Determination seismic effect of buildings and structures, taking into account changes model of external relations within the life cycle

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Abstract. This research paper discusses the problem of the strain state formation in the bearing system through its lifespan. It is demonstrated that in the general case the seismic events (being quite rare natural acts) can impact the structures which, by the time an earthquake hits, will experience strains developed during the period preceding the earthquake. Consequently, the accurate seismic load calculation for the bearing system in view of the seismic events shall account for the strain state developed in the structures prior to the seismic event. Analysis of the customary computational techniques used in seismic load calculations for bearing systems and employing the response spectrum method reveals, that in the context of a single-stage calculation method it is possible to introduce only one model of external relations that corresponds to either the long-term loading effect or to the short-term seismic loads. Such approach is not aligned with the true-life pattern of external relations, which is subject to changes through the life span. For the purposes of accurate prediction of seismic response in buildings, it is proposed to use a multistage calculation method with the stage-to-stage inheritance of the stress-strain state. At that, at any stage it is possible to modify the properties of external relations. Compared are the calculation results of the seismic impact test model employing the customary calculation techniques and the multistage calculation method with adjustment of the external relations model to correspond with the lifespan mode. The outcome of the research proves that the use of the customary single-stage calculation method leads to significant simplification of the bearing system strain model, as well as to inaccuracy of the seismic response prediction result. Based on the research outcome, the single-stage calculation method is advised. It permits to take into account developments in the external relations model through the building lifespan.

1. Introduction
In event of earthquakes, buildings and structures constructed in compliance with the requirements of earthquake engineering should sustain damage of no more than the level determined by the standards.
 Nonetheless, the seismic response analysis of structures during the true-life earthquakes proves that buildings of different structural systems demonstrate damage of remarkably different degrees (for instance, papers [Ошибка! Источник ссылки не найден., Ошибка! Источник ссылки не найден., Ошибка! Источник ссылки не найден.]) – ref. Table. 1.

| Item no. | Type of building structure | Average degree of damage $d$ | Coefficient of variation $v$ |
|----------|----------------------------|-----------------------------|-----------------------------|
| 1        | Multi-storey large-panel buildings | 1.1                         | 0.18                         |
| 2        | Buildings of cast-in-situ reinforced concrete | 1.5                         | 0.17                         |
| 3        | Multi-storey braced-frame buildings of precast concrete buildings (IIS-04 series) | 2.3                         | 0.37                         |
| 4        | Stone buildings of cast-in-situ reinforced concrete girds and inclusions forming a defined framework | 1.3                         | 0.56                         |
| 5        | Stone buildings of cast-in-situ reinforced concrete girds and inclusions not forming a defined framework | 2.2                         | 0.59                         |
| 6        | Stone buildings of cast-in-situ reinforced concrete girds | 2.8                         | 0.43                         |

The seismic response analysis in buildings is not only indicative of different average degree of damage sustained by the load-bearing systems, but also of high values of the coefficient of variation for particular types of building structures ($v = 0.37 ÷ 0.59$). This points to significant deviations in specific values in the degree of damage from its average value. It is evident that the reason for such variables for the coefficient of variation can be not just any particular aspects of various structural systems. These differences are expressed by average response to damage. It seems reasonable to assume that the prominent scatter of damage rates results from other factors. Among such other factors are specifics of the stress-strain state formation in the bearing system at the time of seismic action.

Earthquakes, in fact, do occur quite rarely: the predicted seismic activity takes place with a frequency of several decades, and that is shown on the Russian Federation seismic zoning maps [Ошибка! Источник ссылки не найден.]. In overall, by the time the earthquake hits, a building will be in operation for several years. As a result, strains and corresponding stresses will develop in the bearing system. Consequently, an earthquake will impact structures with the initial strains and stresses. At that, different types of the bearing systems receive response to strains in different ways. For instance, the buildings of the concrete masonry bearing walls (according to [Ошибка! Источник ссылки не найден.]) receive remarkably different degrees of damage if there are strengthening reinforced concrete inclusions, or absence thereof. Nonetheless, this scenario is not taken into consideration within the context of the existing ways to perform the seismic load calculations. The seismic load calculations are done on the grounds of the superposition concept by way of separately loading the unstrained structural design of the bearing system. This type of calculation technique does not give a true picture of the bearing system performance in time.

