SOME ANALYTICAL MODELS IN THE EARTHQUAKE ENGINEERING AND SOME WAYS OF REDUCING THE SEISMIC LOAD

I.M.Eisenberg[I], N.A.Nikolaenko[II], A.M.Zharov[III],

A.T.Stohl[III], Yu.P.Nazarov[IV]

SUMMARY

The research programme under way at present in the laboratory of the structural earthquake resistance (TsNIISK) involves a series of interdependent problems such as those of seismic risks, of constructing models of the ground motions and of new models of structures as well as problems of developing methods of reducing the seismic load due to the predicted self-adjustment of dynamic properties of structures when at earthquake. The general target of the project is to develop practical methods of structural analysis for a severe earthquake effect.

Below given are some results of the studies carried out within the project.

The sections of the paper were written by:

Section I - A.M.Zharov
Section II - I.M.Eisenberg
Section III - N.A.Nikolaenko, A.T.Stohl and Yu.P.Nazarov

I. A generalized model of an earthquake effect.

The need of more correct evaluations of structural safety at a rather strong earthquake has led to presentation of a structure as non-elastic models. Such models proved to be useful also when one should ascertain seismic danger of a construction site or evaluate probable damages

---

I/Head of Laboratory of Structural Earthquake Resistance, TsNIISK, Dr.Sc.(Eng.);

II/Senior Research Worker, Professor, Dr.Sc.(Eng.),TsNIISK;

III/Senior research worker, Cand.Sc.(Eng.), TsNIISK;

IV/Junior research worker, Cand.Sc.(Eng.), TsNIISK.

in erecting these or those types of structures in such regions. Unlike many other existing methods of ascertaining damages due to earthquakes, using this method makes it possible to take into account dynamic properties of buildings, their constructive specific features, strength characteristics of their members and the extent of their antiseismic reinforcement as well. In this case the damage caused by the earthquake is associated with damages in the non-elastic structural model, which parameters depend on the above mentioned.

When non-elastic design models of structures are used the earthquake effect should be formalized in a different way. This is, first of all, attributed to the fact that in evaluating structural safety by the new method one cannot restrict to a single design effect but a set of effects should be used since by the end of the structure's life, its total damage becomes a result of all the earthquakes the structure was subjected to during its life. Hence, it is evident that a detailed description of the seismological situation in the construction district should be known to evaluate more correctly the safety of non-elastic systems exposed to seismic effects.

The earthquake regime of the construction site means a population of characteristics of the totality of earthquakes in the given construction site being steady during a sufficiently long survey period.

With this definition of the seismic regime a series of earthquakes observed at a certain locality will present an ergodic sequence. If the ergodic sequences are long enough, the probability of all non-ergodic sequences will strive to zero and that of ergodic ones - to unity.

For each construction site with a given seismic regime the generalized seismic effect will mean a set of all random ergodic sequences of the seismic effect. In particular, a registered sequence of instrumental records of the ground earthquake motion in a given site is one of the realizations of the generalized seismic effect.

Thus, in a general case the generalized seismic effect is a random sequence of random functions, but when numerically expressed, it may have more partial cases.

If to consider the behaviour of a non-elastic system exposed to such effects, the value of injury (for systems without rehabilitation, repair) will rise with time. For systems with rehabilitation, losses will rise. The average speed of damage rise depends on the type of the system, its dynamic parameters, the quality of its structural antiseismic measures and, certainly, characteristics of the seismic regime. If to select the type of a dynamic non-elastic system and to fix its parameters, the average speed of damage rise in such a standard system may serve as a generalized characteristic of the seismic risk of the construction site depending on the parameters of the seismic regime only [1,2] .

The dynamic system with the Prandtl type diagram being the minimum extension of elastic systems, is used as a standard one.

For a more detailed description of seismic danger a few standard dynamic systems can be used.

The analysis of the structure is done under the supposition that all the seismic effects possible at a given site are somehow divided into k classes [3] due to the applied calculation methods or seismological characteristics.

The i-th class effect will cause in the considered class of structures a Δ i damage, which is a randon value with a certain distribution function. The shape of the function and its numeric characteristics depend upon mechanical characteristics of the structure and the extent of its earthquake-resistant reinforcement.

Damageability of the structure $\delta(\nu)$ by the end of a sufficiently long period of survey t is evaluated supposing that during that time some random number of earthquakes happen relevant to different classes.

$$\delta(\nu) = \sum_{i=1}^{K} \nu_i \Delta_i \, , \; \left(\sum_{i=1}^{K} \nu_i = \nu\right) \tag{1}$$

where ν_i is the number of earthquakes of the i-th class.

