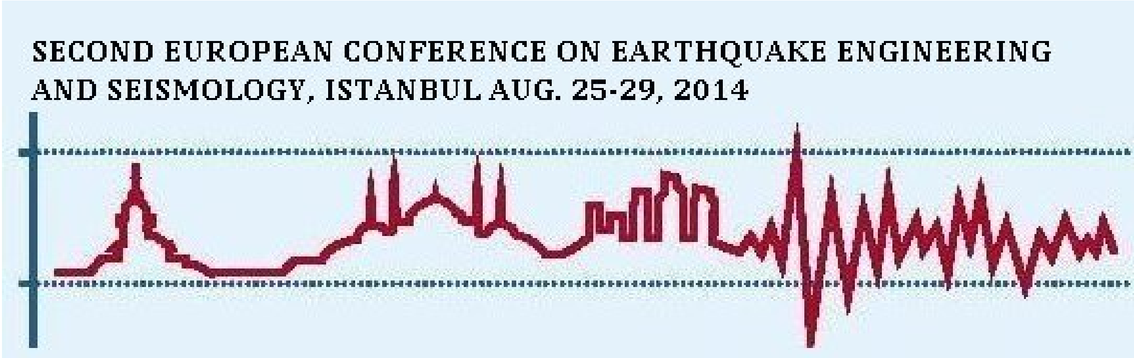

POUNDING EFFECTS DURING AN EARTHQUAKE, WITH AND WITHOUT CONSIDERATION OF SOIL-STRUCTURE INTERACTION

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ABSTRACT

The pounding between adjacent buildings can cause both architectural and structural damages. The paper presents some aspects related to the Vrancea seismic motions pattern, a review of observed damages after a strong earthquake due to pounding of buildings in Romania, a few causes of pounding, an analytical and numerical modeling study. For the behavior of buildings under structural pounding, an analysis with and without consideration of soil-structure interaction is done.

INTRODUCTION. VRANCEA SEISMIC SOURCE.

In Vrancea a very small mantle volume of approximativ 30×70×160 km hosts earthquakes that occur repeatedly with magnitudes in excess of 7.5. All intermediate-depth earthquakes are contained in the high-velocity volume beneath Vrancea which is bigger than the seismogenic volume (Wenzel et al, 2002).

The earthquakes affect large areas, over 50% of the territory, with a predominant NE-SW orientation, the local and regional geological conditions influence the amplitude variation of the seismic motion more than the magnitude or the distance (Georgescu, 2002).

These intermediate depth earthquakes propagate long period waves at long distances, whose impact is significantly amplified in areas of soft alluvial deposits in the southern plain of Romania (including Bucharest) and affect mostly high rise buildings built on them. Thus, the characteristics of Vrancea source effects, more than those of other seismic sources in the world, are the long predominant periods of soil vibration and the important differences between the peak ground acceleration values in many areas.

ROMANIAN REGULATORY PROVISIONS RELATED TO THE MODELING OF SOIL-STRUCTURE INTERACTION PHENOMENON

The deformable soil is modeled as is considered in Seismic Design Code (P100-2006, 2013) by the introduction at the interface of some calibrated Winkler springs depending on the properties of the soil, with linear or nonlinear behavior, Fig. 1.

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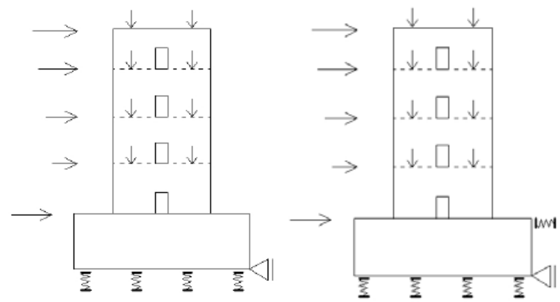


Figure 1. The deformable soil is modeled as is considered in P100-2006, 2013. By the introduction at the interface of some springs (left). By the introduction of some horizontal springs that simulate the strength and stiffness of the surrounding soil (right)

GEOLOGICAL AND DYNAMIC PROPERTIES OF SOILS IN BUCHAREST

Geologically, Bucharest is situated above a sedimentary basin developed in the central part of the Moesic Platform. The soil is made of alternating complexes of non-cohesive soil (sand and/or gravel) and cohesive clays; also an older loessoid cover and younger floodplain deposits (river alluvium, lacustrine deposits, alluvial cones and terraces). The geological types and the shear wave velocities for different soil layers are presented in Table 1 (Toma et al, 2006).

