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Pounding of Adjacent Structures during Earthquakes: A Review of the Current State of Knowledge

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ABSTRACT

This paper presents a review of the current state of knowledge regarding the effects of pounding between adjacent structures during earthquakes. The first part of the paper discuses the problem of seismic pounding along with observations of damage from pounding during recent earthquakes in Mexico and California. Methods that have been proposed to mitigate its effects are described. The assumptions and solution strategies of four available computer programs (SLAM-2, DRAIN-2DP, PC-ANSR and RUAUMOKO) which are capable of carrying out pounding analyses are described in the second part of the paper. Finally, in the third part of the paper, the results of shake table tests of pounding between adjacent 3 and 8-storey single-bay steel framed model structures are presented. The experimental results are compared to the predictions resulting from the programs.

INTRODUCTION

Seismic pounding occurs mainly between adjacent structures exhibiting important differences in mass, stiffness and/or strength. The different dynamic characteristics of the buildings will usually induce out-of-phase lateral vibrations under earthquake ground motions. Pounding will obviously occur if the spacing between the buildings is not sufficient to allow them to vibrate freely. Each time a collision occurs, the buildings are subjected to short lateral impact forces not taken into account in the conventional design process. These impact forces produce high-amplitude, short-duration local accelerations which could induce damage to structural members or mechanical/electrical components of the buildings. Furthermore, earthquake pounding can amplify the dynamic responses of the buildings. The problem of pounding is particularly acute in many large cities located in seismically active regions where, due to land usage requirements, buildings are constructed near to each other.

The objective of this paper is to provide information to practising engineers on how to consider and possibly mitigate the pounding problem in the design or retrofit process of a building. The assumptions and solution strategies of available computer programs which are capable of carrying out pounding analyses are described. Also, the results of shake table tests of pounding between adjacent structures are compared to the predictions of the various programs.

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OBSERVATIONS OF DAMAGE FROM POUNDING

The magnitude of the pounding problem has never been demonstrated better than during the 1985 Mexico City earthquake. Pounding was responsible for more than 40% of the damaged buildings. Furthermore, 15% of the collapsed buildings was attributed to pounding (Rosenblueth and Meli, 1986).

Pounding damage in the San Francisco area was observed immediately after the 1989 Loma Prieta earthquake, and was reported by an investigation team sent by the U.S. government (Kasai and Maison, 1991). More than 200 cases of pounding involving more than 500 buildings were observed. Architectural damage was reported in more than 79% of the buildings visited, while 21% of the same buildings suffered significant structural damage. Typically, pounding occurred between low-rise unreinforced masonry buildings constructed in the 1930's. Most of these buildings were initially in contact with each other.

MITIGATION OF POUNDING POTENTIAL

Mitigation of the pounding potential between adjacent structures can be achieved by: i) allowing an adequate separation between buildings or ii) linking adjacent buildings to force in-phase vibrations.

Separation Between Buildings

The most obvious way to eliminate pounding is to allow a sufficient separation between adjacent buildings. Although building codes prescribe minimum separations between adjacent structures, non-technical factors often govern the choice of distances. Owner responsibilities in case of pounding damage have yet to be clearly defined. The opposition from owners, engineers and architects against building code requirements arise mainly from high land costs and limited lot sizes.

Many modern building codes require that adjoining buildings must be separated by the sum of their maximum design lateral displacements. An investigation by Kasai et al. (1991) on the U.S. Uniform Building Code (UBC, 1990) has revealed that the required separations, which ignore the phase between the building motions, are excessive. The same conclusions were reached by Filiatrault et Cervantes (1995) regarding the separation requirements of the National Building Code of Canada (NBCC, 1990).

