Developing Vulnerability and Risk Theory for seismic risk management

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SUMMARY:

Some problems of the vulnerability and risk theory have been studied. These are the problem of optimizing investments in a detached structure, the problem of optimizing investments in a block of structures, and that of estimating the cost range of earthquake engineering projects as well as estimating the cost range of insurance of structures in seismic prone areas. To solve these problems, a method of estimating earthquake engineering efficiency has been developed. Different variants of vulnerability functions are presented. The parameters of the proposed functions for regions of Russia with different seismic hazard have been obtained. The proposed solutions take into account both economic and social losses caused by an earthquake. To take into account social losses, a special parameter was introduced. It is the ratio of insurance cost of human life and the cost of housing space per one person in the region under consideration. A task of investments distribution between several buildings is analyzed. It is shown that the optimum investments distribution between similar buildings can be unequal. The problems of commercial value and public efficiency as well as of regional and specialized (industry) efficiency are considered.

To estimate the cost range two ways were analyzed. The first way estimates the value of production cost and the second way takes into account the use cost of earthquake strengthening.

Some examples of estimating earthquake engineering efficiency are considered.

Key words: vulnerability, risk, investment optimizing, investment distribution, economic losses, social losses

1. INTRODUCTION

Engineering methods of seismic risk management are determinant in earthquake engineering in Russia. There are different guidelines and standards the observance of which is to provide seismic risk control. But economic methods can be more effective than engineering ones. Among economic methods the following should be stressed:

- Estimating the efficiency of investments in earthquake engineering and defining the optimum investments for each structure.
- Optimizing the investment distribution among members of a certain group of structures.
- The control of the cost range of buildings in earthquake prone areas
- Insurance of earthquake engineering

All the above mentioned ways of economic management should deal with economic and human losses. All these ways are based on estimating economic efficiency of earthquake engineering. The design formula of this estimation was proposed by Academician L.Kantorovich in the middle of the fifties of the last century. This formula was included in the guidelines published by the USSR Academy of Sciences in 1962 (Keylis-Borok et al, 1962). During the ensuing years this formula was developed by other researchers (Perelmuter, 2000, Sakharov et al, 2007). Henceforward the following formula will be used:

$$E(K_s) = -I_{inv}(K_s) + f \cdot \left[P_0 - Pm(K_s) - (1 + \alpha \cdot P_0) \cdot \sum_{I=5}^{10} \left(D(K_s, I) - Ins(K_s, I) \right) \cdot L_I \right] \quad (1.1)$$

where:
$I_{inv}(K_s)$ is the investment in the aseismic strengthening of the structure which is to provide its seismic resistance degree (SRD) equal to the value K_s;
P_0 is an annual income of the owner expected from the building operation;
f(к,T) is the ratio which takes into account the discounting of receipts and expenses;
$D(K_s,I)$ is the damage caused by the earthquake with intensity I for a building with SRD equal to the value K_s;
α is the index of the building stop time τ for recovery work after the earthquake; this time was set as proportionate to the value $D(K_s,I)$;
T is the structure life-time;
L(I) is the region shakability which is equal to the average number of earthquakes with intensity I per year;
$Pm(K_s)$ is the annual insurance payment;
$Ins(K_s,I)$ is the insurance coverage caused by the insurance event.

All estimations are carried out below using the traditional assumption that earthquakes are a Poisson flow of events.

2. PRESENTATION OF THE VULNERABILITY FUNCTION

The vulnerability function should be defined in order to use formulas (1.1). To this end we used different data about damages after past earthquakes. Such data can be found in seismic scales and literature (Poltavtsev, 1995; Sackharov, 2004; and others). The volume of bridge damages caused by earthquakes is described in the “Guidelines for estimating the earthquake resistance of bridges in operation”, which were adopted in the former USSR in 1988. Now these Guidelines are in law in Turkmenistan. The view of the vulnerability function in accordance with these Guidelines is shown in Fig.1. Two ways of presenting the vulnerability function on the basis of the above mentioned data were used.