Table 1. Geological and dynamic properties of soils in Bucharest

Geological type 1…7	Depth of the upper limit (m)	Averaged density (g/cm^3)	Averaged V_s (m/s)
Recent sediments (organic soil and clay-rich)	0	1.10	102
Upper sandy-clayey complex (loessic deposits and sand layers)	0.5…5	1.75	302 234…380
Colentina gravel complex (cross-stratified sand and gravel with interbedded clayey layers)	5.0…12	1.99	335 225…280
Intermediate clay complex (brown and grey clays, with sandy intercalations)	10…20	2.07	378
Mostistea sand complex (grey, fine-grained sands with lenticular intercalations of clay)	15…30	2.00	400
Lacustrine complex (clay and silty clay, with lenticular sandy layers)	35…50	2.14	442
Fratesti sands complex (sands and gravel)	100…180	2.05	500

OBVIOUS CASES OF POUNDING OF BUILDINGS IN BUCHAREST UNDER 1977 AND 1990 VRANCEA EARTHQUAKE INPUT

The effect of pounding between buildings was observed under 1977 and 1990 Vrancea earthquake input and since then the size of the seismic joint/separation gap was modified in the codes. Often, these effects have been suspected to be a reason for partial or total collapse of buildings, so the study of the pounding between buildings, in this context of Vrancea seismicity, is important.

In Bucharest, for instance, *in the case of the 1977 Vrancea earthquake*, the partial collapse of a 10-story building, which was the end of unit of a block of buildings along the east side of Bd. Magheru, happened, and some reasons for a pounding effect contribution exist. Some other cases of pounding of adjacent buildings of different heights and stiffnesses existed.

It is worth of mentioning that before 1940's the earthquake design codes were not applied and the reinforced concrete structures were quite irregular in plan and on height. Later on, between 50's and 77's, building configuration was rather regular, and although the relative overall deformation was calculated function of structures deflections, the code required a rather small seismic joint of few centimeters. This was related to the knowledge level of the period, as well as to the very reduced design forces considered in the codes.

In the following, some effects of the pounding are presented in Fig. 2…9 (Fattal et al, 1977).

Figure 2. Damage due to pounding of the Casata building with the next structure (Slight tilt of this building to the right) (Fattal et al, 1977)

Figure 3. Pounding damage to other structures in the building block next to Casata (Fattal et al, 1977)

Figure 4. Exterior view of multistory apartment building. General lack of emphasis placed on the quality of masonry construction when used in filler walls, parapets and other non-load bearing applications (Fattal et al, 1977)

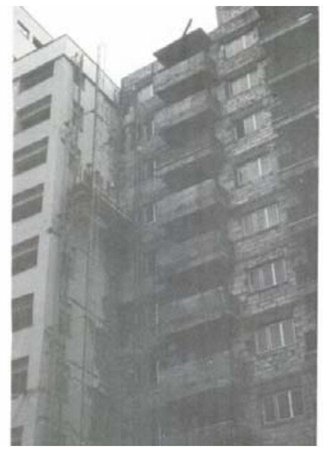


Figure 5. Rear view of building show fig. 4 showing pounding damage including partial collapse of several masonry filler walls and possibly structural damage to a fifth story corner column in the adjacent building (Fattal et al, 1977)

Figure 6. Pounding damage to adjacent buildings (Fattal et al, 1977)

Figure 7. Pounding damage between adjacent buildings (Fattal et al, 1977)

Figure 8. Heavy pounding damage to buildings with adjacent corners. Damage occurred mostly in the frame structure including the rupture of a corner column in the story opposite the top of the next building (Fattal et al, 1977)

Figure 9. Same pounding damage viewed from the opposite side (Fattal et al, 1977)

A frame building located next to a shear wall structure which showed no visible signs of exterior damage; the most severe pounding damage occurred as a result of the collision between taller frame building and a shorter structure having adjacent corners.

