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STUDY OF NON-LINEAR OSCILLATIONS OF THE HIGH-RISE BUILDINGS

Annotation. *Seismic calculations are based on the hypothesis that maximum seismic horizontal displacements of inelastic systems are equal to displacements of elastic systems of equivalent frequencies.*
Analysis of strong earthquakes of recent years (San Francisco, USA, 1971, Spitak, Armenia, 1988, Kobe, Japan, 1995 and others) led scientists to the conclusion that this hypothesis cannot be recognized as acceptable. In a number of cases, the maximum horizontal displacements turned out to be 2–3 orders of magnitude higher than the maximum displacements of elastic systems. For example, a displacement graph based on the 1985 Mexico City earthquake shows that the actual plastic displacements are 100 times the expected plastic displacements. In the case of other earthquakes, there are hundreds of subtle inconsistencies. The quantitative results concluded that the intensity of building vibrations exceeded 1.5 times the 9-point design seismic intensity ÷2.5 and that a special approach, including the need to consider impact effects, is needed and is particularly serious in such zones. This should also be taken into account. Inelastic deformations are indicated. The new calculation is used to study non-linear oscillations caused by impulsive actions of a continuous system. In the case of elastic vibration, changing the mass gives very different results. Reducing the lower mass by a factor of 3 reduces the displacement by a factor of ≈2.2 for the upper mass and ≈2.4 for the second mass. The same impact was applied to a 16-story building and the stiffness distribution of the rods was studied in different ways. The stiffness was constant everywhere, constant within 4 stories, where it varied linearly and parabolically with height. Displacements during the course of the pulse shock were greater in the stiffer buildings. Furthermore, the vibration decreases in amplitude by a factor of 3 or more for the upper mass and by a factor of 4 for the lower mass. The force on the upper rod is reduced by a factor of 4 and the force on the lower rod is reduced by a factor of 6. This will make it possible to perform calculations for a small time scale, which is necessary to take into account high-frequency oscillations that occur in the epicentric zone.
Keywords: *building; seismic; epicenter zone; impact depends; discrete-continual system.*

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Introduction

It is known that the nature of seismic impact depends on the distance from the epicenter zone. Ground displacements are of pulsed nature in the direct vicinity of the epicenter zone [1, 2]. Provide analysis of both, the case of impacting the building located directly at the fissure area and the records of locations near the joint fissure: Taiwan, Kobe, Loma Prieta, Northridge and Whittier (USA).

On the basis of the analysis the conclusion was made that in quantitative respect, intensity of the building oscillation exceeds 1.5÷2.5 times the intensity provided 9-point design seismicity pointing to the fact that in such zones construction requires special approach, including necessity of taking into consideration of the shock effect and this is particularly severe in such zones.

It should also be taken into consideration that the recommendations for design of the high-rise buildings emphasize necessity of calculation of non-elastic deformations and their restriction.

Thus, the issue is provision for non-elastic work of the building structures caused by shock effect in the high-rise buildings.

Work provides consideration of the issue of study of non-linear oscillations of the carcass building as discrete-continual system, where the building is exposed to the pulsed displacement of the ground and the rods binding the localized masses work only for shift, according to Prandtl scheme.

Study area and methods

Let us consider oscillation of several masses resulting from horizontal pulse YF shift of the ground (Fig. 1).

