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Seismic design optimization considering base-isolation system

Оптимизация сейсмостойкого проектирования с учетом применения сейсмоизоляции

A.Y. Ivanov*,
St. Petersburg State University of Architecture and Civil Engineering, St. Petersburg, Russia
S.A. Chernogorskiy,
Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
M.P. Vlasov,
St. Petersburg State University of Architecture and Civil Engineering, St. Petersburg, Russia

Аспирант А.Ю. Иванов*,
Санкт-Петербургский государственный архитектурно-строительный университет, Санкт-Петербург, Россия
к.э.н., доцент С.А. Черногорский,
Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия
д.э.н., проф. М.П. Власов,
Санкт-Петербургский государственный архитектурно-строительный университет, Санкт-Петербург, Россия

Key words: optimization procedure; earthquake engineering; structural damage; seismic base isolation; nonlinear static pushover analysis; averaged response spectrum; capacity curve; economic effect; life-cycle

Ключевые слова: метод оптимизации; сейсмостойкое проектирование; конструктивный ущерб; сейсмоизоляция; нелинейный статический метод расчета; усредненный спектр отклика; кривая несущей способности; экономическая эффективность; жизненный цикл здания

Abstract. Structural seismic design optimization researches reviewing shows that existing economic effect assessment methods take into account only traditional seismic retrofit schemes excluding base-isolation system employment. The purpose of this study is to obtain economic optimization which allows to compare the economic effect *E* of base-isolated structure among with traditional seismic retrofit schemes. Here the approach is proposed of earthquake caused damage state D_{rel} computation in base-isolated structure considering repair works with due regard to its life-cycle *N*. The example of damage state D_{rel} evaluation for base-isolated and traditional retrofitted structures is performed considering different seismic intensities. It is shown how the value of damage state proceeds according to the building life-cycle *N* in each case. The economic effect *E* for these cases is estimated with the aid of proposed optimization algorithm.

Аннотация. Исследования в области оптимизации конструктивных решений сейсмостойкого проектирования показали, что существующие методики оценки экономического эффекта различных проектов не рассматривают применение сейсмоизоляции, принимая во внимание только традиционные варианты сейсмоусиления. Целью работы является получение алгоритма оптимизации конструктивных решений по экономическому критерию, который позволит сравнить экономический эффект *E* от применения сейсмоизоляции наряду с традиционными вариантами сейсмоусиления конструкций. Предложена методика по определению наступившего в результате землетрясения ущерба D_{rel} в сейсмоизолированном здании с учетом возможных ремонтных работ на протяжении жизненного цикла здания *N*. Приведен пример расчета ущерба D_{rel} сейсмоизолированного здания и произведен сравнительный анализ с альтернативными вариантами проектов сейсмоусиления при воздействиях различной интенсивности на протяжении рассматриваемого жизненного цикла здания *N*. Выполнена оценка экономического эффекта этих вариантов *E* по предложенному алгоритму оптимизации.

1. Introduction

The economic optimization problem of buildings structural design is paramount among others and specifically important in earthquake engineering. Therefore, this study proceeds the problem initiated in [1] and associated with economic optimization of seismic structural design considering the base-isolated structures. To provide calculations of economic effect using the method proposed previously in [1], it is necessary to define damage state of base-isolated building caused by earthquakes of different intensities.

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So, the research object in this article is the economic optimization algorithm, which consider the employment of base-isolation system for seismic retrofit of the building.

Economic optimization in earthquake engineering has been developed for the last 15 years [1, 2, 3], and the problem of economic effect assessment in seismic structural design was initiated in [4] at the first time. However, the problem is that the above research works did not propose an algorithm that associates the results of building seismic response computations to economic indicators for characterizing the building damage state. Another problem is that the optimization criteria in these works, except [1], is presented insufficiently specific. In article [1] that the economic effect with consideration of a building life-cycle is assigned as optimization criteria. The cost value of damage state is taken into account with consideration of repair work cost after a certain amount of seismic events. Nevertheless, the main shortage of study [1] is that it was limited by a small range of frame types and seismic retrofit schemes[1] which were engaged for economic analysis. Also the procedure of frames seismic response and damage state evaluation contains many uncertainties and theoretical assumptions. These circumstances led to provide the present study to reduce afore-mentioned drawbacks.

The problem of economic optimization in earthquake engineering was investigated by native and foreign scientists A.M. Yaglom [4], A.M. Uzdin, Yu.L. Rutman [1], M. Papadrakakis, N.D. Lagaros, M. Fragiadakis [2], Y.K. Wen, Y.J. Kang [5, 6] and others.

The big research work for developing of analysis methods and practical employment of seismic base-isolation systems was done by scientists J.M. Kelly [7], R. Scinner, W. Robinson [8, 9], A. Martelli [10], M. Higashino, Sh. Okomoto [11], A. Chopra [12], O.A. Savinov [13], Ya.M. Ayzenberg [14], S.V. Polyakov [15], Yu.L. Rutman [16, 17], A.M. Uzdin [18], Yu.D. Cherepinskiy [19], A.V. Kurzanov were involved in the researching of the seismic behavior of base-isolated structures as well.