The overall strain and formation of the stress-strain state in the bearing system is mostly determined by the strain properties of the foundation. In the structural design these properties are represented by the external relations model. The external relations model should possess the actual characteristics of the foundation strain state, i.e. the model should modify along with the changes in strain parameters of the foundation. However, usually, when designing the buildings of large scale development projects, the related calculations are done using a single (and constant) model of external relations.
Within the context of research herein, the carried out analysis comprises several dozens of the constructed building projects. The outcome permits to state that the vast majority of calculations of the bearing systems was carried out employing the external relations model which corresponds to the load action from the basic load combination. It is noteworthy, that the seismic load calculation was carried out under the conditions of the strain properties of soils corresponding to the long-term load action and which cannot be acknowledged as adequate.

2. Problem statement and research methods

It appears evident that during the computational analysis of the bearing system through the building full lifespan there should be consideration of the fact that the building bearing system and the related structural design exist in their several states, which differ in design models. Changes in the key parameters define each model: characteristics of action, pattern of external relations, physical relations defining the stress-strain state. At that, no scenario of the structural design is self-sufficient. Furthermore, each subsequent scenario inherits the stress-strain state the bearing system formed at the previous stage.

Figure 1 gives the overall view of the bearing system strain diagram. The diagram shows three main stages of the building lifespan, i.e. Stage A: building construction mode; Stage B: main design period mode with long-term loads; Stage C: mode of short-term/unique load actions. Nonetheless, the customary techniques of the forecast calculation for the stress-strain state of bearing systems normally account for only one of the possible design scenarios. This calculation analysis technique cannot be adopted as reliable because it does not embrace the working mechanisms for the stress-strain state formation (ref. Fig. 1).

Through the lifespan, the design model of the structure does not stay constant. Thus, in the building construction mode, the load-bearing model of structures changes, usually (but not always!) in generation mode, and the external relations model changes in degradation mode (strain property in soil increases along with increasing loads).

It is quite evident that the strain properties of the foundation impact to the greatest extent the stress-strain state of foundation structures (foundations slabs) and the lower tiers of the building bearing structures. Thus, taking into account the formation and modification of the external relations model through the lifespan seems appears mandatory in order to obtain an accurate forecast for the stress-strain state of the building load-bearing structures.

The fact that earthquakes occur quite rarely should be taken into consideration. Consequently, the most conservative forecast outcome for the stress-strain state of the load-bearing structures can be obtained under the conditions of the load-bearing system in the state of strain which developed during the period of operation preceding the earthquake. As a result, the stress-strain forecast design should be performed using a multistage calculation technique, each stage of which corresponds to a particular lifespan stage of the structure: the stage of the bearing system construction, the stage of the main period of operation, the stage of unique (seismic) actions. This approach to the computational analysis is aligned with the generalized strain pattern of the bearing system as it is shown in Fig. 1.

The techniques to solve the structural design problems, in the context of which the multistage calculation method of the stress-strain formation is implemented with the stage-to-stage inheritance
of the stress-strain state, are well worked out analytically [Ошибка! Источник ссылки не найден., Ошибка! Источник ссылки не найден., Ошибка! Источник ссылки не найден.], and instrumented in the problem-oriented software packages (for instance, [Ошибка! Источник ссылки не найден.]) by way of using the multistage calculation method. The crucial distinction of this technology if compared with the well-known step-by-step methods is the principle of adherence to the design coordinates of the ’mounted’ group of structures (elements of the structural design). Still, at the same time the coordinates of the preceding stage are kept in the way corresponding to the design of the strain pattern formed at the preceding stage.

Figure 2 gives the overall flowchart of the multistage method of computation.

