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IMPACT OF ADJACENT NON-SYMMETRIC MULTISTORY BUILDINGS AS A SEISMIC RESPONSE

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Abstract

The common situation in towns is existence of so-called "continuous buildings" where buildings are virtually connected, usually on both lateral sides, even though the lateral walls for two buildings are not the same. If the two adjacent buildings were built strictly according to technical building codes, with the appropriate separation gap, their impact would have never happened - they would oscillate during earthquakes independently from each other. However, it is not easy to implement sufficient separation gaps in each case. Hence, in reality, the main aspect of seismic response of two adjacent multistory buildings is their possible impact due to an earthquake. Adjacent buildings, if constructed in accordance with the building codes, in event of an earthquake will oscillate independently. However, if their relevant dynamic characteristics are substantially different and if the separation gap between them is insufficient, the pounding between adjacent floor slabs at the same level is to be expected. The final result of collision between buildings may be a substantial damage, or even worse, their collapse.

The paper is analyzing a possible pounding of adjacent multistory buildings with the same story heights due to the same earthquake excitation with a given dominant direction. Buildings are treated as non-symmetric with respect to their stiffness and/or mass characteristics, so the mathematical model is three-dimensional, i.e. each floor slab is undergoing the planar motion in its plane with three DOFs each.

Possible impact of buildings is analyzed by combination of a direct numerical integration of the corresponding differential equations of motion and the classical analysis of an impact of two rigid bodies in planar motion. In the case of pounding between adjacent slabs the sudden change in kinematic state immediately before and after the collision is determined by solution of the corresponding collision equations. Formulation of the impact equations is based upon the usual assumptions of the impact theory in classical mechanics, with introduction of the coefficient of impact to account the local dissipation of energy in the zone of collision.

Numerical procedure is illustrated by numerical examples. Both cases were considered: the first one when the separation gap is sufficient, so the buildings are oscillating independently and the second one when the separation gap is insufficient, so the pounding between buildings is occurring during the earthquake.

The corresponding computer program is developed in order to perform numerical simulations. Besides determination of the time history of adjacent multistory non-symmetric buildings due to earthquake acceleration with a given dominant direction, including the analysis of the possible pounding, the code may also have the practical application to determine the necessary dilatation gap between buildings in order to prevent the pounding for a given earthquake.

Keywords: pounding between non-symmetric buildings; coefficient of impact; time history analysis; earthquake effect

1. Introduction

Adjacent buildings respond to earthquake excitation independently one from another. However, if their relevant dynamic features are considerably different and if the initial distance between them is insufficient, impact of the two buildings is possible. The issue of the adjacent buildings impact has been given a special attention since the Mexico City Earthquake in 1985 when the pounding of adjacent buildings was the main cause of collapse in many cases [1]. Out of about 330 relatively multi-story buildings that were heavily damaged or demolished during that earthquake, pounding with neighboring buildings occurred in more than 40% of cases, while in 15% of demolition the pounding was direct cause [2].

Analysis of the possible pounding of buildings during earthquake is a rather complicated and still unexplored field of the applied mechanics. Numerical and analytical investigations of that problem are relatively rare. In the essence there are two main approaches to that problem. One is based on the introduction of the special linear visco-elastic impact elements between two adjacent buildings, which are being activated after the contact of the two oscillating masses [3-5]. The stiffness of such impact elements is assumed as relatively high (much higher than the stiffness of the buildings), so the impact forces are being simulated, while the viscous damping is estimated according to evaluation of dissipation of energy during collision, by assuming some correlation with the impact coefficient. In [5] buildings are treated as the equivalent single-degree-of-freedom systems, while in [3] and [4] the buildings are considered as multy-degree-of-freedom systems. In the other approach the conditions of the contact-impact problem between certain parts of neighboring buildings are imposed as restrictions of the differential equations of motion by the Lagrange multiplier method [6]. In all of these papers buildings are treated as symmetric systems, where each slab is performing only a translation with one degree of freedom.

This paper is presenting the analysis of the possible pounding of multi-story non-symmetric buildings in the event of an earthquake. Buildings are treated as three-dimensional systems, where each floor slab is performing the planar motion in its horizontal plane, with three degrees of freedom each (translations u and v and rotation ϕ). Therefore, a building with N stories has 3N degrees of freedom. The approach used here is based upon the approach presented in [7] and [8], where the possible pounding of single-story non-symmetric buildings was analyzed. The possible pounding is analyzed by the combination of direct numerical integration in the time domain step-by-step and the classical impact analysis of the two rigid bodies in planar motion.

2. Possible impact of slabs at the same level of adjacent buildings

In the case of an earthquake, neighboring buildings with the same story heights, built in accordance with technical building codes, will oscillate independently. However, if their relevant dynamic characteristics are substantially different and if the separation gap between them is insufficient, then it is quite possible that pounding between slabs at the same level will occur.

Fig. 1 is presenting two arbitrary slabs A and B at the same level of the two adjacent non-symmetric buildings. In order to describe slab positions during their planar motion the common global (inertial) coordinate system Oxy is adopted, as well as the two material (or local) coordinate systems $S_1\xi_1\eta_1$ and $S_2\xi_2\eta_2$, assumed in the center of mass of each slab. In the initial configuration (prior to the earthquake), axes of local systems are parallel with axes of the global one.