The damage state for traditional seismic design schemes was evaluated in [1] with the help of capacity curves. There are also some studies, which consider inelastic seismic response of structures and dynamic properties [20, 21]. These curves were developed using pushover analysis concept. Pushover analysis is the nonlinear static analysis method that allows to evaluate the structural seismic performance of the building under a seismic excitation. This method became popular in foreign code provisions [22, 23, 24, 25] in the last the last 20 years. The basic pushover theoretical foundations were given by H. Krawinkler, G.D.P.K. Seneviranta [26, 27], V. Kilar, P. Fajfar [28], A.K. Chopra, R.K. Goel [29]. Nonlinear static pushover analysis for the last 5 years has also attracted the attention of scientists Yu.I. Nemchinov, N.G. Maryenkov, A.K. Khavkin, K.N. Babik [30], A.V. Sosnin [31, 32], K.T. Chkhikvadze, Ts.G. Tsiskreli, N.Sh. Chlaidze, L.D. Kadzhaya [33]. At the present time this method is not included in Russian seismic code [34] as an acceptable analysis procedure. Nowadays various studies are provided mainly by foreign researchers which investigate the possibility of pushover analysis utilization for different types of structures [35, 36], its compatibility with nonlinear dynamic analysis [37] and its modifications [38]. The big interest for the current research is represented by the study [39], where the application of a N2, extended N2 and modal pushover methods was demonstrated for the base-isolated building frames with lead rubber bearings analysis.

The issue of inelastic behavior of base-isolated buildings, which the present article is deal with, is analyzed in studies [40–42]. As it is seen, the number of studies, which consider the inelastic behavior of base-isolated structures, is small. There is an experimental investigation of inelastic behavior of base-isolated cantilever structure with friction pendulum bearing isolators [40]. The article [39] is aimed to consider the effect of higher modes and to compare different pushover methods for base-isolated frame analysis, but we have to give more clear and understandable procedure for engineering-economical practical purposes of fast cost-effectiveness estimation.

Therefore, the purposes of current research work are:

1. to propose the economic optimization algorithm, which should consider the base-isolated building;
2. to estimate the damage state in base-isolated building;
3. to define the optimal type of seismic retrofit scheme according to proposed criteria.

For achieving these purposes, following problems have to be solved:

1. the objective function and variable parameters of economic optimization algorithm need to be defined;

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[1] Seismic retrofit scheme means the term “anti-seismic measures” named in [1].

2. the procedure for damage state evaluation of base-isolated building due the various seismic input need to be developed;

3. the analytical model of the building need to be developed and the proposed optimization algorithm need to be implemented to it.

2. Methods

2.1. Optimization criteria and procedure

Some types of seismic traditional structural retrofit schemes Frame S_{PS} and Frame S_{MS} was considered along with the typical Frame S_{tip} designed without any seismic considerations, and the economic optimization criterion was proposed in [1]. The possible damage was defined as:

$$D(I)=D_{pr}(I)+D_{rel}(I), \qquad (1)$$

where D_{pr} defines the prevented damage, D_{rel} defines the real damage and D defines the damage that occurs in Frame S_{tip}, I – earthquake intensity[2]. These economic parameters allow to formulate the optimization criterion as follows:

$$E = -K_{ant} + f(k,N)\sum_{I=I_{min}}^{I=I_{max}} L(I)\cdot D_{pr} \qquad (2)$$

where K_{ant} – seismic retrofit cost (otherwise the building may collapse due the seismic ground shaking, and there would not be income profit, or it would be decreased, as the damage would limit the production output); $f(k,N)$ – cost adjustment factor in accordance with recommendations given in [1] under equation $f(k,N)=\left(\frac{1}{k}-1\right)[1-(1-k)^N]$. Here $k=\frac{d+d^*}{1+d}$, where d^* - depreciation rate (the parameter which determines reduction of building value over the time inverse to its maintenance period) d – annual profitability of manufacturing; $L(I)$ – average number of rate I earthquakes on the building site; N – time after the maintenance start (years).

In the Eq. (1) $D\text{-}D_{pr}=D_{rel}$ the real damage, as well as the prevented damage, contains the following:

- repair and replacement cost of injured structural elements;
- losses of equipment inside facility;
- losses in profit due to idle period when repairing.

The usage of two types of damage in the optimization criteria provides substantially more universal criteria as it said in [1]. If the typical frame is designed without any seismic considerations, then $K_{ant} = 0$ and $D_{pr}(I) = 0$. Thus, financial losses after earthquakes are defined by the damage $D(I)$, considering a number of certain seismic events with different intensities I, and by the adjustment of repair cost with respect to building life-cycle. If it is applied any type of seismic retrofit scheme like S_{PS}, S_{MS} [1], or if it is a base-isolated Frame S_{SIS}, then real damage $D(I)_{rel}=D(I)\text{-}D(I)_{pr}$ is less then $D(I)$, while financial losses increase with the rising of K_{ant}. The optimization objective function E_{eff} is defined by relationship of these parameters.

The prevented damage $D(I)_{pr}$, the real damage $D(I)_{rel}$ and the $D(I)$ damage in Frame S_{tip} can be obtained with the help of capacity spectrum pushover method. For providing computation according this method, firstly, the building capacity (pushover) curve need to be constructed. The capacity curve allows to forecast building damages and the kind of a structural failure corresponding to the roof displacement. The structural damage need to be associated with financial loss given by financial curve, which helps to provide calculations by Eq. (1).