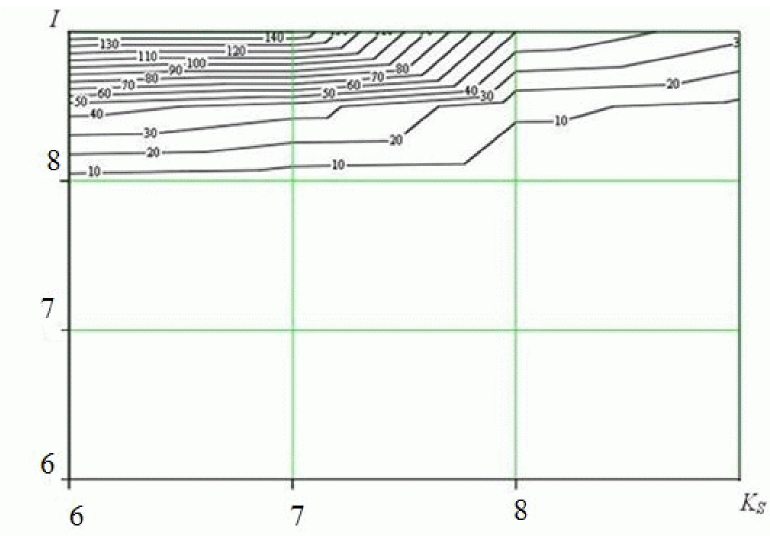

Figure.1. The view of the vulnerability function for bridges (% of structure cost)

The first way presents the vulnerability function as a probability function. The Weibull law turned out to be the most convenient probability function to approximate real vulnerability functions. Fig.2 illustrates the presentation of the set of vulnerability functions for brick buildings on the Weibull law basis.

The second way presents the vulnerability function as follows

$$D(K_s, I) = A_0\left(1 - e^{-\alpha\left(\frac{I}{K_s}\right)^{\nu}}\right) \tag{2.1}$$

This formula (2.1) automatically provides the following conditions

$$\lim(D)\big|_{K_S\to\infty} = 0\,;\;\; \lim(D)\big|_{I\to\infty} = A_0\,;\;\; \lim(D)\big|_{K_S\to 0} = A_0 \;\;\; \lim(D)\big|_{I\to\infty} = 0\,. \tag{2.2}$$

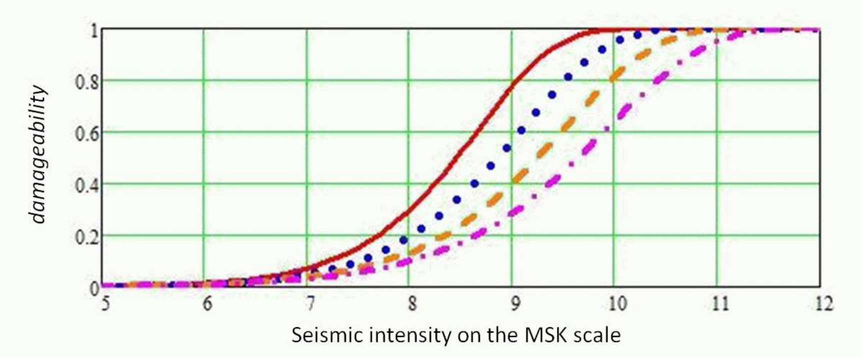

Figure 2. Vulnerability function D(Ks,I) for brick buildings
Solid curve – for Ks=6 on the MSK scale; point curve – for Ks=7 on the MSK scale;
dotted line – for Ks=8 on the MSK scale; dash-and-dot line– for Ks=8 on the MSK scale

Three parameters A_0, α and ν can be defined using the information about structure damages caused by earthquakes with different intensity in accordance with seismic scales.

For special engineering construction, which are not described in the seismic scale, one has to use performance based designing (PBD), which foresees scenarios of structure damages accumulation. On the basis of such scenarios we can foresee and estimate the level and the cost of structure damages and then to define the values of A_0, α and ν. In all cases the correspondence of approximation (2.1) to the real facts was set using the least-squares method.

An example of the proposed dependence (2.1) is shown in Fig. 3. This dependence includes four characteristic points, which are shown on the curve D(I).

There is no damages left-of-point 1.

Between points 1 and 2 a certain increase in damage accumulation takes place and the velocity of damage accumulation also increases.