It is shown [1] that

$$m_1\{\delta(\nu)\} = \sum_{i=1}^{K} m_1\{\Delta_i\} \, m_1\{\nu_i\} \, , \tag{2}$$

$$D\{\delta(\nu)\} = \sum_{i=1}^{K} \left(D\{\Delta_i\} \, m_1\{\nu_i\} + m_1^2\{\Delta_i\} D\{\nu_i\}\right) , \tag{3}$$

where $m_j\{\cdots\}$ and $D\{\cdots\}$ are the initial moment and variance of the random value in curly brackets, respectively.

If to assume, as usual, that the number of earthquakes of the i-th class follows the Poisson law with the average value μ_i , then expression (2) and (3) can be written as follows;

$$m_1\{\delta(\nu)\} = t \sum_{i=1}^{K} m_1\{\Delta_i\} \, \mu_i \, , \tag{4}$$

$$D\{\delta(\nu)\} = t \sum_{i=1}^{K} m_2\{\Delta_i\} \, \mu_i \, . \tag{5}$$

The average speed of damage rise (or losses due to them) is equal to:

$$m_1\{\bar{\delta}\} = \sum_{i=1}^{K} m_1\{\Delta_i\} \, \mu_i \, , \tag{6}$$

where $\bar{\bar{c}} = \frac{1}{t} \bar{\bar{\delta}}(\nu)$.

The variance of the value $\bar{\bar{\delta}}$

$$D\{\bar{\delta}(\nu)\} = \frac{1}{t} \sum_{i=1}^{K} m_2\{\Delta_i\} \mu_i \tag{7}$$

at a sufficiently long survey period t strives to zero, and so the value itself strives to a determinate one.

Relationships (2) - (7) permit the contribution of each class of earthquakes to the total damage of the structure to be ascertained. As can be seen from the expressions the contribution depends greatly upon the event being repeated.

Concrete examples of evaluation of damageability of structures for sites of different seismic regimes show that even for regions with the same design seismisity damageability of structures varies a lot due to other seismological parameters.

The proposed model of the generalized effect allows the process of selecting optimum parameters of the structure of a site with a certain seismic regime to be formalized.

II. Self-adjusting systems with rigid members disengaging during-earthquake.

During the recent years some new methods of reducing the earthquake loads were developed in the U.S.S.R. The methods are based on the predicted changing (self-adjustment) of rigidity, spectrum of natural frequencies and other dynamic characteristics of the structure under an earthquake due to disengagement or engagement of special rigid members.

Buildings with such a system of earthquake protection have already been built in some seismic regions of our country, e.g. at the Baikal-Amur main railroad, in Sevastopol and are under construction elsewhere.

Experimental studies have been conducted recently on models and in field using the powerful vibration machine.

By means of analogous and digital computers seismic response and safety of such systems were studied analytically.

The results of disengagement of reserve members or interior braces of the system depends upon two phenomena. One is associated with adaptation of the system to the spectral composition of the given single seismic process. This phenomenon is essential when at the same site there exist compatible probabilities of occurrence of more or less narrow band seismic motions differing from each other in dominant frequencies, e.g. earthquakes due to far off and near epicentres.

In cases when the mathematical model of seismic motions of the ground can be presented as a class of narrow band random processes in a sufficiently wide field of dominant frequencies, this phenomenon in a proper design can reduce the seismic response by 1.5-2.5 times as compared to the seismic response of stationary systems without disengaging reverse members or inner braces.

The adaptation mechanism of such a system will be illustrated by an example when two narrow band effects on a non-stationary system with a disengaging member are predicted with the same probability.

The registered accelerogram of the Gazli earthquake on May 17, 1976 will be used as a model of the earthquake ground motion with a high dominant frequency. The registered accelerogram of the Bucharest earthquake on March 4,1977 will be used as a model of the earthquake effect with relatively low dominant frequencies. Spectra of accelerations, velocities, displacements under the two effects were constructed for a wide class of linear, non-linear and non-stationary systems with different dissipative characteristics.

