave velocities depending on the local soil conditions do not influence the pseudo-static response values, dynamic response components show important modifications.

It can be concluded that the variation of the wave velocities depending on the local soil conditions where the bridge supports are constructed, has important effects on the dynamic behaviour of the bridge. Also, to be more realistic in calculating the bridge responses, the variability of the ground motions should be incorporated in the analysis of long span structures.

References

Allam, S. M., Datta, T. K., 1999, Seismic Behaviour of Cable-Stayed Bridges Under Multi-Component Random Ground Motion, Engineering Structures, Vol. 22, pp. 62-74.

Allam, S. M., Datta, T. K., 2000, Analysis of Cable-Stayed Bridges Under Multi-Component Random Ground Motion by Response Spectrum Method, Engineering Structures, Vol. 22, pp. 1367-1377.

Clough, R. W., Penzien, J., 1993, Dynamics of Structures, Second Edition, McGraw-Hill, Inc., New York.

Der Kiureghian, A., Neuenhofer, A., 1991, A Response Spectrum Method for Multiple-support Seismic Excitations, Report No. UCB/EERC-91/08, Earthquake Eng. Res. Center, College of Engineering, University of California, Berkeley, CA.

Der Kiureghian, A., Keshishian, P., Hakobian, A., 1997, Multiple support response spectrum analysis of bridges including the site-response effect and MSRS code, Report No. UCB/EERC-97/02, Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, CA.

Dumanoglu, A. A., Soyluk, K., 2000, Stochastic Analyses of Cable-Stayed Bridges Subjected to Different Ground Motions at Supports, Turkish Earthquake Foundation, TDV/TR 032-54 (In Turkish).

Harichandran, R. S., Vanmarcke, E. H., 1986, Stochastic variation of earthquake ground motion in space and time, Journal of Engineering Mechanics, Vol. 112, No. 2, pp. 154-174.

Harichandran, R. S., Hawwari, A., Sweiden, B. N., 1996, Response of Long-Span Bridges to Spatially Varying Ground Motion, Journal of Structural Engineering, Vol. 122, No. 5, pp. 476-484.

Hawwari, A. R., 1992, Suspension Bridge Response to Spatially Varying Ground Motion, Ph. D. Thesis, Michigan State University, Michigan.

Soyluk, K., Dumanoglu, A. A., 2000, Stochastic Analysis of Cable-Stayed Bridges Subjected to Multiple-Support Excitation, Advances in Civil Engineering, IV. International Congress, Gazimagusa, Vol. 3, pp. 1249-1258.

Soyluk, K., 2002, Stochastic Analysis of Cable-Stayed Bridges Subjected to Spatially Varying Ground Motions, Ph. D. Thesis, Karadeniz Technical University, Trabzon (In Turkish).

Sweidan, B. N., 1990, Stochastic response of deck arch bridges to correlated support excitations, Ph. D. Thesis, Michigan State University, Michigan.

Wung, C. D., Der Kiureghian, A., 1989, STOCAL-II: computer-assisted learning system for stochastic dynamic analysis of structures, part I theory and development, Report No. UCB/SEMM-89/10, Department of Civil Engineering, University of California, Berkeley, CA.