2.2. Damage state and response spectrum developing for SIS buildings

As it was said, the damage state for traditional seismic design schemes is evaluated with the help of capacity curve, and this curve can be plotted using pushover concept. For developing this curve it is necessary to have the acceleration response spectrum which corresponds to the building foundation

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[2] The intensities of earthquakes are measured in terms of rate by MSK-64 scale.

motion. In the case of traditional seismic design[3], it is considered that the motion of the foundation coincides with the ground motion. In this case, the response spectrum is taken from seismic code [34]. Nevertheless, if it is supposed by seismic retrofit scheme the base isolation system (SIS) implementation, the code spectra applying is not justified [25] and this approach is not acceptable. The movement of the superstructure (structure located on SIS) does not coincide with the movement of the substructure (foundation of the structure). Thus, before calculating the economic effect by Eq. (2) the difference between substructure (kinematic foundation) and superstructure (building) motions have to be considered.

The current situation in seismic design practice of base-isolated building usually does not deal with inelastic behavior of superstructure and does not consider its damage caused by earthquake. This is related to the fact that the several code provisions prohibit yielding of base-isolated structures. However, for providing comparable economic analysis of different frame types and solution of structural optimization problem along with varying base-isolator types, it is necessary to consider the possibility of approximate damage, which could be caused to the base-isolated frame by earthquakes of different intensities.

The damage state of base-isolated building can be defined as the result of inelastic structural behavior of the structural elements of the building caused by the earthquake of sufficient intensity. Inelastic structural behavior leads to financial losses in terms of repair cost. So, for economic optimization problem solution the damage state need to be defined as a financial loss for repair works after every earthquake which can occur on the building site. To quantify the value of the damage state it is necessary to associate it with some seismic response parameter of the frame. Here this parameter becomes the frame roof displacement that is why a superstructure (frame) response spectrum have to be developed. This procedure is based on tier-by-tier spectrum approach and implies the following steps:

1. Accelerations of the substructure are obtained through a numerical simulation process involving nonlinear time history analysis of "superstructure - SIS" system response to seismic ground shaking. It is assumed here that the superstructure is extremely rigid. The analysis is performed for representative ground motion ensembles which are grouped by intensities in terms of the rate.

2. When acceleration of substructure for every time history from the ensemble are calculated, it becomes possible to develop the superstructure response spectrum. Therefore, a single degree of freedom system (SDOF) calculation is performed. The oscillator is subjected to total acceleration values from the previous step time history analysis, and the ensemble of response spectrums is obtained. The final superstructure response spectrum for each group of seismic ground shaking intensity can be defined with the help of the statistical analysis as the sum of mathematical expectations assessment and estimation of the standard deviation. Thus, by averaging spectral acceleration values the superstructure response spectrum can be developed

2.3. Economic optimization for SIS buildings

Based on the superstructure response spectrum, the roof displacement, the structural damage of the frame and the corresponding financial loss could be defined with the help of simplified nonlinear static pushover analysis. Then the optimization algorithm described before can be applied. In the case of comparing economic effect from using different types of seismic base isolators, the variable parameters become SIS mechanical characteristics. Therefore, not only the structural repair cost (this kind of loss may not occur) contributes life-cycle investments, but SIS price increase it as well. In the present study it is shown, how the economic effect of base-isolated frame comes out respect to other retrofit schemes proposed in [1].

2.4. Structural model and numerical simulation

2.4.1. Structural frame and SIS characteristics

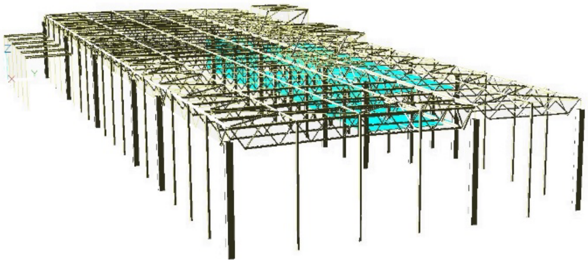

Figure 1. Industrial building Frame S_{tip}

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[3] In this study and [1] the traditional seismic design implies strengthening of loadbearing structures by increasing the main reinforcement of the concrete columns and steel structures elements profile sections

The frame which is used for instance of the damage state evaluation process in building with SIS and for representation the economic optimization concept along with other frame types has been already presented in [1]. This is the industrial building frame given in Figure 1, but for the case of SIS applying the foundation framework was designed supported by elastomeric isolators. All strength characteristics of elements sections of Frame SSIS are similar to Frame Stip in study [1]. Total building dead weight plus anticipated live loads is assumed equal to 28000 kN. The construction of SIS building implies to design the foundation framework located on elastomeric isolators. These isolators are presented of two types: with maximum vertical load on one support 1400 kN and with maximum vertical load on one support 600 kN. The combination of these supports with the consideration of relative vertical load distribution composes the layout for the foundation framework (kinematic foundation). The chosen construction parameters of base-isolation supports provide natural frequency of isolation system f = 0.4 Hz.

