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THE CONCEPT OF DAMPING TUNING FOR SEISMIC ISOLATION

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SUMMARY

The tuning of damping for base isolating system are considered. The main conclusions of our investigations are the following: the base isolated systems are to be overdamped. The recommended friction force is to be about 15-20% of the weight of the structure. In this case the values of the accelerations maximums of the structure are acceptable both for design and unforeseen input. In overdamped structures the accumulation of the isolated building damages will be growing gradually. It is not so dangerous as isolating bearings collapse, which is possible for low-dampened structures.

INTRODUCTION

Seismic isolation is recognized as an efficient means of earthquake protection. Hundreds of base isolated buildings have been built all over the world. The analysis of base isolated structures is considered in monographs which were published in the USA [Kelly, 1997], New Zealand [Skinner, Robinson, McVerry, 1993], Russia [Uzdin, Dolgaya, 1997] and other countries.

Despite these investigations, the selection of damping parameters has no standardized solution. In practice, one can unnethighly fall into a dangerous fallacy about the possibility of using lightly-damped isolation. This paper analyses the influence of damping on isolated structure behavior.

2. . THE MAIN TERMS AND EQUATIONS

This investigation is based on the analysis of the non-linear oscillation equations for a base isolated system with a dry friction damper (DFD). We performed

- numerical modeling of the seismic oscillations of about 6000 isolated systems using synthetic and real accelerograms
- analytical study of the equations of motion for harmonic impact.

For numerical modeling studies the traditional calculation scheme was used (fig.1.)

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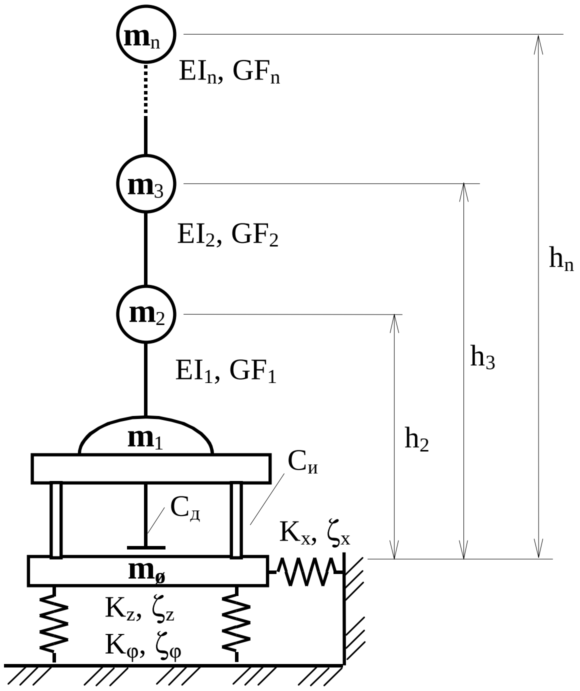

Figure 1: The calculation scheme of base isolated structure

The equations of motion were presented in non-dimensional form in accordance with the above-mentioned monographs. In this case the equations of motions are as follows:

$$\sum_{j=1}^{\text{т}} m_{ij}\ddot{\eta}_j + \sum_{j=1}^{n} b_{ij}\dot{\eta}_j + \sum_{j=1}^{n} r_{ij}\eta_j + \sum_{j=1}^{n}\frac{F_{ij}}{A_{max}g} + \sum_{=1}^{n} c_{ij}\delta_{ij} = -\sum_{j=1}^{\text{т}} m_{ij}\alpha_j\ddot{\eta}_0(t), \qquad (1)$$

where $\ddot{\eta}_i$ and $\ddot{\eta}_0$ are the non-dimensional accelerations of the mass m_i and of the base accordingly, ($\ddot{\eta}_o^{(max)} = 1$), $\ddot{\eta}_i = \frac{\ddot{y}_i}{A_{max}g}$, y_i is the i-th generalized displacement, A_{max} is the maximum amplitude of acceleration as a fraction of gravity; m_{ij}, b_{ij} and r_{ij} are the coefficients of inertia, viscous damping and stiffness, c_{ij} is the stiffness coefficient of the damper, connecting the mass m_i with m_j; δ_{ij} is the residual displacement in the DFD, *connecting the mass m_i with m_j; α_j – the projection of the impact on the j-th generalized displacement direction.*

·Let us use the *reduction* conventional friction ratio defined as follows

$$\bar{f} = \frac{|F|}{Mg}, \qquad (2)$$

where M is the mass of the structure.