As a consequence of an earthquake, due to sudden beginning of the planar motion of slabs, at any instant of time the slabs A and B may occupy any of the following mutual positions: to be without any contact, to have a contact at a single point or to overlap with certain areas. In the first case there is obviously no impact between slabs. If the contact at a single point of the two slabs is established, it does not necessarily mean the impact has occurred, because a contact at a point is just the necessary, but not the sufficient condition of an impact. Namely, it is possible that the contact at a point has occurred, but in such a way that the velocities of that common point of both slabs are either equal to zero, or with such senses as to indicate the separation of slabs at the next instance, so there is no impact, only connection. If the slabs are overlapping, it means that the impact has already occurred in some previous instant of time that has to be determined.

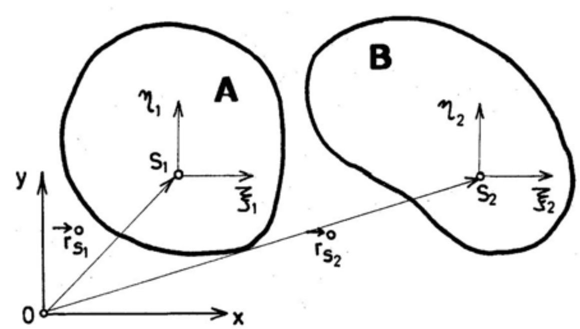
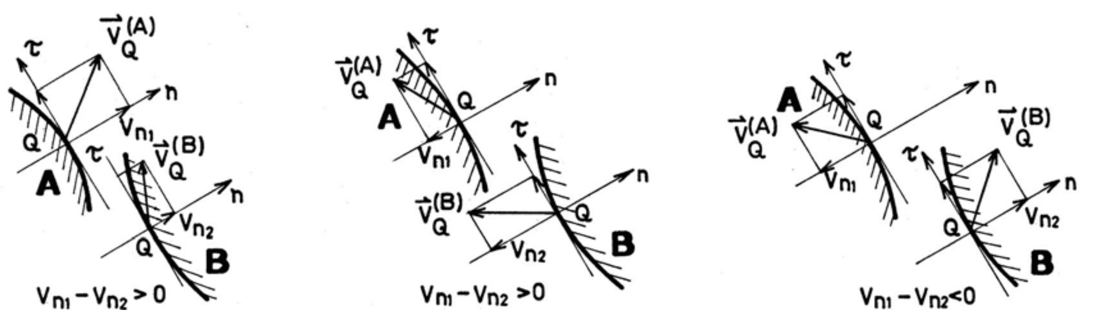


Fig. 1 – Slabs at the same level of adjacent non-symmetric buildings in the initial configuration

2.1 The conditions of impact of two slabs

The necessary and sufficient conditions [8] of impact of the two slabs at some point Q, during their planar motion are formulated as:

- the position condition of impact: the contact of slabs is established at a single point,
- the velocity condition of impact: the difference of projections of velocities of both slabs at the point of contact must be such to indicate the tendency of overlapping of slabs at the next instant of time, Fig. 2 (a, b - tendency of slabs overlapping, c - tendency of slabs separation at the next instant of time).



a) **b)** **c)**

Fig. 2 – The velocity condition of impact

If the vectors $\vec{r}_Q^{(A)}$ and $\vec{r}_Q^{(B)}$, and also $\vec{v}_Q^{(A)}$ and $\vec{v}_Q^{(B)}$, denote the position vectors and the velocity vectors of the point Q of both slabs A and B, expressed with respect to the same inertial (global) coordinate system and if $\vec{n}$ denotes the unit vector of the outward normal with reference to the contour of one of the slabs, then the conditions of impact of slabs may be expressed in the vector form as:

$$\vec{r}_Q^{(A)} - \vec{r}_Q^{(B)} = 0 \qquad (\vec{v}_Q^{(A)} - \vec{v}_Q^{(B)})\vec{n} > 0 \tag{1}$$

or, in the scalar form as:

$$x_Q^{(A)} - x_Q^{(B)} = 0 \qquad y_Q^{(A)} - y_Q^{(B)} = 0 \tag{2}$$

$$v_{n1} - v_{n2} > 0 \tag{3}$$

If $\vec{n}$ is the ort of the outward normal with respect to the contour of slab A at the point Q, then

$$v_{n1} = \vec{v}_Q^{(A)} \cdot \vec{n} \qquad v_{n2} = \vec{v}_Q^{(B)} \cdot \vec{n} \tag{4}$$

and also, if $\vec{n}$ is defined as the outer normal for the contour of the slab B at the point Q, then v_{n1} is referring to slab B and v_{n2} to slab A:

$$v_{n1} = \vec{v}_Q^{(B)} \cdot \vec{n} \qquad v_{n2} = \vec{v}_Q^{(A)} \cdot \vec{n} \tag{5}$$

2.2 Impact analysis of two slabs

According to the usual approach to impact analysis in the classical mechanics, impact between two bodies is the process that happens during infinitely small time interval. Also, all displacements during that infinitely small interval of time are neglected; only the velocity fields of both bodies undergo abrupt change. Internal impact forces are being developed at the points of collision, according to the principle of action and reaction. If the friction between two bodies is neglected, as in the usual approach, then those internal impact forces are acting along the normal direction with respect to tangential plane at the point of impact. Also, the intensity of internal impact forces is infinitely high, so their corresponding impact impulses developed during infinitely small time interval of impact are the quantities of finite values. As opposed to that, impulses of all other "non-impact" forces are infinitely small, due to their finite intensities and infinitely small time interval. The possible friction forces during the impact are neglected, so the impact forces between slabs have the known direction coinciding with the normal to the contour line of the slabs and they are of the opposite senses and equal intensities due to the Law of Action and Reaction.

