Statistical modeling of a seismic isolation object under random seismic exposure

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Abstract. Using probabilistic methods, the reliability and seismic resistance of a large-panel building on kinematic foundations (KF) at the seismic isolation site in Almaty is analyzed. The building is modeled by a nonlinear single-mass system with an experimental deformation diagram. Seismic impact is modeled by a random process with a given correlation function. To calculate probabilistic characteristics, the method of statistical tests is used (Monte-Carlo method). The seismic impact parameters are set in accordance with the “Map of the seismic zoning of the Republic of Kazakhstan” by the median values of peak accelerations. 2 accelerograms of the 1990 Baysorun earthquake were chosen as the impact model. Therefore, these accelerograms were taken as the basis for modeling the seismic effects of a random process. Generation of realizations of a stationary random process is performed by recursive filtering. The influence of the number of statistical tests (artificial accelerograms) on the accuracy of calculating the moments of the distribution function of displacements was investigated. According to the results of a Monte Carlo calculation using 5000 realizations, the reliability of the building is determined (probability of failure-free operation). Conclusions about system effectiveness of seismoisolation of kinematic type for the influence specified like buildings at regional parameters are drawn.

1. Introduction

In Almaty, a seismic isolation system based on seismic insulating kinematic foundations (KF) developed at KazNIISA JSC [1–3] has spread. Over 40 buildings of various floors were built in Almaty and over 300 in the Russian Federation.

Currently, new maps of seismic zoning of the territory of the Republic of Kazakhstan, which are probabilistic in nature, are being introduced. There are maps of seismic zoning of the Republic of Kazakhstan taking into account the frequency of earthquakes 1 time in 475 years and 1 time in 2475 years. The maps show the median values of peak accelerations. The city of Almaty is located in a highly seismic area, where earthquakes with a magnitude above 7 have repeatedly occurred. In 1911, an earthquake with a magnitude of 8 took place.

In the city of Almaty, a seismic isolation testing ground is operating, consisting of three buildings equipped with engineering-seismometric service stations. Devices are installed on 9-floor large-panel buildings with kinematic foundations, with fluoroplastic gaskets and an analog building with conventional strip foundations [3].
It is advisable to obtain updated estimates of the earthquake resistance of buildings on seismic insulating supports, taking into account the available experimental data, probabilistic models of seismic impact, instrumental data of the engineering-seismometric service, as well as modern computing tools - computer mathematics systems. It is advisable to evaluate seismic stability by the values of the probability of failure-free operation - reliability W.

2. The mathematical model of the building and the impact

2.1 Probabilistic model of seismic impact

It is convenient to take into account the complex nature of seismic impact, which is a stochastic process of soil oscillation in space and time, using random function theory methods. At present, in the problems of the theory of seismic resistance, two classical types of approximations of correlation functions used by V. V. Bolotin are most popular with domestic and foreign scientists [4]:

\[ K(\tau) = \sigma^2 e^{-|\alpha|\tau} \cos \omega \tau \tag{1} \]

corresponds not to a differentiable random process, but

\[ K(\tau) = \sigma^2 e^{-|\alpha|\tau} \left( \cos \omega \tau + \left( \alpha / \omega \right) \sin \omega \tau \right) \tag{2} \]

twice differentiable random process. Here \( \sigma^2 \) – the variance of the process, characterizing the intensity of the earthquake; \( \alpha \) – correlation parameter characterizing the degree of attenuation of the curve; \( \omega \) – frequency.

There are various methods for digital modeling of a random process with a given correlation function [5].

One of the fastest and most convenient is an algorithm based on recursive filtering (autoregression) [5]. The basic calculation formula for autoregression (moving average) is:

\[ y_k = \sum_{i=0}^{m} a_i x_{k-i} - \sum_{i=1}^{n} b_i y_{k-i}, \tag{3} \]

where \( x_{k-i} \) – discrete implementations of a random process at the system input, \( y_k \) – discrete implementations of a random process at the output (in this case, accelerograms); \( a_i \), \( b_i \) – coefficients of the autoregressive model with a moving average; \( m \) and \( n \) are positive numbers \( (m \leq n) \). This method does not have a methodological error, and the parameters of the modeling algorithm are expressed explicitly through the parameters of the correlation function. If the form of the correlation function is complicated (for example, the continuous transfer function of the forming filter has multiple poles), then the recurrence algorithms become approximate.

The seismic effect was modeled by a stationary random process, which is obtained by multiplying the realizations of the stationary process by a deterministic envelope. The determinate envelope is adopted in the form of a fractional rational function Aptikaeva F.F. [6]

\[ A = A_{\text{max}} \frac{3d}{9t^2 - 9td + 4d^2}. \tag{4} \]
The value of \( d \) is the effective duration of the seismic impact (duration of exposure with an intensity of at least half the maximum – pulse width).

