A study on earthquake pounding between adjacent structures

K. Kasai[I], B.F. Maison[II], V. Jeng[III], D.J. Patel[IV], and P.C. Patel[IV]

ABSTRACT

Analytical research on pounding is presented. It includes development of pounding dynamic analysis programs, parameter studies on building pounding response as well as appurtenance response, a spectrum method to obtain peak pounding responses, actual case studies, and a spectrum method to determine required building separations to preclude pounding.

INTRODUCTION

Pounding Incidents. - Investigations into past earthquake damage have shown that collisions between adjacent buildings during earthquakes have been one of the causes of severe structural damage. This collision, commonly called 'structural pounding' occurs during an earthquake when, due to their different dynamic characteristics, adjacent buildings vibrate out of phase and there is insufficient separation distance between them.

Many incidents of seismic pounding have been reported to date. Pounding of adjacent buildings has made damage worse, and/or caused total collapse of the buildings. The earthquake that struck Mexico City in 1985 has revealed the fact that pounding was present in over 40% of 330 collapsed or severely damaged buildings surveyed, and in 15% of all cases it led to collapse (Rosenblueth and Meli 1986). This earthquake illustrated the significant seismic hazard of pounding by having the largest number of buildings damaged by its effect during a single earthquake (Bertero 1986). The writers have surveyed the damage due to pounding in the San Francisco Bay area during the recent 1989 Loma Prieta Earthquake (Kasai and Maison 1991). Significant pounding was observed at sites over 90 km from the epicenter thus indicating the possible catastrophic damage that may occur during future earthquake having closer epicenters.

Code Provisions Regarding Pounding. - Past aseismic codes did not give definite guidelines to preclude pounding. Because of this and due to economic considerations including maximum land usage requirements, there are many buildings world-wide which are already built in contact or extremely close to one another that will suffer pounding damage in future earthquakes. The 1990 Uniform Building Code (UBC) based on the 1988 provisions by the Structural Engineers

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[I] Assist. Prof., Dept. Civil. Eng., Illin. Instit. of Tech., Chicago, IL 60616.
[II] Structural Engineer, SSD Engineering Consultants Inc., Berkeley, CA 94704.
[III] Adjct. Assist. Prof., Dept. Civil Eng., Illin. Instit. of Tech., Chicago, IL 60616.
[IV] Grad. Assist., Dept. Civil Eng., Illin. Instit. of Tech., Chicago, IL 60616.

Association of California (SEAOC) gives more detailed requirements for building separations, yet the SEAOC commentary (Section 1H.2.1) indicates the need for research to verify the recommendations. The resulting required separations are "large" and controversial from both technical (difficulty in using expansion joint) and economical (loss of land usage) views.

Research Needs. - Based on above, research into the pounding problem is necessary in order to determine proper seismic hazard mitigation practice for already existing buildings as well as new buildings. The previous research is somewhat limited in scope and it is generally not in a readily usable form for practicing engineers (Maison and Kasai 1990). Continued research is urgently needed in order to provide the engineering design profession with practical means to evaluate and mitigate the effects of pounding. The following describes the writers' research.

POUNDING TIME HISTORY ANALYSIS PROGRAMS

Idealization. - The writers have developed two micro-computer pounding analysis programs SLAM and SLAM-2, which are made publicly available (Maison and Kasai 1988, 1990). The programs idealize buildings as three-dimensional (3-D) multi-degree-of-freedom (MDOF) systems. The SLAM program assumes that a building laterally collides with a rigid adjacent building and the SLAM-2 (Fig. 1) program considers that both buildings are flexible. Pounding is assumed to occur at a single floor level having a rigid diaphragm. The pounding problem is idealized as having two linear states: in State 1, the buildings vibrate without contact, and in State 2 the buildings are in contact. A nonlinear problem results as the response oscillates from one linear state to the other. These idealizations were made as a starting point in the pounding investigation in order to make the problem manageable, while retaining important pounding dynamic characteristics.

Advantages. - Unlike most of the past research based on the single-degree-of-freedom (SDOF) modeling, the 3-D MDOF approach used by SLAM and SLAM-2 give information on the distributions of important response quantities such as story displacements, drifts, shear, overturning moments (OTM's), torques, and accelerations through the height of the multi-story building modeled. The programs employ a theoretically exact solution scheme (Maison and Kasai 1990), and they are also computationally efficient.

BUILDING RESPONSE UNDER POUNDING

SLAM-2 Analyses Results. - An existing 15-story steel moment resistant frame building (Building A, period = 1.13 sec) is assumed to collide with an adjacent flexible 8-story building (Building B, period = 0.8 sec.). Three cases are considered for the floor mass of Building B: one-third; one; and three times the floor mass of Building A. SLAM-2 dynamic analyses were conducted using 0.4g artificial earthquakes (Kasai et al. 1990). Throughout this paper, local contact stiffness (Fig. 1) is set to 50000 k/in considering the past studies (Maison and Kasai 1990). Fig. 2 shows the case where buildings A and B have the same floor mass. Pounding is a severe load condition. Sudden stopping of displacement (Fig. 2(a)) at the pounding level results in large and quick acceleration pulses in the opposite direction, and the peak floor accelerations can be more than 10 times those from the no-pounding case (Fig. 2(b)).

In both buildings, pounding produces peak drifts, shears, OTM's, torques, and accelerations at various story levels that are greater than those from the no pounding case (e.g., Fig. 3). Building midheight pounding (Building A) increases shears above pounding level as well as accelerations in the vicinity of the impact (Figs. 3(b) and (c)). Building top level pounding (Building B) decreases the peak shears over the entire building height with the exception of the stories in the vicinity of the impacts (Figs. 3(b) and (c)). As the difference in the relative mass increases, the adverse effects of pounding increase in the building having the lessor mass. These locations of pounding amplified responses correspond to the observed damage locations in the recent earthquake (Kasai and Maison 1991).