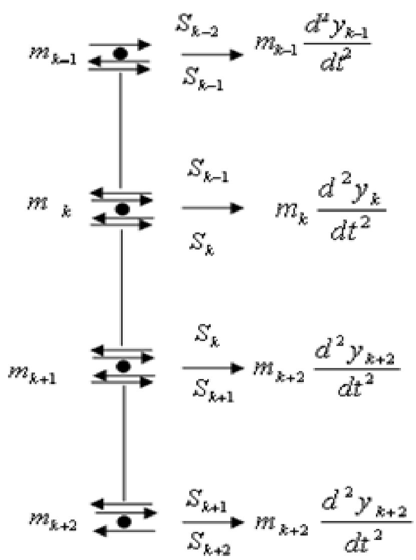

Fig. 1

At the same time, let us assume that S force is applied to the center of gravity of the mass. Hence, movement of the mass is conditioned by S force only, being the counteraction of the rod, which, depending on the condition of the rod (elastic or plastic), could depend on linear displacement of the rod end (in case of elastic condition) or any unknown relationship (in case of plastic condition) S = F(y). Let us divide oscillation time into small Δt sections and assume that S is constant in each section, i.e. $S = \sum S_i$ [3, 4]. Let us take any m_k mass. Differential equation of its movement will be:

$$m_k \frac{d^2 y_k}{dt^2} + S_{k-1} - S_k = 0 \ .$$

If we present each of the forces in a form of sum:

$$S_k = \sum_{i=1}^{I-1} S_{k,i} \ ,$$

and integrate with zero initial conditions, we shall obtain:

$$y_k = -\sum_{i=1}^{I} \frac{\left(t_I - t_{j-1}\right)^2}{2m_k} S_{k-1,i} + \sum_{i=1}^{I} \frac{\left(t_I - t_{j-1}\right)^2}{2m_k} S_{k,i} \ .$$

As we have noted earlier, the rod works only in case of shift and therefore, elastic displacement of its end, taking into consideration the shear deformation, will be $\frac{Sl}{GF}$, where G is the displacement modulus and F – rod crosssection. It is clear that in the oscillation process, where S achieves its limiting value S_L (Fig. 1), the rod end will have maximal elastic displacement $\frac{S_{L.} l}{GF}$ and some more plastic displacement Δ_{Pl}.

Condition of continuity between m_k and m_{k+1} masses, for the first section Δt, could be recorded as follows:

$$-S_{k-1,1}\frac{\Delta t^2}{2m_k} + \left(\frac{\Delta t^2}{2m_k} + \frac{\Delta t^2}{2m_{k+1}} + \frac{l}{GF}\right) S_{k,1} - S_{k+1,1}\frac{\Delta t^2}{2m_{k+1}} = 0 \ .$$

For the second step:

$$-S_{k-1,2}\frac{\Delta t^2}{2m_k} - S_{k-1,1}\frac{(2\Delta t)^2}{2m_k} + \left(\frac{\Delta t^2}{2m_k} + \frac{\Delta t^2}{2m_{k+1}} + \frac{l}{GF}\right) S_{k,2} + \left[\frac{(2\Delta t)^2}{2m_k} + \frac{(2\Delta t)^2}{2m_{k+1}} + \frac{l}{GF}\right] S_{k,1} -$$
$$-S_{k+1,2}\frac{\Delta t^2}{2m_{k+1}} - S_{k+1,1}\frac{(2\Delta t)^2}{2m_{k+1}} = 0$$

For any I step:

$$-S_{k-1,I}\frac{\Delta t^2}{2m_k} - \sum_{i=1}^{I-1} S_{k-1,i}\frac{\left(t_I - t_{i-1}\right)^2}{2m_k} + S_{k,I}\left[\Delta t^2\left(\frac{1}{2m_k} + \frac{1}{2m_{k+1}}\right) + \frac{l}{GF}\right] +$$
$$+\sum_{i=1}^{I-1} S_{k,I}\left[\left(t_I - t_{i-1}\right)^2\left(\frac{1}{2m_k} + \frac{1}{2m_{k+1}}\right) + \frac{l}{GF}\right] - S_{k+1,I}\frac{\Delta t^2}{2m_{k+1}} - \sum_{i=1}^{I-1} S_{k+1,i}\frac{\left(t_I - t_{i-1}\right)^2}{2m_{k+1}} = 0$$