In the case of the 1990 Vrancea earthquake, a large 11 -storey apartment block collapsed along the expansion joint/seismic gap, Fig. 10…13 (Pomonis et al, 1990).

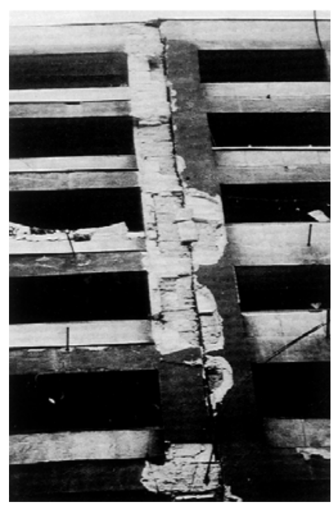


Figure 10. General view of the building Colentina 81, block 84/I, where occurred pounding between two structural parts of this large complex (Pomonis et al, 1990)

Figure 11. Close view of the collapsed plasterboard along the seismic gap line, the apartment building, 1990 Vrancea earthquake (Pomonis et al, 1990)

Figure 12. Colentina district, damage down the seismic gap line, due to pounding (Pomonis et al, 1990)

Figure 13. Damage to the expansion joint in another part of Bucharest (Pomonis et al, 1990)

COMPARISONS OF PROVISIONS RELATED TO THE SEISMIC JOINT (SEPARATION GAP) BETWEEN TWO ADJACENT BUILDINGS

Evolution of the seismic joint/separation gap dimension is followed in all codes for the design of civil and industrial buildings in seismic regions, from 1963, 1970, 1978, 1981, 1992, 2006, 2013, with relevance to the involved effects on the response of an assembly of several adjacent buildings.

In the case of first two design codes, P13-63 and P13-70, in addition to the special recommendations, the need of seismic joints was analyzed case by case, so it would not come to a fragmentation of building in parts with insufficient dimensions to ensure rigidity and resistance to horizontal seismic loads; the separation gap coincided with expansion joints and compaction, or sections of separation between areas with and without basement. In P13-70 there is a relationship for seismic joint size, which takes into account the height of the two adjacent buildings, their fundamental periods, seismic coefficients, resulting higher or equal to 2 cm (P13-63 and P13-70).

P100-78 and P100-81 codes specify clearly the purpose of such seismic joint, which was to separate construction sections with different characteristics (mass, stiffness, height) to allow them to oscillate independently under the action of seismic load. The calculation takes into account the total displacements of the two parts of building/adjacent buildings under the action of horizontal seismic load, at the upper level of part with lower height, resulting also greater than or equal to 2 cm (P100-78 and P100-81).

Furthermore to the provisions of previous legislation, P100-92 code recommends that sections/ buildings that undergo the pounding shock to have an enhanced mass by establishing an additional number of bays. The calculation remains the same. It is accepted a seismic joint less than 2 cm where impact forces are determined or where between those two buildings damping devices are located (P100-92).

P100-2013 retains all provisions of P100-2006, but changes the computing relationship, the seismic joint width being calculated as the square root of the sum of squares of the maximum of two independent structural units under the action of seismic design loads, corresponding to the ultimate limit state, determined at the top level of the building with smaller height (P100-2013).