2.2 Mathematical model of a seismically insulated building

Further, we will carry out the description of the probabilistic methods for calculating a seismically insulated building using the example of a building on kinematic foundations, which was built in Almaty and equipped with an engineering-seismometric service station [7, 8].

The typical building is a large-panel residential building of the 158 series, a single-access block section. Dimensions of the building: length 17.4 m, width 12.9 m, height 31.5 m. The building has 9 floors with a height of 3 m each with an additional technical underground and a semi-aisle attic. On a building with KF, kinematic foundations are based on a cross ribbon at the intersection of the walls. Depth 3.8 m.

The building is designed for areas with a seismicity of 9 points.

The ground conditions at the construction site are boulders, category 2 seismic properties. Groundwater level 20 m.

The early building was tested with a vibrating inertia machine. Therefore, there are experimental data on its behavior [3].

To analyze possible displacements due to reactive forces at the level of kinematic foundations (KF) under seismic loads and also to assess the reliability of such buildings, a single-mass cantilever system with a concentrated mass and a deformation diagram corresponding to the KF level can serve as an acceptable design model. Earlier tests of the facilities made it possible to obtain the complete information necessary for assessing seismic response and reliability.

A nonlinear differential equation is integrated

\[
\ddot{x} + \mu \dot{x} + R(x) = -m\ddot{x}_{0i},
\]

Where \( R(x) \) – is the nonlinear restoring force,

\( \ddot{x}_{0i} \) – i-th accelerogram,

\( \mu \) – inelastic drag coefficient (Voigt hypothesis),

\( m \) – mass of the building,

\( x \) – horizontal movement.

The calculation model of the building has the following inertial and dissipative characteristics (Q = mg, g-acceleration of gravity):

\[ Q=24300 \text{ kN}; \mu=44 \text{ kH-cм/cм}. \]

The deformation diagram of the single-mass system is adopted corresponding to the indicated weight (Figure 1).

The criterion for failure here is the achievement of the maximum permissible displacements \( [x_{\text{max}}] \). According to the data of static tests [3], it was taken \( [x_{\text{max}}] = 10 \text{ cm} \). Reliability (probability of failure-free operation) \( W = W (|x| < [x_{\text{max}}]) \).

The calculations are performed by the method of statistical tests (Monte Carlo method) using the capabilities of the licensed computer mathematics system MATLAB.

To assess the quality of the impact model, we will calculate the probabilistic characteristics and reliability of a seismically insulated building on kinematic foundations.

To solve the problem, the modules of the computer mathematics system MATLAB are used.
Figure 1. The strain diagram at the level of KF at various vertical loads

It is advisable to assess the behavior of seismic isolation systems taking into account regional characteristics. KazNIISA JSC operates a network of engineering-seismometric service stations on buildings, which records seismic events in real time. The result is instrumental records of accelerations, displacements, and velocities, the peaks of which can be kinematic characteristics of earthquakes. Table 1 shows the most significant earthquake accelerograms recorded by both ISS stations and stations of the Institute of Seismology of the Republic of Kazakhstan.

Table 1. Parameters of the normalized correlation function (2)

| Title earthquakes        | $\alpha_1$ | $\omega_1$ | Acceleration, cm/s² |
|--------------------------|------------|------------|---------------------|
| Zhalanash-Tyupskoe, 1978 | 6.59       | 12.22      | 35                  |
| Zhalanash-Tyupskoe, 1978 | 9.80       | 18.26      | 29                  |
| Zhalanash-Tyupskoe, 1978 | 7.85       | 16.07      | 18.5                |
| Zhalanash-Tyupskoe, 1978 | 51.71      | 42.34      | 20                  |
| Zhalanash-Tyupskoe, 1978 | 9.74       | 25.19      | 14                  |
| Bakanassky, 1980         | 51.79      | 18.65      | 7.5                 |
| Bakanassky, 1980         | 14.04      | 11.57      | 4.4                 |
| Kungei, 1982             | 8.17       | 16.29      | 12.6                |
| Baysorunskoe, 1990       | 2.4        | 27.63      | 699.2               |
| Baysorunskoe, 1990       | 5.74       | 39.02      | 436.9               |
| Baysorunskoe, 1990       | 2.13       | 24.38      | 64                  |
| Baysorunskoe, 1990       | 7.24       | 26.96      | 44.4                |
| Average value            | 14.77      | 23.28      |                     |
We will carry out the calculation of a seismically insulated building taking into account the regional characteristics of the seismic impact for the city of Almaty - a metropolis with a population of more than 2 million people. According to the current Seismic Zoning Map of the Republic of Kazakhstan, the median acceleration values in the city are equal at a repeatability of once every 475 years, 0.38g, and at a time of 2475 years, 0.73g. Here g is the acceleration due to gravity.