Fig. 3 presents two separated slabs, with masses m_1 and m_2, during the impact and the corresponding internal impact impulses $\vec{I}_1$ and $\vec{I}_2$ whose line of action is the normal $\vec{n}$ defined with reference to one of the slabs at the point of impact Q. Impact impulses are oriented in such a way that it corresponds to the pressure on the slabs, because impact forces are reaction forces of one-sided restrains, so $\vec{I}_1 = -I\,\vec{n}$ and $\vec{I}_2 = I\,\vec{n}$. It should be noted that all the values immediately before the impact are denoted with (...)', and all the values immediately after the impact with (...)''.

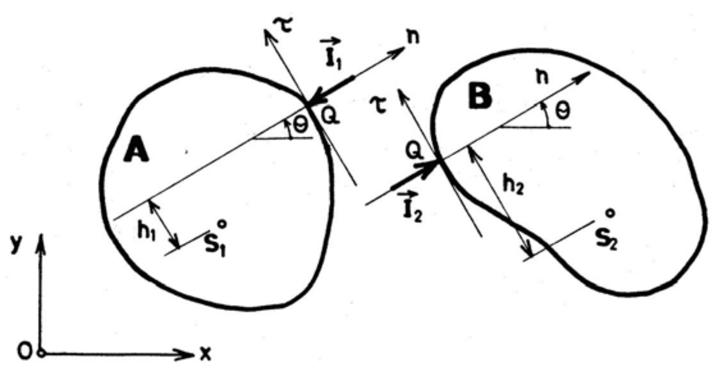


Fig. 3 – Separated slabs during the impact

The process of impact is described by the Law of Momentum and the Law of the Moment of Momentum in the finite forms, written for each separated slab (i=1,2), immediately after and immediately before the impact:

$$\vec{K}_i^{''} - \vec{K}_i^{'} = \vec{I}_i \tag{6}$$

$$\vec{D}_i^{''} - \vec{D}_i^{'} = \vec{H}_i = \vec{r}_i \times \vec{I}_i \qquad \Rightarrow \qquad D_i^{''} - D_i^{'} = H_i \tag{7}$$

where:

- $\vec{K}_i = m_i \cdot \vec{v}_i$ are the vectors of the momentum of the slab *i* (m_i is the mass and $\vec{v}_i$ is the velocity of the center of mass of the slab *i*),

- $D_i = J_{\zeta_i} \cdot \dot{\varphi}_i$ are the vectors of the moment of momentum of the slab *i* (components that are perpendicular to slabs), while J_{ζ_i} is the central mass moment of inertia for the axis perpendicular to slab, and $\dot{\varphi}_i$ is the angular velocity of rotation of the slab around the vertical axis,

- $\vec{I}_i$ are the impact impulses between slabs and

- H_i are the impulse moments with respect to the centers of mass of slabs, i.e. with respect to the central axes perpendicular to slabs ζ_i .

If the Laws (6) and (7) are written for each of the separated slabs in the scalar form, with respect to the global system Oxy, one obtains:

Slab (A):

$$m_1\dot{u}_1^{''} - m_1\dot{u}_1^{'} = -I\cos\theta \tag{8}$$

$$m_1\dot{v}_1^{''} - m_1\dot{v}_1^{'} = -I\sin\theta \tag{9}$$

$$J_{\zeta 1}\dot{\varphi}_1^{''} - J_{\zeta 1}\dot{\varphi}_1^{'} = I\,h_1 \tag{10}$$

Slab (B):

$$m_2\dot{u}_2^{''} - m_2\dot{u}_2^{'} = I\cos\theta \tag{11}$$

$$m_2\dot{v}_2^{''} - m_2\dot{v}_2^{'} = I\sin\theta \tag{12}$$

$$J_{\zeta 2}\dot{\varphi}_2^{''} - J_{\zeta 2}\dot{\varphi}_2^{'} = -I\,h_2 \tag{13}$$

Presented six equations (8)-(13), besides the six unknown generalized velocities immediately after the impact, contain also the seventh unknown quantity, which is the internal impact impulse I. In order to solve this system of equations, the coefficient of impact (or the coefficient of restitution) k is introduced as:

$$k = \frac{\left|v_{n2}^{''} - v_{n1}^{''}\right|}{\left|v_{n1}^{'} - v_{n2}^{'}\right|} \qquad k \in [0,1] \tag{14}$$

where $v_{ni}^{'}$ and $v_{ni}^{''}$ (i=1, 2) represent the components of velocities of points Q of both slabs in direction of the outward normal n immediately before and immediately after the impact. The coefficient of impact is the real number in the interval [0, 1]. The case of k=1 represents the ideally elastic impact where there is no global loss of kinetic energy. The case k=0 represents the ideally plastic impact with the largest loss in the total kinetic energy which is spent for the plastic deformation of the material of both slabs.

