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METHODS FOR EVALUATING THE CHARACTERISTICS OF THE STRESS-STRAIN STATE OF SEISMIC BLOCKS UNDER OPERATING CONDITIONS

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The concept of the vibration and seismic isolation of heavy mining machines, buildings, and structures with rubber seismic blocks is considered. The concept of the seismic isolation of structures is very topical. In Japan, New Zealand, France, Greece, England, USA, and in a number of other countries, it is successfully used for the earthquake protection of such important structures as nuclear power stations, schools, bridges, museums, office and residential buildings. Seismic isolation systems including rubber blocks are most commonly used. The known publications in these countries do not present analytical calculations and technological peculiarities of manufacturing elements. In Ukraine, this concept was extended by developing seismic isolation blocks for the earthquake protection of residential buildings and vibration isolation blocks for the vibration protection of heavy equipment (weight of up to 300 t, used in Russia, Ukraine) and residential buildings. Results of static and dynamic tests of a parametric series of rubber seismic blocks for the vibration protection of residential buildings are presented. A pile design with anti-vibration rubber mounts is considered. Developed and tested rubber seismic block designs were used to protect against subway and motor vehicle induced vibrations two dwelling houses in Kiev (a ten-section ten-storey and a three-section 27-storey dwelling house) and three houses in Lvov. Vibration and seismic isolation with rubber seismic blocks provides a natural vibration frequency of building in the horizontal plane of under 1 Hz, which complies with the requirements of the state building codes and Eurocode 8 for the design of seismic isolation systems for buildings.

Keywords: vibration isolation, seismic isolation, rubber-metal blocks, settlement, piles with rubber-metal blocks.

Introduction. Vibration and seismic protection system is a promising avenue, which has been developing in recent years in various countries. In Japan, for example, over thousand seismically isolated buildings and bridges have been built. More and more seismically isolated buildings, bridges and other structures are built in various continents. Seismic isolation is most commonly used in Japan, China, USA, Russian Federation, Canada, New Zealand, and Italy. Seismic isolation systems based on rubber-metal seismic isolation blocks (RMSIB) are widely used to rehabilitate buildings and to build new ones.

Vibration and seismic protection system is designed for the reduction of the seismic response of buildings and their protection from earthquakes. It can protect construction sites from industrial vibrations and shock waves, such as waves from explosions in quarries, from vibration and noise of subway vehicles, as well as motor and rail transport. The use of vibration and seismic protection in Ukraine is regulated by European and national normative documents [1].

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When choosing the layout, parameters and number of seismic blocks required for vibration and seismic protection under real operating conditions, the characteristics of their stress-strain state must be determined by analytic and numerical methods.

To verity analytical and numerical calculations and to use building vibration and seismic protection systems in practice, the Polyakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine and State enterprise "Research Institute of Building Structures" (SE RIBS) have carried out experimental investigations to justify the parameters of rubber seismic blocks, patented their designs, worked out design documentation and made experimental prototypes of three types 340, 400, and 500 mm in diameter with an overall height of the rubber layer of 50, 2×120, 2×70, and 2×50 for each of them. The experimental prototypes of rubber seismic blocks have been made by Ukrainian enterprises.

Analysis and Results of Experimental Investigations. The application of analytic methods for designing rubber structures is limited because of the peculiarities of their stress-strain state, which requires adopting simplifying hypotheses and assumptions [2–4]. The design and improvement of vibration isolators under vibration and seismic actions were described earlier [5–7]. The taking into account of the contact effect of a rubber-metal shock absorber on deformation properties for the case of free contact between rubber and metallic elements was considered in [8].

A procedure for constructing the stiffness matrix of a special finite element, which takes into account the low compressibility of the material, is reported in [9]. Approaches to solving axisymmetric problems of the mechanics of elastomeric incompressible materials in the high strain region on the basis of a semilinear model of material by the finite element method are proposed in [10]. Reference [11] is devoted to the development of a finite element approach to calculating the deformation of a rubber arch shock absorber in a variational formulation for the model of a slightly compressible neo-Hookean material. A calculation of rubber shock absorbers using a finite element moment scheme for slightly compressible materials in a nonlinear formulation is reported in [12, 13].

To experimentally determine the actual stiffness and damping characteristics of RMSIBs, laboratory tests of three types of developed designs under static and dynamic loads in compliance with the requirements given in [14] have been carried out at the SE RIBS. The tests of RMSIBs were carried out in two stages: dynamic tests: determining the vibration frequencies and damping characteristics of mounts and static tests: determining the compressive and shear stiffness characteristics of mounts.