Ground motions used in this study were generated by PEER ground motion database[4]. Ensembles of ground motions compiled in such manner that the amount of earthquake occurrences of a certain rate does not exceed their average number for considered building life-cycle equal to 50 years. Then, in accordance with the amount of ground motions used in [1], it is necessary to provide numerical simulations for Frame Stip for the number of ground motions shown in the last line of Table 1.

Table 1. Life-cycle earthquake occurrences amount and the number of ground motions in ensembles for numerical simulation

	6 rate	7 rate	8 rate	9 rate
Life-cycle earthquake occurrences amount, N = 50 years	5	4	3	1
Ground motions for numerical simulation	15	12	9	3

2.4.2. Nonlinear time history analysis and mean response spectrum developing

1. The nonlinear time history analysis is provided for every seismic ground motion record from ensembles for the system "superstructure (equivalent SDOF system) - SIS". The calculation is carried out using Nonlin and MathCad programming. In Figure 2, as an example, the seismic ground shaking record of the rate 9 earthquake is shown. After computation, the maximum acceleration 0.46 m/s^2 was obtained (Fig. 3). The same numerical simulations are provided for all time histories divided into 4 groups accordingly to the rate of earthquake.

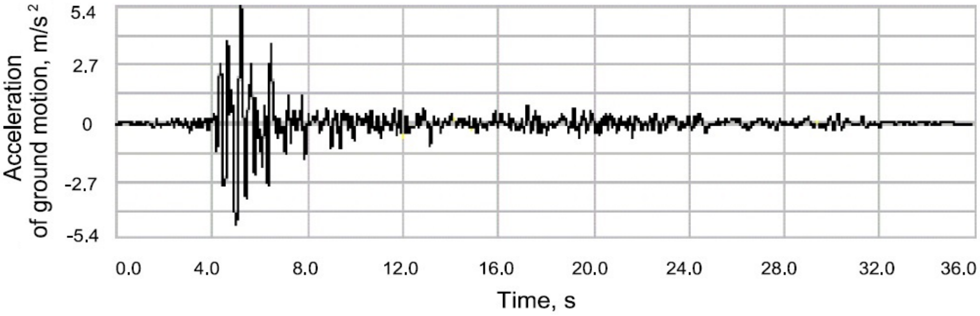

Figure 2. Ground motion record for the rate 9 earthquake

2. The calculation of the single degree of freedom system (SDOF) is provided. The oscillator is subjected to total acceleration values from a previous stage time history analysis (Fig. 3). Thus, the response spectrum is generated in terms "Spectral acceleration – Oscillator frequency" for each kinematic foundation motion, thereat, total acceleration absolute values for discrete oscillator frequencies are fixed. Frequency increments in the peak spectral acceleration range should be small enough not to miss their maxima.

3. The obtained response spectrums are divided into 4 groups depending on the rate of initial seismic ground shaking. Then the statistical processing of response spectrums within each group is performed and oscillator absolute acceleration peak values are derived as well. Consequently, it is possible to determinate the mean response spectrum associated with each group of seismic intensity (Fig. 4).

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[4] https://ngawest2.berkeley.edu/