Between points 2 and 3 the velocity of damage accumulation changes very little and the damages go up quickly. At point 3 any further operation of the building is impossible. In the section between point 3 and point 4 a complete collapse of the building takes place. The overall losses at point 4 exceed the total building cost due to of the secondary losses. Fig.4 shows the dependence D(I) built up for usual buildings on the basis of the seismic scale information.

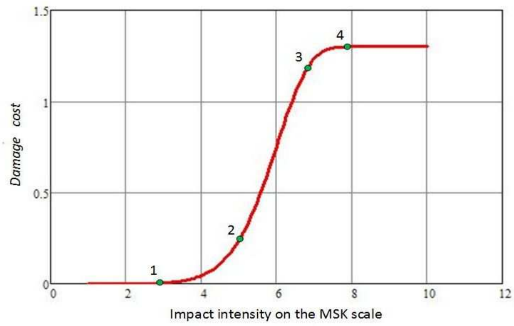

Figure 3. Characteristic dependence of damages on earthquake intensity

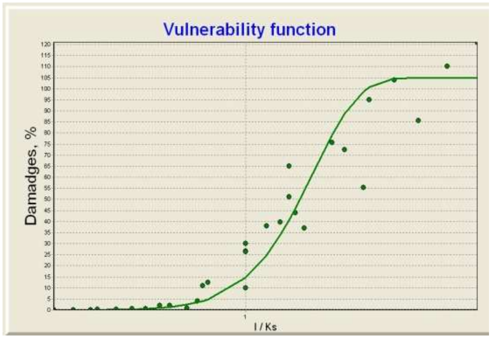

Figure 4. Approximation vulnerability function;
The data about building damages with different SRD in accordance with seismic scale is shown by points

3. PRESENTING THE VULNERABILITY FUNCTION FOR HUMAN (SOCIAL) LOSSES

In practice main losses caused by earthquakes are connected with human or social losses. To take them into account, the proper vulnerability function is to be set. With this aim 2 hypotheses were used.

1) Significant human losses begin to occur when damages in the structure exeed the value D_h ~50-70% of ultimate damages.
2) The relative value of insurance money for the loss of life C_H can be estimated using the following formula:

$$C_H = \frac{C_{ins} \cdot N}{C_0} = \frac{C_{ins}}{C_0 / N} = \frac{C_{ins} \cdot \mu}{Pr \cdot [S]}\ , \qquad (3.1)$$

where:
C_{ins} is the insurance money for the loss of life;
N the number of the human losses;
C_0 is the construction cost, i.e. is the cost of constructing a building or a group of building
Pr is the cost of a square meter of a building;
μ is the ratio of human losses;
[S] is the average floor-space per person in the region.

If the Weibull law is used for approximating the vulnerability function of human losses, one has to change the location parameter in accordance with the abovementioned hypotheses, and the value of damages is to be multiplied by the coefficient C_H.

The value of the least ultimate earthquake intensity I_h which causes human losses can be defined using the following equation:

$$1-e^{-\left(\frac{I_h-Io}{\beta-Io}\right)^{\nu}}=D_h \tag{3.2}$$

By solving this equation one can obtain the value of I_h

$$I_h=Io+\left[\ln\left(\frac{1}{1-D_h}\right)\right]^{\frac{1}{\nu}}\cdot(\beta-Io) \tag{3.3}$$

Thereby the location parameter of the vulnerability function for human losses is set equal to the value I_H and the scale parameter β is set the same as for the vulnerability function for economic damages. The shape parameter ν is set assuming that the 100% human losses occur at the complete collapse of the building.

An example of the vulnerability function for human losses is shown in Fig.5. This function is built for a frame building if the value C_H=1. Parameters of the economic vulnerability function are I_o=1.59, β=8.84 and ν=10.48. For the value D_h=0.5 in accordance with formula (7) one can obtain I_h=8.59. In this case the acceptable value of the shape parameter $\nu \approx 0.8$.