MODELING OF POUNDING WITH AND WITHOUT CONSIDERATION OF SOIL-STRUCTURE INTERACTION

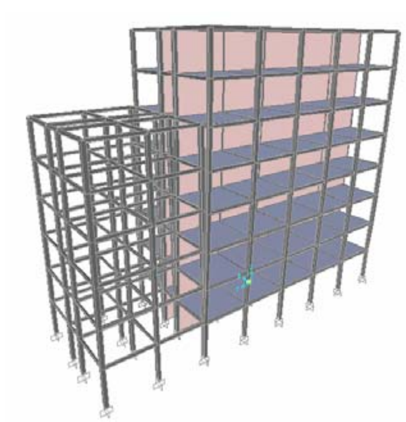
Structural pounding is mainly attributed to the difference in the dynamic properties of adjacent structures (mass, stiffness, and/or strength) and out-of-phase lateral displacements under seismic excitations will result. The impacts occur if these out-of-phase displacements exceed the available separation gap between the structures. The magnitudes of the impact forces and the locations of impacts along the heights of the structures depend on the magnitude of the existing separation gap, the extent of the disparity between the dynamic properties of the impacting structures, and the characteristics of the excitation (Rahman et al, 2000). The properties of the supporting soil must also be taken into consideration due to soil-structure interaction influence on the above aspects.

A parametric study was carried out in order to get the coupled effect of the supporting soil flexibility and pounding between neighboring three dimensional frame models. Pounding is simulated using a Kelvin model for contact element or nonlinear elastic gap elements, a set of springs elements (k_x, k_y, k_z, $k_{\theta x}$, $k_{\theta y}$ $k_{\theta z}$) have been incorporated to simulate the horizontal and rotational movements of the supporting soil, and the models have been excited using Vrancea '77 accelerograms.

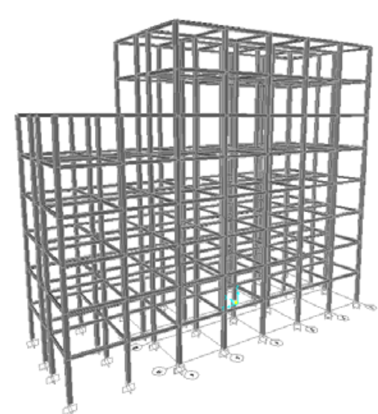
To put into evidence those situations of pounding, when the condition $u_1 - u_2 - g_p > 0$ is satisfied ($u_1 - u_2 - g_p$ is the relative displacement, g_p= gap width between two building models), some displacements for 2 joints at the top of each model were represented according to types of vibration.

Based on the obtained data, the following issues related to the structural response are presented:

- For structures considered at a sufficient distance from each other to avoid pounding, without considering the flexibility of soil, their fundamental periods of vibration are T_{7lev} = 0.67s, with floors and walls, respectively T_{7lev}=0.54s- without floors and walls, and T_{5lev}= 0.42s;
- For structures considered at a sufficient distance from each other to avoid pounding, but considering the flexibility of soil (soil-structure interaction), their fundamental periods of vibration are T_{7lev} = 0.74s, with floors and walls, respectively T_{7lev}=0.54s- without floors and walls, and T_{5lev}= 0.42s;
- The increase/modification of the natural periods of vibration, for these two structures separated by a separation gap of 0.02m, 0.04m, 0.08m, 0.10m, Fig. 14a, b;

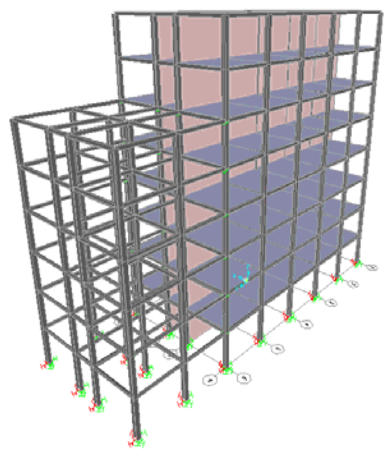


Two frame buildings, A, one of them with floors and walls; T1=0.73s (xz plane), T2=0.39s (yz plane), T3=0.32s (xy plane, torsion), T4=0.28s.

