Features of the buildings’ seismic isolation systems under strong seismic influences with predominant long periods

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Abstract. Real earthquake records differ from each other in a number of spectral parameters, the main one of which is the prevailing oscillations period. It usually varies over a wide range. This work is devoted to the study of the seismic isolation systems’ sensitivity with a sliding foundation belt, kinematic supports and rubber-metal supports to the prevailing period of strong seismic impact. The studies were conducted on the example of a 5-story building with a rigid structural solution with seismic isolation in the foundation part. Seismic impact is presented as a synthesized accelerogram. The main attention is paid to the maximum movement of the building at the seismic isolating supports’ top level, which in reality is limited based on the supports stability and (or) the utility networks safety in the building. The seismic reaction dynamic calculations’ results of the systems under consideration are presented. It is shown that seismic isolation systems with an increase in the predominant period of seismic impact of 9-point intensity lose their advantage and the maximum displacement of the building with long-period influences becomes unacceptably large.

Introduction

It is known that, along with accelerations, the buildings foundations soil seismic oscillations’ prevailing periods have a significant effect on the seismic reaction of buildings. If they are equal or close to the periods of natural buildings oscillations, then dangerous resonant oscillations cannot be avoided. Prevailing periods of seismic impacts \( (T_j) \) can vary over a wide range from 0.1 s to 2.0 s and more. The periods of buildings and structures’ natural oscillations are in the same range. If the buildings oscillations periods mainly depend on their parameters and structural rigidity, then seismic effects depend on the parameters of the earthquake source, magnitude, energy, source depth, hypocentral distance and soil-geological conditions of the seismic waves’ propagation medium. It has been established that long-period impacts generate strong distant centers of earthquakes and short-period, close centers.

Seismic isolation systems in the form of sliding, swinging and softly moving supports [1–9] lead to an increase in the horizontal compliance of buildings at their installation levels. Accordingly, the periods of natural oscillations of these buildings also increase. This, first of all, is the seismic isolation effect, expressed in the reduction of seismic loads acting on buildings and structures. This means that if seismic effects are realized in the form of high-frequency oscillations, then flexible systems have an undeniable advantage due to the remoteness of their own oscillation periods from the prevailing period of seismic impact.

If both high-frequency and low-frequency influences or only the low-frequency ones pose a threat to a settlement, these systems lose their advantage, as there can be resonant or near-resonance oscillations
that lead to a significant increase in the seismic response of buildings. Therefore, it is important to know
the influence degree of long-period effects on the seismic response of buildings with seismic isolation
and on the seismic isolation systems’ operation.

1. Problem statement
The article presents the study results of long-period seismic effects on buildings with different types of
seismic isolation systems made in the form of: a moving foundation belt [1, 2, 4], kinematic foundations
[7, 8] and rubber-metal supports [1, 2, 9]. As an example, a 5-story building of a rigid structural solution
with a period of the first natural oscillations tone close to 0.2 s was taken. The choice of this building
type is due to the fact that the seismic isolation systems show their qualities in rigid buildings better.

The calculated dynamic model of the building is presented in the form of a 6-mass cantilever bar,
where the mass at number zero \( m_0 \) concentrated at the top of seismic isolating supports. The mass
values are: \( m_0 = 3.4 \text{kN} \cdot \text{s}^2/\text{cm} \); \( m_5 = 3.75 \text{kN} \cdot \text{s}^2/\text{cm} \); \( m_5 = 4.31 \text{kN} \cdot \text{s}^2/\text{cm} \). The floor stiffness values are:
\( k_1 = 1.71 \cdot 10^5 \text{kN/cm} \). Viscous friction coefficients are: \( \beta_1 = 80.8 \text{kN/s/cm} \). The “restoring force-
displacement” dependencies \( (R_0-Y_0) \) and attenuation coefficients characteristic of seismic isolation
systems are given below. Seismic effects are specified in the form of synthesized accelerograms (non-
stationary random processes) obtained on a computer using the parameters and modeling algorithm
given in the literature sources [10, 11]. The exposure lasts 30 seconds, and the maximum acceleration

corresponds to a 9-point earthquake intensity. In the calculation program for printing, the impact
parameters and the seismic response of the system are given in the form of maximum displacements \( m_0 \),
maximum distortions of floors, floor inertial forces and transverse shear forces. The probabilistic
characteristics of the seismic reaction are determined by the statistical tests’ method with the number of
input implementation impact equal to 30.