The flexible adjacent building cases studied have many trends that are similar to those from a rigid adjacent building case. The rigid adjacent building case, therefore, was the first subject of the writers' study, results of which are discussed below.

SIMPLIFIED THEORY BASED ON SPECTRAL ENERGY

Background. - Through numerous SLAM analytical studies, the writers found that the non-linear pounding peak response of SDOF as well as MDOF systems is not sensitive to the details of the particular earthquake history as long as the earthquakes have a common spectrum characteristics (Kasai et al. 1990). Based on this, the following method to predict the peak pounding responses were developed.

No Pounding and Fixed Spring Systems. - The technique is based on response spectrum analyses of two basic linear systems (Fig. 4): (1) no pounding system (the building vibrating without contact), and (2) fixed spring system (the building vibrating in continuous contact with the adjacent structure). The peak response of the pounding system is predicted by considering the distribution of earthquake energy in both systems in the form of kinetic energy and strain energy in each linear state.

Method. - The peak pounding responses of MDOF system are calculated as follows (Kasai et al. 1990):

$$\{u^-\} = \alpha\{u_{np}\} \qquad \text{, and} \qquad \{u^+\} = \beta\{u_{np}\} + \gamma\{u_{fs}\} \tag{1}$$

in which $\{u^-\}$ and $\{u^+\}$ = the peak negative and positive displacement vectors, respectively; $\{u_{np}\}$ and $\{u_{fs}\}$ = the peak displacement vectors obtained from commonly used multimode response spectrum analysis of the no pounding system and the fixed spring system, respectively. The separation ratio β is defined as the ratio of the at-rest separation distance divided by the peak displacement of the no-pounding system at the corresponding story level. The α and γ are obtained from simple equations consisting of the kinetic energies as approximately computed using the first modal participation factor and earthquake pseudo-velocity spectra (Kasai et al. 1990). Estimations of the other peak pounding responses such as drifts, shears, and OTM's can be made in a similar manner.

Theoretical Predictions and SLAM Analysis Results. - The theory was verified by more than 500 case studies (Kasai and Patel 1990) comparing the theoretical results to those from SLAM analyses. Figs. 5(a) and (b) illustrate the good accuracy of the theory for predicting MDOF pounding system peak response for various separations in a mid-height pounding case and a top pounding case, respectively. Note that vertical location of pounding significantly influences the distribution of story peak responses through the height of the building, and that the shears remain almost the same with the separation ratio from 0 to 2/3.

BUILDING APPURTENANCES UNDER POUNDING

Building Appurtenance Damage. - The writers observed damage to building appurtenances such as electrical and mechanical equipments, building parapets, and curtain walls which was caused by pounding of buildings during Loma Prieta earthquake (Kasai and Maison 1991). As discussed earlier (Fig. 2(b)), the peak floor accelerations can be more than 10 times those from the no-pounding case. It was also found that a rigid adjacent building case gives the results similar to those from a relatively heavy flexible adjacent building case (e.g., 1-mass and 3-mass building cases in Fig. 3(c)). The following studies consider the rigid adjacent building case (Kasai et al. 1990).

Floor Acceleration Response Spectra for Pounding Case. - The floor acceleration response spectra (FARS) at the top pounding level of the 15-story building are shown in Fig. 6. They indicate that pounding is especially harmful for equipment or secondary systems having short periods (≤1.0 sec). This effect is not covered by existing industrial design spectra. For example, see the Network Equipment-Building System (NEBS) design spectrum given by Bell Communication Research (BELLCORE 1988), which is very close to the FARS of no-pounding case. The FARS in the pounding case can be as much as 30 times higher than those in no-pounding case. Based on these, the commonly considered method of designing the secondary systems to have shorter periods to reduce the system response may be effective only when no pounding occurs, but would be significantly unconservative in a pounding condition.

Neglecting the effect of damping, the acceleration $\ddot{u}_i$ of i-th pounding level during pounding (State 2) is approximately expressed from equilibrium as:

$$\ddot{u}_i = [\ V_{i+1} - V_i - k_s(u_i - s)\ ] \ /\ m_i \qquad (u_i > s) \tag{2}$$

where V_i, u_i, and m_i = story shear, displacement, and mass of the i-th floor level, respectively, k_s = local contact stiffness (Fig. 1), and s = at-rest separation distance. The writers have found that the peak $\ddot{u}_i$ at State 2 is approximately obtained by substituting into Eq. 2 the peak V_i, peak V_{i+1}, and peak u_i that are estimated using the simplified method explained earlier (Eq. 1).

The writers have also found that the ratio between pounding FARS and no-pounding FARS, hereby defined as a spectrum amplification, remains very stable regardless of different separation ratios (0 to about 2/3) and earthquakes types (Fig. 7) (Kasai et al.). Because of this effect and considering Eq. 2, a simplified method of obtaining pounding FARS seems possible.

CORRELATIVE STUDY ON EXISTING BUILDINGS DAMAGED FROM POUNDING

The writers are conducting correlative pounding analyses of actual buildings damaged during Loma Prieta earthquake. The following describes sample analytical study conducted for two buildings.

Mission Street, San Francisco. - The 10 story building is constructed of thick masonry walls (13 inch thickness) combined with 9 steel plane frames. It was built in 1904. This building experienced severe pounding with an adjacent massive 5 story building which occupies most of the city block. Pounding was located at the 7th level in the 10 story building and at the roof level in the 5 story building (Fig. 8(a)). Only 1 to 1.5 inches building separation is present. The 10 story building suffered structural damage above the pounding elevation as evidenced by the large diagonal shear cracks in the masonry piers (Kasai and Maison 1991).

A 3D-dynamic analysis SLAM model for the building consists of combined steel frames and masonry walls. The building pounded near the corner of the building (Fig. 8(a)). Fig. 8(b) shows an analysis result using a 0.4g artificial earthquake. Note the large shear above pounding level and large torsion developed due to pounding. The pounding analysis results appear to explain the observed damage.