In this case the friction force is represented as follows: $F_{ij} = Mgf_{ij}\,\text{sign}V_{ij}$, where V_{ij} is the velocity of the mass m_i relative mass m_j. In these terms equation (1) takes the following form:

$$\sum_{j=1}^{n} m_{ij}\ddot{\eta}_j + \sum_{j=1}^{n} b_{ij}\dot{\eta}_j + \sum_{j=1}^{n} r_{ij}\eta_j + M\sum_{j=1}^{n}\bar{f}_{ij}\,\text{sign}V_{ij} + \sum_{j=1}^{n} c_{ij}\delta_j = -\sum m_{ij}\alpha_j\ddot{\eta}_o \qquad (3)$$

For the scheme shown in fig.1 there is only one damper connecting the mass m_0 with the mass m_1. This damper is characterized by one reduced conventional friction ratio $\bar{f}$ and one damper stiffness C_d=C_{01}.
In analyzing equation (3), we separated the structure displacements as a rigid body from the full mass displacements. It makes the calculation results more accurate, but complicates the assembling of the inertia matrix. The calculation technique is described in the above-mentioned monograph (Uzdin, Dolgaya) and is not discussed futher.

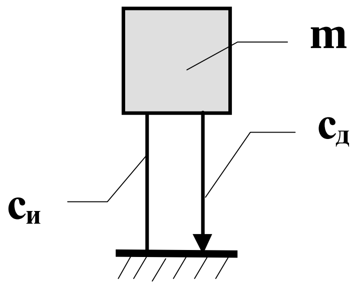

Figure 2: The calculation scheme of base isolated structure for analytic analysis

For the analysis of the base isolated system the calculation scheme presented in fig.2 was used. The structure mass and the isolated system stiffness are designated as m and C_{is} accordingly. The damper stiffness C_d was taken into account. This makes our scheme different from the well known scheme of Den Hartog, described by [Kelly, 1997].
For harmonic excitation the equation of this system *oscillations* takes the form

$$m\ddot{y} + c(y)y + F(\dot{y})\,\mathrm{sign}\,\dot{y} = -A_{max}\, g\; m\; \cos(\omega t + \varphi). \tag{4}$$

In this equation y is the mass displacement relatively to neutral position of the isolating supports, and φ is the phase shift between the mass displacement and the earthquake load. The functions $F(\dot{y})$ and C(y) depend on the DFD condition. For the closed DFD, C(y)=C_{is}+C_d and $F(\dot{y})$=0. For the opened DFD, C(y)=C_{is} and $F(\dot{y})$=F_{fr}, the friction force in the DFD.

Equation (4) was solved independently by [Kolovskiy, 1957] who applied the Bubnov-Galerkin method and by the authors of this paper with the use of a harmonic linearization method [Dolgaya and Uzdin,1998].

3. MAJOR OBSERVATION AND RESULTS

The numerical analysis of base isolated structures has been carried out in different investigations. For example, such investigations are presented in the monograph [Skinner, Robison, McVerry,1993]. In Russia such results are presented in the investigations of professor O.Savinov and his followers and have been published [Savinov and others, 1985], [Uzdin, Sandovich, Samich Amin, 1993].
The investigation reported in this paper has two important distinctives.
The first and most important distinctive is associated with setting the design input (accelerograms). The amplitude A_{max} of all accelerograms was normalized depending on the predominant period of the earthquake T_{eq} according to the regression dependence $A_{max}(T_{eq})$ obtained by [Uzdin, Dolgaya, 1997] on the basis of statistical processing of more than 300 accelerograms of strong earthquakes. The design dependencies $A_{max}(T_{eq})$ are shown in figure 3.