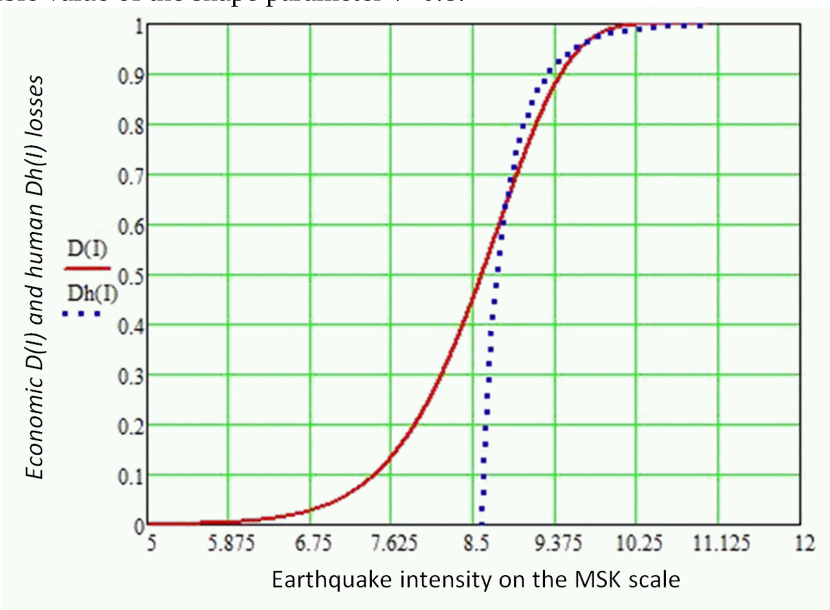

Figure 5. Vulnerability functions for the frame building taking into account economic losses (solid curve) and human losses (dotted curve)

Social losses can be estimated directly using seismic scales and available data. G.L.Koff (1996) gives the average volume of social losses divided by the total number of inhabitants of the affected regions. This estimation is close to that obtained by using formula (3.1).

Indeed, the total insurance payments can be estimated as follows

$$C_{HL}=C_{ins}\cdot H\cdot D_H \tag{3.4}$$

where H is the total number of inhabitants in the region, D_H is social losses, notably the relative number of the death toll.

In this case the total damages are as follows

$$C_H = \frac{C_{ins} \cdot H \cdot D_H}{C_0} \tag{3.5}$$

As opposed to formula (3.1) in which H is the total number of inhabitants in the building under consideration in formula (3.5) H is the total inhabitants number in the region, D_H is the relative number of the death toll in the region, C_0 is the cost of all buildings in the region.

Dividing the numerator and denominator in formula (3.5) by the value H we can get the following result

$$C_H = \frac{C_{ins} \cdot D_H}{\frac{C_0}{H}} = \frac{C_{ins} \cdot D_H}{Pr \cdot [S]} \tag{3.6}$$

As opposed to (3.1), formula (3.5) defines social losses for a region and formula (3.1) does the same for a building.

Taking into account formula (3.5) one can present formula (1.1) as follows

$$E(K_s) = -I(K_s) + f \cdot \left[R_g - Pm(K_s) - Op - (1 + \alpha \cdot R_g) \cdot \sum_{I=5}^{10} \left(D(K_s, I) - Ins(K_s, I) \right) \cdot L_I - C_H \cdot \sum_{I=5}^{10} D_{HL}(K_s, I) \cdot L_I \right] \tag{3.7}$$

Formula (3.7) includes two components of the losses, the second component presenting the social risk, and the function $D_{HL}(K_s, I)$ determines social losses caused by the loads of the earthquake with seismic intensity equal to I for the structure with SRD equal to K_s.

Fig.6 shows that investment efficiency decreases when the value C_{HL} increases. In the case under consideration (the City of Sochi) antiseismic strengthening of structures with only economic responsibility (losses) is not efficient. For the value of C_{HL}=2 the most efficient are structures with RSD equal to 7, and for C_{HL}=10 the optimal value of RSD is equal to 8. The optimal value of RSD is obtained for all values of C_{HL} for the more dangerous region of Krasnaya Poliana.

For structures with economic and social losses the efficiency of investments is due to three main factors.

The first factor is the cost of antiseismic strengthening. Investments are to be covered by decreasing the value of seismic risk. The cost of antiseismic strengthening is to be decreased to increase the efficiency of antiseismic strengthening. For this aim modern systems of seismic protection including seismoisolation and damping devices should be used.

The second factor is the region seismicity. If the frequency of dangerous earthquakes is higher than once per 500 years, investments in antiseismic strengthening will be efficient.

The third factor is the value of C_H. There exists the critical value of C_H, which we designate as $C_H^{(cr)}$. If $C_H < C_H^{(cr)}$, investments in the antiseismic strengthening do not pay.