15th Street, Oakland City Center. - The building is a 7-story residential apartment building. It was built in 1913, and consists of 15 reinforced concrete primary plane frames as well as concrete in-fill shear walls that are typically of 6 inches thick at exterior and interior locations. The building has zero separation with the adjacent building, and pounding occurred at its 3rd level (Fig. 9(a)). The building has a rectangular base plan for the ground, mezzanine, and the 2nd level. Above the 2nd floor it takes the form of a "T" in plan with the stem of the "T" pointing north (Fig. 9(a)). A 3D-dynamic analysis SLAM model of the building includes 41 different types of columns, 22 different types of beams and 83 different types of shear panels. Fig. 9(b) shows example analysis results. Note again, the increase of shear and torsion due to pounding.

SEPARATION DISTANCE TO PRECLUDE POUNDING

Spectrum Difference Method. - Based on random vibration theory and considering a first mode approximation for displacements of elastic multi-story buildings, the writers have found a simplified method to obtain an accurate estimate of the required building separation, s, to preclude pounding. In contrast to the commonly known spectrum modal combination method, it is called a spectrum difference method. The method considers the difference of vibration phase between the adjacent buildings. i.e.,

$$s = \sqrt{u_A^2 + u_B^2 - 2\ \rho_{AB}|u_A||u_B|} \qquad (3)$$

In which u_A and u_B are the peak lateral displacements at the possible pounding location under the no pounding condition in Building A and B, respectively, the magnitude of which are simply obtained by the commonly used spectrum approach. The ρ_{AB} is a cross-correlation coefficient. The Eq. 3 is analogous to the double sum combination (DSC) rule commonly used in response spectrum analysis, except that a "minus" ρ_{AB} instead of a "plus" ρ_{AB} is used. Therefore, Eq. 3 is called the double difference combination (DDC) rule. The ρ_{AB} is obtained by substituting the fundamental periods and damping ratios for Buildings A and B into the expressions such as given by Der Kiureghian (1980). Other combination rules commonly known may be the square-root-of-sum-of-squares (SRSS) rule (i.e., $s = \sqrt{u_A^2 + u_B^2}$) or the absolute sum (ABS) rule (i.e., $s = |u_A| + |u_B|$). The use of ABS rule is implied by SEAOC/UBC.

Accuracy of Proposed Rule. - Fig. 10 illustrates the performance of the three rules as compared with time history analysis results using 1940 El Centro earthquake. When the adjacent buildings have the same period, they vibrate in-phase and the absolute relative displacement between them becomes minimum, thus, s becomes minimum and equal to $|u_A - u_B|$, indicating the small separation required to avoid pounding. If additionally the buildings have the same height, then s = 0 (Figs. 10(b) and (c)). These are accurately predicted by the DDC rule, whereas the SRSS and ABS rules are erroneous.

If the adjacent buildings have large damping, s becomes significantly smaller (Figs. 10(c) and (f)), which suggests the feasibility of using interior damper to reduce relative building motions. This is due to the fact that larger damping does not only result in smaller $|u_A|$ and $|u_B|$, but also promotes in-phase vibration of the two adjacent buildings subjected to the same earthquake excitation. Again, the proposed DDC rule captures this effect through the cross-correlation coefficient ρ_{AB}, whereas the SRSS and ABS rules are erroneous. Accuracy of the proposed method has been verified by using 15 different earthquakes as well as varying the period, damping, and height of the buildings.

CONCLUSION

Pounding is a more severe load condition than the case where it is ignored. Continued research is urgently needed in order to provide the engineering design profession with practical means to evaluate and mitigate the effects of pounding. Pursuant to this need, the writers are conducting further research on pounding.

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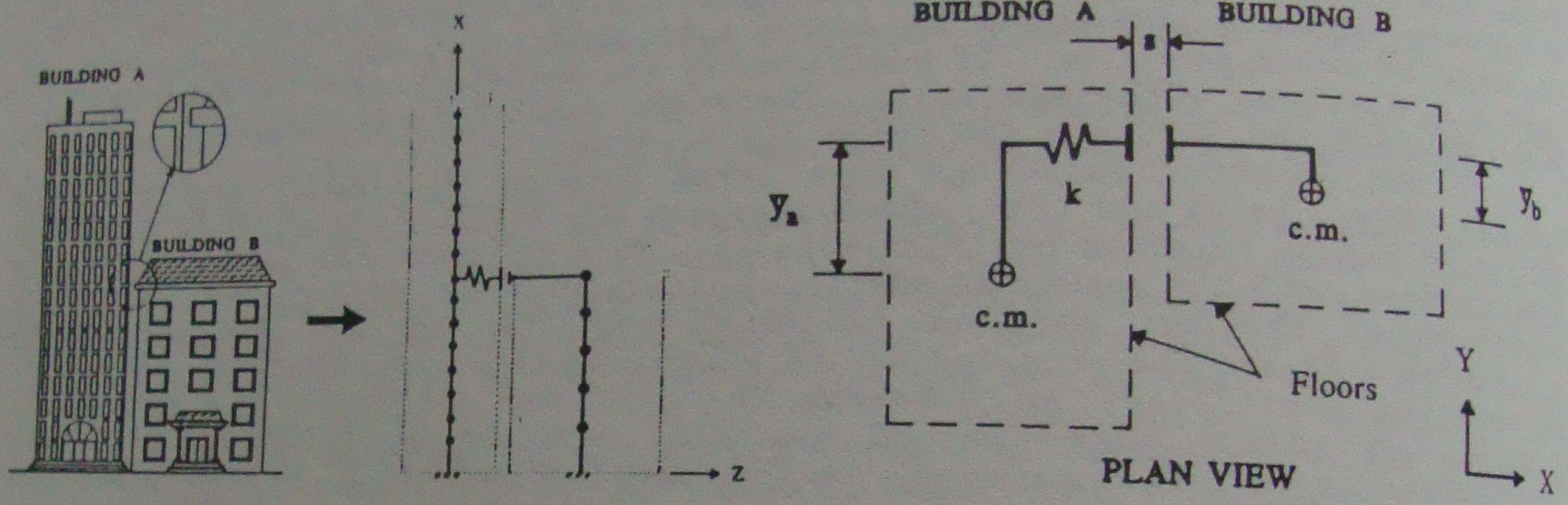


Fig. 1 The pounding problem and SLAM-2 idealization.