Eqs. (8)-(13) may be used to express the unknown generalized velocities of both slabs immediately after the impact as a function of the unknown impact impulse. By introducing these relations into Eq. (14), the unknown impact impulse can be obtained as:

$$I = (1+k)\frac{b}{a} \tag{15}$$

where the coefficients a and b are given by:

$$a = \sum_{i=1}^{2}\left(\frac{1}{m_i} + \frac{h_i^2}{J_{\zeta i}}\right) \tag{16}$$

$$b = v'_{n1} - v'_{n2} \tag{17}$$

It could be established that the coefficients a and b, given by Eqs. (16) and (17), are positive real numbers. It is quite obvious for the coefficient a, which is the sum of positive numbers, and the coefficient b is positive because it represents the velocity condition of impact, given by Eq. (3).

3. Analysis of the possible impact of adjacent buildings during earthquake

Two adjacent multi-story non-symmetric buildings, with different numbers of stories N_1 and N_2 are considered. It is assumed that story heights of both buildings are the same and that both buildings are exposed to the same earthquake excitation, defined by the accelerogram $\ddot{u}_g(t)$. The dominant earthquake direction is defined by the angle β measured in the horizontal plane with respect of the axis x of the global coordinate system.

Differential equations of motion of both buildings are given by:

$$\mathbf{M}_1\ddot{\boldsymbol{\delta}}_1 + \mathbf{C}_1\dot{\boldsymbol{\delta}}_1 + \mathbf{K}_1\boldsymbol{\delta}_1 = -\mathbf{M}_1\mathbf{b}_1\ddot{u}_g(t) = \mathbf{g}_1(t) \tag{18}$$

$$\mathbf{M}_2\ddot{\boldsymbol{\delta}}_2 + \mathbf{C}_2\dot{\boldsymbol{\delta}}_2 + \mathbf{K}_2\boldsymbol{\delta}_2 = -\mathbf{M}_2\mathbf{b}_2\ddot{u}_g(t) = \mathbf{g}_2(t) \tag{19}$$

where $\mathbf{M}_i$, $\mathbf{K}_i$ and $\mathbf{C}_i$ represent the matrices of mass, stiffness and damping, while $\boldsymbol{\delta}_i$ and $\mathbf{g}_i$ represent the vector of generalized displacements and the loading vector for each building.

The process of analysis of the possible pounding of buildings starts by the simultaneous solution of the equations of motion of both buildings using the α method of direct numerical time integration. It means that within the each time interval Δt the equivalent "static" problem is solved at first for one, and then for the other building:

$$\mathbf{K}_i^*\boldsymbol{\delta}_{i,n+1} = \mathbf{g}_{i,n+\alpha}^* \qquad (i=1,\ 2;\ \ n=1,\ 2,...,\ n_{t-1}) \tag{20}$$

where $\mathbf{K}_i^*$ are the effective stiffness matrices and $\mathbf{g}_{i,n+\alpha}^*$ are the effective loading of buildings. By solving the linear algebraic equations Eq. (20) one obtains the vectors of the generalized displacements of both buildings at the end of the considered time interval. With obtained vectors of generalized displacements the vectors of generalized velocities and accelerations for both buildings, at the end of considered time interval, are calculated as:

$$\dot{\boldsymbol{\delta}}_{n+1} = \frac{\gamma}{\beta \Delta t}\boldsymbol{\delta}_{n+1} - \frac{\gamma}{\beta \Delta t}\boldsymbol{\delta}_{n} - \left(\frac{\gamma}{\beta} - 1\right)\dot{\boldsymbol{\delta}}_{n} - \left(\frac{1}{2\beta} - 1\right)\ddot{\boldsymbol{\delta}}_{n} \tag{21}$$

$$\ddot{\boldsymbol{\delta}}_{n+1} = \frac{1}{\beta \Delta t^2}\boldsymbol{\delta}_{n+1} - \frac{1}{\beta \Delta t^2}\boldsymbol{\delta}_{n} - \frac{1}{\beta \Delta t}\dot{\boldsymbol{\delta}}_{n} - \left(\frac{1}{2\beta} - 1\right)\ddot{\boldsymbol{\delta}}_{n} \tag{22}$$

After that, starting with the top floor of the lower building and down to the first floors, the mutual positions of the corresponding slabs at the same level of both buildings is established. It means that using the obtained generalized displacements at the end of the time interval, spatial coordinates of the slab areas for each building are determined, of course, with respect to the same global coordinate system.

If, at the end of considered time interval, not a single pair of neighboring slabs at the same levels is not in a contact, simultaneous solution of differential equations of motion of both buildings is continued for the next time step (or time interval). Of course, obtained vectors of generalized velocities and accelerations at the end of the previous time interval are treated as the initial velocities and accelerations at the beginning of the next time interval.

If, while checking the positions of slabs at the same level, one obtains that a contact at a point is established, then one must check if also the velocity condition of impact is satisfied too, which means that the collision of considered slabs has occurred at the end of considered time interval. Of course, it is also necessary to check if the impact has occurred between any other pair of slabs at the same level, because it is quite possible that impact happens between several pairs of slabs at the same time. In such a case, to all pairs of slabs that are in the condition of impact, instead of velocities obtained according to relation Eq. (21), velocities that are calculated according to the classical collision of two rigid plates in planar motion, as presented by Eqs. (8)-(13), are imposed. Therefore, the generalized velocities of slabs, i.e. velocities of the centers of mass and the angular velocities of slabs, obtained by numerical integration according to relation Eq. (21), are treated as velocities immediately before the impact, while velocities immediately after the impact, which are calculated according to analysis given in section 2, are considered as the initial velocities at the beginning of the next time interval.