This expression is valid if the rod is elastic but if it is in the plastic condition, the following component will be added:

$$\Delta_{k,Pl} = \Delta_{k,I} + \sum_{i=1}^{I-1} \Delta_{k,i} \ .$$

If we add and move to the left side only the components containing $S_{k,I}$ and $\Delta_{k,I}$, we obtain:

$$S_{k,I}\left[\Delta t^2\left(\frac{1}{2m_k}+\frac{1}{2m_{k+1}}\right)+\frac{l}{GF}\right]+\Delta_{k,I} = \sum_{i=1}^{I} S_{k-1,I}\,\frac{\left(t_I - t_{i-1}\right)^2}{2m_k} -$$
$$-\sum_{i=1}^{I-1} S_{k,I}\left[\left(t_I - t_{i-1}\right)^2\left(\frac{1}{2m_k}+\frac{1}{2m_{k+1}}\right)+\frac{l}{GF}\right]+\sum_{i=1}^{I-1} S_{k+1,i}\,\frac{\left(t_I - t_{i-1}\right)^2}{2m_{k+1}} - \sum_{i=1}^{I-1}\Delta_{k,i} \ .$$

Taking the following designations into consideration:

$$tl_1(n) = \frac{\left(n\times\Delta t\right)^2}{2m_1} + \frac{\left(n\times\Delta t\right)^2}{2m_2} + \frac{l_1}{GF}, \quad tl_2(n) = \frac{(n\Delta t)^2}{2m_2} + \frac{l}{GF},$$

$$Dlm(n) = tm_2(n)\cdot S_{21} + tm_2(n-1)S_{22} + ... + tm_2(2)S_{2,n-1} - tl_1(n)S_{11} - tl_1(n-1)S_{12} - .... - tl_1(2)S_{1,n-1}$$

$$Tlm(n) = YF(n) + tm_2(n)S_{11} + tm_2(n-1)S_{12} + ... + tm_2(2)S_{1,n-1} - tl_2(n)S_{21} - tl_2(n-1)S_{22} - .... - tl_2(2)S_{2,n-1}$$

$$tm_2(n) = \frac{(n\Delta t)^2}{2m_2}, \ \ tm_1(n) = \frac{(n\Delta t)^2}{2m_1}, \ \mathrm{FL{=}l/GF}\ .$$

We shall have:

$$S_{k,I}\left[tm_k(1) + tm_{k+1}(1) + FL\right] + \Delta_{k,I} = S_{k-1,1}tm_k(I) + S_{k-1,2}tm_k(I-1) + \ldots + S_{k-1,I}tm_k(1) -$$
$$- S_{k,1}\left[tm_k(I) + tm_{k+1}(I) + FL\right] - S_{k,2}\left[tm_k(I-1) + tm_{k+1}(I-1) + FL\right] - \ldots -$$
$$- S_{k,I-1}\left[tm_k(2) + tm_{k+1}(2) + FL\right] + S_{k+1,1}tm_k(I) + S_{k+1,2}tm_{k+1}(I-1) + \ldots +$$
$$+ S_{k+1,I}tm_{k+1}(1) - \sum_{i=1}^{I-1}\Delta_{k,i}$$

Equation recorded for the lower rod will contain additionally the ground displacement *YF*.

Obtained system of equations could be solved by the method of sequential approximations. For each *DT* interval, in the right side, we give some (zero) values to the values subject to calculation and compare with the values of previous approximation, when the difference falls below the required accuracy, we move to the following time interval. At the same time, for each interval, each rod there is checked whether the obtained force exceeds its limiting value. If it exceeds, than the force increment is assumed to be zero and instead, the plastic displacement is calculated by means of the above formulas.

Calculation results

Calculations were made to study non-linear oscillations of the structures where as the bearing structures of the building, at each level, the metal piles located with 6 m intervals are used in both directions [6–10]. The piles are made of two N20A channel bars, covered with 20x20 m reinforced concrete slab of 16 cm thickness. Height of the piles is 4 m, displacement yield point τ_s =1600 kg/cm^2, aggregate crosssection of the channel bars is 800 cm^2, and weight of the reinforced concrete slab is 15.000 kg. As a result of the earthquake the base of the building is subject to pulsed displacement $W = ate^{-\beta t}$, where a is initial velocity and $\frac{1}{\beta}$ time, when displacement is maximum.