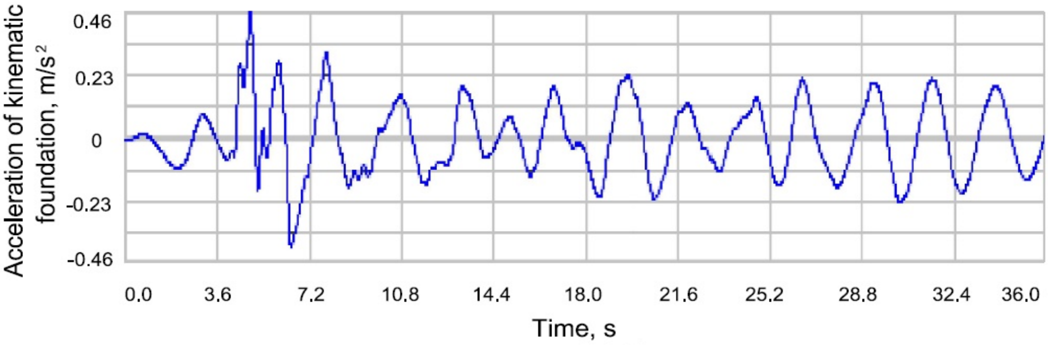

Figure 3. Computed kinematic foundation motion for the rate 9 earthquake

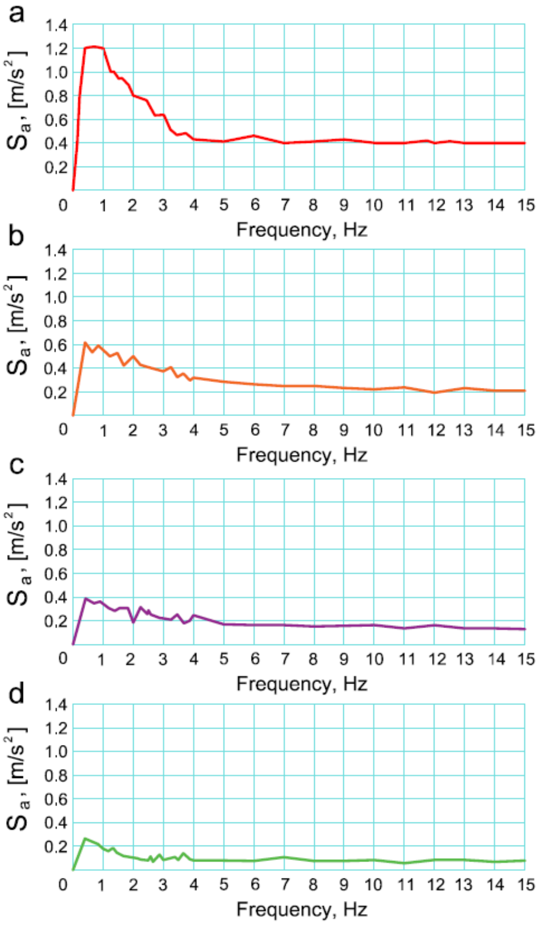

Figure 4. Mean of response spectrums represents time histories ensembles of (a) rate 9 earthquakes (b) rate 8 earthquakes (c) rate 7 earthquakes (d) rate 6 earthquakes

2.4.3. Calculating maximum structural displacement using simplified nonlinear static analysis procedure

Further calculations consist in applying simplified nonlinear static analysis procedure, in particular, the capacity spectrum (pushover) method “A” [20], for calculation the maximum structural displacement. If the maximum structural displacement is computed, then it becomes possible to estimate the structural damage by the displacement demand. The procedure implies the performance of the step-by-step process, the essence of which is as follows:

1. Mean values of response spectrums obtained at stage B are transformed from the Sa vs Frequency format to the Sa vs T format. Then, accordingly to capacity spectrum procedure “A” used for determining system performance point, 5 % elastic response spectrums are constructed from the mean ones. The obtaining results are converted then from the standard Sa vs T representation to Acceleration–Displacement Response Spectra (ADRS) format. Figure 5 shows the mean of 5 % simplified (by enveloping peaks of the initial Sa vs T spectrum) damped elastic response spectrum conversion from the standard simplified Sa vs T format to ADRS format associated with the ensemble of rate 9 ground motions.

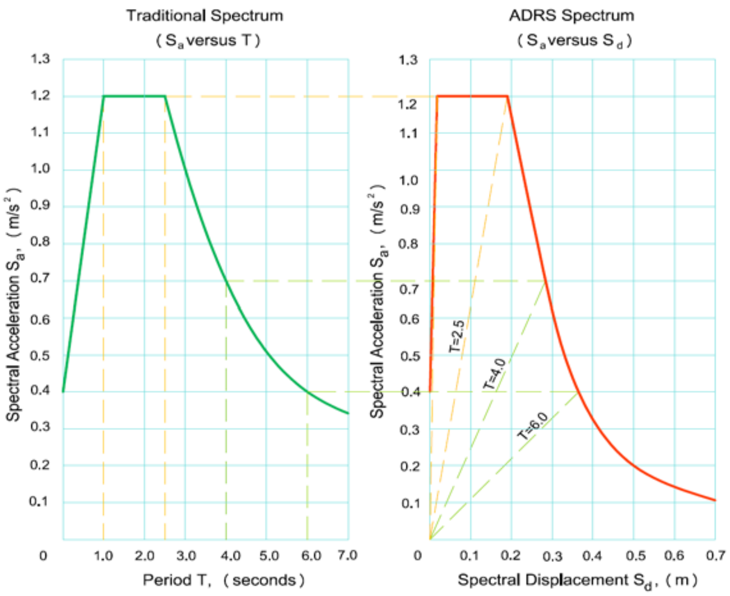

Figure 5. Mean of response spectrums conversion from S_a vs T to ADRS format associated with the ensemble of rate 9 ground motions

2. The obtained in [1] capacity curve for Frame Stip is converted to a capacity spectrum which have to be plotted in ADRS format as well using equations and provisions provided by [24–26]. Computations are performed for 2 points, which was calculated in [1] and used for Frame Stip capacity curve construction. The amount of these points corresponds to the number of selected performance levels. To provide further analysis, the building is substituted with equivalent single-mass system, and modal participation factor PF1, modal mass coefficient α, parameters w and ϕ are computed with consideration of this assumption. Figure 6 depicts the conversion of the capacity (pushover) curve to the capacity spectrum for Frame Stip.

3. A trial performance point is selected. The first choice of the trial performance point could be the displacement obtained using the equal displacement approximation [20]. The construction of this point is given in Figure 7.

4. A bilinear representation of the capacity spectrum is developed emanating from the requirement of the approximate equality of the area designated A1 and the area designated A2. These areas are formed by the rotation of a straight line starting from the trial performance point (Fig. 7).

5. The spectral reduction factors SRA and SRV are calculated as given by equations in [7]. Therefore, the reduced 5 % damped elastic response spectrum, called the demand spectrum, can be developed by the multiplication of the 5 % damped elastic response spectrum points by spectral reduction factors SRA and SRV. The characteristic points of the constant acceleration (horizontal) range of 5 % damped elastic response spectrum are multiplied by the spectral reduction factor SRA and the points of the constant velocity (descending) range are multiplied by the factor SRV. Demand spectrum points are obtained by intersecting horizontal projections of computed spectral acceleration ordinates with lines of constant period radiating from the origin.