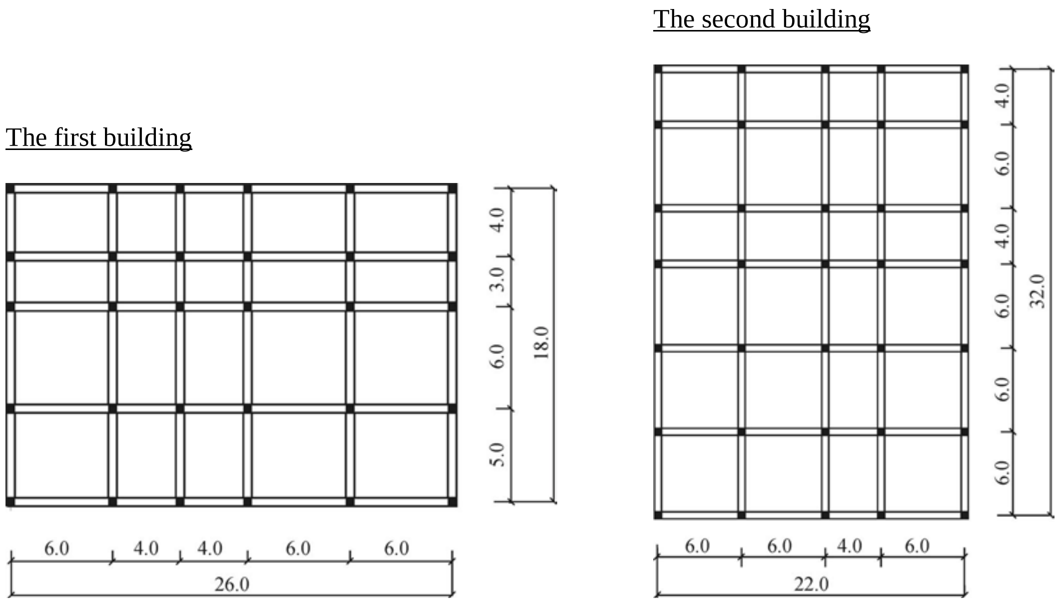
If, during the process of checking the positions of pairs of slabs of the same level, at the end of the time interval, one obtains the situation of interlapping of slab areas, it means that the impact has already occurred sometimes within the considered time interval. In that case, the beginning of previously considered time interval is considered again and the time stepping procedure is done again, but now with the time interval reduced by half with respect to the previous time step, in order to capture the moment of impact just at the end of considered time step. If that is achieved, then it is the previously considered situation of the impact at the end of the time interval, so the impact is considered as previously explained. After the collision analysis for considered (reduced) time interval is performed, the usual simultaneous time integration of both buildings, given by Eq. (20), is done again, but with the originally selected time interval and not with the reduced one as obtained in the case of slabs overlapping.

4. Numerical example

In order to implement presented analysis of the possible pounding of non-symmetric multi-story buildings, the corresponding computer code, called Impact_3D [9], was developed. The code, besides producing the time history response of multi-story non-symmetric buildings due to a given accelerogram, may have also the practical aspect in determination of the necessary separation gaps between neighboring buildings.

As an illustrative example, two neighboring multi-story non-symmetric buildings with seven and ten floors and with the same story heights are considered. The plans of both buildings, with the necessary geometric and mass data, are presented in Fig. 4. Natural periods of the first mode of free vibrations of considered adjacent buildings, using the commercial code Tower 6, are obtained as 0.765s and 1.119s.

Fig. 5 presents the mutual configuration in plan of considered buildings, with d denoting the separation gap between them. Also, adopted coordinate systems are presented: the global system Oxy and the local ones $S_1\xi_1\eta_1$ and $S_2\xi_2\eta_2$, which are assumed in the center of mass of floor slabs, as well as the characteristic points on the contours of both adjacent buildings.



Basic data		First building	Second building
Number of stories: N		7	10
Cross section of columns: b/h [cm]		45/45	50/50
Cross section of beams: b/h [cm]		35/60	35/60
Slab thickness: d_{pl} [cm]		20	22
Modulus of elasticity: E [kN/m^2]		3.15*10^7	3.15*10^7
Story masses:	$m_1=...=m_{N-1}$ [kNs^2/m]	555	845
	m_N [kNs^2/m]	530	810

Fig. 4 – Plan of the neighboring non-symmetric buildings

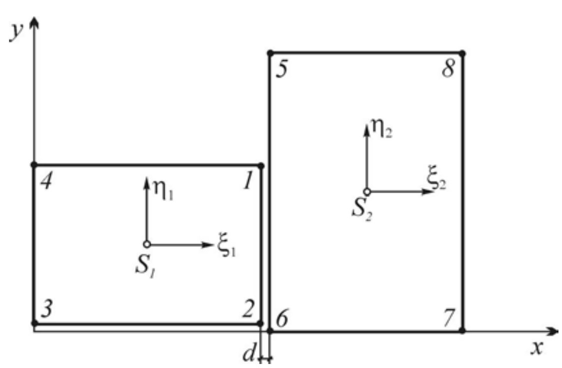


Fig. 5 – Disposition of the characteristic points of the contours of adjacent buildings