Calculations are made for two-, five- and sixteen-storey buildings.

In case of two-storey buildings, the effect of change of the masses on the values of elastic and plastic displacement, as well as the values of the caused forces is studied (Fig. 2, 3).

a = 25
β = 8

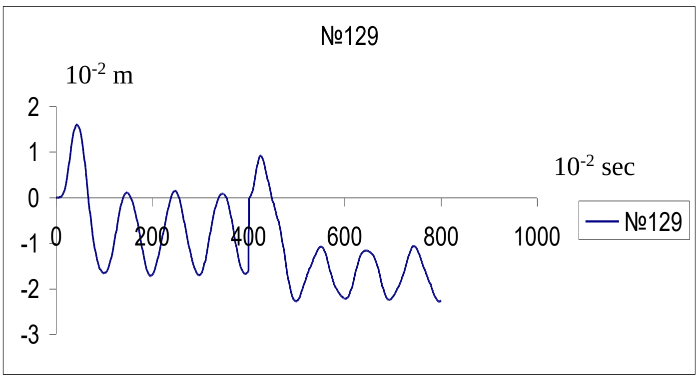

Fig. 2. Displacements of the elastic-plastic system

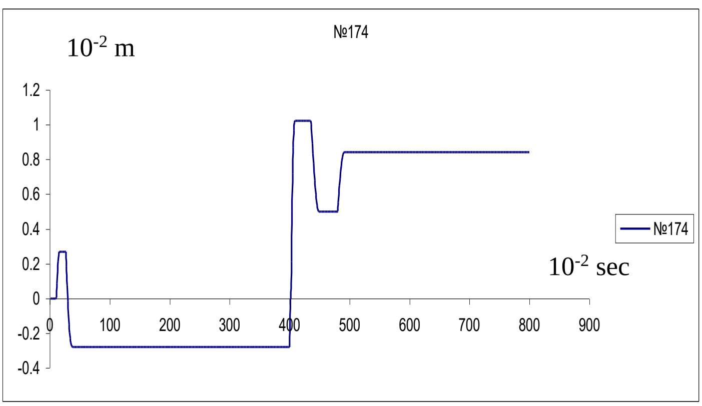

Fig. 3. Plastic displacements

In case of five-storey building, effect of the repeated pulse is studied (Fig. 4, 5).

In case of sixteen-storey building, effect of change of the stiffness with height on the elastic-plastic displacements and force values is studied (Fig. 6 and 7).

Fig. 6 shows the building with the constant stiffness for whole height, while Fig. 7 shows the one with the stiffnesses constant within four storeys, decreasing from bottom to top. Note, that in case of two-mass system, the oscillations of the upper mass commences on the abscissa, point 0, while lower mass – from the point 400. Drawings for five and sixteen points were developed in the similar way.