An approximate method to improve the accuracy on required building separations has been proposed (Jeng et al., 1992). This method, based on random vibration concepts, is exact for a white noise ground motion and for first mode responses of both adjacent buildings. The minimum required separation, s_{AB}, between two adjacent buildings A and B, is given by:

$$s_{AB} = \sqrt{u_{Amax}^2 + u_{Bmax}^2 - 2\gamma\, u_{Amax} u_{Bmax}}$$

where u_{Amax} and u_{Bmax} are the maximum displacements of building A and B respectively, at the level where contact is expected, and obtained from a first mode spectral analysis; and:

$$\gamma = \frac{8\zeta^2\left(1+\frac{T_B}{T_A}\right)\left(\frac{T_B}{T_A}\right)^{3/2}}{\left[1-\left(\frac{T_B}{T_A}\right)^2\right]^2+\left[4\zeta^2\left(1+\frac{T_B}{T_A}\right)^2\left(\frac{T_B}{T_A}\right)\right]}$$

where T_A and T_B are the fundamental elastic periods of buildings A and B respectively and ζ is a modal viscous damping ratio common to both buildings. This does, however, assume that a designer has access to the period of the building on the adjacent site.

Linkage of Adjacent Buildings

The elastic vibrational response of coupled buildings was recently investigated by Westermo (1989). It was found that structural coupling not only reduces the pounding potential but also increases the seismic forces on the structure which had the smallest base shear when uncoupled. The idea of using energy absorbing linkage systems was implemented with a pair of adjacent office buildings in Japan (Kobori et al., 1988). The multi-axis linkage system between the buildings can develop stable hysteresis loops and is designed to yield during a major seismic event only. Experiments have confirmed the satisfactory performance of the system.

COMPUTER PROGRAMS FOR SEISMIC POUNDING ANALYSES

The first study on simplified MDOFS considered a single linear-elastic building with only one level colliding elastically on an adjacent rigid barrier (Maison et Kasai, 1990a). The building was assumed to have degrees-of-freedoms and masses concentrated at each floor. The solution strategy, based on a modal superposition technique, considered two uncoupled linear problems, depending on whether contact is present or not. The procedure was embedded into a microcomputer program named SLAM (Maison et Kasai, 1990b). This program uses the dynamic characteristics generated by the general computer program SUPER-ETABS (Maison et Neuss, 1983) to perform the pounding analysis of the building. The results of this study showed that large shear forces are developed below and above the contact level. After a collision, a shear wave propagates through the building. Similar observations are reported by Sinclair (1993). The levels above the contact point experience large amplifications of interstorey drifts, shear forces and overturning moments (up to 240% for shear). The maximum responses of levels below the contact points are reduced, however, compared to the maximum responses when pounding does not occur. As expected, the maximum base shear occurs when the roof of the building is colliding. The same researchers have improved the capabilities of their model by creating another microcomputer program, SLAM-2, capable of considering two colliding linear-elastic buildings (Kasai et al., 1991). Again, it was shown that the effect of pounding is critical in a light building colliding into a heavy one.

Apart from the elastic SLAM-2 code, three computer programs are currently available to allow a seismic pounding analysis of adjacent inelastic structures: PC-ANSR, DRAIN-2DP and RUAUMOKO. The program PC-ANSR (Maison, 1992) is a microcomputer version of the well known general purpose three-dimensional nonlinear time-step analysis ANSR-1 code (Mondkar and Powell, 1975).

The program includes different element types and, for pounding analysis, an elastic gap element. Several dynamic solution procedures are available in PC-ANSR including the Newton-Raphson iteration method within a time-step. The elastic gap element implemented in the program produces the following impact force, F_I, between two nodes i and i+1:

$$F_I = k(x_{i+1} - x_i - u_{i,i+1}) \text{ for } x_{i+1} - x_i - u_{i,i+1} \le 0$$
$$F_I = 0 \text{ for } x_{i+1} - x_i - u_{i,i+1} > 0$$

where x_i and x_{i+1} the displacements of nodes i and i+1 respectively, $u_{i,i+1}$ is the initial separation between nodes i and i+1 and k the spring stiffness of the gap element.