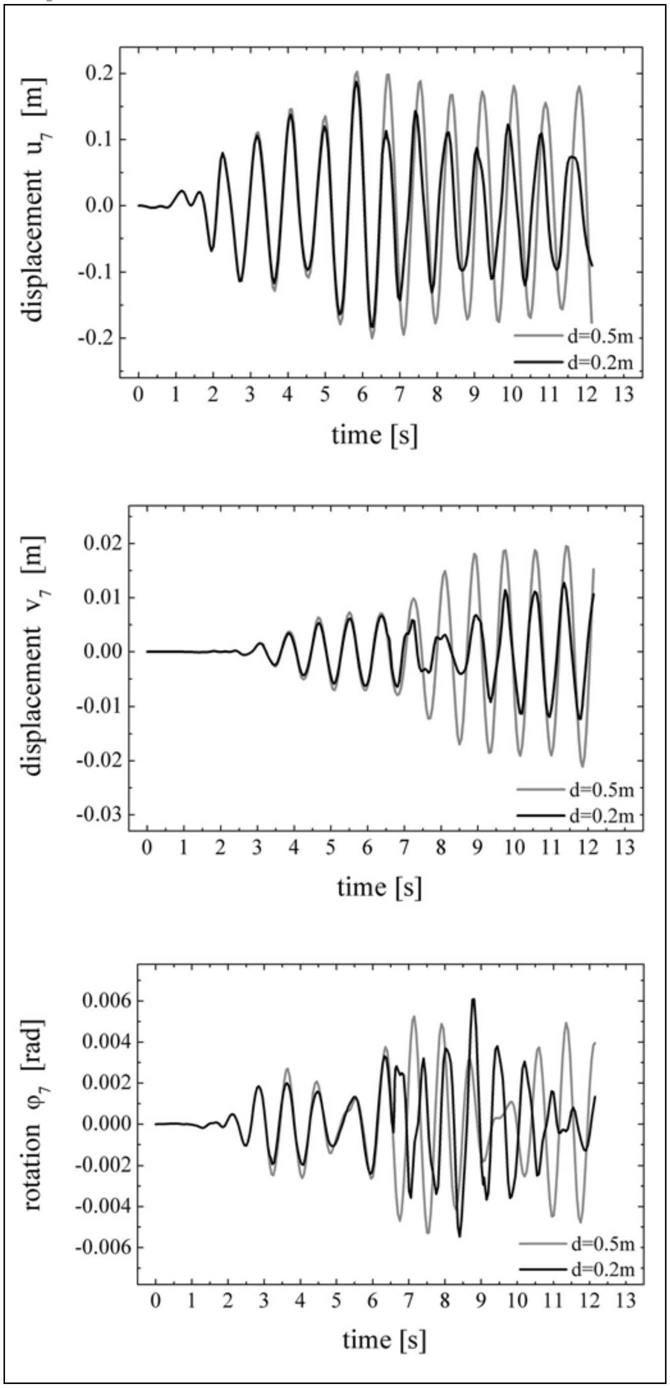
Considered buildings are exposed to the earthquake whose frequency contents corresponds to the El Centro record, from December 1940, direction N-S, with the dominant direction along the x axis ($\beta=0°$). The accelerogram is scaled to the maximum acceleration equal to 0.32g ($g=9.81m/s^2$). Calculations are performed twice: once with the separation gap of more than sufficient value (d=0.5m), so the buildings are oscillating independently during the earthquake, and the second time with the separation gap of smaller value (d=0.2m), so the pounding between slabs during earthquake may occur. In this case, the coefficient of impact is assumed at the value of k=0.5. The time response of buildings was calculated during the complete duration of El Centro earthquake (12.2s) and the adopted time step was $\Delta t=0.05s$.

During the earthquake pounding has occurred 11 times: eight times between slabs at the seventh floor, two times between slabs at the sixth floor and once between slabs at the fifth floor. Also, the contact of slabs of the seventh floor has occurred once, but the pounding did not happen, because the velocity condition at the point of contact was not satisfied at the same time. The first pounding occurred, at the time t=3.1257s, between slabs at the seventh floor, which was to be expected, since the seventh floor is the top floor for the first (lower) building.

Figs. 6-11 are presenting the time response of both buildings, due to considered earthquake excitation, or rather, the time response of their slabs at the seventh floor (which is the top floor for the lower building). The gray line is used for the time history response for the case when the separation distance is sufficient (d=0.5m), so there is no pounding, while the black line represents the second case when the separation gap is insufficient (d=0.2m), so the pounding happened.

The time history response of the generalized coordinates u_7, v_7, φ_7 of the center of mass of the seventh floor for both buildings is presented in Figs. 6 and 7.

In the case of independent oscillations of buildings, i.e. in the case when the separation gap is sufficient (d=0.5m), the maximum displacements of the center of mass of the slab at the seventh floor with respect to axes x and y (i.e. u_{7max} and v_{7max}) for the first building are equal to 20.1cm and 2cm (Fig. 6), and for the second building 16.2cm and 0.9cm (Fig. 7).