a = 50
β = 8

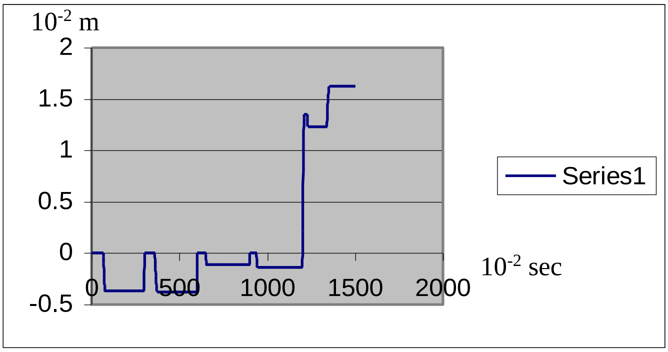

Fig. 4. Plastic displacements in case of five storeys

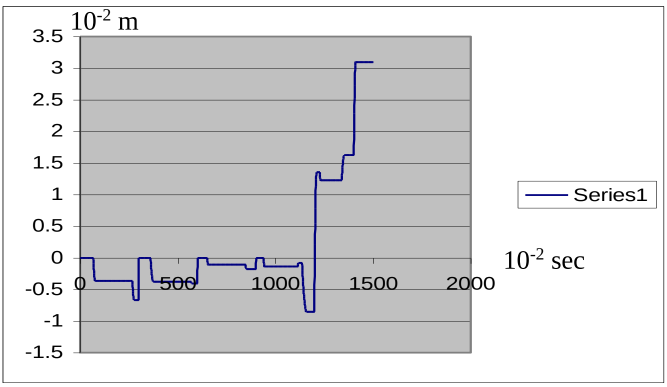

Fig. 5. Plastic displacements for repeated pulse

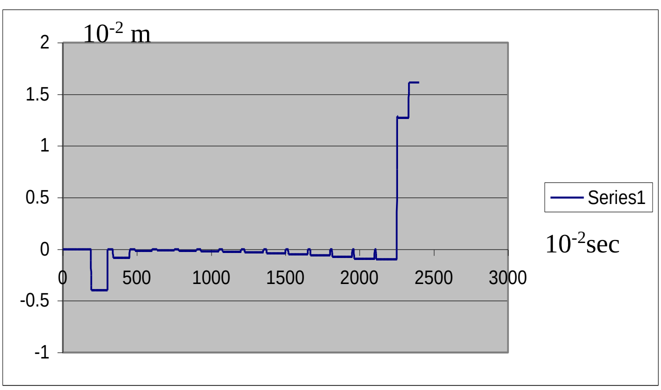

Fig. 6. Plastic displacements for constant system

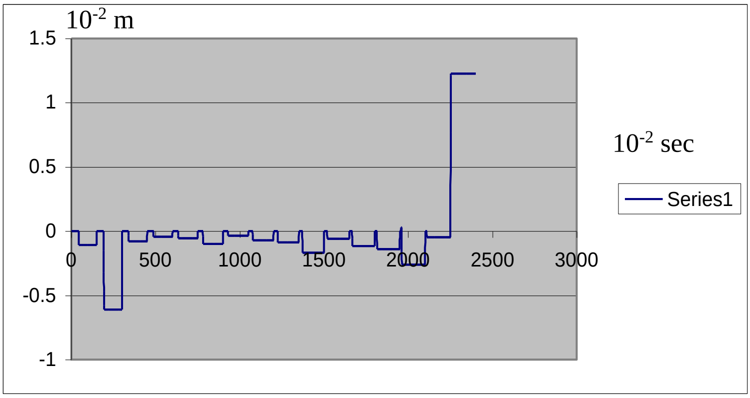

Fig. 7. Plastic systemns for variable system

Conclusions

1. In case of pulse impact, the displacements of the elastic-plastic system are smaller than the ones of elastic oscillations (where there is no plastic section) [5].

2. In case of elastic-plastic system, after completion of the impact oscillation takes place in relation to the residual plastic displacement.

3. In case of pulse impact one and the same acceleration may be caused by different velocities and values of displacement and force correspond to them. Hence, in the area adjacent to the joint fissure, where the impact is of pulsed nature and it would be reasonable to take velocity for seismic zoning, rather than acceleration.

4. In case of the repeated shock, depending on the moment of oscillation when the repeated shock takes place, the results will be different. Given physical laws, applicable to the material, the force cannot exceed the limiting value, while it can decrease significantly. In case of unrestricted displacement they can increase significantly.

5. In case of two-mass system, decrease of the lower mass three times caused insignificant change of displacement of the upper mass, while it reduced plastic displacement almost three times, where oscillations continue. Displacement of the lower mass increased by ≈30% and plastic displacement reduced almost two times. In case of reduction of the upper mass three times the displacement increases almost three times for both masses.

