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Soil-structure interaction effects on structural pounding

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ABSTRACT : We examine the pounding of two neighbouring buildings during the Montenegro earthquake and analyse the effect of interaction between the structures and the soil on the vibration behaviour of the buildings. The structures and the soil are modeled with finite elements and the soil is described using boundary elements. The nonlinear calculations are performed in the Laplace and time domains.

1 INTRODUCTION

Pounding between structures can occur during an earthquake if the buildings have different dynamic characteristics and they are only a small distance apart from each other. Research concerning structural pounding is lacking in comparison to other earthquake related problems, e.g. uplift or column fairlure, even though pounding between structures during quakes has lead to damage and collapse of a number of buildings (Bertero 1987). Many studies model the structures by two or a row of single degree of freedom systems (Anagnostopoulos 1988; Wada, Shinozaki & Namura 1984; Wolf & Skrikerud 1980) or by using multiple degree of freedom spring–mass–systems or frame structures (Liolios 1990; Papadrakakis, Mouzakis & Bitzarakis 1990; Kasai, Maison & Patel 1990; Maison & Kasai 1990). Westermo 1989 proposes an interstructural connection to avoid structural pounding. All published papers fail to consider soil– structure interaction (SSI).

In this paper we address the influence of soil–structure interaction on the pounding of buildings. Two neighbouring frame structures on a half–space are described by beam elements with continuously distributed mass, and the half–space is represented by constant boundary elements. The pounding of the buildings is caused by the Montenegro earthquake.

2 *NUMERICAL METHOD*

2.1 Stuctural element

The vibration of a structural member with uniformly distributed mass can be described by the following partial differential equation

$$EI\, u_{,xxxx} + m\, \ddot{u} + c\, \dot{u} = p(t) \qquad (2.1.1)$$

where EI represents the flexural rigidity, u the displacement, m the mass, c the damping, and p the load. $(\ )_{,x}$ and $(\dot{\ })$ indicate the partial space and time derivative, respectively. Is equation (2.1.1) transformed into the Laplace domain one obtains

$$EI\, u_{,xxxx} + m\, s^2 + c\, s = p(s) \qquad (2.1.2)$$

where $s = \delta + i\omega$ represents the Laplace–paramenter, ω is the circular frequency, and p(s) the transformed load. Equation (2.1.2) can be expressed by the conditions at both ends of the member (see Fig. 1). The vibrations u can then be defined by the algebraic matrix equation

$$U_b = K_b\, u_b + P_b \qquad (2.1.3)$$

where U_b and u_b are the force and displacement beam end conditions, and K_b and P_b represent the dynamic stiffness of the member and the dynamic load, respectively (See Hilmer & Schmid 1988).

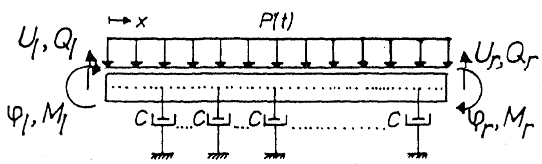

Figure 1. Structural element with positive nodal displacements and forces.

2.2 Soil element

Wave spreading in a linear elastic soil can be expressed by the equation of motion

$$(c_p^2 - c_s^2)\, u_{j,ji} + c_s^2\, u_{i,jj} + p_i/\varrho = \ddot{u}_i \qquad (2.2.1)$$

where c_p and c_s are the propagation velocities of the compression and shear waves respectively, ϱ is the mass density of the soil, and u_i the time dependent displacement. p_i is the body force per unit volume. The transformation of equation (2.2.1) into the Laplace domain leads to

$$(c_p^2 - c_s^2)\, u_{j,ji} + c_s^2\, u_{i,jj} + s^2 u_i = -p_i/\varrho \qquad (2.2.2)$$

where u_i and p_i are the displacements and body forces, respectively.