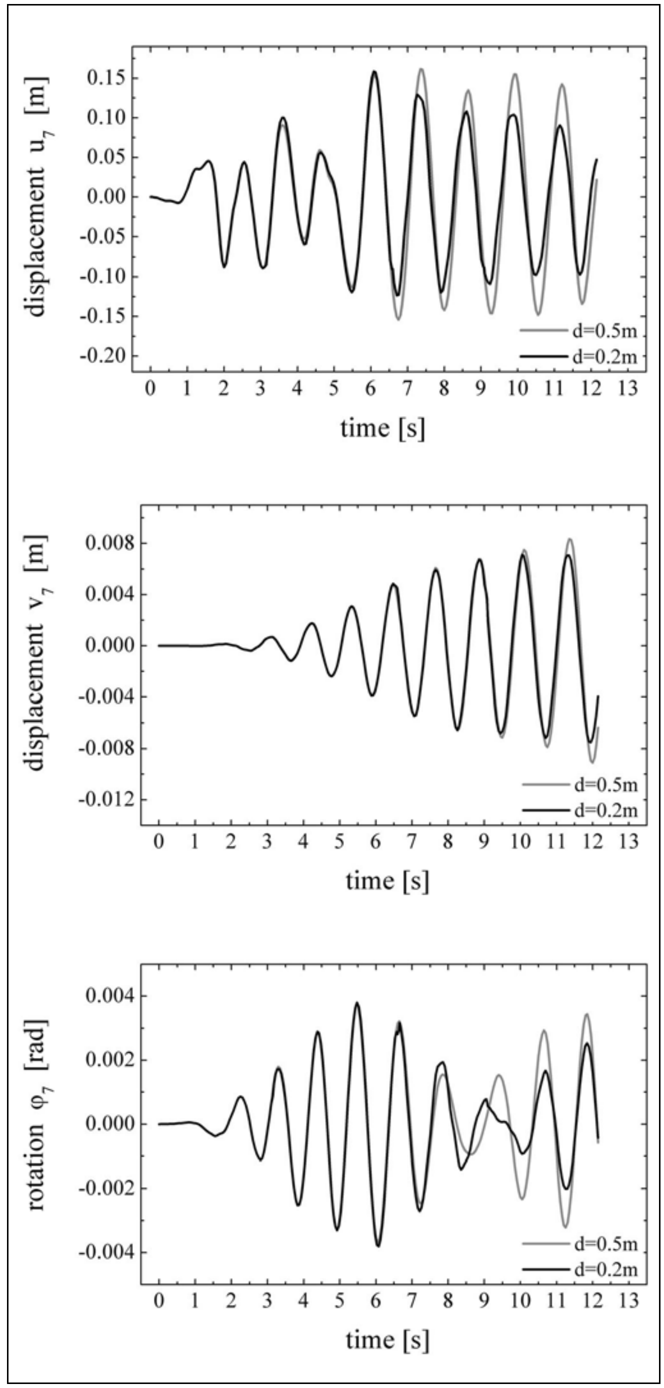


Fig. 6 – Time history of generalized displacements u_7, v_7 and φ_7 of the first building

Fig. 7 – Time history of generalized displacements u_7, v_7 and φ_7 of the second building

Figs. 8 and 9 are presenting the time history response of displacements with respect to x axis (in direction of the accelerogram) of the characteristic points "1" and "2" of the slab 7 of the first building, i.e. $u_7^{"1"}$ and $u_7^{"2"}$, while Figs. 10 and 11 present the time history response of characteristic points "5" and "6" of the slab 7 of the second building, i.e. $u_7^{"5"}$ and $u_7^{"6"}$.

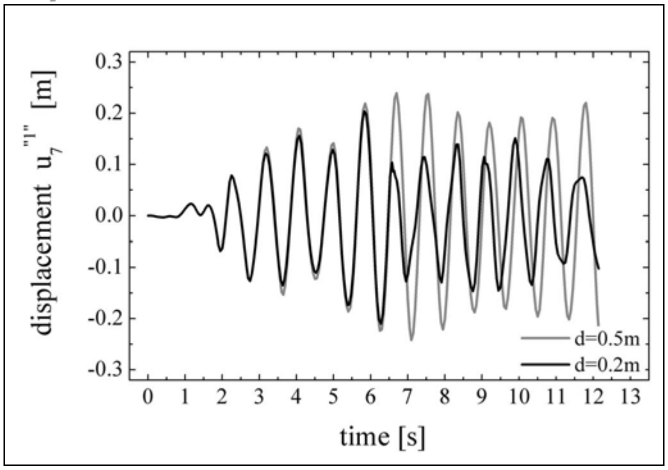


Fig. 8 – The time history response of displacements $u_7^{"1"}$ (the first building)

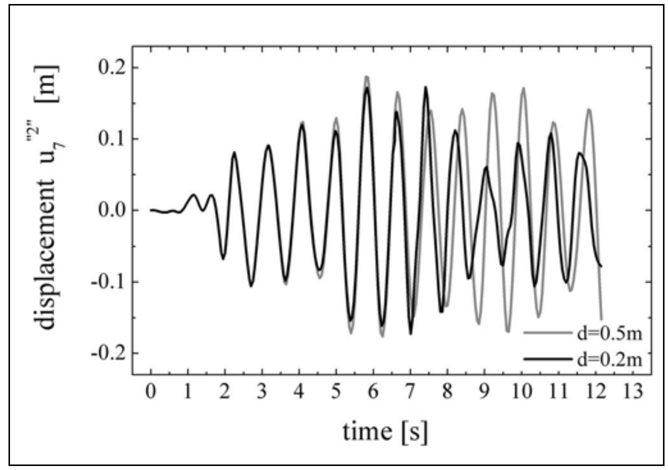


Fig. 9 – The time history response of displacements $u_7^{"2"}$ (the first building)

The maximum displacements of the characteristic points "1" and "2" of the seventh floor slab of the first building in direction of axis x (i.e. $u^{"1"}_{7\,max}$ and $u^{"2"}_{7\,max}$) during the independent oscillations of buildings are equal to 24.2cm and 18.8cm (Figs. 8 and 9).