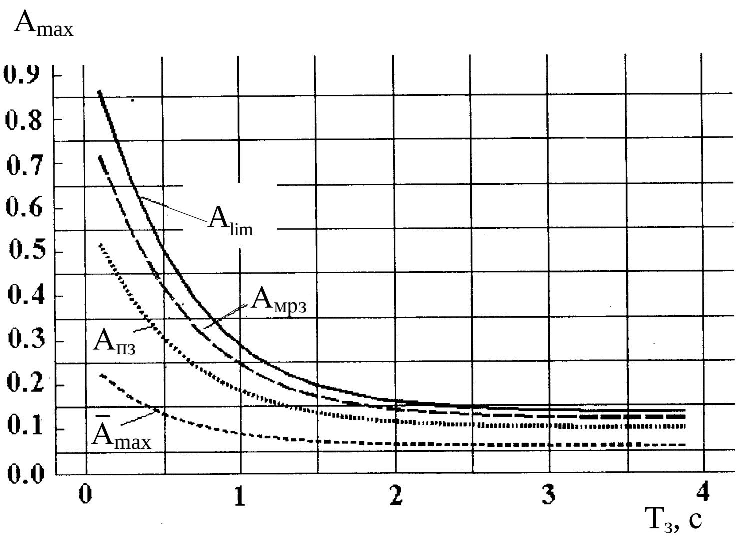

Figure 3: Dependencies of design accelerations maximum on predominant earthquake period.

We have used here the following notation:
A_{lim} is the acceleration of the strongest possible earthquake for the building site according to seismology conditions; A_{mde} is the acceleration of the maximum design earthquake with a probability exceedance 1:10000; A_{de} is the acceleration of the design earthquake with a probability of exceedance of 1:1000; and $\overline{A}_{max}$ is the mean value of A_{max}.
The second distinctive is the number of calculations. During the investigation more than 6000 isolated buildings with a hard construction scheme were calculated. The range of the fundamental period of buildings was from 0.2 to 0.4 s. The fundamental period of the base isolated buildings ranged from 1 to 4 s. Shear waves velocities varied from 200 to 2000 m/s^2. The aforesaid allowed us to summarize the results obtained for a wide class of hard isolated structures. Inasmuch as detailed results of numerical investigation were published in the proceedings of international conferences [Uzdin, Dolgaya and Indeykin, 1996],[Uzdin and Dolgaya,1997] only the main result of these investigations are presented here. The typical dependencies of accelerations maximum A_{max} and the mutual displacements of isolated parts of the structure are shown in figure 4.

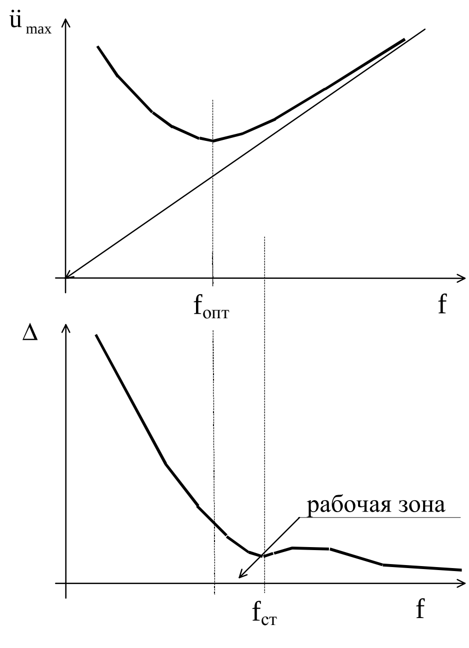

Figure 4: Dependence $\ddot{u}_{max}(f)$ и Δ(f).

The analysis of these dependencies makes it possible to mark out two values of the reduction conventional friction ratio – the optimal reduced conventional friction ratio $\bar{f}_{opt}$ and the stabilizing the reduced conventional friction ratio $\bar{f}_{st}$. When $\bar{f} = \bar{f}_{opt}$, the acceleration value is a minimum. When $\bar{f} > \bar{f}_{st}$, the mutual displacement changes insignificantly with decreasing friction ratio.