In a numerical example periods of natural vibration of the initial (prior to disengagement of braces) and ultimate (after disengagement of braces) system conditions were assumed as T_o=0.25 and T_n=1.25. With these magnitudes of natural vibration periods of the initial and ultimate systems the equivalent systems of constant rigidity would have produced maximum response values in the Gazli and Bucharest earthquakes respectively. For a system of constant rigidity with the assumed 5 per cent damping from the critical one the following maximum values of seismic response were obtained: for the Bucharest earthquake (the N.S.component) with T=0.25 s acceleration = 262.7 cm/s^2, displacement = 0.416 cm, with T=1.25 s acceleration = 630.7 cm/s^2, displacement = 24.96 cm; for the Gazli earthquake (the E.W. component) with T=0.25 s acceleration = 990.1 cm/s^2, displacement = 1.567 cm, with T=1.25 s acceleration = 374.6 cm/s^2, displacement = 14.82 cm. Response values varied,i.e. the threshold level x_r at which braces disengage in portions of the response of the initial system in the Gazli earthquake. Values of the maximum response of the system at the initial and ultimate (final) states depend, certainly, on the threshold value x_r at which reserve members disengage. Thus, for instance, with x_r equal to 0.5; 0.6 and 0.95 cm the values of maximum accelerations of the system comprise 316 and 371; 378 and 372; 600 and 381 cm/s^2 respectively.

The analysis permits to infer the following: if a structure is exposed to earthquakes caused by near and far off epicentres with different spectral composition, the application of a system with readjusting-during-an-earthquake rigidity and period of natural vibrations, i.e. structures with disengaging braces can bring about considerable reduction in seismic load. Quantitative values of the efficiency of the method of seismic insulation depend on specific characteristics of the ground motion. When for earthquake models accelerograms of the Gazli and Bucharest earthquakes were taken, values of the design earthquake response were reduced by 2.7 and 2.4 respectively by using adaptive systems with disengaging braces as compared to systems of constant rigidity.

Absolute values of the maxima of seismic response of structures of constant rigidity at earthquakes in Gazli and Bucharest are so large (990.1 and 630.7 cm/s^2), that substantial non-elastic deformations or damages are inevitable in conventional structures.

Values of the maxima of seismic response of adaptive systems with disengaging reserve members during earthquakes in Gazli and Bucharest constitute 371.8 and 262.7 cm/s^2, i.e. do not exceed the design values of loads according to the Building Code and can be safely taken up by structures at the elastic stage of deformation.

Another phenomenon associated with the behaviour of non-stationary systems with reserve members does not depend directly upon the spectrum width. It takes into account the efficient time of the seismic process and can manifest itself both during narrow band and wide band processes. The part played by this phenomenon can be found out only by applying probabilistic methods of analysis [5] .

The analysis has indicated that the use of reserve members is most efficient in designing systems of higher safety when probabilities are small of the seismic effect level being risen thus causing disengagement of reserve members and failure of the ultimate system (e.g. in case of nuclear reactors and other systems of specific higher safety).

These are the two aspects of the seismic behaviour and efficiency of non-stationary systems of adaptive earthquake protection with disengaging inner braces and reserve members.

III. Some problems of mechanics analysis of structural earthquake response.

One can single out a problem of evaluating stability of solutions in terms of the Lyapunov theory and technical theory of stability for non-linear differential equations, describing vibrations of structures under seismic effects, the problem of ascertainments of solutions of these equations in terms, of the stochastic theory methods.

The present section of the paper sets forward a mathematical model [6] which is of great practical value, namely, the model describing small spatial vibrations of structures. The model corresponds to the evaluation of an elastic system. The solution given in the paper for the new design model of a structure resolve themselves to standard methods of the dynamic analysis.

Design models of structures can be divided into two groups. The first group includes symmetrical systems for which the mass centre coincides with the rigidity centre, the second one includes asymmetrical systems, which mass centre and rigidity centre do not coincide. Most structures are asymmetrical. Asymmetry leads to linear interdependence of vibrations in different space directions.

To analyse a structure (as a spatial system) for seismic effects [6] in a general case one should know vectors of the translatory motion of the base $\ddot{\vec{X}}_o$ and rotation $\vec{\alpha}_o$ or modules of these vectors and guiding cosines of their components. One should have simultaneous records of the base movement on the surface in three orthogonal directions, in which all the required data on the vectors $\ddot{\vec{X}}_o$ and $\vec{\alpha}$ can be obtained. The vectors $\ddot{\vec{X}}_o$ and $\vec{\alpha}$ are characteristics of the field of the ground seismic motions. Below these characteristics will be looked upon as functions of time only, assuming that within the plan of the structure they vary insignificantly.