Using Betti's theorem and the fundamental solution of the wave equation, equation (2.2.2) is transformed into a boundary integral equation

$$c u_j(x^\alpha) = \int_\Gamma (t_k U_{kj}^{*\alpha} - T_{kj}^{*\alpha} u_k)\, d\Gamma \qquad (2.2.3)$$

with c = 1 for a point inside the soil and c = 0.5 for a point on the smooth soil boundary. t_k and u_k are the tractions and displacements at the soil boundary Γ, respectively. $U_{kj}^{*\alpha}$ and $T_{kj}^{*\alpha}$ are the influence functions for the displacement and traction, respectively.
The discretization of the soil boundary into a number of boundary elements leads to the same number of algebraic equations

$$T\, u = U\, t \qquad (2.2.4)$$

where the coefficients of the matrices T and U are the integrals of the influence functions over the boundary elements.
The dynamic stiffness K_s of the soil is obtained when the displacements u and the tractions t are condensed to the displacements u_s and the nodal forces p_s of the structure–soil interface.

$$K_s\, u_s = p_s \qquad (2.25)$$

2.3 Soil – structure system

In order to couple the structures with the soil, we at first transform the DOFs of the soil elements into the DOFs of the foundations of the structures (contact DOFs). The coupling is achieved by equating the displacements and the equilibrating interacting forces at the contact area between the structures and the soil.

Pounding between buildings during an earthquake is taken into account by performing the calculations in the Laplace and time domain. We begin the analysis by transforming the load and the governing equation of the soil–structures system into the Laplace domain. Then we transform the response to the time domain. We then check the response at a predefined contact point for pounding. If the structures come into contact at time t_i, we set the displacements at the contact point to be equal, and caculate the unbalanced load beginning from time t_i. If the structures separate, only the unbalanced load has to be determined. We then transform the system equations and the unbalanced load to the Laplace domain and caculate the response increment. We now superpose the response increment to the total response beginning at a time t greater than t_i, and check again for a new pounding. The calculations are completed when there is no more pounding (see Fig. 2).

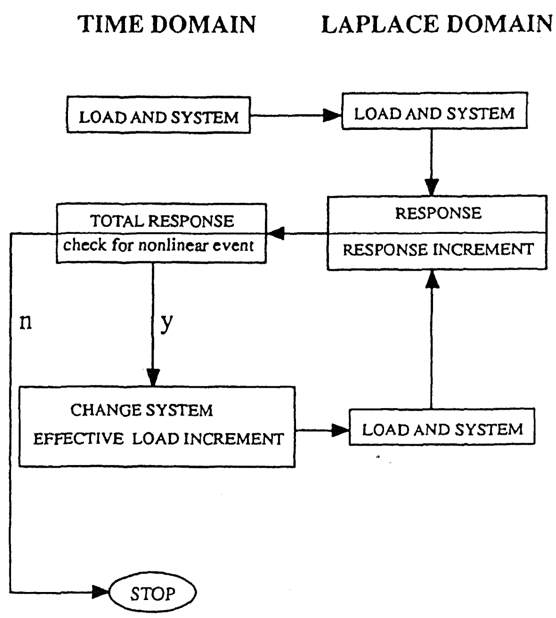

Figure 2. Flow chart of the nonlinear dynamic analysis.

3 STRUCTURAL POUNDING WITH SOIL–STRUCTURE INTERACTION

The behaviour of two neighbouring buildings during an earthquake is considered (Fig.3). The buildings are supposed to be frame structures on a half–space with a distance of 0.02 m from each other. The soil has a density ϱ of 2 kNs^2/m^4, a Poissons ration ν of 0.33, and no

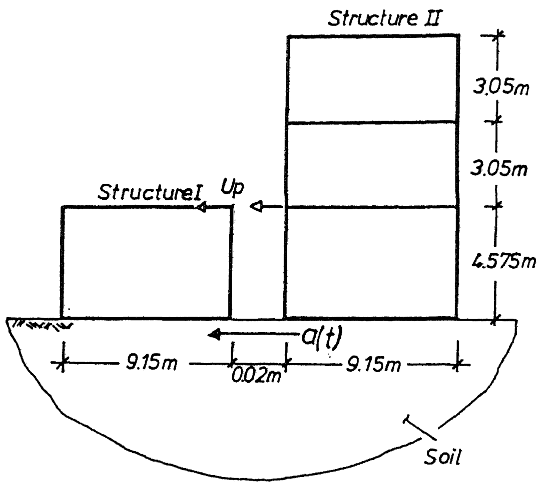

Figure 3. Actual soil–structure system.