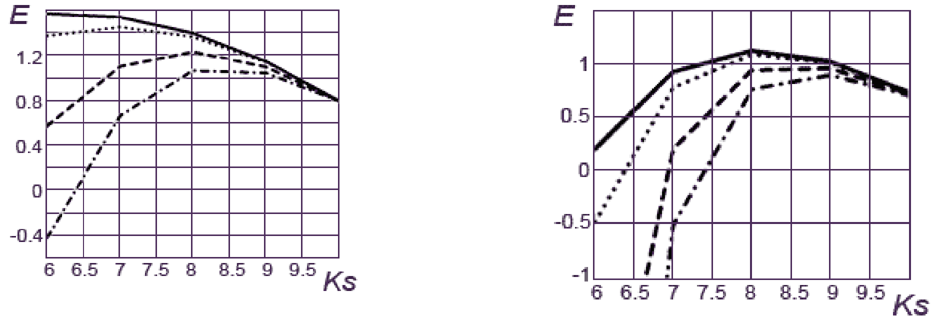

Figure 6. Some results of estimating the seismic isolation efficiency of base isolated structures obtained using formula (3.7)
The graph for Sochi is on the left and the graph for Krasnaya Poliana is on the right
solid for CHL =0, point for CHL=2, dotted for CHL=10, dashdot for CHL=20

The value of $C_H^{(cr)}$ depends on the region seismic danger and the value of C_H is defined by the degree of the national economy development. In accordance with our investigations C_H≈7…12 for the USA and the EU. For Russia this parameter is equal to 2…4. It means that the efficiency of the antiseismic strengthening of similar structures is different for different regions.

4. THE RELIABILITY OF RISK ESTIMATION

An important question of seismic risk estimation and of using the risk forecast for decision-making is reliability of this forecast, which is defined by the degree of uncertainty of the initial data and the stability of the forecast in spite of errors in these data. These questions have been studied widely for the last 10 years after the methods of economic risks management began to be used by insurance firms and were included into the government programs of developed countries.

According to the main formula (1.1) for estimating seismic risk, all uncertainty can be divided into two groups: the uncertainty, defined by seismic danger (function L(I)) and the uncertainty defined by the vulnerability function D(I).

The definition of seismic danger is considered to be a problem of seismologists. In regard to Russian seismologists, it is possible to judge the quality of their forecasts by the following fact. On the territory of the former USSR since 1948 there have been 27 strong earthquakes and only three of them took place in the areas regarded by seismologists as seismically dangerous. In the countries with the developed seismometric service and fixed places of ruptures of the earth crust along which seismic focuses can appear, for example in the USA where along the Saint-Andreas break dozens of seismological and geophysical centers are located, it is possible to speak about a certain degree of reliability of seismological information. Nevertheless, even in these areas every new earthquake brings unexpected results.

In spite of the complexity of the question under consideration seismologists present more and more information about seismic danger. Now in Russia three maps of seismic danger with earthquake frequency of one time per 500, 1000 and 5000 years are in use. In the near future it is planned to put into operation maps with frequency of one time per 200 and 10000 years. A lot of experts in developed countries use the prevailing periods of seismic input in the investigated region, the regional seismic spectra and the accelerogram ensemble. On this basis the damageability of buildings can be predicted.

The analysis of the question under consideration should be made separately for the risk forecast of mass building in the region and for risk estimations of certain buildings or a group of buildings.

Damages of mass building are estimated on the basis of seismic scales, and seismic danger is set using maps of seismic zoning. In this case the risk dispersion is defined by the known formula

$$D_R = \int_0^\infty (R - D(I))^2 p(I)\,dI = \int_0^\infty D(I)^2 p(I)\,dI - R^2 \tag{4.1}$$

Attempts of the numerical analysis of damageability on the basis of calculation by a linearly-spectral technique or using time-history processes, leading to the seeming accuracy of calculation, encounter a number of difficulties leading, in essence, to the uncertainty of forecasts. First of all, it is connected with a high degree of uncertainty of setting the regional spectra or a package of design accelerograms. A well known expert in the field of risk estimating, professor E.Durukal (2006) carried out calculations of losses for Coast of the Marmara Sea using the generalized characteristics of seismic danger (maps and input intensity) and using spectra of possible seismic input. In the first case the losses accounted for 14 % from building cost and in the second case they came up to 28 %.