A Hertzian contact element has been implemented recently in the well known DRAIN-2D code (Kanaan and Powell, 1973). The microcomputer version of the program incorporating this contact element is called DRAIN-2DP (Cervantes and Filiatrault, 1993). This program consists of a series of subroutines which carry out a step-by-step dynamic analysis. Several types of inelastic elements have been developed for this program over the years. Only Newmark's constant acceleration scheme is available as a dynamic solution procedure. The contact element implemented in the program produces the following impact force, F_I, between two nodes i and i+1:

$$F_I = k(x_{i+1} - x_i - u_{i,i+1})^n + c(\dot{x}_{i+1} - \dot{x}_i) \text{ for } x_{i+1} - x_i - u_{i,i+1} \le 0$$
$$F_I = 0 \text{ for } x_{i+1} - x_i - u_{i,i+1} > 0$$

where x_i, x_{i+1}, $\dot{x}_i$ and $\dot{x}_{i+1}$ are the displacements and velocities of nodes i and i+1 respectively, $u_{i,i+1}$ is the initial separation between nodes i and i+1, k the spring stiffness of the impact element, n is a power factor (equals to 1.5 for a pure Hertzian contact) and c a viscous damping constant.

RUAUMOKO (Carr, 1994) is a general purpose two-dimensional nonlinear time-step analysis program developed at the University of Canterbury over the past two decades. The program has a variety of member types including a contact element similar to that described earlier for the program DRAIN-2DP. The program has both implicit and explicit time integration methods for small and large displacement analyses. Real-time graphics showing the deformations and locations of nonlinear behaviour in the structure are available. A variety of damping models are also available. The program also has an accompanying post-processor program for graphically displaying the time-history results. The program has been used for pounding studies (Sinclair, 1993; Carr and Moss, 1994) and for many other studies where impact occurs such as when rocking structures make contact with their foundations. One feature not found in many other programs is the use of a four-node definition of the members so that arbitrary rigid links may be used to connect members into the structure, thereby avoiding the many stiff dummy members used to model the structure such as found in the example described below. However, to maintain comparison with the other programs, this feature was not used in the first computer model quoted in this paper. The elimination of these dummy members and their nodal degrees-of-freedom considerably reduces the computational times.

EXPERIMENTAL STUDY

Description

The first correlative study on pounding test and analysis has been carried recently (Filiatrault et al., 1994). Shake table test results of pounding between adjacent 3 and 8-storey single-bay steel framed model structures were compared with the predictions of SLAM-2, PC-ANSR and RUAUMOKO.

Two adjacent 1/8 scale single-bay moment resisting steel framed models, one 3-storey the other 8-storey, were tested on an earthquake simulator. The overall floor plan dimensions of both models are 0.8 m x 0.8 m. The 8-storey frame is 4 m high, while the height of the 3-storey frame is 1.5 m.

The same two-dimensional model was developed for each computer program considered. The model was calibrated, based on preliminary test results, to match the experimental responses for the no pounding case. The purpose of this calibration was to isolate the pounding effect for the evaluation of the capabilities of the different pounding analysis programs. A detailed description of the numerical model is shown in Figure 1.

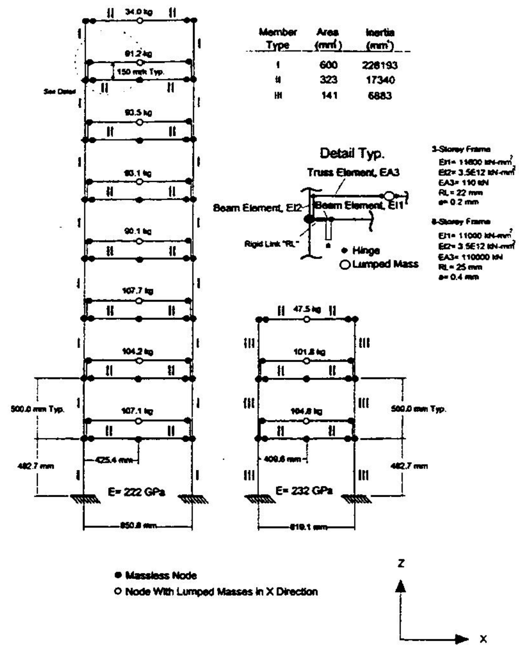

Figure 1 Numerical Model.