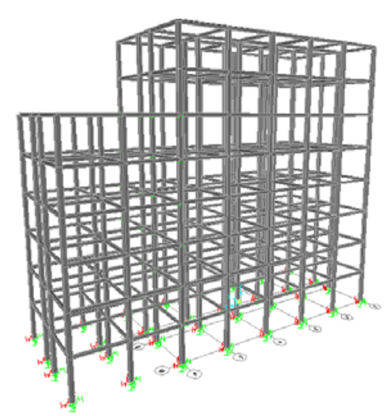


The same two frame buildings, B, but without floors and walls; T1=0.47s (xz plane), T2=0.46s (yz plane), T3=0.38s (xy plane torsion), T4=0.29s.

Figure 14a. Two adjacent buildings (three dimensional frame models), with separation gap of 0.02m, having different dynamic characteristics, with pounding between them (C.S.I. SAP2000 Advanced v14 Structural Analysis Program, Computers and Structures Inc., 2007).



Two frame buildings, A, one of them with floors and walls; T1=0.80s (xz plane), T2=0.38s (yz plane), T3=0.31s (xy plane, torsion), T4=0.23s.



The same two frame buildings, B, but without floors and walls; T1=0.50s (xz plane), T2=0.47s (yz plane), T3=0.41s (xy plane torsion), T4=0.37s.

Figure 14b. Two adjacent buildings (three dimensional frame models), with separation gap of 0.02m, having different dynamic characteristics, with pounding between them and considering the flexibility of soil.

- Variation of T_1 related to different separation gap, Table 2, 3;

Table 2. Variation of T_1, related to different separation gap, for the assembly of two adjacent buildings, one of them with floors and walls (A)

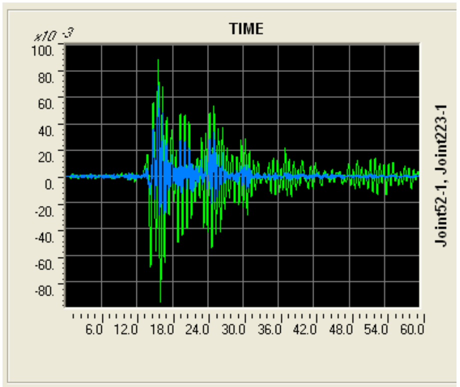
T_1	Separation gap			
	0.02m	0.04m	0.08m	0.10m
without SSI	0.73s	0.70s	0.67s	0.67s
with SSI	0.80s	0.74s	0.73s	0.73s

Table 3. Variation of T_1, related to different separation gap, for the assembly of two adjacent buildings, without floors and walls (B)

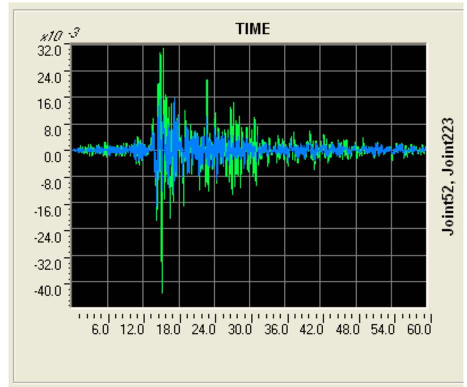
T_1	Separation gap			
	0.02m	0.04m	0.08m	0.10m
without SSI	0.47s	0.46s	0.45s	0.45s
with SSI	0.50s	0.47s	0.46s	0.46s

- Top floor UX displacements, impact forces (from $u_1 - u_2 - g_p$), for different separation gap values, and comparisons with the results obtained for pounding buildings with fixed-base are presented, Fig. 15…19 (52 belongs to the structural model with 7 levels and 223 to the structural model with 5 levels);