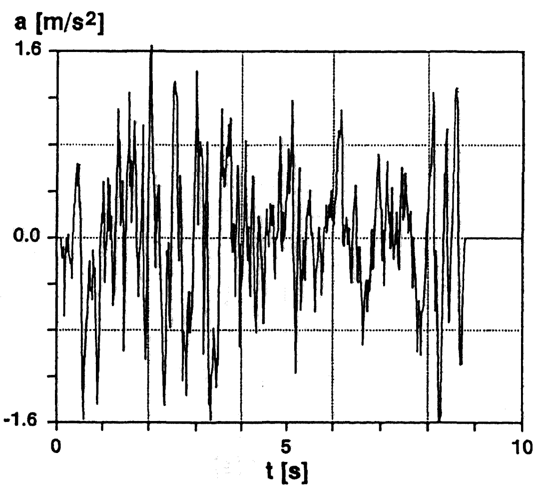

Figure 4. Montenegro earthquake: acceleration – time history.

material damping. The shear wave velocity c_s is 189.7 m/s. The excitation a(t) was chosen to be the N–S component of the Montenegro earthquake in the town of Ulcinj on 15.04.1979 at 6.20 am (Petrovski, Naumovski, Zelenovic 1980). The maximum acceleration during the quake was 1.646 m/s^2 (Fig.4).

The frame structures are modeled by finite elements and for the description of the soil, boundary elements are used. Figure 5 displays the FE–BE model and the degrees of freedom of the buildings and the soil in the contact area. In table 1 the material constants for the structures are given. They exhibit a material damping which is described by a Kelvin–chain with the parameters E1=1.0 and En=10^{29} (Hillmer & Schmid 1988). The numbering of the corresponding structural members is given in

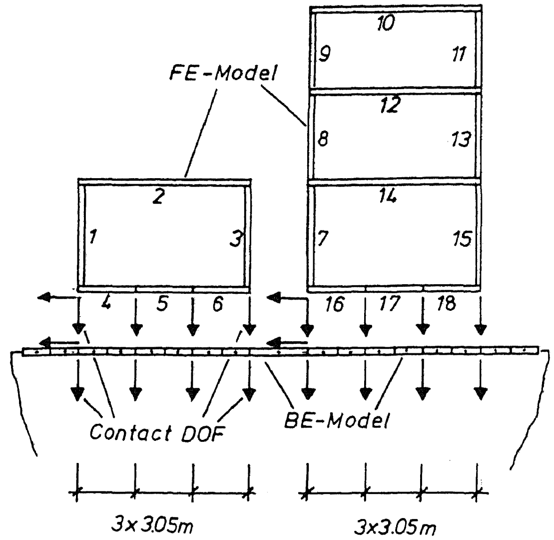

Figure 5. Idealized FE–BE system.

Table 1. Material data of the structures

Finite element No.	m [kN. s^2/m^2]	EI [kNm^2]
1, 3, 7, 15	0.067	2.1 * 10^4
1, 14	2.447	2.0 * 10^5
4, 5, 6, 16, 17, 18,	2.447	1.0 * 10^4
8, 9, 11, 13	0.033	9.8 * 10^3
10	1.209	1.1 * 10^5
12	2.358	2.0 * 10^5

Figure 5. We assume the contact occurs at the first floor level at point P (see Fig. 3).

Figures 6 and 7 indicate the influence of the soil on the vibration behaviour and on the internal forces of the structures. The stiffness of the soil–structure system decreases if the effect of the soil is taken into account. This leads to higher amplitudes and lower frequencies which in turn means lower internal forces acting on the buildings. The effect of the radiation damping can clearly be seen from the decrease of the dynamic response at the end of the excitation.