<u>Analytical and Experimental Results</u>

Figure 2 compares analytical and experimental relative displacement time-histories at the top of the 3-storey frame for the S00E component of the May 18, 1940 El Centro base excitation scaled to a Peak Horizontal Acceleration (PHA) of 0.15 g and for no initial separation. The PC-ANSR and RUAUMOKO predictions are in better agreement with the experimental results than the SLAM-2 predictions. It was observed during the tests that pounding occurred between the three floor levels. The SLAM-2 idealization assumes impacts take place only between the third floor levels, while PC-ANSR and RUAUMOKO consider collisions between the three levels. The experimental and analytical time-histories exhibit a displacement off-set which shows that the 8-storey structure limits the deformations of the 3-storey frame.

The third floor impact force time-histories for the El Centro excitation at PHA = 0.15 g and 0 mm separation between the two adjacent buildings are presented in Figure 3. The times and amplitudes of the contact forces are well predicted by the three programs. The experimental curve exhibits a double contact for each impact. After reviewing video and sound tapes of the tests, it was established that this was related to the rotations of the beam-column joints, which caused a relative angle between the points of contact. This misalignment created a grinding impact which lengthened the contact time. This behaviour cannot be captured by the numerical simulation using axial spring elements. The SLAM-2 idealization allows only one impact element to be incorporated in the analysis. This element was specified at the roof of the shorter building. Therefore, the impact forces between the first and second floors cannot be predicted by the SLAM-2 model. Despite this limitation, the impact force time-history predicted by the SLAM-2 model between the third floors still correlates reasonably well with the experimental data. The amplitudes of the impact forces are significant. A maximum impact force of about 7 kN was recorded between the third floor levels when the structures

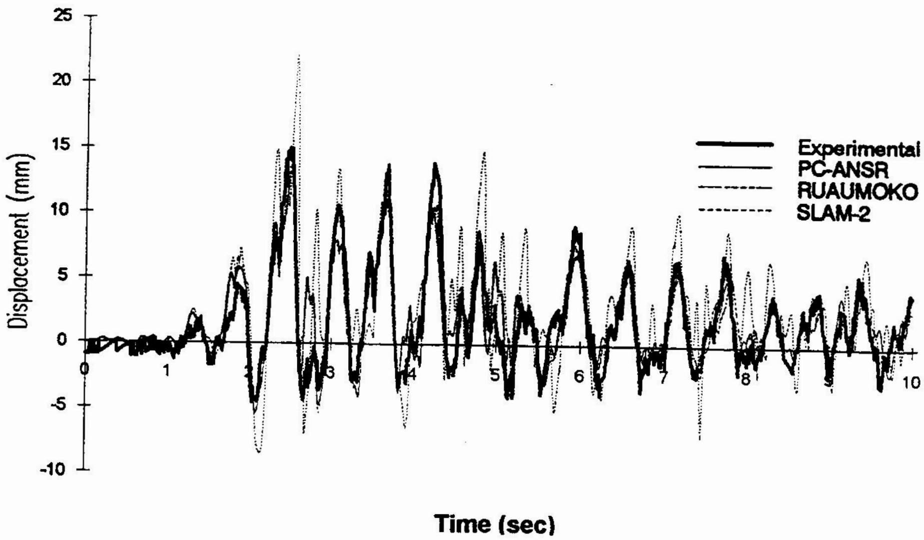

Figure 2 Top of 3-Storey Frame Relative Displacements, 0 mm Spacing, PHA = 0.15 g.

were initially in contact. This value corresponds to 225% of the weight of the 3-storey frame. The corresponding figure for the 8-storey structure is 66%. Table 1 compares CPU times required by the three programs on a 486-33 MHz microcomputer. The SLAM-2 simulations, based on modal superposition and separate time-steps, depending if contact is detected or not, require minute fractions of the execution time necessary by PC-ANSR and RUAUMOKO. RUAUMOKO is four to five times faster than PC-ANSR.

