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ANALYSIS OF METHODS FOR CALCULATING BUILDINGS AND STRUCTURES UNDER DYNAMIC LOADS

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Annotation. The article will consider the analysis of methods of calculating buildings and structures to dynamic effects. Buildings and structures are affected not only by the load of certain elements of it, but also by the force of an earthquake (seismic). As a result, there have been cases of an earthquake affecting buildings and structures, causing it to crash status and decay. This has led to the study of the nature of building exposure through experiments and the emergence of several theories. Thanks to this, scientific work and research was carried out, allowing theories to be created.
Key words: Static, dynamic, spectral, theory, platform, hesitation.

Introduction. For the design of buildings and structures constructed in seismic regions, it is necessary to use the current construction codes and standards, as well as other regulatory guidelines. In regions with seismic intensity of **7–9 points**, structural systems must be verified through **special seismic calculations**.

At present, three stages in the development of the theory of seismic resistance can be istinguished, along with the corresponding methods for calculating buildings and structures under seismic effects:

– **static theory**;
– **dynamic theory**
– **spectral theory**.

Static Theory of Seismic Resistance:

The **static theory of seismic resistance** was scientifically approached to understand the effects of earthquakes on buildings and structures by the Japanese scientist **F. Omori** at the end of the 19th and the beginning of the 20th century. He conducted numerous experiments on brick columns placed on a shaking platform, studying their failure and overturning behavior (1893–1910). Omori carried out measurements of the vibrations of brick buildings during earthquakes (1900–1908), as well as of railway bridges (1902–1910). Later, he performed vibration measurements on two reinforced concrete towers and chimneys with heights of **172 m** and **201 m** (1902–1921).

In his experiments on brick columns, he recorded the **maximum accelerations** and determined the corresponding **inertia forces** by increasing the intensity of the shaking platform vibrations.However, this approach had a limitation: it did not account for **column deformations**. The columns were considered as **perfectly rigid bodies**, and the accelerations along the entire height of a column were assumed equal to the acceleration of the shaking platform (base).

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According to **F. Omori's theory**, the **maximum values of inertia (seismic) forces** are determined by the following expression (1):

$$S = kc\,Q \qquad (1)$$

- kc – **seismic coefficient**, equal to the ratio of the **maximum acceleration** y_{max} to the **acceleration of free fall** g;

- Q – **weight of the considered part of the structure**, expressed as the product of its mass mmm and the acceleration of free fall g.

In a seismic plane, the **direction of inertia forces** can be random, which means that the calculated case may represent an **unfavorable direction** for the structural integrity of the system under consideration [1-10]. Knowing the constant weight of the structure, it is possible to calculate the magnitude of the inertia forces (**seismic loads**). According to the nature of these loads, both weight and inertia are **static**, which is why this approach is called the **static theory of seismic resistance** for buildings and structures.

Omori's static theory made a **significant contribution** to the development of seismic resistance theory [1]. For the first time, the **numerical characteristics of seismic effects** were accurately determined. The static theory was applied in **construction standards** for a long period (until 1957, SN 8-57 "Construction Codes and Regulations in Seismic Regions"). For example, in regions with seismic intensities of 7, 8, and 9 points, the seismic coefficients were taken as 0.025, 0.05, and 0.1, respectively.As mentioned above, this theory is sufficiently accurate for **rigid structures**, but in the early 20th century, experiments on **flexible structures** such as towers and chimneys (based on the ratio of height to the working cross-section of the frame) gave **incorrect results**. These limitations of the theory indicated the **need to account for the dynamic characteristics** of buildings and structures.

Dynamic Theory of Seismic Resistance.

The problem of **seismic resistance**, taking into account the **dynamic properties** and **deformability** of buildings, was first addressed in **1920** by the Japanese scientists **N. Mononobe, S. Okabe, and T. Sano** in the methodology for designing earthquake-resistant structures in seismic regions.

In this work, a solution was provided for a system with **K stiffness** and a single degree of freedom, subjected to the motion of a concentrated mass **m** under the influence of the ground displacement y0(t)y_0(t)y0(t) following a **sinusoidal law**. That is, the process of **stationary harmonic vibrations** was considered, since at that time, sufficient information about the nature of ground motion was not available.

The values of the **seismic load** are determined by the following expression (2):

$$S=kc\beta Q \qquad (2)$$

β – **dynamic coefficient**, determined by expression (3)..

$$\beta = \frac{1}{1-T^2/T_0^2} = \frac{1}{1-\omega_0^2/\omega^2} \qquad (3)$$

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T, ω – **natural period** (4) and **natural frequency** (5) of the system;
To, ωo – **period** and **frequency** of the ground motion.

$$T = 2\pi\sqrt{\frac{m}{K}} \quad (4)$$

$$\omega = \sqrt{\frac{K}{m}} \quad (5)$$

Regarding the introduced coefficient β, the following theoretical considerations can be made. If $T \ll T_o$ and for sufficiently rigid structures, the acceptable value can range from 1 to arbitrarily large values. When the natural period of the ground motion coincides with the system's natural vibration period, $T_0 \approx T$, $S=\infty$, a resonance condition arises. From this, it follows that the maximum seismic load depends solely on the intensity of the ground motion and the dynamic properties of the building. Taking this into account during design minimizes the impact of seismic load on the structure. However, this theory does not consider energy dissipation in the system and the damping of vibrations. Moreover, the sinusoidal law did not allow determination of the instantaneous effect of the first seismic shock.