In dynamic tests, a 5100 kg reinforced concrete block was mounted on four identical RMSIBs. The vibrations of the block in the horizontal and vertical planes were set with a special device and recorded with an eight-channel seismic monitoring system and a Bruel and Kjaer 2148 two-channel spectrum analyzer (Denmark). Based on instrumental recordings of vibration acceleration signals under natural vibrations of the dynamic concrete block–RMSIB system, the dynamic vertical and horizontal (shear) stiffnesses, as well as the damping parameters of the tested RMSIBs were determined.

In static compression tests of mounts, loading was performed with hydraulic jacks in steps of 50–300 kN each on a special test jig, and on a press in steps to a maximum load of 9000 kN, depending on the type of mount, with a duration of each step of 5 min, after which the readings of vertical displacements were taken.

The shear tests of mounts were carried out on a special test jig fitted with hydraulic jacks to create vertical and shear loads. The shear displacements at the top of a seismic mount were measured at vertical loads of 300, 500, 600, and 1000 kN. To allow horizontal displacements of the seismic mount under fixed vertical loads, two fluoroplastic plates were mounted between the upper mount plate and the loading plate. When processing data, changes in the coefficient of friction between the plates depending on the vertical pressure on the mount were taken into account.

Figure 1 shows horizontal load-displacement curves for a RMSIB (rubber elements 500 mm in diameter) with and without lead core at a vertical load on the mount of 1000 kN.

To compressively test mounts, three types of mounts were used: $400 \times 2 \times 70$ mm, $400 \times 2 \times 120$ mm, and $500 \times 2 \times 50$ mm. In compliance with the requirements of the ISO standard and European standard, to determine the state of the RMSIB structure under maximum vertical loads exceeding by a factor of four the design loads, a RMSIB

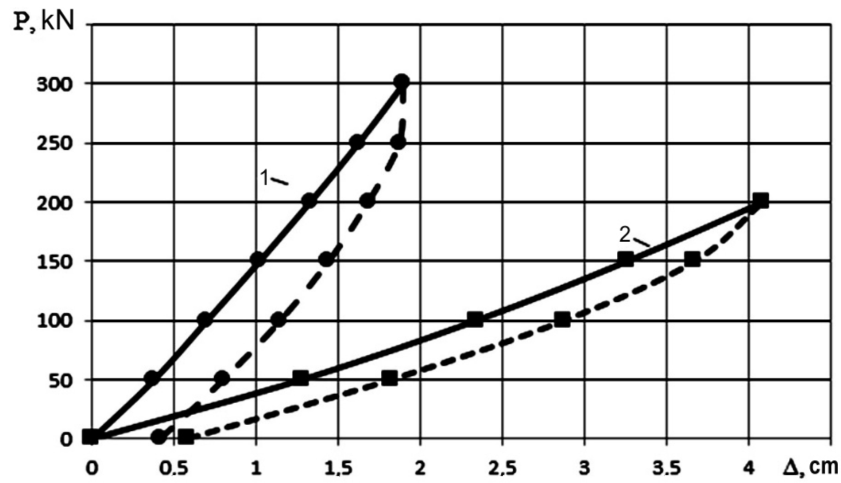

Fig. 1. Load–displacement curves for a RMSIB 500 mm in diameter under shear: (*1*) lead core and (*2*) without core.

specimen was tested with cyclic vertical loads on a press according to a special program: three loading–unloading half-cycles in steps of 300 kN each (duration of each step 5 min) to 3000 kN; two loading–unloading half-cycles in steps of 500 kN each (duration of each step 2 min) to 5000 kN; one loading–unloading half-cycle in steps of 1000 kN each (duration of each step 5 min) to 9000 kN.

At high-cycle compressive loads of 3000–9000 kN, after the complete unloading of the RMSIB, the rubber elements completely took their original shape within 10 min. In that case, no cracks were detected in only of the 12 tested rubber elements made of natural rubber.

Calculation of Rubber Seismic Blocks. The full-scale tests were paralleled by analytical and numerical calculations of different characteristics of the stress-strain state, which allowed us to defect design weaknesses and to make changes at the design stage. Besides, it is not always possible to determine all deformation parameters of rubber seismic blocks in the course of full-scale tests.

Taking into consideration the difficulty in mounting and replacing seismic blocks after their mounting, an adequate and exact calculation of both individual seismic blocks and the built-up structure as a whole must be made at the design stage. Having assumed that seismic blocks will operate in the low strain range during service, preliminary calculation can be made from fairly simple analytical relations. For low strain ($\varepsilon < 0.1$), in the case of uniaxial compression, an analytical relation has been derived between the settlement of a cylindrical rubber layer and the acting load [15]:

$$\Delta = \frac{P_0 h}{3\pi R^2 G}, \tag{1}$$

where P_0 is a compressive load, h and R are the height and radius of the rubber mount, and G is the shear modulus of rubber.