In case of elastic oscillations, change of the masses provides substantially different results. Decrease of lower mass three times causes reduction of displacement ≈2.2 times for the upper mass and ≈2.4 for the second mass. Further oscillation is with the amplitude decreased three and more times for the upper mass, while for the lower mass, amplitude decreases 4 times. Forces in the upper rod decrease 4 times, while in the lower one – 6 times.

Decrease of the upper mass three times, at a time of pulse impact, the maximal amplitude decreases three times for the upper mass and 2 times – for the lower mass. Further oscillation takes place with the four times decreased amplitude for the first mass and five times decreased amplitude for the second one. Force in the upper rod decreases approximately two times and four times in the lower one.

6. In case of five-storey building, where $\alpha = 50$ and $\beta = 8$, in all five rods there are plastic displacements. Maximal displacement is in the lower rod (1.62 cm), in two upper ones – much lower (0.37 cm) and even lower in the third and fourth rods (0.11 and 0.14 cm). Maximal displacements in three lower rods are almost equal (2.3 cm) and slightly lower in the upper two rods (1.9 and 1.8 cm).

Comparison of these values with the elastic oscillations provides dramatically different results. Maximal displacements are in two upper rods and they are two times greater than for the elastic-plastic displacements.

7. Repeated pulse impact is much more significant for the elastic oscillations, compared with the elastic-plastic ones.

8. Sixteen-storey building was studied for the same impact, with different stiffness distributions of the rods. Where stiffness is constant everywhere, constant within four storeys and changes with height linearly and parabolically. Displacement in the process of pulse impact process was greater in the buildings with higher stiffness.

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ДОСЛІДЖЕННЯ НЕЛІНІЙНИХ КОЛИВАНЬ ВИСОТНИХ БУДІВЕЛЬ

Анотація. Сейсмічні розрахунки базуються на гіпотезі про те, що максимальні сейсмічні горизонтальні переміщення непружних систем дорівнюють переміщенням пружних систем з еквівалентною частотою. Аналіз сильних землетрусів останніх років (Сан-Франциско, США, 1971 р., Спітак, Вірменія, 1988 р., Кобе, Японія, 1995 р. та інші) привів вчених до висновку, що цю гіпотезу не можна визнати прийнятною. У ряді випадків максимальні горизонтальні переміщення виявлялися на 2–3 порядки вищими за максимальні переміщення пружних систем. Наприклад, графік переміщення, заснований на землетрусі в Мехіко 1985 року, показує, що фактичні пластичні зміщення в 100 разів перевищують прогнозовані пластичні зміщення. У випадку інших землетрусів також присутні сотні невідповідностей. За кількісними результатами статті було зроблено висновок, що інтенсивність коливань будівлі в 1,5 раза перевищила 9-бальну проектну сейсмічну інтенсивність ÷2.5 і що в таких випадках потрібен особливий підхід до прогнозування, що включає необхідність врахування ударних впливів. На це також треба звернути увагу. Були враховані непружні деформації. Новий розрахунок використовується для дослідження нелінійних коливань, викликаних імпульсними діями безперервної дії. У випадку пружних коливань зміна маси дає зовсім інші результати. Зменшення нижньої маси загалом в 3 рази зменшує переміщення (в 2,2 – для верхньої будови і 2,4 – для нижньої будови, відповідно). Такий самий вплив було застосовано до 16-поверхового будинку, де розподіл жорсткості стрижнів було досліджено різними способами. Жорсткість була постійною всюди в межах перших 4 поверхів, а далі вона змінювалася лінійно та параболічно з висотою. Зміщення під час імпульсного удару були більшими в більш жорстких будівлях. Крім того, амплітуда вібрації зменшується в 3 або більше разів для верхньої будови та в 4 рази для нижньої будови. Зусилля на верхньому стрижні зменшується в 4 рази, а на нижньому стрижні – в 6 разів. Це дає можливість виконувати розрахунки для малого масштабу часу, який необхідний для врахування високих частот коливань, що виникають в зоні епіцентру землетрусу.

Ключові слова: будівля; сейсміка; зона епіцентру землетрусу; залежність від дії; дискретно-континуальна система.

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