The consequences of the pounding with respect to the dynamic response at the point of contact P between the two structures is pointed out in Figures 8 and 9. Not considering the soil–structure interaction, the vibration of structure II (dotted line) is comparable to the case without pounding. Structure I (solid line) clearly vibrates with smaller amplitudes, during some periods there is hardly any vibration at all (compare Figures 8a with 8b). Consideration of SSI changes the dynamic charac–

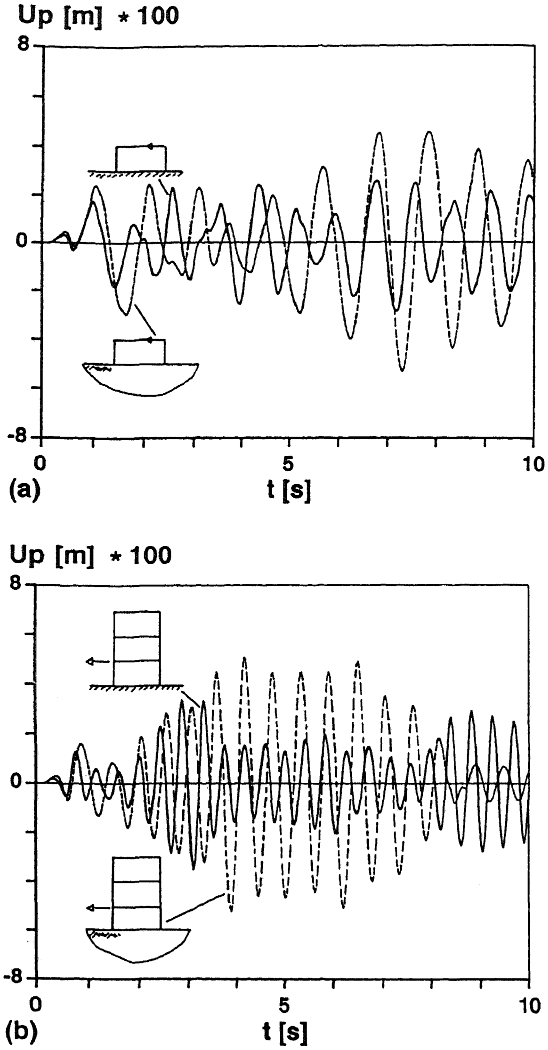

Figure 6. Influence of the soil on the time history of the displacement U_p (a) of structure I, and (b) of structure II at contact point P.

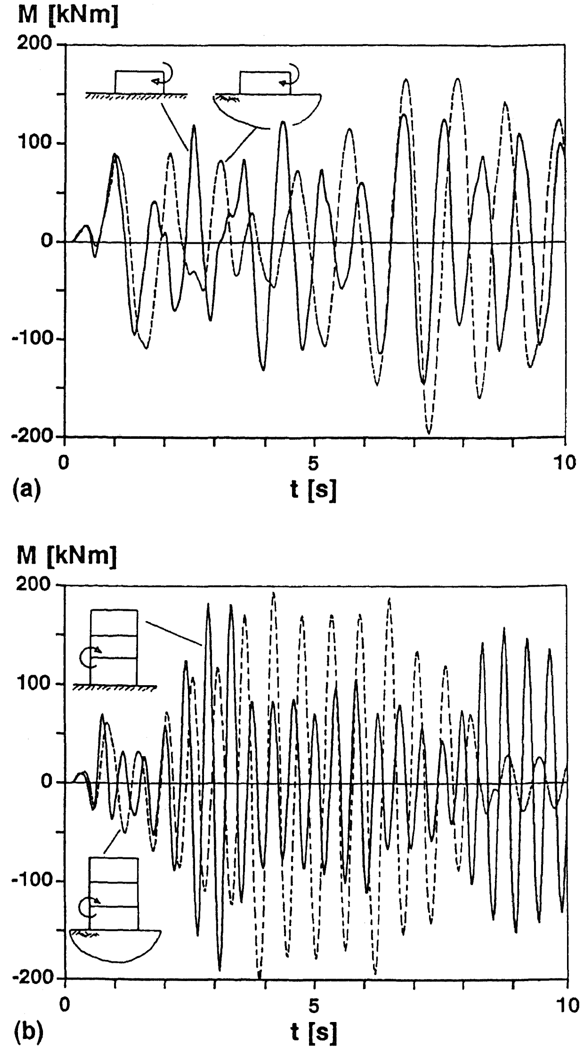

Figure 7. Influence of the soil on the time history of the bending moment M (a) of structure I, and (b) of structure II at the contact point P.