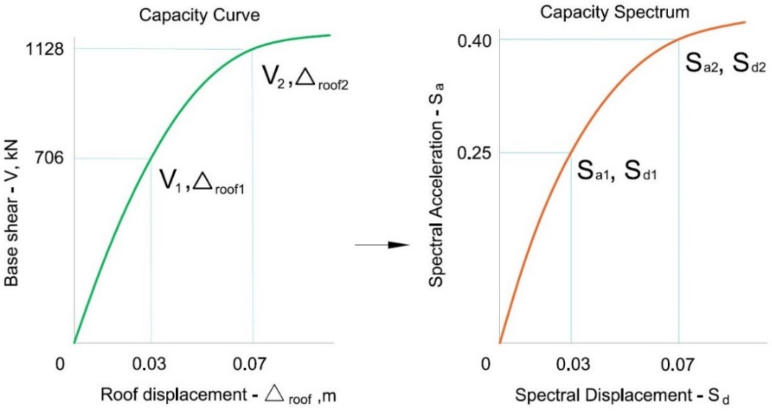

Figure 6. Capacity (pushover) curve to capacity spectrum conversion for Frame S_{tip}

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6. Drawing the demand spectrum on the same plot as the capacity spectrum develops the intersection point. This point represents the condition for which the seismic capacity of the structure is equal to the seismic demand imposed on the structure by the specified ground motion [22]. If this point is within acceptable tolerance, then the trial performance point is the performance point and the displacement represents the maximum structural displacement expected for the demand earthquake. If the demand spectrum does not intersect the capacity spectrum within acceptable tolerance, then the obtained intersection point becomes a new trial point and computations are provided again.

In case of this computation, a few iterations have been provided before the demand spectrum intersects the capacity spectrum in the trial performance point obtained on previous step within acceptable tolerance (the first and the last iterations are shown on Figure 7). Thus, the result displacement represents the maximum structural displacement expected for the seismic demand. As the calculation is performed for the multi degree of freedom system, so it is necessary to convert the maximum structural displacement value back into the MDOF format using the equation (14) denoted in [10]. Figure 7 depicts that the considering seismic demand causes the structural displacement which leads the frame to collapse. On the financial curve plotted for the Frame Stip in [1] the obtained performance point is outside the range of displacements limited by performance objectives (Fig. 8a). According to the idea proposed in [1] this fact designates that the considering seismic demand induces the maximum possible damage state equal to 1. In the same way, computations are conducted for ensembles of rate 8, 7 and 6 seismic demands. The corresponding financial curves are plotted in Figure 8b-d. The results of these calculations are summarized in Table 2.

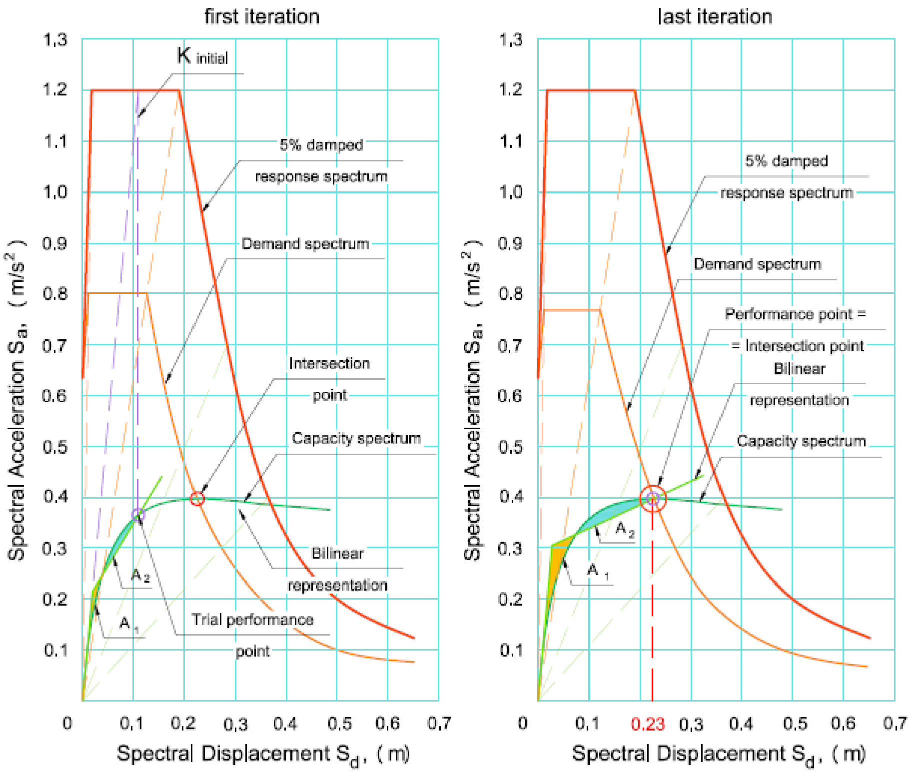

Figure 7. Performance point search using the capacity spectrum method "A" of nonlinear static analysis

Table 2. Nonlinear static analysis results of Frame S_{tip} considering all possible earthquakes of different intensities on the site with due regard to its life-cycle