Table 1. CPU Times, PHA = 0.15 g.

Program	CPU Time (s)	
	Gap = 15 mm	Gap = 0 mm
SLAM-2	25[1]	50[1]
RUAUMOKO	6830[2]	89700[3]
RUAUMOKO (4 Node Beams)	5132[2]	50540[3]
PC-ANSR	34200[2]	351000[3]
[1]Time-step=.01s and .001s when contact is detected; [2]Time-step=.00125s; [3]Time-step=.0001s		

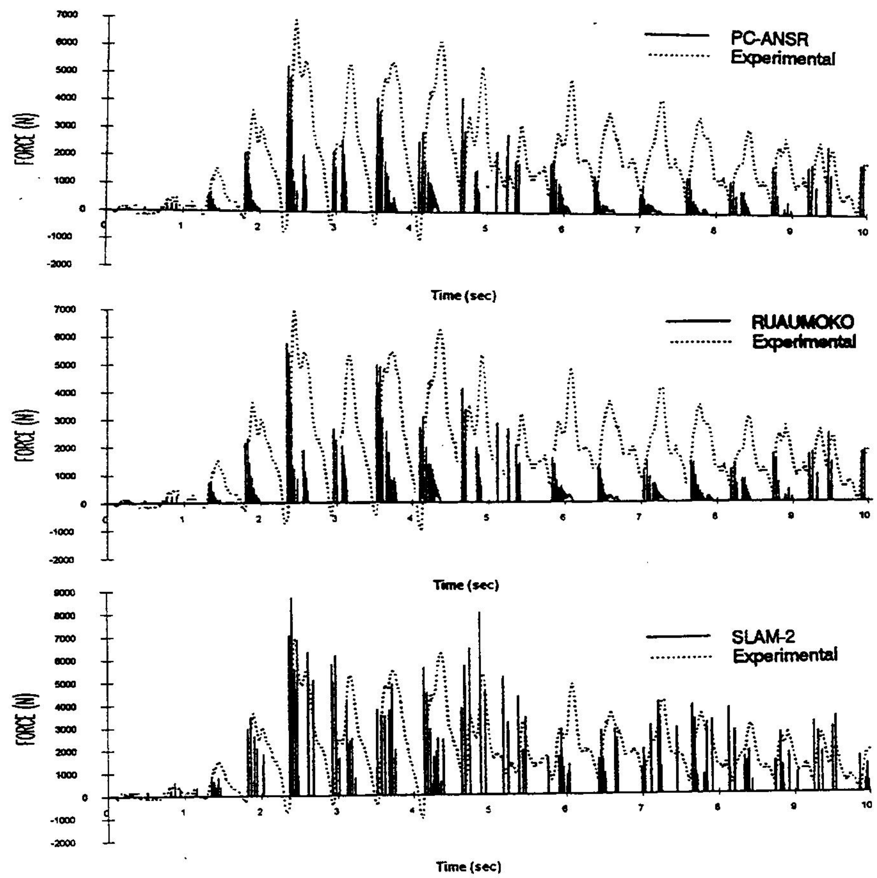

Figure 3 Third Floor Impact Force
Time-Histories, 0 mm Spacing, PHA = 0.15g.

CONCLUSION

The problem of structural seismic pounding is complex and, at present, is not appropriately addressed in building codes. For now, designers should consider this problem on a case-by-case basis. This paper has provided information on the analytical tools available to structural engineers to consider seismic pounding in dynamic analyses. The results of shake table tests between building models have provided an opportunity to evaluate the predictive capabilities of three different pounding analysis programs.