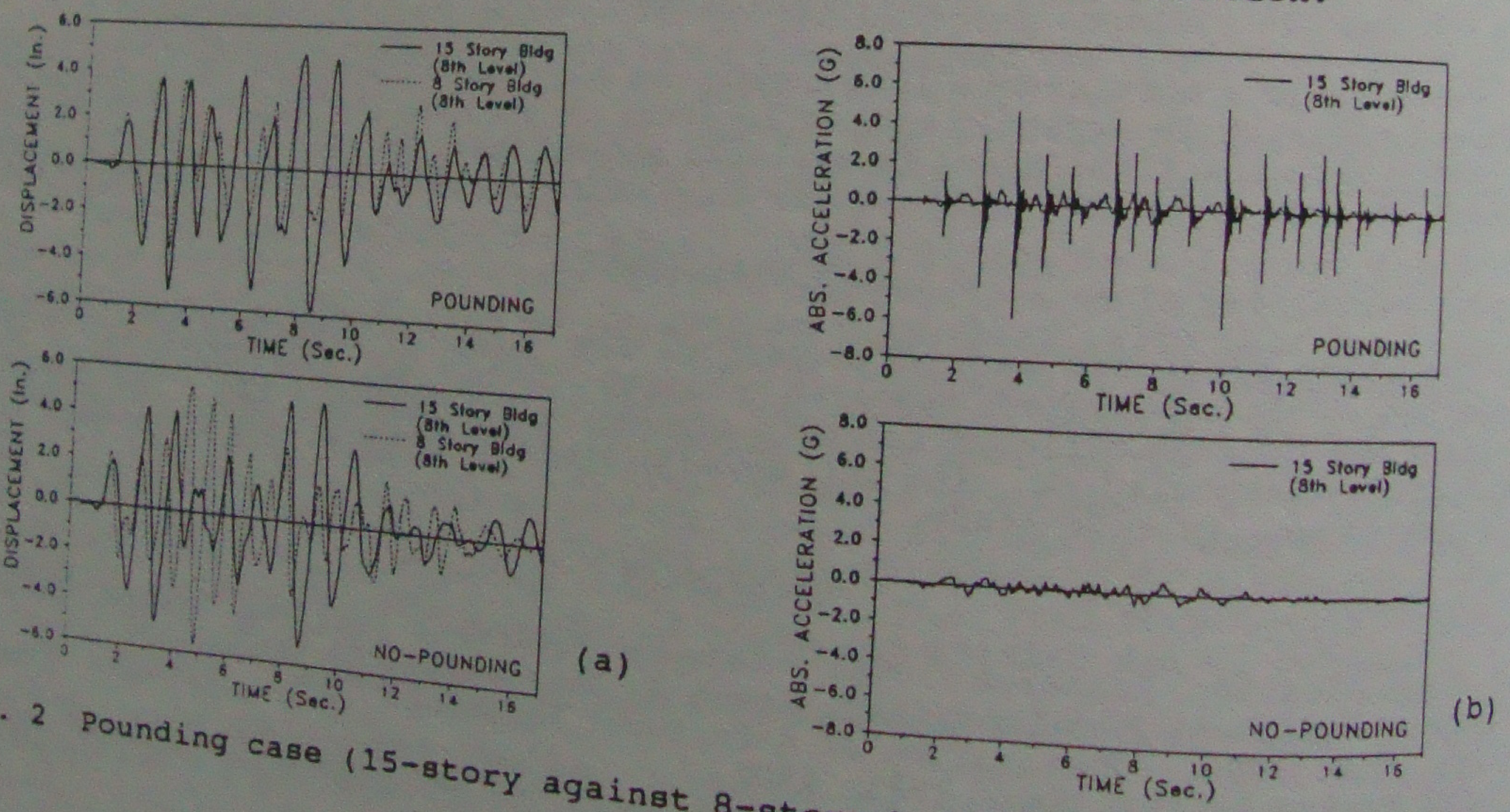


Fig. 2 Pounding case (15-story against 8-story building) vs. no-pounding case.

