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IMPLICATIONS OF OBSERVED POUNDING OF BUILDINGS ON SEISMIC CODE REGULATIONS

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ABSTRACT

The main objectives of this paper are: to review the history of observed damage after significant earthquake ground motions (EQGMs) due to adjacency hazards, of which pounding of buildings is just one potential source, as well as the conclusions and recommendations formulated after the 1985 Mexico City experience; to discuss briefly the technical and socio-economic problems created by adjacency hazards, with particular emphasis on pounding, for the earthquake-resistant design (EQ-RD) of new adjacent buildings and for the seismic evaluation and upgrading of existing hazardous adjacent buildings; to assess the rationality and reliability of present seismic code regulations for EQ-RD of new adjacent buildings, as well as the standards and/or procedures for the upgrading of existing adjacent buildings; and to formulate recommendations regarding what is needed to improve the state of the art and particularly the state of the practice by improving and/or developing new seismic code regulations for the abatement of the seismic risks that can be generated by adjacency hazards.

KEY WORDS

Adjacency hazards; adjacent buildings (structures); earthquake-resistant design; hammering; pounding; seismic code regulations; and seismic upgrading.

INTRODUCTION

Introductory Remarks

Pounding Between Buildings. Field inspections of the performance of buildings after significant earthquake ground motions (EQGMs) in urban areas reveal that pounding between adjacent buildings is technically one of the main sources of damage among the different types of damage that can result from ***seismic adjacency hazards***.

Seismic Adjacency Hazards. In the glossary used in the *Standards of Seismic Safety for Existing Federally Owned or Leased Buildings (ICSSC RP4) and Commentary* developed by the Interagency Committee on

Seismic Safety in Construction (ICSSC) (Todd, 1994), the ***seismic adjacency hazards*** are defined as follows:

> *Hazards caused when adjacent buildings interact during an earthquake. Includes pounding, effects of one building buttressing another, falling hazards from an adjacent building, and the consequences of damage to common structural elements, such as party walls (single bearing walls supporting two adjacent buildings constructed on separately defined parcels of land).*

The above potential sources of danger can create complex technical and socio-economic problems. The complexity of these problems varies depending on whether the problem at hand is one of design and construction of new adjacent buildings, or one of evaluation of the presence and relative seismic risk of any one of the above adjacency hazards in existing buildings and, if one exists, how to remedy it with technical and economical efficiency. In general, the problems involved in seismic evaluation and upgrading existing buildings with an adjacency hazard are more complex than those involved in the earthquake-resistant design (EQ-RD) and earthquake-resistant construction (EQ-RC) of new adjacent buildings. This is particularly true when the adjacent buildings have different owners and even worse if one or more of the adjacent buildings under consideration are condominiums. As pointed out by Arnold (1995) and discussed later, the socio-economic problems that can arise because of the need to involve owners of adjacent buildings in costly studies, design and construction work in which they may not wish to participate can be very complex and difficult to resolve. Although only the technical problems due to pounding between adjacent buildings will be discussed herein, it should be clearly noted that the other problems of adjacency must also be addressed if we are to achieve effective mitigation of seismic risks in our urban areas.

<u>Review of the History of Pounding Between Adjacent Buildings</u>. Adjacency effects due to EQGMs have been noted because they caused some building distress in most of the past significant EQs that have shaken urban areas, and the existence of the problem created by these effects, particularly due to pounding, was brought to the attention of the engineering community by building codes in the 1950s (UBC, 1955 and SEAOC, 1959). Pounding is a problem related to the separation between adjacent buildings, and occurs when the spacing between buildings is not sufficient to allow them to vibrate or move freely laterally. In 1961 Blume *et al.* wrote, "The question of what width of separation is sufficient must be considered primarily a matter of engineering judgement. Arbitrary rules could cause severe hardship in some cases, and would be inadequate in others." However, perhaps because of the lack of dramatic collapse and/or severe damage, professionals and researchers did not pay the needed attention to the importance of this problem until the 1971 San Fernando EQ, when severe structural damage to the basement of the main building at a separation joint and the collapse of a stair tower of the then recently constructed Olive View Hospital (Bertero, 1973 and Mahin *et al.*, 1976). Researchers' interest in conducting detailed studies on this kind of seismic hazard was triggered by the high number of engineered buildings that suffered severe damage and even collapse in Mexico City as a consequence of pounding during the 1985 Michoacan earthquakes. As reported by Bertero (1986), analysis of the information available on the observed damage of buildings in Mexico City reveals that in over 40% of the collapsed or severely damaged buildings, pounding between adjacent buildings occurred, and in at least 15% pounding was the primary cause of building collapse.