At low strains ($\varepsilon < 0.1$) in the case of unfixed ends, a refined relation has been derived between the settlement of the rubber layer and the applied load:

$$\Delta = \frac{P_0 h}{3\pi R^2 G}\left[1 - \frac{R}{h\sqrt{6}} \tanh \frac{h\sqrt{6}}{R}\right]. \tag{2}$$

When calculating seismic mounts, it must be taken into account that the ends of the rubber layer are vulcanized to the metal plates. Then the corrected value of the real load P, which takes into account stiffness increase owing to the fixing of the ends:

$$P_0 = P/\beta, \tag{3}$$

where β is the coefficient of stiffness increase owing to the fixing of the ends, $\beta = 10.413\rho^2$ after Payne, $\beta = 0.92 + 0.5\rho^2$ after Lavendel, $\rho = R/h$, must be substituted for the load P_0 in formulas (1) and (2).

Earlier [15], it was proposed to calculate the coefficient β from the formula:

$$\beta = 1 + 0.83\rho^2. \tag{4}$$

If the strain level is higher than the level $\varepsilon > 0.1$, then significant errors were obtained in the calculation from formulas (1) and (2). In this case, it is expedient to use formulas for finite strains under uniaxial compression:

$$\Delta = h - \frac{R}{2\sqrt{\chi}} \ln \frac{\frac{1}{2}\left(\sqrt{1+\chi\frac{4h^2}{R^2}}+1\right)+\frac{h}{R}\sqrt{\chi}}{\frac{1}{2}\left(\sqrt{1+\chi\frac{4h^2}{R^2}}+1\right)-\frac{h}{R}\sqrt{\chi}}, \tag{5}$$

where $\chi = \dfrac{P}{\pi R^2 G}$.

The settlement of the seismic block was calculated using formulas (1) and (3) (Fig. 2). The height of the structure $h = 50$ mm, radius $R = 250$ mm. Material: 2959 rubber, its mechanical characteristics: shear modulus $G = 1.76$ MPa, Poisson's ratio $\nu = 0.499$.

However, using formulas (1) and (3), one can find the relation-ship only between such general deformation characteristics as settlement and applied compressive force in a linear formulation. More detailed information on the stress-strain state of seismic blocks can be obtained only by numerical methods since when developing an adequate mathematical model of deformation of rubber structures, the low compressibility of the material, deformation nonlinearity and other properties must be taken into account. This results in cumbersome mathematical models and the impossibility of using them in calculations by analytical methods.

One of the efficient methods for solving problems of the mechanics of rubber structures is finite element moment scheme for slightly compressible materials. According to this scheme, the components of the displacement vector and strain tensor, as well as the volume change function are expanded into a series, and in accordance with a certain rule, a number of terms are retained [12].

Approaches to solving a geometrically nonlinear problem of the mechanics of rubber structures on the basis of the finite element moment scheme (FEMS) are reported in [16] and reduce to the iterative solution of a system of the form:

$$K_{(n)}\bar{u}^{(n)} = \bar{P}_{(n)} - \bar{N}_{(n)}, \tag{6}$$

where $K_{(n)}$ is the global stiffness matrix of the structure, $\bar{u}^{(n)}$ is the nodal displacement vector, $\bar{P}_{(n)}$ is the nonlinear additive vector, and n is the number of iteration.

The results of finite element calculations and calculations in a nonlinear formulation from formula (5) are shown in Fig. 3. It can be seen that the results match qualitatively, and that notable numerical differences are observed only at high strains (of up to 0.4). Analysis of the plots in Figs. 2 and 3 allows one to select the parameters of seismic mounts and their number depending on supposed operating loads.

Technical Solutions and Mounting of RMSIBs. Seismic isolation blocks are manufactured on the basis of standard rubber elements of predetermined size (in Ukraine, RMSIBs with diameters of rubber elements of 340–500 mm were tested, which were used in the seismic isolation of multistorey buildings).