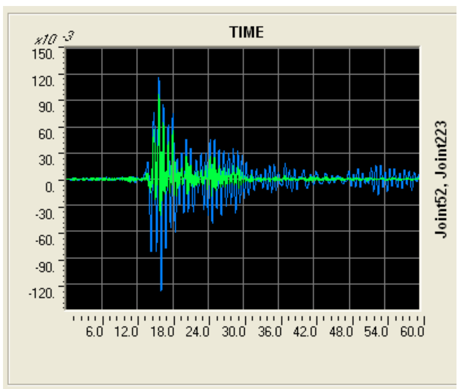
On the left side of Fig. 15, top floor UX displacements, for different separation gap values, for structural model A, are presented, and, analogous, on the right side, top floor UX displacements, for different separation gap values, for structural model B.



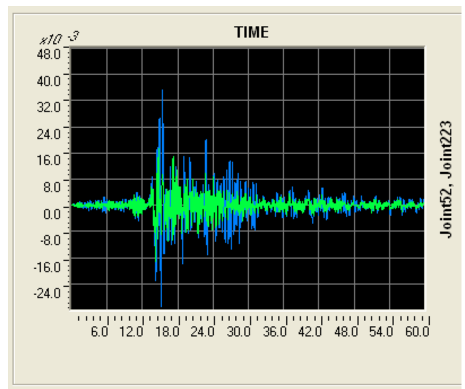
UX displacement (A), max is 8.920e-02 at 1.558e+01
(separation gap 0.02m) without SSI



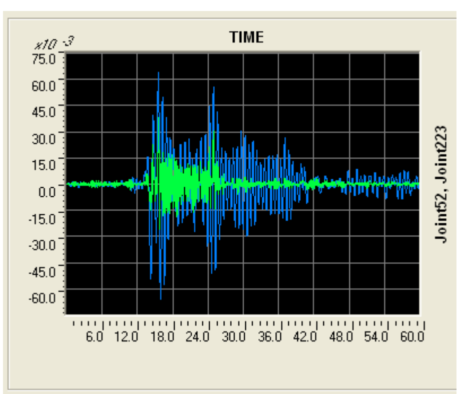
UX displacement (B), max is 3.088e-02 at 1.540e+01
(separation gap 0.02m) without SSI



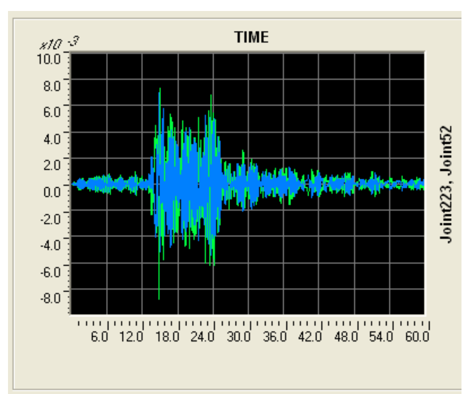
UX displacement (A), max is 1.169e-01 at 1.564e+01
(separation gap 0.02m) with SSI



UX displacement (B), max is 3.525e-02 at 1.542e+01
(separation gap 0.02m) with SSI

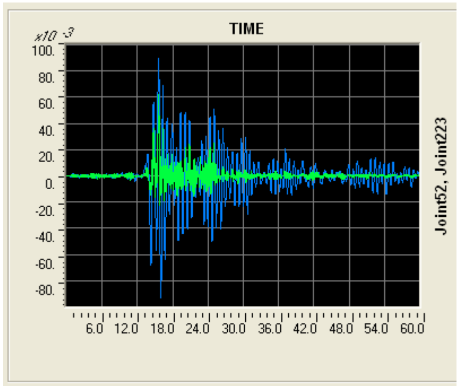


UX displacement (A), max is 6.382e-02 at 1.556e+01
(separation gap 0.04m) without SSI