The area of the friction ratio $\bar{f}_{opt} > \bar{f} > \bar{f}_{st}$ was named the working region. The acceptable value of friction ratio for base isolated systems is to be found in the working region. When $\bar{f} < \bar{f}_{opt}$, both the maximum structure accelerations and the mutual displacement are high. When $\bar{f} > \bar{f}_{st}$ the acceleration increases with increasing $\bar{f}$, and the mutual displacement does not change significantly.

According to the numerical calculations the value $\bar{f}_{st}$ does not depend on the structure and *impact* parameters.

The optimal friction ratio increases insignificantly with increasing predominant earthquake period and decreases to zero with increasing of the fundamental isolated structure period T_{is}. The value T_{is} for which $\bar{f}_{opt} = 0$ is termed the critical period of the isolated system.

The theoretical basis of these results was obtained by means of analytical investigations.

In the course of these analytical investigations we obtained the amplitude-frequency dependence (AFD). The critical value of friction ratio $\bar{f}_{cr} = \pi/4$ was obtained in a manner similar to that obtained for the scheme described by professor [Kelly, 1998].

When $\bar{f} > \bar{f}_{cr} = \pi/4$, the AFD is limited at the upper point by the following value

$$\varsigma_{max}^{(р ЊЌ)} = \frac{\bar{f}}{\kappa^2\left(1 - \frac{\pi}{4\bar{f}}\right)} \tag{5}$$

where $\kappa = k_d / k_{is}$ is the damping frequency-to-isolating frequency ratio.

When $\bar{f} < \bar{f}_{cr} = \pi/4$, the AFD is non-limited, i.e. it has an infinite resonance peak.

Real earthquake excitation has a polyharmonic composition and a structure will generally respond to the most dangerous (resonance) input component with frequency $\omega \approx k_{is}$. This component leads to the displacement increasing for each impact, if $\bar{f} < \bar{f}_{cr}$. On the contrary, when $\bar{f} > \bar{f}_{cr}$ mutual displacements practically do not change. Thus, the stabilizing friction ratio, presented by the authors of this paper, can be estimated by the formula:

$$f_{st} = \bar{f}_{cr} \bullet A_{max} \tag{6}$$

The value of A_{max} can be calculated by the formula presented in the paper [Uzdin and Dolgaya,1997]. In accordance with that paper, the random value A_{max} is distributed according to the Weibull law. Thus, the f_{st} value has a similar distribution.

We would like to stress an additional region(overdamped region) of the friction ratio $\bar{f}_{cr} < \bar{f} < \bar{f}_{min} = \pi/2$ obtained in our investigations. In this region the mutual displacement keeps on decreasing and the maximum acceleration increases slowly. In many cases the displacement decrease is more important than the acceleration increase. Besides an error in tuning, which results in shifting the f value from the working region to the region of small damping (underdamped region), increases both the accelerations and displacements of the system. But an error in tuning which results in shifting the f value from the working region to the overdamped region aggravates only the accelerations of the system. Thus, it is less dangerous to overdamp the system than to underdamp it.

The analytical solution makes it possible to show that the existence of an optimal friction ratio is associated with the polyharmonic input composition. At high damping, the increase of building accelerations takes place. This increase is caused by the high-frequency components of the input accelerations. At low damping, the resonance oscillations for low-frequency components of the input predominate.

The critical period T_{cr} is caused by the fact that at large periods of the isolated structure oscillation in the resonance regime can not be achieved during the time of the earthquake.
The value of damping predetermines the destruction scenario of the isolated structure. In underdamped structures, isolating bearings will be destroyed first which can result in the collapse of the building. In overdamped structures the accumulation of the isolated building damages will be growing gradually. Thus, the second destruction scenario is less dangerous, than the first one.
Another important problem for base isolated structures is their behavior for unforeseen input. Damages for usual (non-isolated) structures and base isolated overdamped structures accumulate gradually as the earthquake force increases. But the term “overdamping” is relative and depends on the earthquake force. The recommended value of friction ratio in accordance with [Uzdin, Dolgaya, 1997] should be calculated by formula (6). According to this formula, the recommended value of friction ratio doubles with increasing earthquake intensity of one unit (degree) on the MSK scale. This fact is illustrated in figure 5.