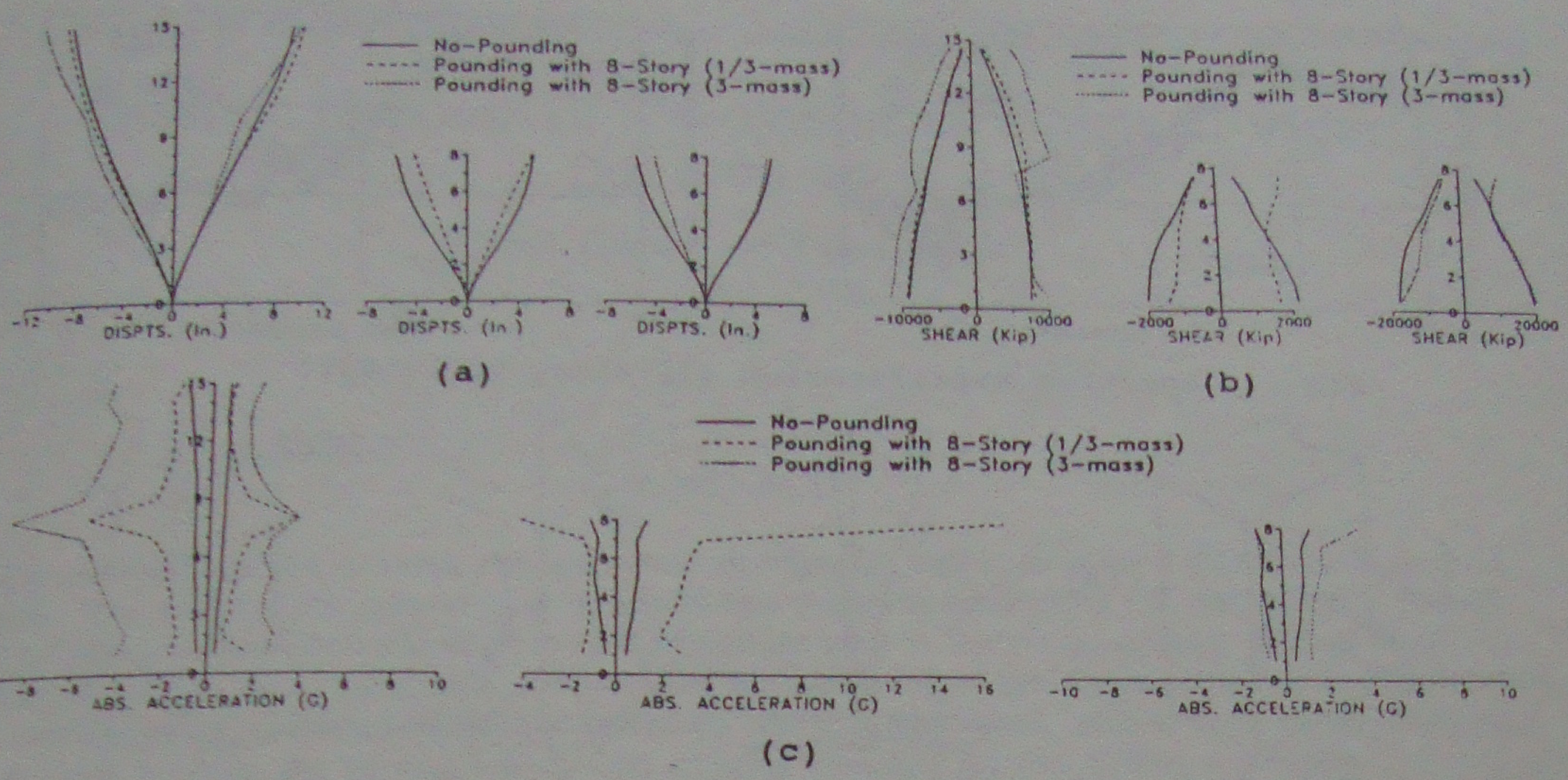


Fig. 3 Response envelops (pounding case vs. no-pounding case).

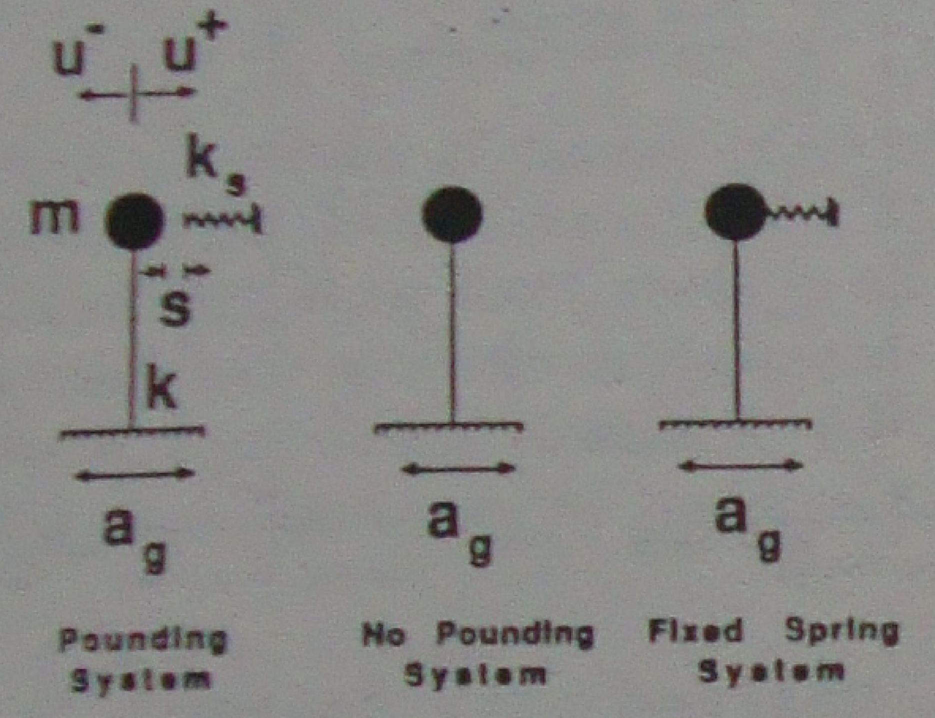
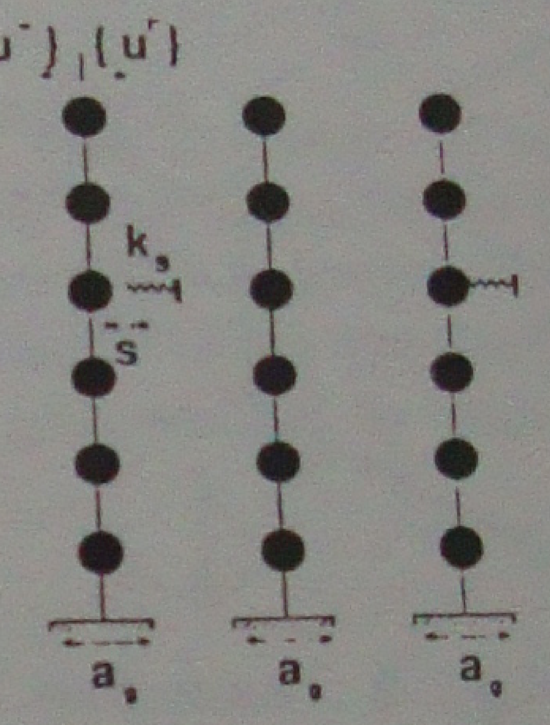