teristics of the system. Structure II (dotted line) vibrates as in the situation with no pounding but at the end of the excitation the displacement is much smaller, even smaller than the displacement of structure II without the effect of SSI. The displacement of structure I (solid line) is reduced by the contact between the two buildings. Close to the end of the excitation this displacement increases.

Figures 10 and 11 present the effect of the pounding on the displacement and bending moment of structure I at the point of contact. Is the SSI not included, the pounding (dotted line) leads to a reduction in displacement and bending moment throughout the time period examined. Taking the effect of SSI into account, pounding (dotted line) during the first eight seconds also reduces displacement and bending moment but causes these dynamic responses to increase near the end of the excitation. The bending moment has a time history similar to that of the displacement, whether or not SSI is included. We believe that the reason for this is the position of the point of contact, chosen at the floor level.

4 SUMMARY

The interaction between structure and soil with respect to the vibration of two neighbouring structures during an earthquake is investigated, taking into consideration the effects of pounding between the structures. The buildings and the soil are modeled using FE and BE,

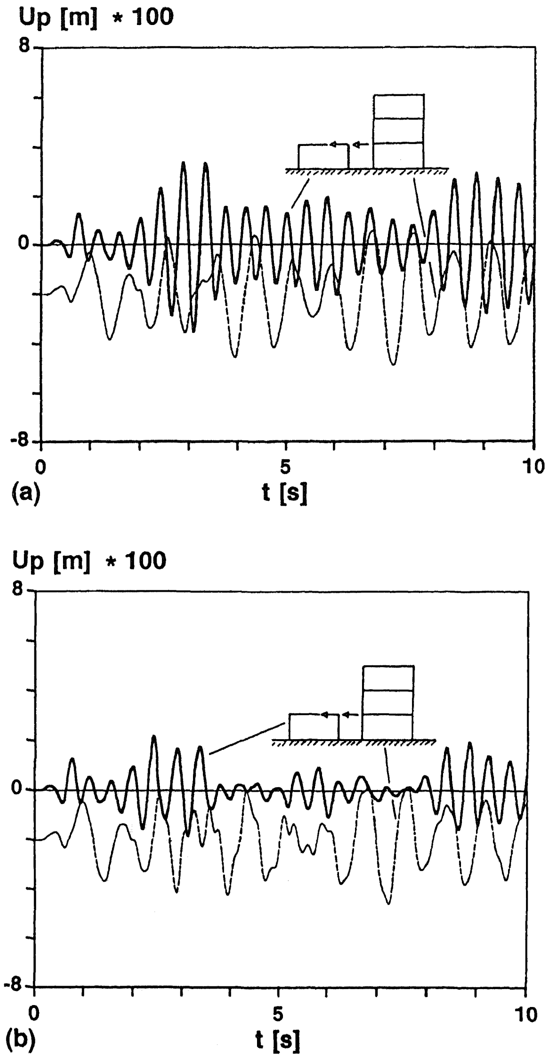

Figure 8. Vibration of the structures not considering SSI (a) without pounding, and (b) with pounding.