Although pounding has been observed in most of the significant EQGMs that have occurred in urban areas since the 1985 Michoacan EQs, and particularly after the 1989 Loma Prieta EQ and the recent 1995 Kobe EQ, the number of *adjacent engineered buildings* severely damaged and dramatically suffering from partial collapse due to pounding in Mexico City in 1985 may in fact be the highest in the history of this kind of EQ damages. As a consequence of the observed dramatic failures, the following questions were raised: What are the main reasons for the observed damaging and in many cases devastating pounding of adjacent buildings? Considering that the historic center of Mexico City is crowded with adjacent buildings without any significant separation, why did only a relatively small number of these buildings suffer severe damage? An attempt to answer these questions motivated the preliminary study reported by Bertero (1986).

<u>Types of Observed Pounding Damage</u>. In analyzing the observed damage due to pounding, the damaged buildings were grouped by Bertero (1986) according to their types and relative separations into the following three categories: ***(1) adjacent units of the same building separated through expansion (or construction) joints; (2) units of the same buildings or adjacent different buildings which are far apart but connected by***

one or more pedestrian bridges; and (3) adjacent different buildings. In connection with this way of grouping the damaged buildings, it is of interest to note that during the 1995 Kobe EQ the damage to the bridges in the above category (2) was very high in amount as well as severity. Furthermore, the number of medium-rise buildings that underwent severe overturning was large, and in several cases buildings overturned across the street, inducing damage to the building across the street. Another type of damage due to interaction of adjacent buildings, i.e., pounding, which was observed after the Kobe EQ and which was already noted after the Loma Prieta EQ (EERC, 1989), was the "*pushing*" of the end (usually the corner) building of a series of buildings built very closely adjacent to each other along a block.

Conclusions From Analyses of the Observed Pounding Damages in Mexico City. From the observed performance of adjacent buildings in Mexico City during the 1985 earthquakes and the results of the preliminary studies, the following preliminary conclusions were drawn: (1) In over 40% of the collapsed or severely damaged buildings, pounding between adjacent buildings occurred, and in at least 15% pounding was the primary cause of collapse. Relative to the total number of adjacent buildings with very small separations that exist in the center of Mexico City, the number of buildings severely damaged by pounding is very small. (2) Although severe pounding was the result of insufficient separation between adjacent buildings, this insufficiency in general cannot be attributed to just one specific reason. It was the result of a combination of several of the following factors: (a) the unexpected severity of the ground motion and the consequent insufficiency of the minimum seismic code requirements for the design of structures, particularly for lateral and torsional stiffnesses and strengths; (b) inadequate building configuration and structural system to resist lateral shaking and particularly torsional effects (lack of redundancy of structural defense lines, particularly against inelastic torsional deformations); (c) cumulative tilting due to foundation movement; and (d) improper maintenance. (3) Comparison of Mexican and U.S. earthquake regulations indicates that if buildings were designed and constructed to satisfy just the minimum code requirements, and if ground motions like those recorded at the SCT station could occur in U.S. cities, the problem of pounding between adjacent buildings located in soft soils could be even more serious in the U.S. than in Mexico City.

Recommendations Formulated After the 1985 Michoacan EQs. (1) Thorough studies should be conducted of the performance of adjacent buildings in Mexico City in order to investigate the primary causes of such performance and to improve present code requirements by determining proper separations between the different types of adjacent buildings. This will require integrated analytical and field experimental studies. (2) The probabilities of ground motions like those recorded at SCT happening in U.S. cities should be investigated so that a more thorough assessment can be made of the implications of the observed performance of adjacent buildings in Mexico City on U.S. EQ-RD and EQ-RC practices. Furthermore, in order to conduct a thorough assessment, it would be necessary to study the differences between the building technology used in Mexico City and that used in U.S. regions of high seismic risk, particularly regarding the type of RC structural system and proportioning and detailing of its critical regions, foundation, nonstructural elements, workmanship, inspection and maintenance, all of which are important factors in the seismic response of the entire soil-foundation-building system. (3) Economical solutions for retrofitting existing adjacent buildings which do not have adequate separation to avoid severe damage due to pounding should be investigated.