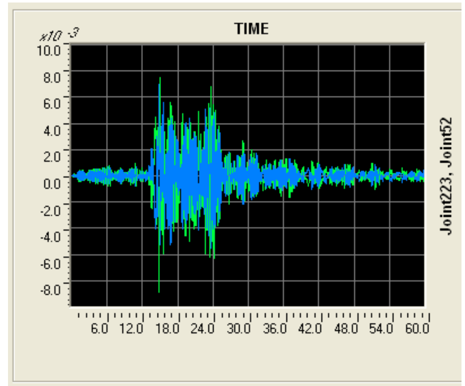


UX displacement (B), max is 7.318e-03 at 1.502e+01
(separation gap 0.04m) without SSI

Figure 15. Top floor UX displacements, for different separation gap values, for structural models A, B (C.S.I. SAP2000 Advanced v14 Structural Analysis Program, Computers and Structures Inc., 2007).



UX displacement (A), max is 8.993e-02 at 1.558e+01 (separation gap 0.04m) with SSI



UX displacement (B), max is 7.473e-03 at 1.502e+01 (separation gap 0.04m) with SSI

Figure 15 (cont). Top floor UX displacements, for different separation gap values, for structural models A, B (C.S.I. SAP2000 Advanced v14 Structural Analysis Program, Computers and Structures Inc., 2007).

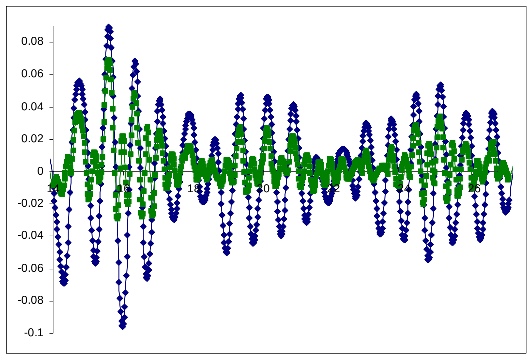


Figure 16. U_1 displacements of 52-223 points (no of collisions between buildings: 25). Frames A, without SSI

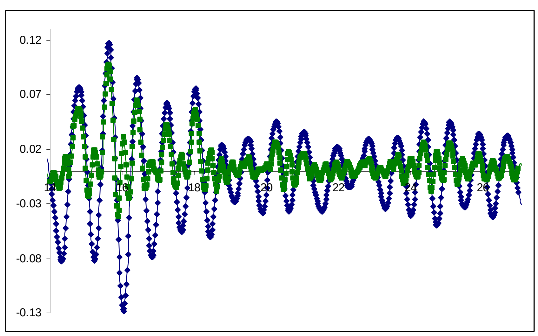


Figure 17. U_1 displacements of 52-223 points (no of collisions between buildings: 50) Frames A, with SSI

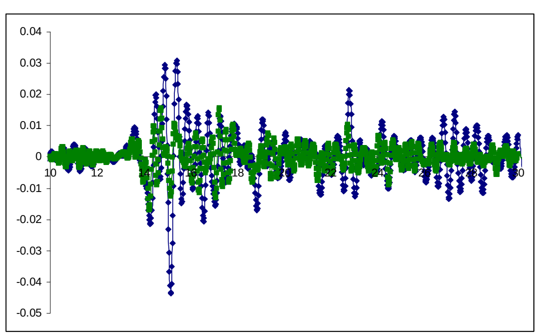


Figure 18. U_1 displacements of 52-223 points (no of collisions between buildings: 13). Frames B, without SSI

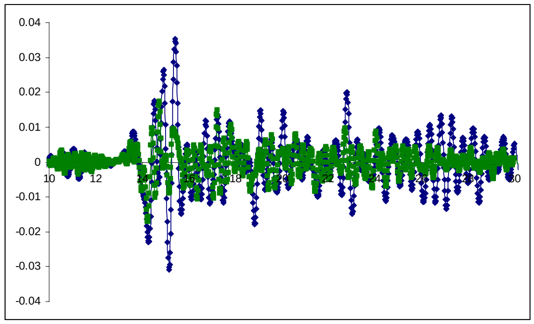


Figure 19. U_1 displacements of 52-223 points (no of collisions between buildings: 16). Frames B, with SSI