![Figure 2. Overall flowchart of the strain pattern for the bearing system through the lifespan (A – construction/generation mode; B – main design period mode with long-term loads; C – mode of short-term/unique load actions).](image)

Given below is the legend adopted for the purposes of representation in Figure 2:

- \( N_{rak} \) – complete set of the model finite elements;
- \( N_r, N_{r+1} \) – set of the model finite elements at stages \( r \) and \( r+1 \) respectively;
- \( F_r, F_{r+1} \) – rigidity of the external connections at stages \( r \) and \( r+1 \) respectively;
- \( K_r, K_{r+1} \) – generalized stiffness matrix of the model at stages \( r \) and \( r+1 \) respectively;
- \( P_r, P_{r+1} \) – load factor at stages \( r \) and \( r+1 \) (cumulative load + stage loads);
- \( \Delta U_r, \Delta U_{r+1} \) – increment of displacements at stages \( r \) and \( r+1 \);
- \( S_r, S_{r+1} \) – tensions/stresses at stages \( r \) and \( r+1 \);
- \( X_{ir}, Y_{ir}, Z_{ir} \) – coordinates of \( i \)-th node (as determined within the project) of the finite elements group \( N_{rak} \), included into the model at stage 1;
- \( X_{ir+1}, Y_{ir+1}, Z_{ir+1} \) – coordinates of \( i \)-th node determined by the strained state of the finite elements at stage \( r+1 \).

The flowchart of the multistage method of calculation proves the possibility to carry out the design analysis not only in the structural design generation mode, but (which seems significant in the context of the problem under study) in the mode of the stiffness parameters degradation in view of the structural design elements including the external relations model.

Application of the multistage method of calculation makes it possible to study the strain and development (increase/decrease) processes in stiffness of the elements of the load-bearing structure model, as well as the elements of the external relations model. The external relations model functions as an essential component of the entire design model of the structure. The principal regulatory documents and national legislation govern the mandatory adherence to the interaction between the building and the soil body (with the parameters of such interaction being the external relations model itself).
The external relations model through the lifespan develops considerably. The parameters of the external relations model are obtained by the prediction of the strain values in the soil base under the load. The forecast for strains in soil is predetermined by the soil physical and mechanical properties, and which are evaluated in the course of engineering and geological surveys. The key parameter that impact the strain pattern of the base is the factor of proportionality in the ‘stress-strain’ system, and which is referred to as the elasticity/strain modulus. The difference between these moduli of strain and elasticity lies in presence of the permanent residual strain. The elasticity modulus determines the reversible part of strain which disappears once the load is removed (Hooke’s law). The total strain modulus also accounts for the plastic (irreversible) strains. Much depends on the structural relations between the particles and the porosity of soil.

The methods to evaluate the strain parameters in soils under various loading conditions of the base were researched to the desired degree, and are incorporated into the regulations in force [10].

It is noteworthy that the rate of load application strongly impacts on the value of the foundation strain parameters, which should also be taken into account when selecting the external relations model values. As regards the conditions of the long-term load action (main period of operation), the strain parameters should be calculated on the grounds of the strain modulus; as for the conditions of the short-term dynamic (seismic) load action, the soil elasticity modulus should be used to determine the strain parameters. Consequently, the external relations model should be of a variable nature and should correspond to the structure lifespan stage.

In order to evaluate how changes in parameters of the external relations model impact the structural elements of an earthquake-resistant building through its lifespan, the design analysis of a test model was done (Fig. 3). The main characteristics of the model correspond to the buildings within large scale development projects: load-bearing system of a braced frame type; structures are made of reinforced concrete class B30, longitudinal reinforcement of bars class A400, transverse reinforcement of bars class A240; foundation slab 800 mm thick, floor slabs 200 mm thick, columns 500×500 mm in section; loads sustained by the floor slabs are constant (5.5 kPa), long-term (4.0 kPa), temporary short-term (4.0 kPa).

The external relations model is adopted by way of the coefficients of soil reaction system (the model by V.G. Fedorovsky [11]), and is given in Fig. 4.

The values of the coefficients of soil reaction for the main load combination (type A): \( C_{1.01} = 300 \text{ t/m}^3 \); \( C_{1.02} = 400 \text{ t/m}^3 \); \( C_{1.03} = 500 \text{ t/m}^3 \).