2. The study results analysis

2.1 Buildings with a seismic isolation system with a sliding foundation belt and elastic and rigid
restraints
The design characteristics of the seismic isolation system elements are: friction coefficient - slip
\( f_R = 0.12 \); rigidity of bilateral elastic limiters \( r_1 = 60 \text{kN/cm} \); stiffness of hard limiters \( r_2 = 0.6 \cdot 10^7 \text{kN/cm} \).
Elastic limiting gaps \( \Delta_1 = 3 \text{cm} \) and the hard restraints are \( \Delta_2 = 12 \text{cm} \). The attenuation coefficient is
\( \beta_0 = 0 \). The system seismic response dependence on the prevailing exposure period \( T_j \) at maximum
acceleration of exposure equal to 400 cm/s² is shown in Figure 1.
Figure 1 shows that the maximum elastic reaction ratio in the mass concentration level without seismic isolation to the maximum elastic reaction obtained for the same level of the system with seismic isolation is indicated by $\gamma$. From this figure it follows that with an increase in the period $T_j$ coefficient $\gamma$ decreases especially with $T_j > 0.6$ s.

In these cases, the system oscillates with stops on the hard displacements restraints, which causes a surge of inertial forces. If to remove the building restraints at the level of the sliding foundation top, then the movements reach several tens of centimeters, which is unacceptable.

In addition, the elastic reactions on the upper floors in the building with seismic isolation are reduced to a lesser extent in relation to the elastic reactions in the lower floors due to the elastic movement restraints influence, the system stops which lead to the building’s oscillation second form realization.

Figure 2 shows the probabilities plots not exceeding the gaps of the rigid displacement limiters under the impacts with different $T_j$, determined by statistical testing. It follows from the figure that with increasing $T_j$, the probabilities of the system stopping against hard restraints increase. At $T_j \geq 1.0$ s they are close to 1.

For example, when $T_j = 0.6$ s, the system in 4 cases out of 30 worked with hard restraints stops, and when $T_j = 1.4$ s - in 29 cases out of 30.

Reducing the maximum acceleration of seismic effects leads to a corresponding decrease in the maximum displacement of the building at the top of the sliding belt. For example, at the maximum acceleration of 200 cm/s$^2$ and the change interval of the prevailing period $T_j$ from 0.2 s. to 2.0 s., the maximum displacement of the system at the considered level was 9.0 cm. This means that the system worked without any emphasis on dangerous rigid displacement restraints and the displacements remained within acceptable limits. However, here the seismic isolation system showed its effectiveness only, with periods $T_j < 1.0$ s. With large predominant periods, the seismic response of a building without seismic isolation turned out to be lower than of the buildings with seismic isolation due to the rigid building natural oscillations periods remoteness without seismic isolation from the prevailing long periods of exposure.
2.2 Building with seismic isolating kinematic foundations

In the beginning, we will consider the same building, but already with a seismic isolation system in the kinematic foundations form, representing the sphere parts freely supported with the foundation plates [3, 7]. The dependence “$R_0 - Y_0$” in this case corresponds to a soft nonlinearity curve [7], and the attenuation coefficient $\beta_0 = 1.6 \text{ kN} \cdot \text{s/cm}$.