Fig. 4
Proposed theory
on pounding



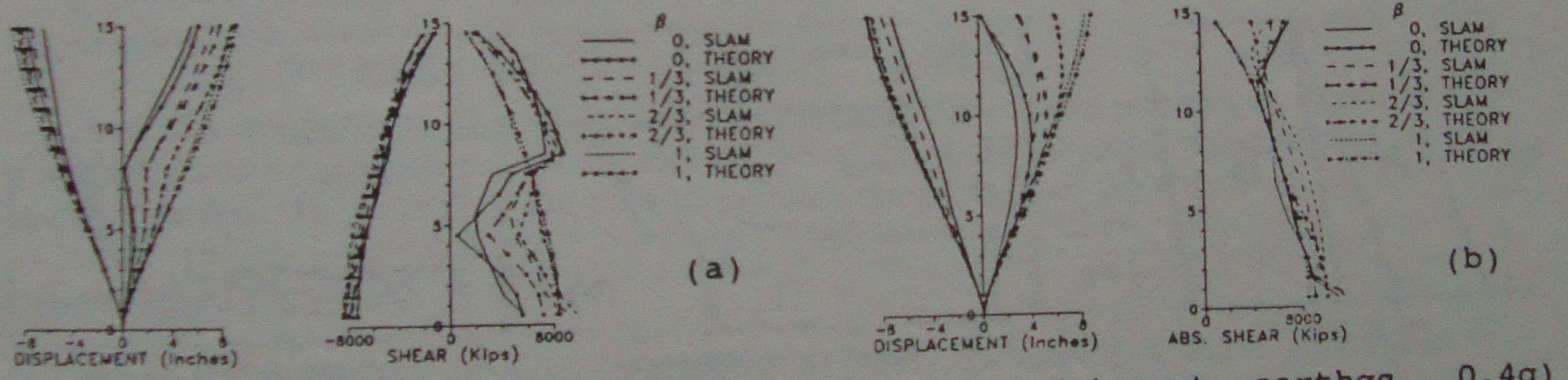


Fig. 5 Theory vs. average of SLAM-analysis results (six art. earthqs., 0.4g)

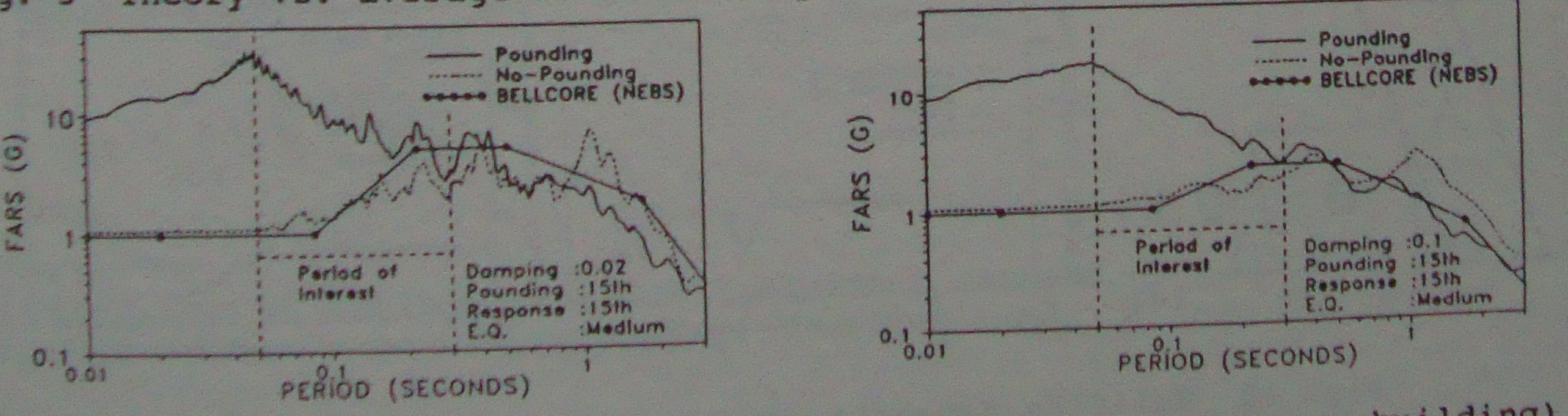
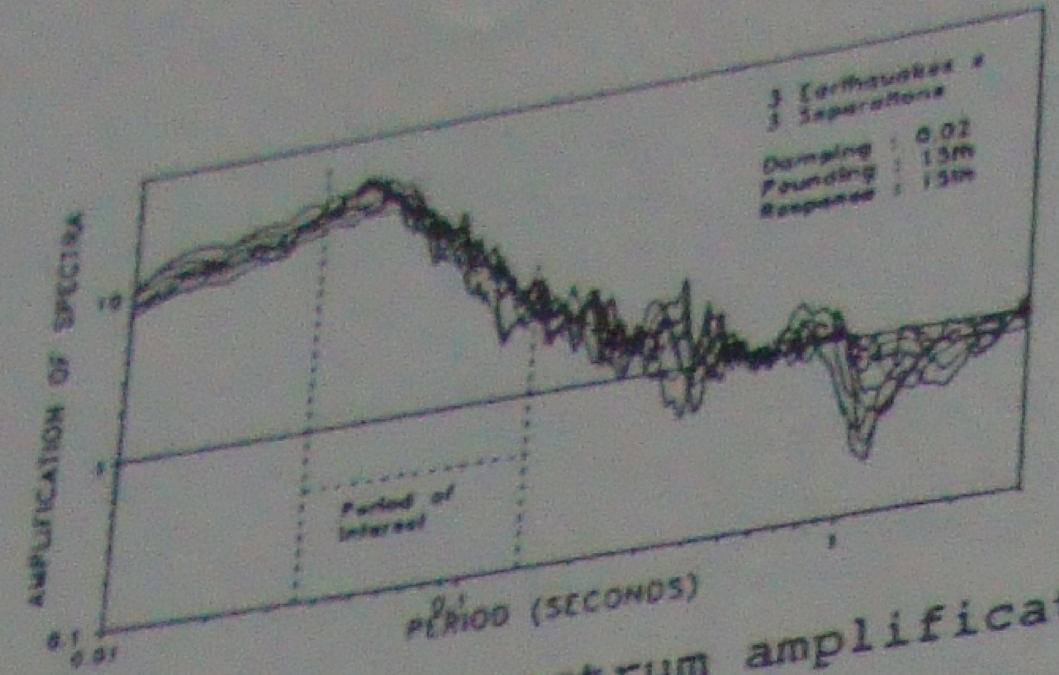