The two indicated acceleration values are most closely associated with two accelerograms of the 1990 Baysorun earthquake from Table 5 with acceleration peaks of 699.2 cm / s² and 436.9 cm / s². The differences between the peak values of acceleration from the values normalized by the Seismic Zoning Card are 2-8% here. Therefore, these accelerograms can be taken as initial ones for simulating seismic impact by a random process. Table 2 shows some parameters of instrumental records – accelerograms.

A quick analysis of Table 2 shows that the accelerograms are well centered. Instrumental recordings are high-frequency. The predominant periods and carrier frequencies are determined by spectral density using the Toolbox Signal Processing Toolbox SCM MATLAB. With a total exposure duration of more than 8 seconds, the effective duration (duration of oscillations with an amplitude of more than half the maximum) is 2.5 seconds, i.e. approximately 30% of the total duration. Effective duration is one of the characteristics of the recommended determinable envelope (5).

The ratio of the maximum accelerations of the components is 1.6.

Table 2. Accelerogram parameters

| Options                      | Component 1 (N-S) | Component 2(E-W) |
|-------------------------------|-------------------|-------------------|
| Accelerogram maximum, cm / c² | 699.2             | 436.92            |
| Accelerogram minimum, cm / c² | -589.85           | -375.53           |
| Dispersion, cm² / s⁴          | 69.64             | 72.05             |
| RMS value, cm / s²            | 8.34              | 8.49              |
| Span, cm / c²                 | 1289.05           | 812.450           |
| Average value, cm / s²        | 4.193             | 6.098             |
| Median value, cm / s²         | 1.600             | 9.845             |
| Spectral density maximum      | 42.20; 36.58      | 39.69             |
| Frequency, 1 / s              | 3.66; 4.76        | 4.88              |
| Period, c                     | 0.27; 0.21        | 0.20              |
| Duration of oscillations with an amplitude of more than half the maximum (effective duration), s | 2.52 | 2.50 |

Figure 2 shows the spectral curves of ß characterizing both the spectral composition of the indicated earthquake and the possible dynamic effect. The effects are fairly narrowband.
3. Results and discussion

We perform a probabilistic calculation of a seismically insulated building at the two indicated peak acceleration values with average values of the parameters of the correlation function (2) from Table 3. The calculation was performed by the Monte Carlo method using 5000 realizations of a random process with correlation function (2). Realizations of the random process were generated by the recursive filtering method (1). The ordinary differential equation (5) was integrated, where, due to the essentially nonlinear operation of the structures, the internal viscous friction parameter was taken to be 44.0 kN·sec / cm. The integration of equation (5) was carried out by the Adams method of the predictor-corrector type of variable order. The calculation results in table 3.

The Ex value for a repeatability of 475 years is 3. That is, the empirical distribution function of the displacement values is close to the normal law. For repeatability of 2475 years, the excess coefficient is positive. This means that the empirical distribution is more peaked than normal, i.e. the histogram columns in the center of the distribution should be higher than the normal distribution curve.

The displacement values at the basement level are within the range of 1.84-4.07 cm and the median values of 1.71-3.78 cm.

The reliability value W with a repeatability of 475 years is very high 1.0, and with a repeatability of 2475 years a very high 0.9974. Reliability estimates are accurate, as obtained with a large number of implementations.
Table 3. The values of the probabilistic characteristics of displacement and the reliability value \( W \) of a seismically insulated building

| Options                      | For repeatability 475 years | For repeatability 2475 years |
|------------------------------|-----------------------------|-----------------------------|
| Average value, cm            | 1.84                        | 4.07                        |
| Median value, cm             | 1.71                        | 3.78                        |
| Standard deviation, cm       | 0.64                        | 1.45                        |
| The coefficient of variation | 0.57                        | 0.36                        |
| Reliability \( W \)          | 1.00                        | 0.9974                      |
| Failure probability \( R \)  | 0.00                        | 0.0026                      |
| \( Ax \)                     | 1.33                        | 1.15                        |
| \( Ex \)                     | 3.00                        | 1.88                        |

Nevertheless, it is advisable to assess the effect of the number of realizations of a random process on the estimates of the probabilistic characteristics of displacement values at the level of the kinematic foundation. Table 4 shows the calculation results.

It has been established that to determine the average, median, and standard deviation displacement values, it is sufficient to use from 1000 to 5000 realizations of the random process. For reliability, it is enough to use from 5000 implementations. For asymmetry values (third point), \( Ax \) is sufficient to generate from 15,000 realizations. The kurtosis value \( Ex \) is more variable. The value of \( Ex \) begins to be established from 35,000 implementations. Reliable \( Ex \) values were obtained using 100,000 realizations of a random process (artificial accelerograms).