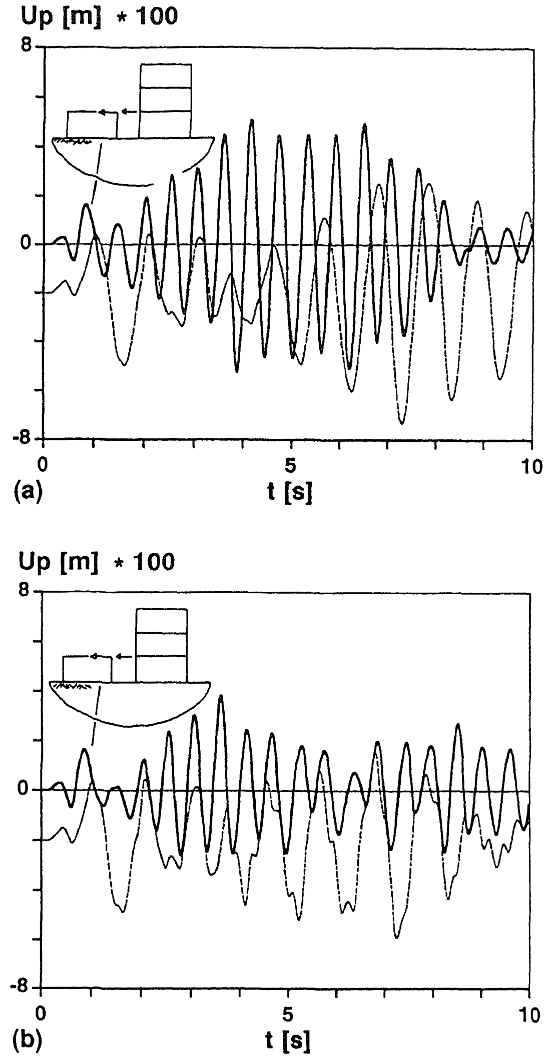

Figure 9. Vibration of the structures including SSI (a) without pounding, and (b) with pounding.

respectively. The calculations are performed in the Laplace and time domains. The results disclose : SSI changes the dynamic characteristics of the structure–soil system. The buildings vibrate with higher amplitudes and lower frequencies. The internal forces are reduced.

Does pounding occur, the responses considering SSI cannot be derived from responses not taking these effects into consideration because the systems do not display identical dynamic characteristics in both cases. In oder to obtain more realistic vibration behaviour it is necessary to additionally consider the influence of a structure on its neighbour through the soil due to pounding, and multiple contact points together with the damage caused by pounding.

REFERENCES

Anagnostopoulos, S. A. 1988. Pounding of buildings in series during earthquakes. Earthquake Engineering and Structural Dynamics 16: 443–456

Bertero, V. V. 1987. Observations on structural pounding. Proc. of the International Conference "The Mexico Earthquake 1985. Factors Involved and Lessons Learned": 264– 278. New York: ASCE.

Hillmer, P. & G. Schmid 1988. Calculations of frameworks with local nonlinearities subjected to dynamic loads with the help of Laplace transform. Inginieur–Archiv 58: 148–160.

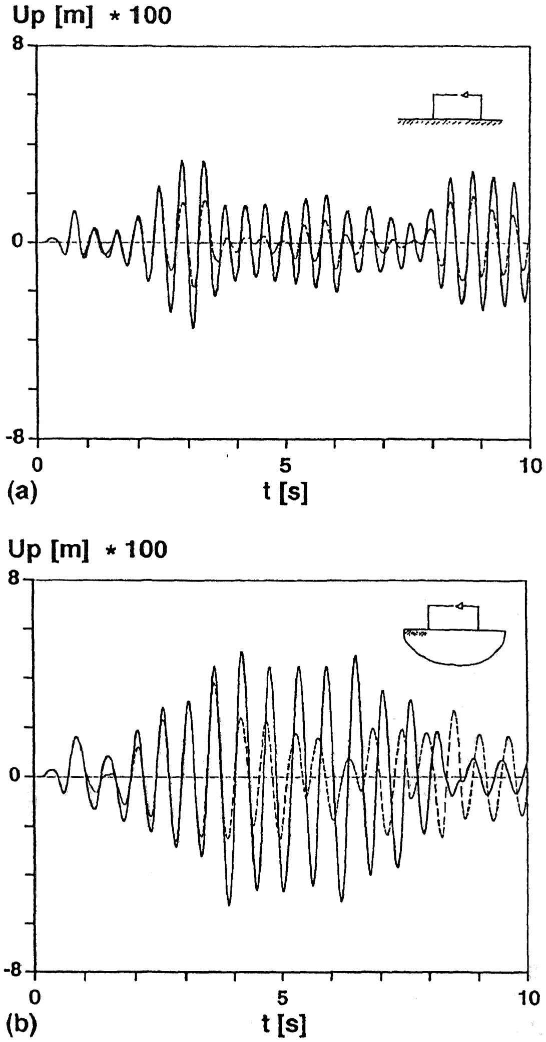

Figure 10. Influence of pounding on the time history of the displacement U_p of structure I (a) without, and (b) with the effects of SSI.