Studies on Pounding and Other Adjacency Problems Conducted After the 1985 Mexico City Experiences. As a consequence of the great importance of pounding damage on the observed severe damage of buildings in Mexico City after the 1985 Michoacan EQs, several researchers have conducted analytical studies and lately even integrated analytical and experimental studies on the pounding problem. Special technical sessions have been held on this problem in world and national conferences on earthquake engineering, and numerous papers have been published on this topic in the pertinent literature. Some recent studies, such as those by Filiatrault *et al.* (1995a and 1995b), Papadrakis *et al.* (1995), Athanassiadou *et al.* (1994), Anagnostopoulos *et al.* (1992) and Jeng *et al.* (1992) contain extensive lists of references. A search conducted by the author at the EERC library showed 57 publications on this problem since 1988. On the other hand, the damages caused by the two other problems of adjacency hazards that have been identified previously have not yet been well documented and studied.

Objectives and Scope

Objectives. Besides the above brief review of the observed EQ damage due to adjacency hazards, the main objectives of this paper are: to discuss briefly the technical and socio-economic problems that can be created by adjacency hazards in the EQ-RD of new adjacent buildings as well as for the seismic evaluation and upgrading of existing hazardous adjacent buildings; to assess the implications of the observed pounding damage on current practice by analyzing the rationality and reliability of present seismic code regulations regarding the EQ-RD of new adjacent units of the same building or new different adjacent buildings as well as of the technical standards and/or procedures for the upgrading of existing adjacent buildings; and to formulate recommendations regarding what is needed to improve the state of the art and particularly the state of the practice through the improvement of current code provisions and/or the development of new seismic codes or technical standards for the abatement of the seismic risks that can be generated by adjacency hazards.

Scope. To achieve the above objectives, this paper has been divided into four main parts. The ***first part*** is the above ***Introduction***, which briefly reviews the observed EQ damage due to adjacency hazards, their different types, and the conclusions and recommendations formulated as a consequence of the 1985 Mexico City experience. The ***second part*** is devoted to identifying the ***primary technical reasons*** for the different problems created by adjacency hazards, as well as the ***socio-economic issues*** involved. In the light of the identified technical reasons for the observed damage due to pounding, the ***third part*** of the paper is devoted to analyzing the ***implications of the observed damage on the state of the practice as reflected in the current seismic code regulations and standards*** in the EQ-RD of new adjacent buildings and the seismic evaluation and upgrading of existing hazardous adjacent buildings. The ***fourth part*** is devoted to formulation of ***recommendations regarding what is needed to improve the state of the art and particularly the state of the practice in mitigating the seismic risks that can be generated by adjacency hazards.***

PRIMARY CAUSES OF DAMAGE DUE TO POTENTIAL SOURCES OF ADJACENCY HAZARDS: TECHNICAL AND SOCIO-ECONOMIC ISSUES

Technical Issues. Obviously the primary reason for damage due to adjacency hazards is insufficient separation. This is the case when the adjacency hazards in one building are created by deficiencies in an adjoining building through common elements (walls and/or columns), as well as in the case of pounding of buildings separated by a relatively large distance but linked by bridges at certain stories, and in some cases the danger that a medium-rise building will overturn across a street. A series of questions arise from the observation of damage due to adjacency hazards: What could constitute a sufficient separation? What parameters control sufficiency of separation? Is the damage the result of inadequate code regulations regarding minimum separation? Is it due to violations of the minimum code requirements? These are very difficult questions to answer (Bertero, 1986). As mentioned earlier in the conclusions offered in the Introduction, in the case of the observed damage in Mexico City after the 1985 EQs, after preliminary analysis of the available data it appeared that the insufficient separation between the adjacent buildings that suffered severe damage due to pounding was the result of a combination of several factors, and could not be attributed to any one factor.

To summarize: the experiences from inspection of adjacency damages, particularly those due to pounding, appear to confirm that the minimum separation required by seismic codes, or the separation resulting from designer judgement or design practice not mandated by the enforced seismic codes, is usually adequate for avoiding severe pounding damage in adjacent well designed, constructed and maintained buildings. On the other hand, the rationality and reliability of the current requirements of the U.S. seismic codes, as well as those of other countries, are questionable in the case of two adjacent buildings located on or near the sources of very severe EQGMs (near-source effects) and in which one or both offer significant irregularity in plan and/or elevation.