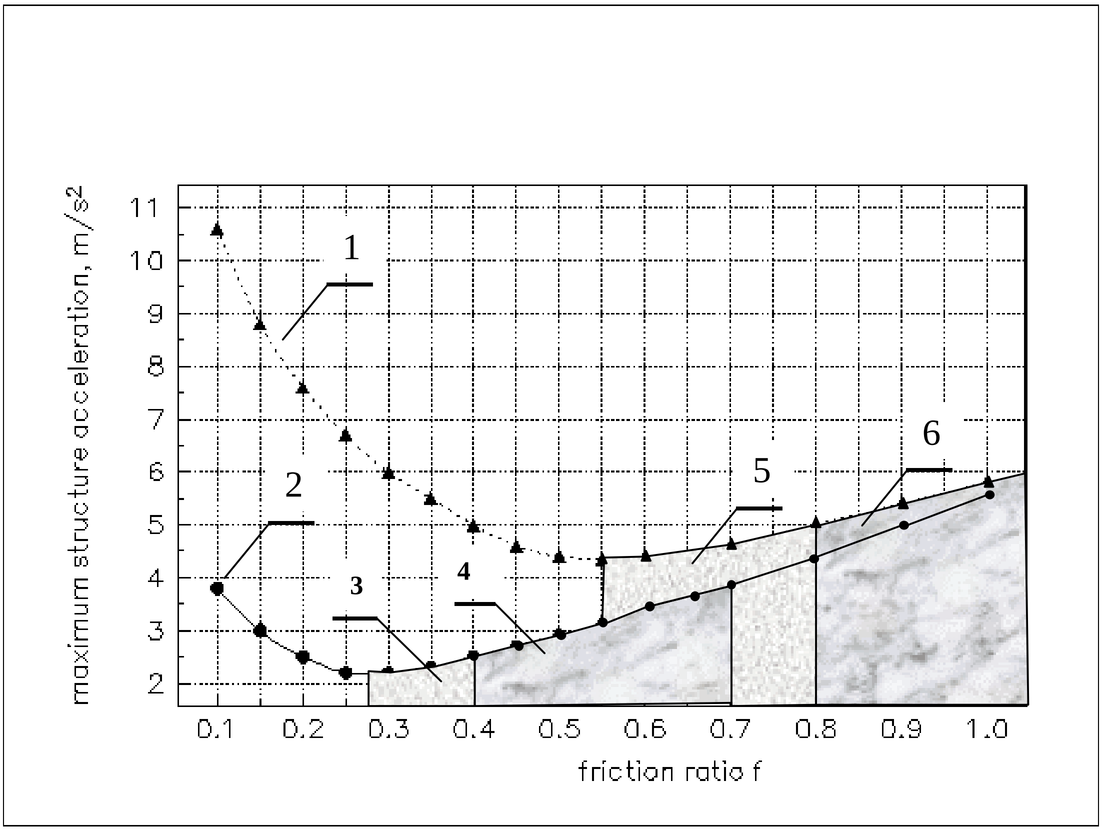

Figure 5: Dependencies of accelerations maximum on friction ratio

1 – for earthquake intensity I=9 degree on MSK scale; 2 – for I=8.
3 – working area for I=8; 4 – overdamped area for I=8;
5 – working area for I=9; 4 – overdamped area for I=9.

The area of recommended values of friction ratio (working region) for earthquake input with intensity I=8 on MSK scale is situated much more to the left than the similar region for I=9.
Fig.5 shows, that for the value f from the area 3, the system accelerations are low for I=8, but for I=9 the friction force is not enough and the system accelerations are too high and dangerous.
The setting of the value f in the overdamped region (area 4 in fig.5) ensures an acceptable value for the system accelerations (although this value is not optimal) for the design impact at I=8 and not very high acceleration at I=9.
We would like to stress that for the design input (I=8) the isolated part of the system will be overloaded and for an unforeseen impact (I=9) the isolating part (isolating bearings) will be overloaded.

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