Unfortunately, it is impossible to estimate the results of different authors, because all input data and the main method of analyzing are considered as commercial classified information and are unavailable. Questions of estimating losses are analyzed in the paper of J.Bommer, R.Spence and R.Phino (2006), where the authors discuss the problem of closed information for calculating losses.

In spite of this situation one can stress two aspects of the problem.

First, all information about seismic danger is incomplete and inauthentic. This is the reason for making all conclusions on the basis of the most general and indisputable seismological data. They are a macro-seismic degree of danger on the MSK scale taking into account the data of micro-seismic zoning and general energy characteristics of possible seismic impact. If some accelerograms ensemble has been used to estimate damages, it is necessary to generate the most dangerous accelerograms for the structure under consideration within the limits of the input intensity. The above mentioned approach minimises the number of the casual parameters, which describe seismic danger.

Secondly, we cannot characterise risk and other parameters by the one and only value, because they are random variables. In most cases authors operate with the damage population mean, i.e. seismic risk. Thus, it is necessary to remember that a visual representation of a random variable is a dim stain. The standard of seismic risk at distributing the number of earthquakes by the Poisson law is estimated by the formula

$$\sigma_D(K_s) = \left[\sum_{I=5}^{10} D_0^2(I, K_s) L(I)_I \right]^{1/2}, \tag{4.2}$$

where L is seismic shakability of the building site (the average number of earthquake per year).

The dependence of efficiency of investment E (K), and also the dependences $E \pm \sigma_D$ are shown in fig.7. The obtained variability of the result is predetermined by the Poisson law.

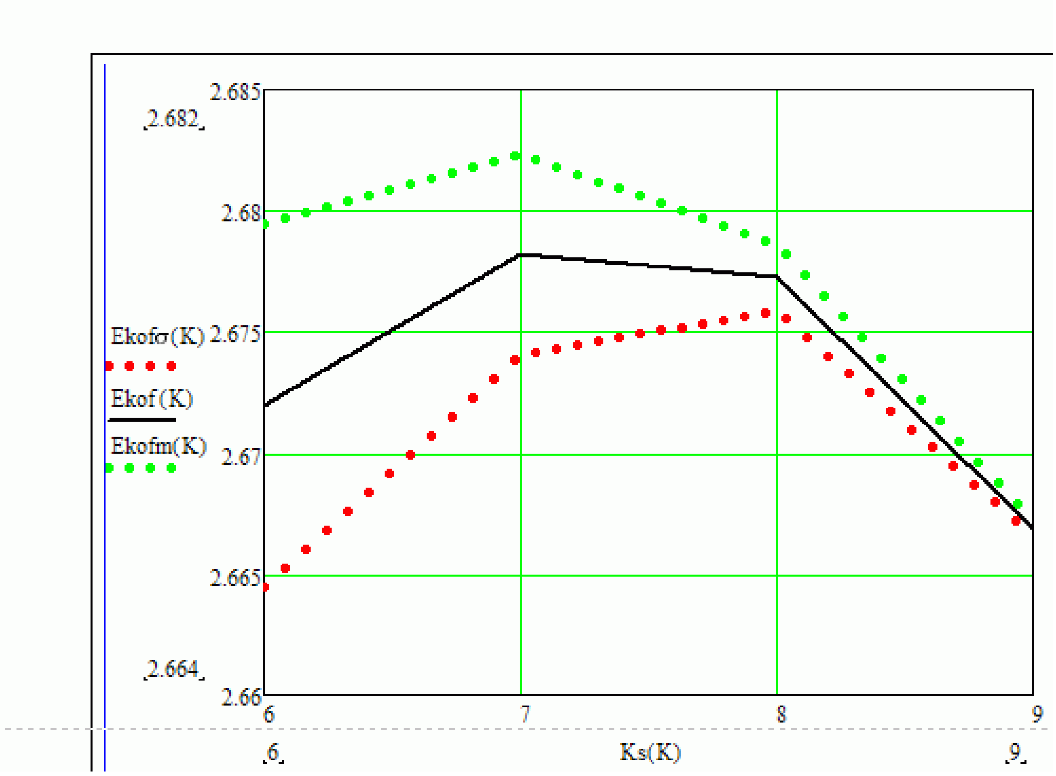

Figure 7. The dependencies of efficiency of investment E and E±σD on the structure resistant degree K_s