Socio-Economic Issues. As pointed out in the Introduction, in EQ-RD of new adjacent buildings in urban areas located in regions of high seismicity, the separation that would be required to avoid the effects of hammering of adjacent medium and tall adjacent buildings could lead to serious socio-economic problems, particularly in urban areas because of the high cost of land. The socio-economic issues, as well as the technical issues, become significantly more complicated when seismic evaluation and upgrading of existing adjacent buildings is needed, particularly if the adjacent buildings have different owners, because usually this will require the owner who sees the need for upgrading his or her building either to conduct the needed and costly studies of the seismic vulnerability of the adjacent building, or to convince the other owner to pay. If the different owners do not agree, or if one of them refuses to finance the needed upgrading, it becomes very difficult for one owner to have the upgrading work done. As pointed out by Arnold (1995), the socio-economic problems involved in the upgrading of adjacent buildings are particularly critical when adjoining buildings have common structural elements along the property line. *In this case, upgrading is very difficult, if not impossible, without the neighbor's involvement, and probably some degree of rehabilitation to his or her property. While in engineering terms it may seem obvious that it is in the adjoining owners' best interest to cooperate in evaluation and mitigation, in socio-economic terms there may be many reasons, valid or otherwise, for reluctance (Arnold 1995).*

IMPLICATIONS OF OBSERVED POUNDING FOR CURRENT SEISMIC CODES

The implications of observed effects of pounding between adjacent buildings in Mexico City after the 1985 Michoacan EQs for the Mexico EQ-RD code requirements enforced at the time of the EQs and for the 1985 Emergency Regulations, as well as for U.S. EQ-RD and construction practices as reflected in the 1985 UBC and SEAOC recommendations have been discussed elsewhere (Bertero, 1986). Herein, only the implications of the observed pounding damage and the results of some of the numerous studies that have been conducted on pounding of adjacent buildings since 1986, for the present 1994 UBC and the 1995 SEAOC proposed changes for the 1997 UBC will be briefly discussed.

1994 UBC Requirements

As pointed out previously, the technical problems created by pounding are traditionally associated with minimum separations between buildings, which is how the seismic codes deal with them. Section 1631.2.11 of the 1994 UBC states:

> *All structures shall be separated from adjoining structures. Separation shall allow for $3(R_w/8)$ times the displacement due to seismic forces. When a structure adjoins a property line not common to a public way, that structure shall be set back from the property line by at least $3(R_w/8)$ times the displacement of that structure. **EXCEPTION:** Smaller separations or property line setbacks may be permitted when justified by rational analyses based on maximum expected ground motions. As a minimum, building separations or property line setbacks shall not be less than $(R_w/8) \geq 1$ times the sum of displacements due to code-specified seismic forces.*

Allowable Displacement Due to Seismic Forces. According to the 1994 UBC, section 1628.8.2, the "*calculated story drift shall not exceed $0.04/R_w$ or 0.005 times the story height for structures having a fundamental period of less than 0.7 second. For structures having a fundamental period of 0.7 second or greater, the calculated story drift shall not exceed $0.03/R_w$ or 0.004 times the story height.*" **EXCEPTIONS** are given that permit these drift limits to be exceeded.

From analysis of the above 1994 UBC regulations, the following observations can be made: (1) these regulations are very similar to the SEAOC 1985 Tentative Lateral Requirements (SEAOC Seismology Committee, 1985), which have already been discussed (Bertero, 1986); (2) the UBC regulations address only the problems of potential adjacency hazards for the EQ-RD of new buildings, and neglect the problems that these hazards can create in existing adjacent buildings, which the author considers are the most pressing problems that need to be solved to reduce the seismic risks of our urban areas (there is a huge inventory of existing adjacent buildings with insufficient separation in most cities); and (3) the rationality and reliability of the established minimum separation and of the drift limits through the empirical expressions based on the use of the numerical coefficient R_w have been seriously questioned [a more rational establishment of the drift limit is the one recommended in the 1991 and 1995 editions of the NEHRP provisions (FEMA, 1992 and 1995)], and these regulations do not address the large lateral displacement that can be induced by near-source effects (Iwan 1994, Hall *et al.* 1995), which were revealed by the EQGMs recorded during the 1994 Northridge and 1995 Kobe EQs. Furthermore, these regulations do not address properly the effects of subsoil on the dynamic characteristics of the entire building system (superstructure, nonstructural components and contents, foundation and soil), and consequently on the possible pounding response between adjacent buildings. As noted recently by Chouw *et al.* (1995), "***Depending on the subsoil conditions, a building system on subsoils can behave very differently than a system built with fixed base.***"