Figure 3 shows the dependence of the building maximum movement at the top of the kinematic foundations ($Y_0^{\text{max}}$) from the prevailing period $T_j$ seismic impact of 9 points intensity. The figure shows that for the periods $T_j > 0.6$ s, the system movements become unacceptably large. Figure 4 shows the graphs of the building maximum elastic reaction in question without a seismic isolation system and with kinematic foundations. It also follows from them that for $T_j > 0.6$ s, the seismic isolation efficiency of the building is reduced.

We studied the kinematic supports of slightly different type as well [6, 12], but these supports’ operation under long-period influences turned out to be similar to those considered above.

2.3 Buildings with rubber-metal seismic isolating supports (RMSIS)

Due to the high horizontal compliance with large vertical compressive loads, the possibility of increasing energy absorption due to lead cores, as well as their compactness and manufacturability, they are widely used in world practice [1, 9, 13, 14]. To study the effectiveness under long-period impacts, we took the “FIP INDUSTRIALE” company supports with technical characteristics corresponding to the LRB-SN 500 / 100-110 (with lead core) and SI-H 300/100 (without lead core) markings [15]. Depending on effective stiffness ($E_s$), the supports are divided into flexible, semi-rigid and rigid. Moreover, for the flexible RMSIS with a lead core $E_s = 35.3 \text{ kN/cm}$, semi-rigid $E_s = 44.2 \text{ kN/cm}$, hard $E_s = 58.5 \text{ kN/cm}$. For RMSIS without lead core, effective stiffness of flexible $E_s = 76.1 \text{ kN/cm}$, semi-rigid $E_s = 144 \text{ kN/cm}$, hard $E_s = 197.7 \text{ kN/cm}$.

The experimental dependencies “$R_0 - Y_0$” corresponding to these supports are approximated by the mathematical expressions, allowing to obtain a linear relationship for RMSIS with a lead core [16]. The attenuation coefficient is: $\beta_0 = 12.2 \text{ kN/s/cm}$.

One of the rubber mounts effectiveness criteria under seismic action is their maximum movement at the top level. Figure 5 shows the graphs of the RMSIS maximum displacements with lead cores installed under the 5-story building under consideration, with a 9-point seismic impact with various $T_j$. 

![Figure 3. Graphs of the maximum displacement $Y_0$ of a 5-story building with kinematic foundations](image1)

![Figure 4. Graphs of the maximum elastic reaction of a 5-story building: 1 - without seismic isolation, 2 - with kinematic foundation](image2)
Figure 5. RMSIS maximum displacements schedules with lead cores installed under a 5-story building with a 9-point seismic impact with various $T_j$.

The same graphs for RMSIS without a lead core are shown in Figure 6.

Figure 6. Graphs of the maximum displacements of RMSIS without lead cores installed under a 5-story building with a 9-point seismic impact with various $T_j$.

An increase in displacements of $Y_0$ with an increase $T_j$, but to a lesser extent than with a sliding belt and kinematic foundations also follows from these figures. In addition, it can be seen that the presence or absence of a lead core does not significantly affect the maximum supports’ movement.

It should be noted that in all the above-mentioned cases of seismic insulating supports, an increase in the seismic reaction of the building during long-period influences is also observed in comparison with the seismic reaction of the building without seismic isolation.

Summary

The predominant period of seismic impact has a significant impact on the maximum movement of buildings at the top of seismic insulating supports, although to a lesser extent, on the systems with rubber-metal supports and, to a greater extent, on the systems with a sliding foundation belt and kinematic supports. With an impact intensity exceeding 8 points, for the seismic isolation systems with a sliding foundation belt and systems with kinematic supports, these movements become unacceptably large, and their restriction with the help of rigid stops of the restraints leads to an increase in the buildings’ seismic response. Therefore, the above-studied seismic isolation systems are effectively used in the seismic areas where high-frequency seismic effects are predicted. And if 9-point impacts with predominant high and low frequencies are expected, then it is rational to introduce the restraint elements
into these seismic isolation systems, designed to quickly turn off under high-frequency influences and not turn off under strong low-frequency influences. This will disable the seismic isolation system from the hazardous long-period influences.

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