Ground motion ensembles	Maximum displacement	Damage from caused by a single earthquake D_{rel}	Damage from caused by all earthquakes for considered life-cycle
Rate 6	*0.01*	*0*	*0*
Rate 7	*0.02*	*0*	*0*
Rate 8	*0.06*	*0.011*	*0.033*
Rate 9	*0.23*	*1*	*1*

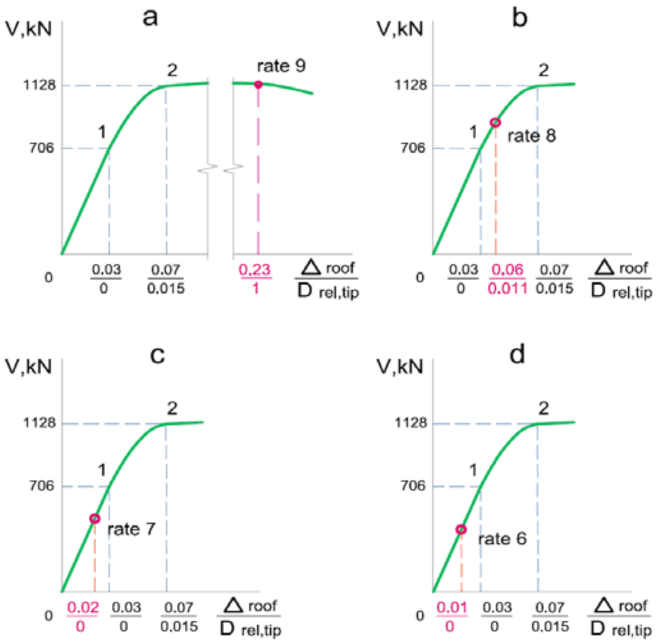

Figure 8. Financial curves with maximum displacements defined by nonlinear static analysis for time histories ensembles of (a) rate 9 earthquakes (b) rate 8 earthquakes (c) rate 7 earthquakes (d) rate 6 earthquakes

2.4.4. Economic effect estimation and seismic retrofit cost

As was quantified in [1], the cost of Frame S_{tip}, including cost of materials and construction works cost, is C_{tip} = 15.9 million rubles. The SIS cost for isolating the entire building is defined as the total cost of considering isolators combination plus seismic foundation framework supported by them. The cost of all supports in accordance with the commercial offer received by the manufacturer plus the seismic foundation framework cost is K_{ant}=0.037 in fractions of the total building cost. Therefore, all necessary data for the economic effect *E* calculation using Eq. (2) are now available.

Values of the economic effect *E* are calculated at seven points that characterize financial loss at a certain moment of building life-cycle. The results are plotted in terms of «economic effect *E* – building life-cycle *N*», each frame corresponds the respective curve. When calculating parameter *f(k,N)* the variable, which characterizes the profitability, is applied equal to *d* = 0.1 and *d** = 0.03, but its value may change depending on the size of income profit

3. Results and Discussion

The diagram in Figure 9 shows that economic effect curves for Frame $S_{\neg PS}$ and Frame $S_{\neg MS}$ are parallel and the curve for Frame SSIS is descending with time. This is associated specifically with the fact that the rate 8 earthquakes drives Frame SSIS into inelastic range and leads to some structural damage and the rate 9 earthquakes causes completely collapse of this frame. Represented at Figure 9 curves were developed by values of total structural damage obtained in Tables 1–3 in study [1] and in Table 2 of this paper. However, as it was previously noted in [1–3, 5, 6], not only structural elements become defected after earthquake, but also non-structural ones (partition walls, false ceiling and etc.) are failed. Furthermore, the utility systems, MEP, technological equipment and site landscaping could be damaged that represents financial losses related with business interruption. Considering this, the approximate assumption that the total damage increases twice in comparison with the structural one (as it was supposed in [1]), is admitted here. Consequently, the economic effect variation is plotted on the graph at Figure 10. Thus, the biggest economic effect E at the end of the building life-cycle can be achieved, as before, applying $S_{\neg PS}$ seismic retrofit scheme. The small economic effect of base-isolated Frame SSIS can be explained by the low initial strength of some elements of the frame itself and small effective SIS construction or mechanical parameters.

In this paper and in the study [1] only 4 types of structural frame is compared: Frame Stip designed without any seismic considerations, partially-reinforced Frame S¬PS, maximum reinforced Frame S¬MS and base-isolated Frame SSIS. However, the greater economic effect at the different life-cycle stages could be achieved considering more options of seismic retrofit schemes, for example:

1. Performing partial reinforcement of the most stressed structural elements in Frame SSIS, for instance, reinforced-concrete columns and braces in truss system. In this case, SIS cost may be decreased;

2. Performing various types of a more effective (in terms of seismic input reduction), but more expensive SIS, and compare economic effects. For instance, the analysis could be provided for some types of rubber elastomeric isolators [7], as it was done in [39], especially high damping soft type isolators. In another case, friction pendulum seismic isolation bearings, discussed in [16], or the similar ones [40] could be considered as well.

3. Involving supplemental damping devices in base isolated frame if it is necessary.

4. As the obtained results have shown, the big problem is still the capacity curve construction and the calculation of points, which could characterize adequately the structural performance of the building.