REFERENCES

Carr, A.J. and Moss, P.J., 1994. "Impact Between Buildings During Earthquakes", Bulletin of the New Zealand National Society for Earthquake Engineering, 27:2, 107-113.

Carr, A.J., 1994. "RUAUMOKO User's Guide", Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

Cervantes-Hernandez, M. and Filiatrault, A., 1993. "Modélisation du cognement séismique pour les structures inélastiques", Report No. EPM/GCS-1993-09, Ecole Polytechnique, Montreal, Canada.

Filiatrault, A. and Cervantes, M., 1995. "Separation Between Buildings to Avoid Pounding During Earthquakes", Canadian Journal of Civil Engineering, 22(2), (in press).

Filiatrault, A., Wagner, P., Cherry, S. and Ventura, C.E., 1994. "A Shake Table Study on the Pounding of Buildings During Earthquakes", 5th U.S. National Conference on Earthquake Engineering, Chicago, Ill., Vol. II, 671-680.

Jeng, V., Kasai, K. and Maison, B.F., 1992. "A Spectral Difference Method to Estimate Building Separations to Avoid Pounding", Earthquake Spectra, 8(2), 201-203.

Kanaan, A.E. and Powell, G.H., 1973. "DRAIN-2D: A General Purpose Computer Program for Dynamic Analysis of Inelastic Plane Structures", Report EERC 73-6, Univ. California, Berkeley, CA.

Kasai, K. and Maison, B.F., 1991. "Observation of Structural Pounding Damage from the 1989 Loma Prieta Earthquake", 6th Canadian Conference on Earthquake Engineering, Toronto, 735-742.

Kasai, K., Maison, B.F., Jeng, V., Patel, D.J. and Patel, P.C., 1991. "A Study on Earthquake Pounding Between Adjacent Structures", Sixth Canadian Conference on Earthquake Engineering, Toronto, 93-100.

Kobori, T., Yamada, T., Takenaka, Y., Maeda, Y. and Nishimura, I., 1988. "Effect of Dynamic Tuned Connector on Reduction of Seismic Response; Application to Adjacent Office Buildings", 9th World Conference on Earthquake Engineering, Tokyo, 5:773-778.

Maison, B.F. and Kasai, K. 1990a. "Analysis for Type of Structural Pounding",ASCE Journal of Structural Engineering, 116(4):957-977.

Maison, B.F. and Kasai, K. 1990b. "SLAM: A Computer Program for the Analysis of Structural Pounding", National Information Service for Earthquake Engineering, University of California, Berkeley, CA.

Maison, B.F. and Neuss, C.F. 1983. "SUPER-ETABS: An Enhanced Version of ETABS Program", Report to the National Science Foundation, J.G. Bouwkamp Inc.

Maison, B.F. 1992. "PC-ANSR: A Computer Program for Nonlinear Structural Analysis", National Information Service for Earthquake Engineering, University of California, Berkeley, CA.

Mondkar, D.P. and Powell, G.H. 1975. "ANSR-1: General Purpose Program for Analysis of Nonlinear Structural Response", Report No. EERC-75/37, University of California, Berkeley, CA.

NBCC, 1990. "National Building Code of Canada", Associates Committee on the National Building Code, National Research Council of Canada, Ottawa, Ontario.

Rosenblueth, E. and Meli, R. 1986. "The 1985 Earthquake: Causes and Effect in Mexico City", Concrete International, 8(5): 23-24.

Sinclair, K.M., 1993. "The Response of Multi-Storey Frames to Seismic Pounding". M.E. Report, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

UBC, 1990. "Uniform Building Code", International Conference on Building Officials, Whittier, CA.

Westermo, B.D., 1989. "The Dynamics of Interstructural Connection to Prevent Pounding", Earthquake Engineering and Structural Dynamics, 18, 687-699.