Table 4. The values of the probabilistic characteristics of displacement and the reliability value \( W \) of a seismically insulated building for a different number of implementations

| Options                      | 1000    | 15000   | 25000   | 35000   | 100000  |
|------------------------------|---------|---------|---------|---------|---------|
| Average value, cm            | 4.10    | 4.09    | 4.04    | 4.06    | 4.06    |
| Median value, cm             | 3.72    | 3.79    | 3.75    | 3.77    | 3.78    |
| Standard deviation, cm       | 1.57    | 1.49    | 1.44    | 1.46    | 1.46    |
| The coefficient of variation | 0.38    | 0.36    | 0.36    | 0.36    | 0.36    |
| Reliability \( W \)          | 0.992   | 0.9957  | 0.9975  | 0.9963  | 0.9960  |
| Failure probability \( R \)  | 0.008   | 0.0043  | 0.0025  | 0.0037  | 0.0040  |
| \( Ax \)                     | 1.68    | 1.34    | 1.25    | 1.32    | 1.33    |
| \( Ex \)                     | 4.49    | 3.17    | 2.56    | 2.96    | 3.33    |
An analysis of tables 3.4 allows us to conclude that the Monte Carlo method (statistical tests) leads to acceptable results when calculating the first two moments of distribution with a fairly small number of statistical tests - 1000-5000 implementations. Reliability values W are also quite accurately determined.

In general, a nonlinear single-mass design scheme is an acceptable idealization of a large-panel building on the kinematic foundations of various designs.

The overall reliability of a seismically insulated building in the case of using the data from Table 3 is presented in the form (W_{475} is the reliability value for seismic impact with a repeatability of 475 years, W_{2475} is the reliability value for seismic impact with a repeatability of 2475 years)

\[ W = W_{475} \cdot W_{2475} \]

Obviously. \( W = 1 \times 0.9974 = 0.9974 \). Thus, the overall reliability of a seismically insulated system is equal to or less than the reliability value with more intense seismic impact. This value of reliability is a quantitative measure of the earthquake resistance of a building.

Thus, a probabilistic analysis of the behavior of buildings with KF makes it possible to quantify the earthquake resistance of buildings by reliability values and evaluate the effect of seismic isolation. The overall result is the sufficient efficiency of the kinematic foundations (KF) under high-frequency exposure.

The undoubted advantage of the probabilistic calculation method for the seismically insulated building proposed here is the consideration of the regional nature of the seismic impact and quantitative information about the parameters of the expected seismic impact from the “Map of seismic zoning of the territory of the Republic of Kazakhstan”.

The authors of the work are convinced that the results of dynamic and static tests of real seismically insulated buildings are invaluable research material. The theory of earthquake resistance is developing quite quickly. Therefore, it is periodically necessary to return to previously obtained experimental data in order to interpret them using new theoretical methodologies and approaches.

Within the framework of using the new regulatory framework of the Republic of Kazakhstan on the basis of Eurocodes, the use of seismic isolation in Almaty seems to be very promising [10-15].

4. Conclusion

1. Estimates of seismic resistance are obtained by the reliability (probability of failure-free operation) of a seismically insulated house on kinematic foundations, taking into account the main parameters of the “Map of seismic zoning of the territory of the Republic of Kazakhstan”. The probabilities of realizing the acceleration values with the normalized repeatability of the seismic impact are taken into account. The reliability assessment and the probabilistic characteristics of the reaction are carried out according to the scheme of the statistical test method (Monte Carlo). Quantitative estimates of reliability W not less than 0.9974.

2. It was found that to determine the average, median, and \( r_m \) displacement values, it is sufficient to use from 1000 to 5000 realizations of the random process. For reliability value, it is enough to generate from 5000 implementations. For the third and fourth moments it is necessary to use a larger number of implementations - for \( A_x \) - at least 15,000 implementations, for \( E_x \) the required number of implementations is approximately 100,000 implementations.

3. Seismic isolation of buildings in Almaty on the basis of kinematic foundations is quite effective.

4. The specified probabilistic method can be used in the calculation of other buildings for which there are experimental data or strain diagrams obtained, for example, by the Pushover method.

5. Studies are recommended to be specified as instrumental records of the engineering-seismometric service of KazNIISA JSC are accumulated and the results of seismic zoning of the territory of the city of Almaty are accumulated.
6. In Almaty, a seismic isolation testing ground is functioning, consisting of three buildings equipped with engineering-seismometric service stations. In total, the network of ISS stations totals 10 seismic stations in Almaty. It is advisable to continue using instrumental records of these stations to adjust seismic impact models [7, 8, 9].

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