Now let's consider another source of uncertainty of estimating risk. It is the function of damageability D (I). For the forecast of risk of mass building in the whole region the damage is estimated on the basis of seismic scales. Naturally, these data have dispersion. In the literature on the subject there are attempts to estimate damages according to structure calculations. Unfortunately, nowadays it is impossible to describe accurately the deformation diagrams of materials beyond the elasticity and character of element damages. However, modern principles of designing allow us to solve the problem of the damages forecast. Performance based designing with the given parameters of ultimate states makes it possible to design scenarios of accumulation of the structure damages. Thus, places of damage concentrations are provided for in the structure. The corresponding fragments of the design can be tested in details and both their deformation diagram and the volume of damages can be described. In this case the problem of reliability of the forecast of damages and the damage size can be easily solved. In our opinion a successful combination of the constructive decision with damageability optimisation has been achieved for some railway bridges in Sochi (2011), where the scenario of damages accumulation was designed with the damages concentrating in bearing knots of spans and piers.

5. CONCLUSION

The purpose of earthquake engineering is to minimise economic and social losses caused by earthquakes, thus providing efficiency of aseismic investments. The management theory of seismic risk is being developed for this purpose. Now the main methods of risks management used in designing are engineering ones. To this end guidelines for earthquake engineering have been worked out. However, in fact, the economic methods, which include optimisation of investment efficiency into antiseismic strengthening taking into account possible insurance, should be more important for risks management then engineering one. Optimisation of investment efficiency makes it possible to set design strengthening volume and the corresponding level of seismic input, which defines in its turn the correctness of using the engineering methods. Thus, such factors, as structure service life and territory seismic danger can be taken into consideration. In our opinion, to reduce the uncertainty of seismic risk forecasting the following two principles should be used:

- Forecasting should be based on the most general and the authentic indicators of seismic danger (macroseismic seismicity, magnitude of possible earthquakes), accepting other characteristics to be the least favorable for constructions,
- PBD with the given parameters of ultimate states and the design of a scenario of damages accumulation should be used.

REFERENCES

Kejlis-Borok V.I., Nersesov I.A., Jaglom A.M. (1962). Methods of estimating the economic benefit of earthquake engineering, Moscow, Publishing House of Academy of Sciences of USSR,46pp.

Perelmuter A.V. Selected Problems of Reliability and Structural Safety. Publishing House of Ukrainian Institute of Steel Constructions (2000) 216 pp.

Sakharov O.A. (2004). The question of the seismic input setting for performance based designing. *Earthquake engineering. Safety of constructions*, №4, p.7-9

Poltavtsev S.I., Ajzenberg J.M., G.L.Koff, Melentev A.M., Ulomov V. I. (1998). Seismic zoning and Earthquake engineering (methods, practice, prospect), Moscow, State Unitary Enterprise TSPP, 259 pp.

Averyanov V. N, Baulin J.I., Koff G. L, Lutikov A.I., Mindel I.G., Nesmejanov S.A., Sevostyanov V.V. (1996). The complex estimation of seismic danger for the city of Grozny (Specification of initial seismicity. Seismic zoning. Seismic risk). Scientific editor S.I.Poltavtsev. Moscow, Publishing house of the building ministry. 107 pp.

Durukal, E., Erdik, M., Sesetyan, K., and Fahjan, Y. (2006), Building Loss Estimation for Earthquake Insurance Pricing, *Proceedings of the 8th US National Conference on Earthquake Engineering*, San Francisco.

Bommer, J., Spence, R and Pinho, R. (2006) Earthquake loss estimation models:time to open the black boxes? *First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC) Geneva, Switzerland, 3-8 September* **Paper Number: 834**

Kuznetsova I.O., Uzdin A.M.,. Zgutova T.V., Haibin Wan, Shulman S.A.(2011). Seismic protection of railway bridges in Sochi**.** *Proceedings of workshop "Bridges seismic isolation and large-scale modeling", Saint-Petersburg, 29.06-03.07, 2010*, p.28-36