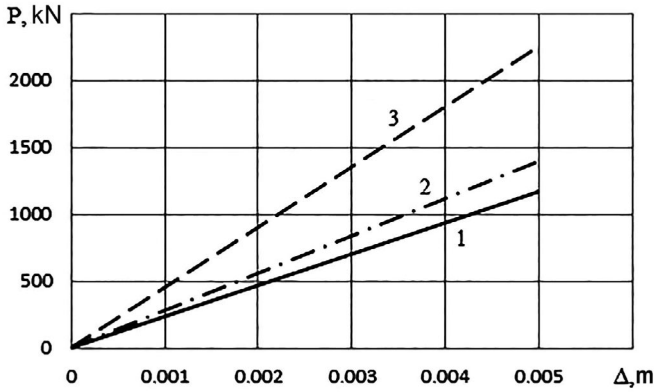

Fig. 2

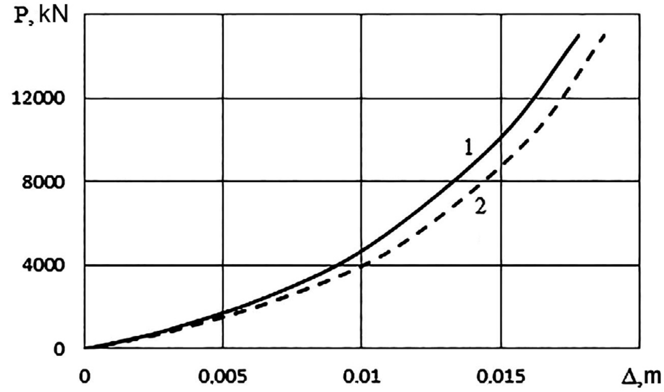

Fig. 3

Fig. 2. Dependence between load and settlement in a linear formulation [(1), (3)]: (*1*) after Payne, (*2*) after Lavendel, and (*3*) according to formula (4).
Fig. 3. Nonlinear dependence of the applied load on the settlement of a seismic support: (*1*) according to formula (5) and (*2*) FEMS.

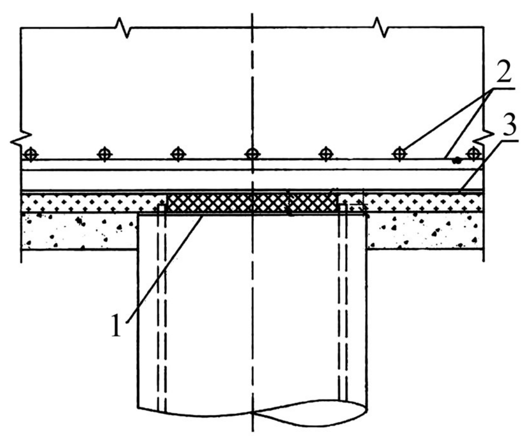

Fig. 4. Layout of a RMSIB on the pile of the vibration isolation system of sections Nos. 1 and 2 of a ten-section dwelling house in Kiev: (*1*) RMSIB, (*2*) lower reinforcement of the grillage, and (*3*) polyethylene film.

The geometric parameters of rubber elements, the compressive and shear stiffness of RMSIBs are determined from the results of the seismic design of a seismically isolated building. RMSIBs are mounted between the lower foundation plate (e.g., on its stiffeners) and the upper monolithic reinforced concrete grillage of the building (Fig. 4).

Variant of mounting RMSIBs at the ground floor level and on the heads of the piles are possible. The lower support plate is fastened with anchors to the stiffeners of the foundation plate or to the pile head, and the upper support plate is fastened to the upper reinforced concrete grillage of the building or to the monolithic walls of the ground floor of the building.

CONCLUSIONS

1. The total horizontal seismic floor loads in large-panel ten-storey buildings with seismic isolation are lower by a factor of up to two compared with the standard design (without isolation). The building's overturning resistance with allowance for seismic loads is ensured (the stabilizing moment is larger by a factor of 2.2 than the overturning one).

2. The percentage of reinforcement of the load-bearing walls of buildings on the lower storeys with seismic isolation is 1.5–2.0 times smaller compared with the case of absence of seismic isolation. These data confirm the effectiveness of using seismic isolation for the considered objects of design-dwelling houses of 9–27 storeys.

3. Developed and tested RMSIB designs were used to protect against earthquakes and subway and motor vehicle induced vibrations dwelling houses in Kiev: a ten-section ten-storey dwelling house and three 27-storey dwelling houses, and three houses in Lvov.

4. Seismic isolation RMSIBs provides a natural vibration frequency of building in the horizontal plane of 1 Hz and less, which complies with the requirements of the state building codes and Eurocode 8 for the design of seismic isolation systems for buildings.

5. Developed RMSIB designs can also be used to protect buildings and structures against the action of ground (rail and motor) and underground (subway) transport, as well as for vibration isolation of heavy machines for different technological purposes to ensure the safe operation of buildings and structures.

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