- Positive values variation of $u_1 - u_2 - g_p$ and the time interval in which are concentrated pounding situations, Fig. 20, 21 (the ordinate represents UX displacements, the abscissa represents the time interval);

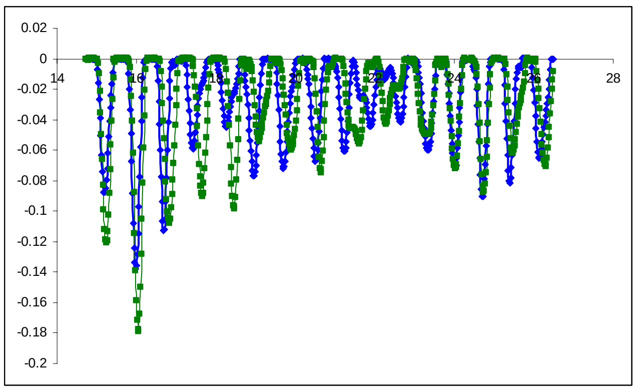


Fig. 20. The frequency of $u_1 - u_2 - g_p > 0$, for frame model A, with floors and walls, without/with considering soil-structure interaction (above the time axis values), and the long period in which are concentrated pounding situations, 14.7s-27s

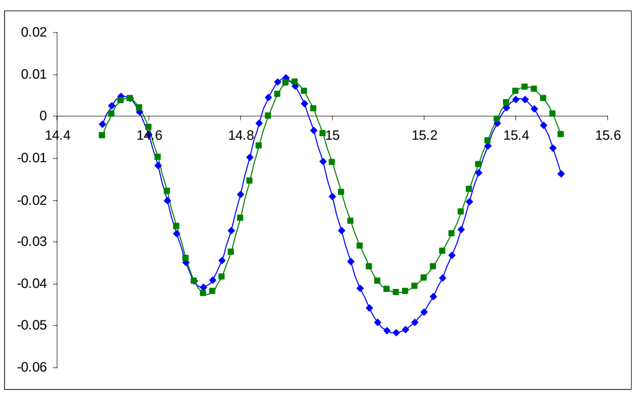


Fig. 21. The frequency of $u_1 - u_2 - g_p > 0$, for frame model B, without floors and walls, without/with considering soil-structure interaction (above the time axis values), and the short period in which are concentrated pounding situations, 14.5s-15.5s

CONCLUSIONS

The effect of pounding between buildings was observed under 1977 and 1990 Vrancea earthquake input and since then the size of the seismic joint was modified (Balan et al, 1982; Berg et al, 1980; Georgescu et al, 1985, 1992, 2002; Georgescu and Radulescu, 1985).

The effects of pounding on dynamic response consist generally in high amplitude, short duration local accelerations, localized degradation of stiffness and strength in impacting columns and beams, the distribution of shear and flexural forces are affected, the amplification or de-amplification of response, high overstresses, increase the displacement at the side opposite to pounding, the gravity and the subsequent P-Δ effect may cause the collapse of the building etc. Also, an increase in the peak displacement response was observed when the gap linking the buildings was very small. Pounding produces acceleration and shear at various story levels that are greater than those obtained from the no pounding case.

For structures having different heights, but with aligned floors levels, the damage is typically concentrated at the top level of the shorter building and at the same level and just above pounding for the taller one. Considering the different separation gaps revealed that the stiffer structures suffer detrimentally whereas the flexible structure benefits. Also, the impact forces decrease as the separation gaps increase.

The effects of nonlinearities, the pounding effects between two adjacent buildings on the behavior of structures can cause both architectural and structural damages. Often, these effects have involved partial or total collapse of buildings, in the context of Vrancea seismicity.

For existing buildings of those generations such impact are likely to repeat during next earthquakes. Besides overall strengthening, that includes a stiffening of structure, a solution to prevent or reduce pounding effects is a target of future studies.

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