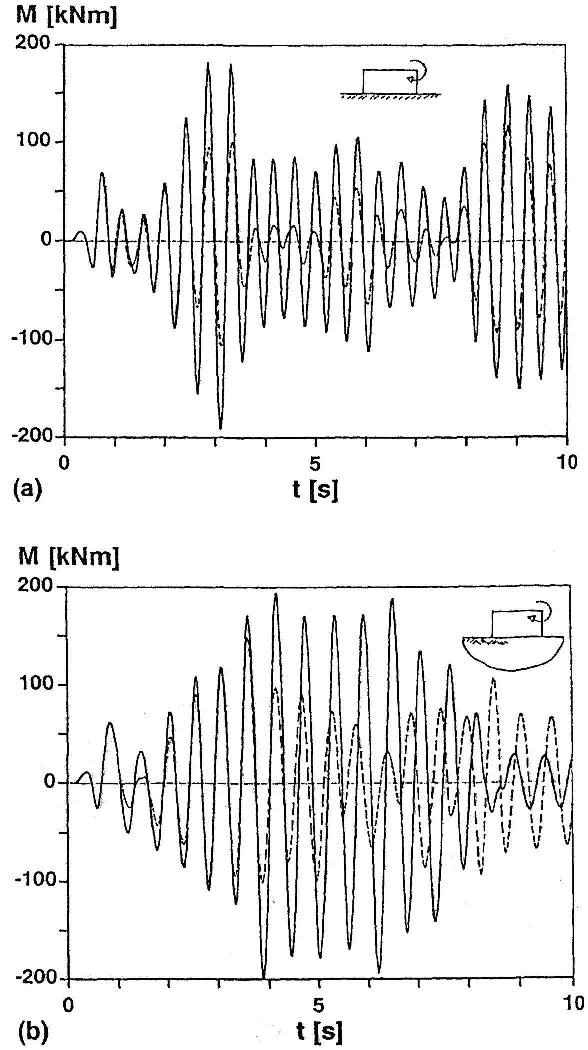

Figure 11. Influence of pounding on the time history of the bending moment M of structure I (a) without, and (b) with the effects of SSI.

Kasai, K., B. F. Maison & D. J. Patel 1990. An earthquake analysis for buildings subjected to a type of pounding. Proc. 4th U.S. National Conference on Earthquake Engineering: 289–298. El Carrito: Earthquake Engineering Research Institute.

Liolios, A.A. 1990. A numerical estimation for the influence of modifications to seismic interaction between adjacent structures. Proc. Earthquake Resistant Construction and Design: 461–467. Rotterdam: Balkema.

Maison, B. & K. Kasai 1990. Analysis for type of structural pounding. Structural Engineering 116: 957–977.

Papadrakakis, M., H. Mouzakis & S. Bitzarakis 1990. Dynamic contact between adjacent structures using a formulation with Lagrange multipliers. Proc. 1th European Conference on Structural Dynamics: 913–920. Rotterdam: Balkema

Petrovski, K., N. Naumovski, V. Zelenovic, S. Stamatovska 1980. Strong-motion earthquake accelerograms. Publication No. 67. Skopje : Institute of Earthquake Engineering and Seismology, University Kiril and Metodij.

Wada, A., Y. Shinozaki & N Nakamura 1984. Collapse of buildings with expansion joints through collision caused by earthquake motion. Proc. 8th WCEE: 855–862.

Westermo, B. D. 1989. The dynamics of interstructural connection to present pounding. Earthquake Engineering and structural Dynamics 18: 687–699.