The values of the coefficients of soil reaction for the seismic loads (type B): \( C_{1.01} = 2400 \text{ t/m}^3 \); \( C_{1.02} = 3200 \text{ t/m}^3 \); \( C_{1.03} = 4000 \text{ t/m}^3 \).

For the purposes of the design experiment, the earthquake action of the intensity at 9 points was observed (soil category 3 in view of seismic properties).

The calculation studies are available in two options.

The calculation studies in option 1 are done employing the superposition principle: all loading instances impact the unstrained design model. In this way, the strained state in the structures that
developed over the main period of operation is not accounted for under the seismic loads action. Given the design analysis is performed within the context of the single-stage calculation, the adopted external relations model is aligned with probable values of the coefficients of soil reaction, i.e. type A relates to the long-term loads conditions (this method is most frequently used in practice to do design calculations for the buildings within large scale development projects).

The calculation studies in option 2 are done employing the multistage calculation method: two stages of the existence of the bearing system are analyzed: the stage of the main period of operation under the main load combination actions and the stage of the seismic loads action. For the first stage, the external relations model of type A is adopted which corresponds to the long-term loads conditions. For the second stage (seismic loads action), the coefficients of soil reaction model of type B is used. The construction stage of the building is not reviewed for the purposes of maintaining simplicity.

The multistage calculation method used to do the design analysis permits to calculate the following main aspects of the stress-strain state formation in the bearing system through the lifespan: the formation of a strained state during the main period of operation employing the external relations model and based on the strain modulus, stress-strain inheritance over the transition to the seismic effects stage. Still, over this transition the external relations model gets replaced by a more rigid one based on Young's modulus. Thus, the multistage calculation method conforms more towards the true-life conditions of the stress-strain state formation in the bearing system.

3. Results and discussion
The seismic load calculation was instrumented by SCAD computer complex [9] using the response spectrum method in accordance with the requirements of the Russian Federation standards [12]. At the outcome of the design analysis, the calculated parameters of seismic effects were obtained which differ significantly (Table 2).

| 1st tone period of natural frequencies, seconds | Seismic load value in fundamental period, tons |
|-----------------------------------------------|-----------------------------------------------|
| Option 1 | Option 2 | Option 1 | Option 2 |
| 1.565 | 1.030 | X | Y |
|        |        | 804 | 717 |
|        |        | 863 | 870 |

These significant differences in dynamic response are justified by different parameters of the external relations model, i.e. for option 1, the rigidity in the external relations model is evaluated on the basis of the strain modulus. This corresponds to a single-stage computation method. For option 2, the rigidity of the external relations model corresponds to Young's modulus. The parameters of the stress-strain behavior of the base are used as the reference in order to obtain the design model dynamic properties, as well as the seismic load in the fundamental period.

The results of the design experiment include obtaining the parameters for the bearing system elements in the stressed state in both options of the design calculation. For the purposes of analysis and comparison of the results, the foundation slab reinforcement parameters are considered integral characteristics of the stress-strain state, which accounts for all main stress components.

With the reference to the research results, given below are the obtained design reinforcement values for the foundation slab (Fig. 5 – 8; because of symmetry, the reinforcement patterns are shown only for one half of the foundation slab).
**Figure 5.** Calculation results for lower reinforcement, in horizontal direction (AS1). Left for option 1, right for option 2.

| 0.01 | 3.87 |
|------|------|
| 3.87 | 7.74 |
| 7.74 | 11.6 |
| 11.6 | 15.46 |
| 15.46 | 19.33 |
| 19.33 | 23.19 |
| 23.19 | 27.05 |
| 27.05 | 30.92 |
| 30.92 | 34.78 |
| 34.78 | 38.64 |
| 38.64 | 42.51 |
| 42.51 | 46.37 |
| 46.37 | 50.23 |
| 50.23 | 54.1 |
| 54.1 | 57.96 |
| 57.96 | 61.82 |

**Figure 6.** Calculation results for lower reinforcement, in vertical direction (AS3). Left for option 1, right for option 2.