Fig. 6 FARS : floor acceleration response spectra (15-story building)



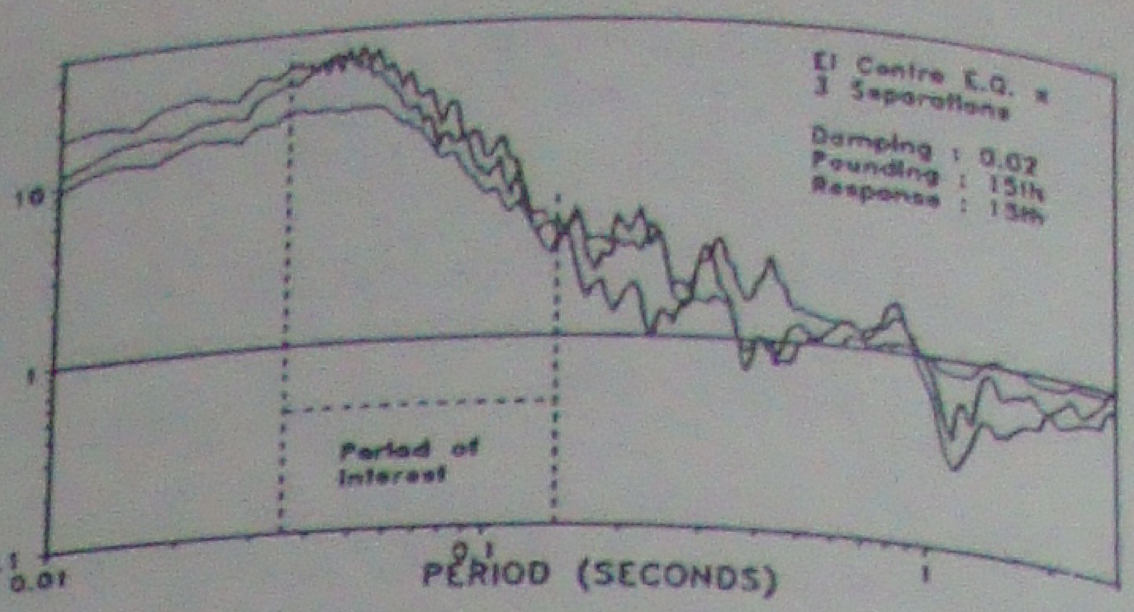


Fig. 7 Spectrum amplification (15-story building).

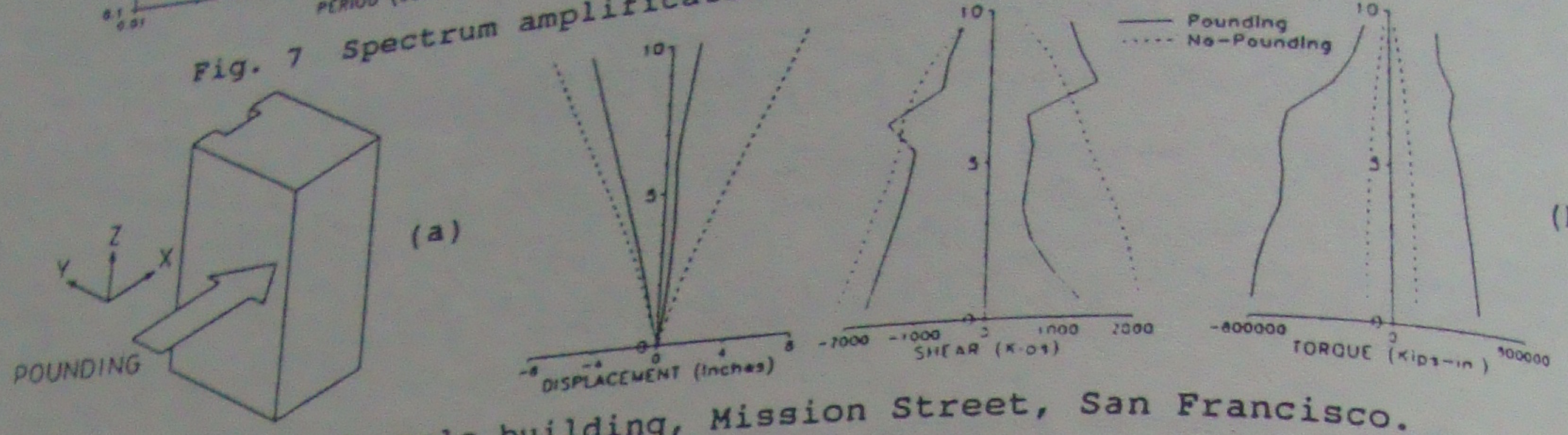


Fig. 8 Example building, Mission Street, San Francisco.