As already discussed by Bertero (1986), application of the above regulations results in very large required separations. For example, for two ten-story (35 m tall) SMRF buildings, the 1994 required gap between these two adjacent buildings should be ≥ (0.0225)35m ≐ 0.79m. Despite this apparently huge spacing, compliance with this code regulation may not guarantee that pounding will not occur, firstly because the code required lateral yielding strength for these two buildings is low, and secondly because of the other possible primary causes of pounding damage that have been discussed previously, to which near-source and subsoil effects sometimes also have to be added.

SEAONC 1995 Strength Design Code Change Proposal for the 1997 UBC. Ten years after the 1985 Mexico City experience, the Seismology Committee of the SEAONC has taken an important step toward improving UBC regulations regarding the required minimum separation for adjacent buildings by proposing to replace 1994 UBC section 1631.2.11 with the following one (section 1648.2.11):

All structures shall be separated from adjoining structures. Separation shall allow for the displacement, Δ_M. Adjacent buildings on the same property shall be separated by at least Δ_{MT}, where

$$\Delta_{MT} = \sqrt{(\Delta_{M1})^2 + (\Delta_{M2})^2}$$

where Δ_{M1} and Δ_{M2} are the displacement of the adjacent buildings.

When a structure adjoins a property line not common to a public way, that structure shall also be set back from the property line by at least the displacement, Δ_M, of that structure. ***EXCEPTION:*** *Smaller separations on property line setbacks may be permitted when justified by rational analysis based on maximum expected ground motions.*

Section 1645.9.2 Determination of Δ_M. *Except as modified by section 1645.5.5, the Maximum Inelastic response Displacement, Δ_M, shall be computed as follows*

$$\Delta_M = 0.7\,R_d\,R_o\,\Delta_s$$

where:

- R_d ≡ *numerical coefficient representative of the global ductility capacity of lateral force resisting systems (given in tables)*
- R_o ≡ *numerical coefficient representing the overstrength inherent in the lateral force resisting system (given in tables)*
- Δ_s ≡ *Design Level Response Displacement, which is the total drift that occurs when the structure is subjected to the design seismic forces*

The equation proposed by SEAONC to compute Δ_{MT} can be considered as a compromise between the requirements of the static method of the 1990 National Building Code of Canada (NBCC) (Filiatrault *et al.* 1995b) and the approximate method proposed by Jeng *et al.* (1992), which is based on random vibration concepts. The 1990 NBCC requires that adjacent buildings be separated by the sum of the anticipated maximum deflection. The study conducted by Kasai *et al.* (1991) showed that the required separations, which ignore the phase between the building motions, are excessive.

CONCLUSIONS AND RECOMMENDATIONS

From the above discussions, the author believes that the following concluding remarks made in 1986 (Bertero) are still valid:

> *To avoid the effects of hammering of adjacent tall buildings, separation would be required that could lead to serious problems in the economical use of usually very expensive real estate. Thus, it appears that to avoid damage between adjacent buildings it is necessary to develop other regulations or requirements than just to specify adequate separation, such as including in the design and detailing of adjacent buildings the possibility of such hammering. One such regulation should be that for two adjacent buildings with inadequate separation, the floor systems of the two buildings should be at the same level. The use of proper dampers between the adjacent buildings could also be effective. A simple solution has been suggested by Rosenblueth and Esteva (Newmark* et al.*, 1971). The problem of proper separation between adjacent buildings urgently requires consideration in our codes. Economical solutions for retrofitting existing adjacent buildings which do not have adequate separation should be researched immediately.*

In view of the results obtained from the analytical and experimental studies conducted after the 1985 Mexico City experience, it is recommended that further investigations be conducted considering both the ***technical problems*** that can be created by ***near-source EQGMs*** and by the ***interaction between buildings with foundation and subsoil*** and the ***interaction between buildings via the subsoil***, and the ***socio-economic problems*** that pounding can generate, particularly in cases where an existing adjacent building needs to be seismically upgraded. There is also a need to investigate the technical and socio-economic problems that can be generated by the other types of adjacency hazards, which unfortunately have not been seriously considered before now.

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