In [6] general mathematical models of spatial vibrations are obtained for structures simulated by any system of bodies for small and arbitrary displacements and rotation angles.

Equations of small oscillations of an assymetric n-mass system with due account of energy dispersion following the viscous inner friction hypothesis have the following form [6,7] :

$$\ddot{\vec{x}} + m_k^{-1}\sum_{i=1}^{n}\left([\beta_{ik}^{(11)}]\dot{\vec{x}}_i + [\beta_{ki}^{(12)}]\dot{\vec{\alpha}}_i\right) + m_k^{-1}\sum_{i=1}^{n}\left([\tau_{ki}^{(11)}]\vec{x}_i + [\tau_{ki}^{(12)}]\vec{\alpha}_i\right) = -\left([\varphi_o]\ddot{\vec{X}}_o + [\ddot{\alpha}'_{01}]\vec{x}_k^{\circ}\right); \qquad (8)$$

$$\ddot{\vec{\alpha}}_k + [\theta_k^{-1}]\sum_{i=1}^{n}\left([\beta_{ki}^{(21)}]\dot{\vec{x}}_i + [\beta_{ki}^{(22)}]\dot{\vec{\alpha}}_i\right) + [\theta_k^{-1}]\sum_{i=1}^{n}\left([\tau_{ki}^{(21)}]\vec{x}_i + [\tau_{ki}^{(22)}]\vec{\alpha}_i\right) = -[\psi_k]\ddot{\vec{\alpha}}_o,$$

where k = I, II, III ..., n is the number of a discrete member of the system; $\vec{x}_k(\dot{\vec{x}}_k, \ddot{\vec{x}}_k)$ and $\vec{\alpha}_k(\dot{\vec{\alpha}}_k, \ddot{\vec{\alpha}}_k)$ are vectors of displacements (velocities, accelerations) and revolution angles (angular velocities, accelerations) of the k-th member of the system; $[\varphi_o]$, $[\psi_k]$ and $[\ddot{\alpha}'_{01}]$ are transformation operators of basis vectors (affine orthogonal tensors of second rank) which are given in [6] for various systems of revolution angles; $[\tau_{ki}^{(st)}]$ and $[\beta_{ki}^{(st)}]$ are matrices of rigidity and factors of energy dissipation following the hypothesis of viscous inner friction (s,t=1.2); m_k and $[\theta_k]$ are the mass and tensor of inertia of the k-th body.

The technique for studying such systems is given in [6,7,8].

REFERENCES

1. Zharov A.M. Obobshchennaya model seismicheskogo vozdeistviya, uchityvayushchaya povtoryaemost zemletryasenii i drugie osobennosti seismologicheskoi obstanovki. In the book "Sovershenstvovanie metodov rascheta i konstruirovaniya zdanii vozvodimykh v seismicheskikh raionakh", TsNIISK, M.,1976.

2. Polyakov S.V., Zharov A.M. Trebovaniya k karte seismicheskogo raionirovaniya strany v svyazi s zadachami proektirovaniya sooruzhenii. In the book "Seismotektonika yuzhnykh raionov SSSR", M., "Nauka", 1978, pp.115-120.

3. Zharov A.M., Nikiporetz G.L. O klassifikatsiyakh seismicheskogo dvizheniya grunta, ispolzuyushchikh instrumentalnye dannye. In the book "Seismicheskaya shkala i metody izmereniya seismicheskoi intensivnosti", M., "Nauka", 1975.

4. Eisenberg I.M. et al. Adaptivnye sistemy seismicheskoi zashchity sooruzhenii. Publishing House "Nauka", 1978.

5. Eisenberg I.M. Safety of Structural Systems with Reserve Elements for Earthquake Protection. Int.J."Earthq.Engineering a. Str.Dyn." Vol.5, 305-318 (1977).

6. Nikolaenko I.A., Nazarov Yu.P. Dinamika i seismostoikost prostranstvennykh konstruktsii i sooruzhenii, 1977, issue 23.

7. Nikolaenko I.A., Nazarov Yu.P. O prostranstvennykh kolebaniyakh sooruzhenii pri seismicheskikh vozdeistviyakh. J.Stroitelnaya mekhanika i raschet sooruzhenii, 1979, No.3.

8. Nikolaenko I.A., Ulyanov S.V. Statisticheskaya dinamika mashinostroitelnykh konstruktsii. Mashinostroenie, M.,1977.