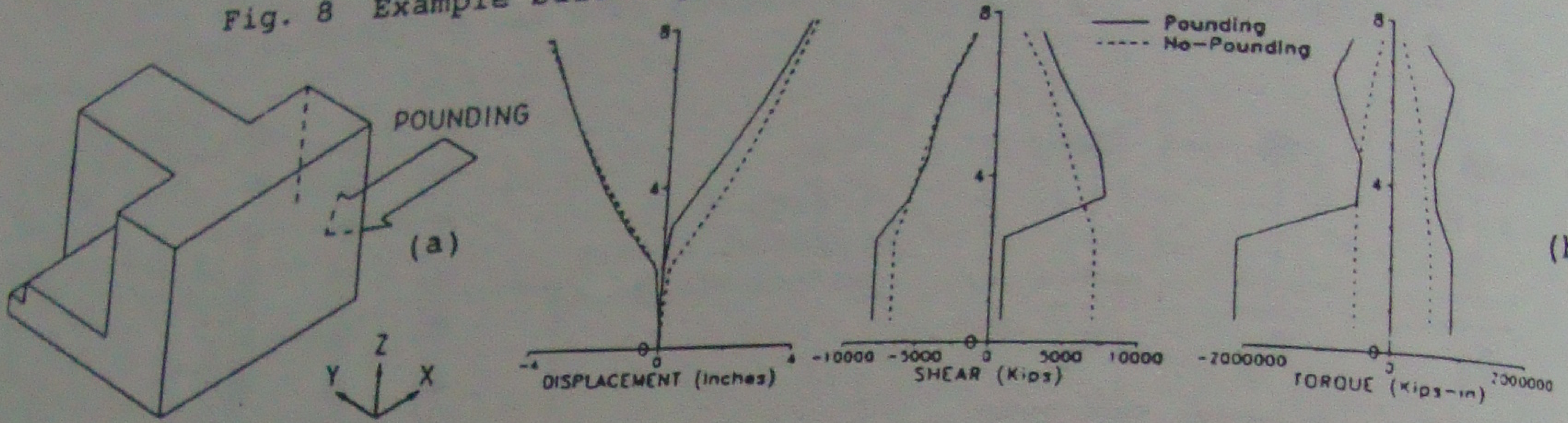


Fig. 9 Example building, 15th Street, Oakland City Center.

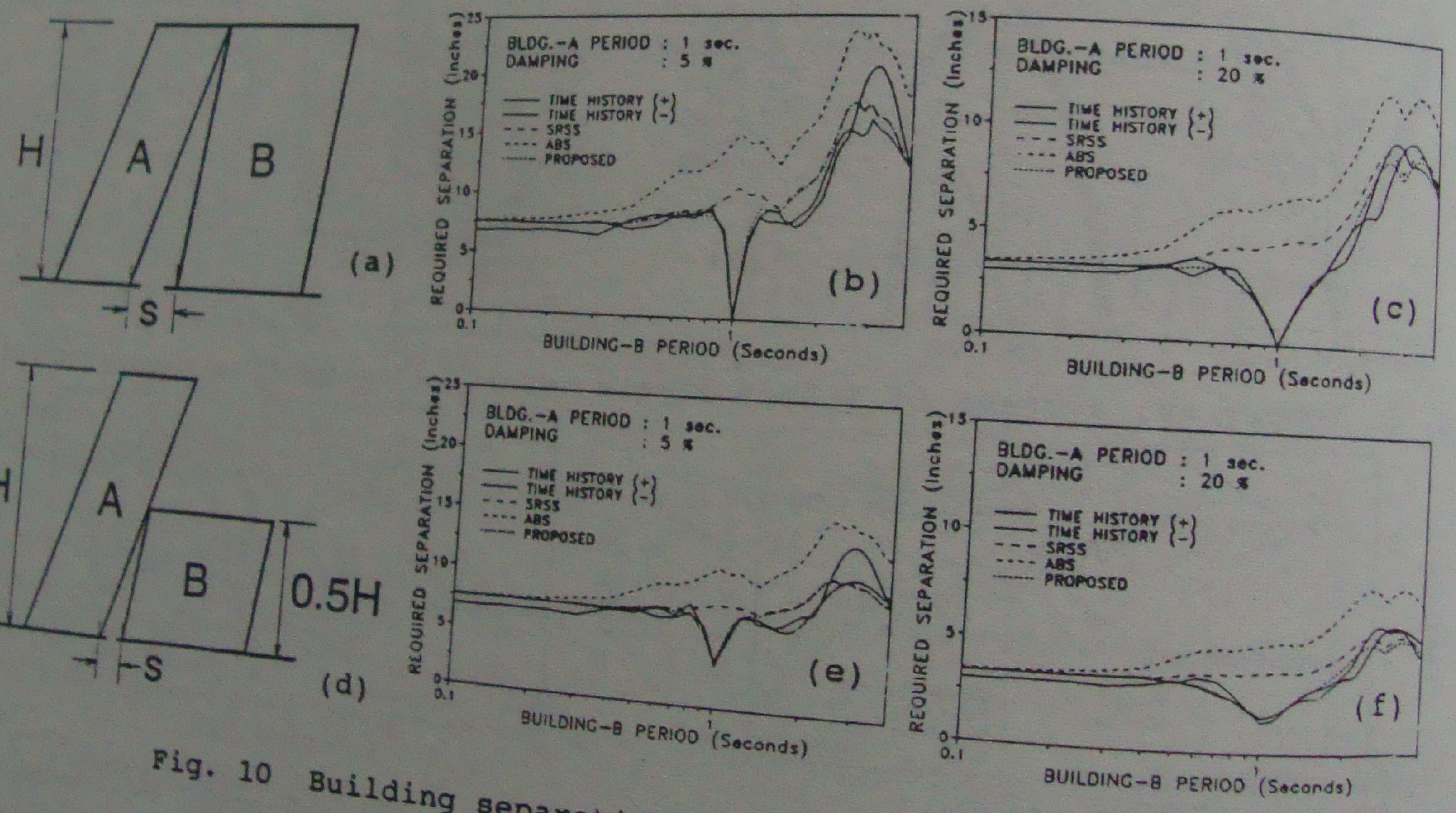


Fig. 10 Building separations required to preclude pounding.