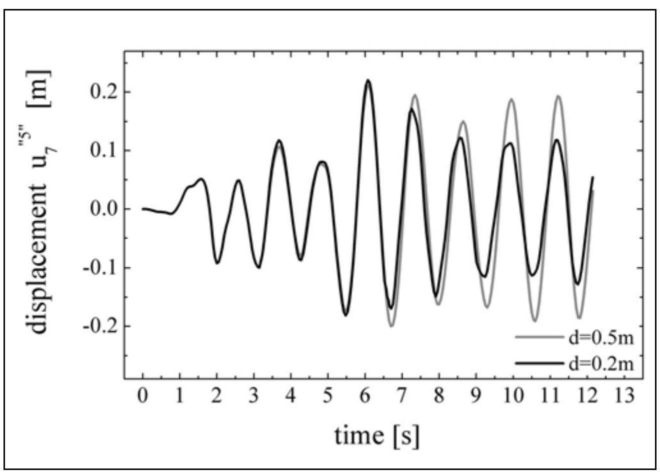


Fig. 10 – The time history response of displacements $u_7^{"5"}$ (the second building)

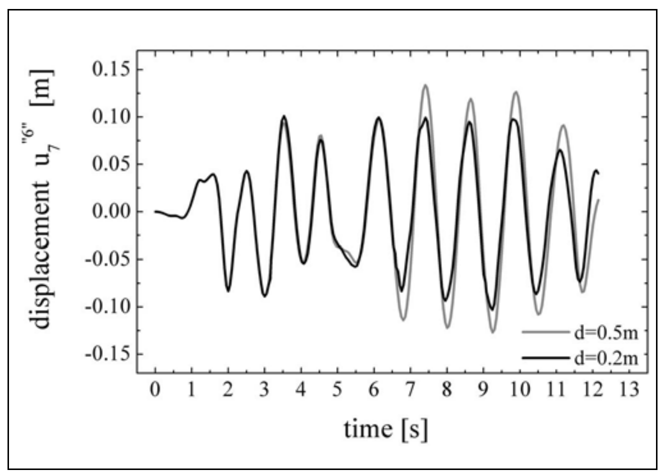


Fig. 11 – The time history response of displacements $u_7^{"6"}$ (the second building)

The maximum displacements of the characteristic points "5" and "6" of the seventh floor slab of the second building in direction of axis x (i.e. $u^{"5"}_{7\,max}$ and $u^{"6"}_{7\,max}$), during the independent oscillations of buildings are equal to 21.2cm and 13.4cm (Figs. 10 and 11).

Having in mind that in the independent oscillations of buildings the maximum values of displacements in direction of x axis for the first building is 20.1cm and 16.2cm for the second building and also that the maximum displacements are occurring about the seventh second (t=6.7 to 7.3s), i.e. in the similar time, one may conclude that for this case the separation gap should be equal to 37cm, in order to prevent pounding. Therefore, the corresponding analyses were also conducted for dilatation gaps of d=35cm and d=37cm, but they are not presented here graphically. In the case when the separation gap was 35cm the pounding of buildings, i.e. slabs of the seventh floor, has occurred two times, namely at times t=6.62s and t=6.72s, while for the case of d=37cm there were no pounding.

5. The final remarks

In accordance with the presented analysis of the possible pounding between buildings with the same story heights during an earthquake, described by the given accelerogram, the corresponding computer program Impact_3D was developed. The code, besides producing the time history response of multi-story non-symmetric buildings due to a given accelerogram, may have also the practical aspect in determination of the necessary separation gaps between neighboring buildings.

In order to illustrate the numerical procedure two neighboring multi-story non-symmetric building of the same story heights, with seven and ten floors are considered (Fig. 7). The time history responses of considered buildings, due to the same earthquake excitation (given accelerogram of El Centro earthquake, from December 1940, component N-S) for the dominant direction in the x axis, $\beta=0°$. Two cases were considered, the first one when the separation gap is sufficient, so the building are oscillating independently, and the second one when the separation gap is insufficient, so the pounding between buildings (i.e. between slabs at the same level) during earthquake is occurring (Figs. 6-11). Also, the minimum possible separation gap is determined in order to prevent pounding in the case of considered buildings due to the given earthquake.

After the analysis of conducted numerical examples one may conclude that the time response of adjacent non-symmetric buildings and the necessary separation gap between buildings depend on the configuration of buildings, their dynamic properties (stiffness and mass distributions) and also on the nature of considered earthquake. It means on the given accelerogram (its frequency content and the maximum acceleration) and the dominant direction of the soil movement, and also on the value of the coefficient of impact, i.e. on the local dissipation of energy in the zone of impact.

5. References

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