| 1 | 4.6 |
| 4.6 | 8.2 |
| 8.2 | 11.79 |
| 11.79 | 15.39 |
| 15.39 | 18.99 |
| 18.99 | 22.59 |
| 22.59 | 26.18 |
| 26.18 | 29.78 |
| 29.78 | 33.38 |
| 33.38 | 36.98 |
| 36.98 | 40.57 |
| 40.57 | 44.17 |
| 44.17 | 47.77 |
| 47.77 | 51.17 |
| 51.17 | 54.56 |
| 54.56 | 58.99 |

**Figure 7.** Calculation results for upper reinforcement, in horizontal direction (AS2). Left for option 1, right for option 2.

| 6.3 | 3.2 |
| 3.2 | 6.1 |
| 6.1 | 9 |
| 9 | 11.9 |
| 11.9 | 14.8 |
| 14.8 | 17.7 |
| 17.7 | 20.6 |
| 20.6 | 23.5 |
| 23.5 | 26.4 |
| 26.4 | 29.3 |
| 29.3 | 32.2 |
| 32.2 | 35.1 |
| 35.1 | 38 |
| 38 | 40.9 |
| 40.9 | 43.79 |
| 43.79 | 46.69 |

| 0.08 | 3.76 |
|------|------|
| 3.76 | 7.43 |
| 7.43 | 11.1 |
| 11.1 | 14.78 |
| 14.78 | 18.45 |
| 18.45 | 22.12 |
| 22.12 | 25.8 |
| 25.8 | 29.47 |
| 29.47 | 33.14 |
| 33.14 | 36.82 |
| 36.82 | 40.49 |
| 40.49 | 44.17 |
| 44.17 | 47.84 |
| 47.84 | 51.51 |
| 51.51 | 55.19 |
| 55.19 | 58.86 |

| 2,84e-003 | 4.25 |
| 4.25 | 8.5 |
| 8.5 | 12.75 |
| 12.75 | 17 |
| 17 | 21.25 |
| 21.25 | 25.5 |
| 25.5 | 29.75 |
| 29.75 | 34 |
| 34 | 38.25 |
| 38.25 | 42.51 |
| 42.51 | 46.76 |
| 46.76 | 51.01 |
| 51.01 | 55.26 |
| 55.26 | 59.51 |
| 59.51 | 63.76 |
| 63.76 | 68.01 |
Figure 8. Calculation results for upper reinforcement, in vertical direction (AS4).
Left for option 1, right for option 2.

The analysis of the design calculation results reveals contrasting variables for the elements reinforcement being the integral indicator of the stress-strain state in the foundation slab.

In view of that, the distribution pattern of the lower design reinforcement AS1 along the transverse diaphragms differs greatly: the customary design techniques (option 1) requires the extremum of the reinforcement to be in the range of the diaphragm adjacent to the middle part of the foundation slab; the multi-stage calculation method requires the extremum of the reinforcement to be next to the exterior zone of the foundation slab.

The diagrams of the lower reinforcement of the foundation slab in the vertical direction (AS3) in both options of the computational study are close, with the values of the extremum differing by 16%.

At the outcome of the calculation experiment, there were obtained different distribution patterns of the upper reinforcement over the foundation slab area for options 1 and 2. Different values of the extremum of the upper reinforcement were defined as well. As for the upper reinforcement in horizontal direction (AS2), the values of the extremum differ by 62% (!). At the same time, the multistage calculation outcome produced lower values for the design reinforcement. More rigid strain parameters gave these results for the foundation as the adopted value for the seismic action mode, which is indicative of the significantly lower strain values for the upper zone of the foundation slab.

4. Conclusions
Registration of developments in the design model through the lifespan of the building, i.e. the external relations model, is in accordance with the true-life conditions for the stress-strain state in the bearing structures. The multistage calculation method with the stage-to-stage inheritance of the stress-strain state makes it possible to resolve the problem in view of modifying the parameters in the design model at any stage of calculation. The customary single-stage calculation method with unchangeable (constant) constituents in the design model, in fact, does not permit to make the accurate calculation forecast for the stress-strain state of the bearing system of buildings and structures sustaining seismic actions. Employment of one type of the external relations model, normally the model reflecting the long-term loads scenario, inevitably results in underestimation of the seismic loads magnitude and in inaccuracy in the stress-strain state forecast for the bearing system structural elements in buildings and structures.

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