The optimization algorithm obtained in this study is specific in comparison with optimization algorithms obtained in studies [1–3]. In article [2] optimization algorithm takes into account the life-cycle cost of the building as well. However, the optimization criterion is not represented clearly. The range of frame types is limited with consideration of traditional seismic retrofit schemes. The article is mostly aimed for comparing the different pushover methods. Study [3] is turned to more general economical problem of seismic hazard, it considers the social losses caused by earthquakes, but it does not propose the tool for structural optimization in earthquake engineering. The optimization algorithm proposed in [1] is supplemented by this paper and gives the especial tool for engineering-economical analysis in seismic structural design.

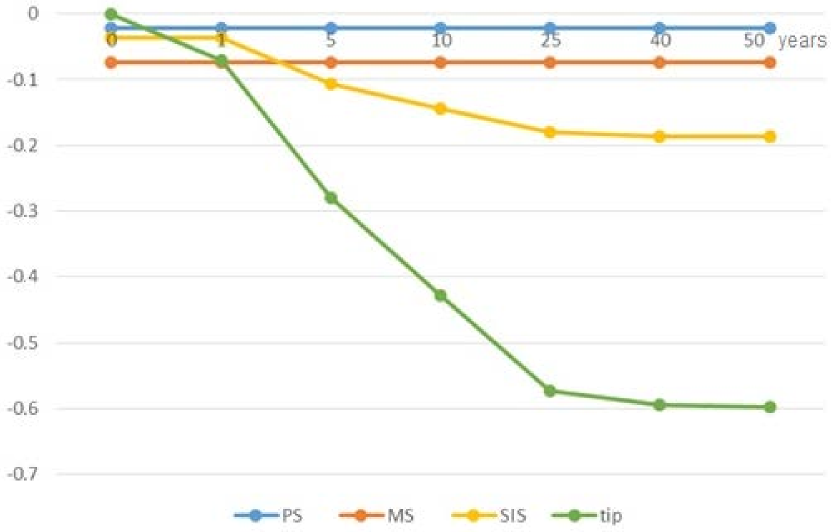

Figure 9. Dependence plot «economic effect *E* – building life-cycle *N*» considering structural damage

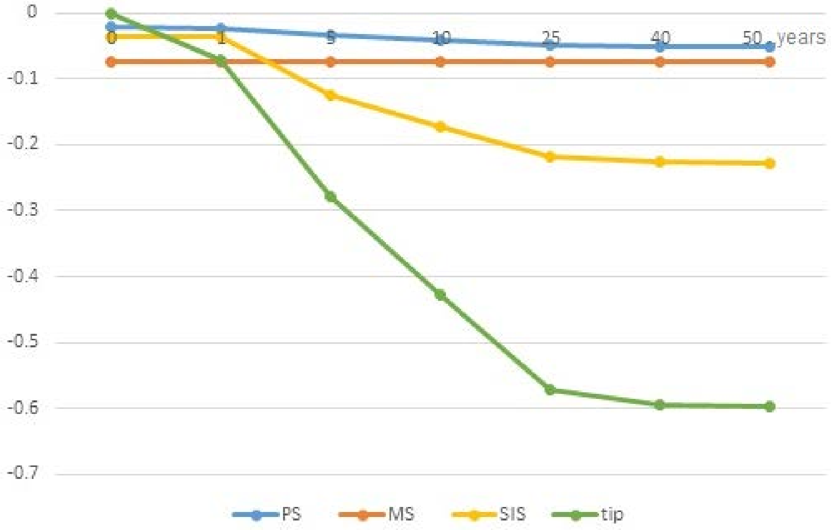

Figure 10. Dependence plot «economic effect *E* – building life-cycle *N*» considering total damage

4. Conclusions

1. In this study the economic optimization algorithm is proposed and it is shown how to use it for the base-isolated frame financial loss estimation along with traditional retrofit schemes. It becomes possible to compare and to find the reasonability of applying any type of mainstream seismic retrofit schemes at the project designing stage.

2. The procedure for estimation the damage state in base-isolated building is proposed by performing the following tasks:

- Consideration of the effect of seismic isolation system implementation with the help of tier-by-tier spectrum approach and time-history analysis of the system "superstructure - SIS";
- Evaluation of the damage state of structural system with a help of nonlinear static pushover analysis capacity spectrum method that allows to take into account the possibility of inelastic behavior in base-isolated frame.

3. The computations were performed and the practical application of proposed economic optimization algorithm and damage state evaluation method was demonstrated by the example of industrial building frame analysis.

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Andrei Ivanov,*
+(950)031-81-62; andreyivanov4@gmail.com

Sergey Chernogorskiy,
+7(911)917-78-16; chernog_sa@spbstu.ru

Mark Vlasov,
+7(965)061-07-87; markvlasov@mail.ru

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Андрей Юрьевич Иванов,*
+(950)031-81-62;
эл. почта: andreyivanov4@gmail.com

Сергей Александрович Черногорский,
+7(911)917-78-16;
эл. почта: chernog_sa@spbstu.ru

Марк Павлович Власов,
+7(965)061-07-87; эл. почта: markvlasov@mail.ru

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