In 1927, K.S. Zavriev adopted a cosine law for ground motion, thereby overcoming the main shortcomings of Mononobe's theory and emphasizing the necessity of considering transient processes. According to Zavriev's theory, the initial ground velocity was assumed to be zero, $y_0(t)=0$, the acceleration $y_0(t)$ reaches its maximum value, and the harmonic vibration takes the following form:

$$y_0(t) = b \cdot cos\left(\frac{2\pi}{T_0}t\right) \quad (6)$$

In tere: b is the amplitude of the ground motion; The inertia forces due to seismic load are calculated similarly to expression (2), but the coefficient β now accounts for the nature of the vibration described in (6) and is expressed by the following formula:

$$\beta = \frac{2}{1-T^2/T_0^2} = \frac{2}{1-\omega_0^2/\omega^2} \quad (7)$$

When T approaches zero (T→0T \to), the coefficient β equals 2. This allowed taking into account the instantaneous effect of the system. This situation contributed to the development of A.G. Nazarov's concept of seismic impulse and indicated that seismic effects can also occur in the form of impulses. By comparing expressions (3) from F. Mononobe's theory and (7) from K.S. Zavriev's theory, it can be concluded that the maximum seismic loads are two times smaller than in the first case. The above-described theories and their rules form the basis of the dynamic theory of seismic resistance of buildings. However, the main issue remained the insufficiently studied nature of ground vibrations. Simplified motion models were used, and it was not possible to apply existing handwritten data on vibrations in analytical solutions. In addition to this problem, other issues existed: the theories mentioned above did not account for the distribution of seismic loads along the height of the building, nor did they consider systems with an infinite number of degrees of freedom (relevant for tall buildings). Questions also began to arise regarding the consideration of inelastic deformations and damage in buildings and structures during an earthquake [11-20].

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Dynamic Theory of Seismic Resistance

The American scientist M. Bio was the first to determine the values of seismic forces using an instrument that recorded ground vibrations. Considering the initial conditions $y_0(0)=0$ and $T_0 \rightarrow T0$, the law of ground motion takes the following differential form. That is, the seismic load S(t) is expressed as a function of the ground acceleration $y_0(t)$ and is given by the following formula:

$$S(t) = m\omega \int_0^t \ddot{y}_0(\tau) \sin\big(\omega(t-\tau)\big)\, d\tau \qquad (8)$$

The expression for the system's maximum acceleration is as follows:

$$\ddot{z}_{max} = \frac{s_{\max}}{m} = \omega \int_0^t \ddot{y}_0(\tau) \sin\big(\omega(t-\tau)\big)\, d\tau \qquad (9)$$

The system's maximum acceleration, as a function of its period $z_{max}=f(T)$ or frequency, is considered its spectral acceleration. For example, an engineer can determine the maximum seismic force of a single-degree-of-freedom system using the structural acceleration spectrum and the natural vibration period T. However, processing the results obtained from ground motion records (accelerograms, velocigrams, and seismograms) is complex, and expressing the results in analytical form makes a closed-form solution of function (9) an exception. Scientist M. Bio proposed using solutions approximated by harmonic analysis, representing $y_0(t)$ as a harmonic sum, resulting in the following form of expression (10):

$$\ddot{z}(t) \approx \sum_{i=1}^{n} \omega \int_0^t \ddot{y_{0\iota}}(\tau) \sin\big(\omega(t-\tau)\big)\, d\tau \qquad (10)$$

An approximate value in this expression can be obtained, but it requires considerable effort. Therefore, a mechanical model was proposed. This model consisted of pendulums (oscillators) attached to a shaking platform, with natural vibration periods ranging from 0.1 to 2.4 seconds. As a result, it became possible to determine the acceleration spectra by measuring the maximum accelerations z_{max} from each pendulum throughout the entire operation of the shaking platform. Analysis of the spectral results produced the standard acceleration spectrum shown in Figure 1.

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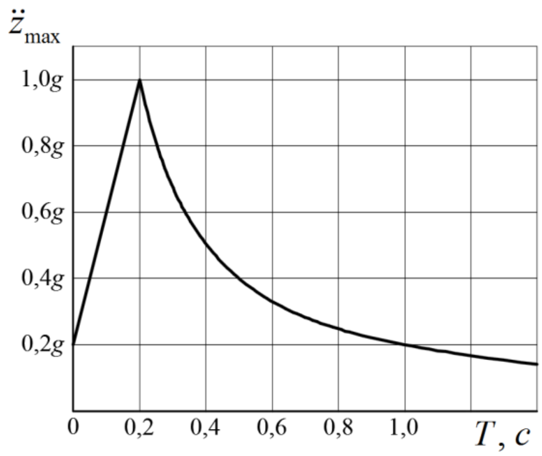

Figure 1. Standard acceleration spectrum

This scientific work was continued in the studies of G. Hausner and G. Kana, where the vibrations of non-conservative systems with one and four degrees of freedom were investigated. The damping of the system was taken into account according to the viscoelastic resistance hypothesis of the German physicist Woldemar Voigt.

This hypothesis states that the system's resistance to external forces depends on the velocity of displacement (y) (11):

$$R_{res} = \beta \dot{y}(t) \tag{11}$$

β – the resistance coefficient, which is a material property determined experimentally.
Taking into account the viscoelastic resistance of the material, the equation of motion for the dynamics of a conservative system yields the following vibration equation:

$$\ddot{y}(t) + 2\varepsilon\dot{y}(t) + \omega^2 y(t) = -\ddot{y}_0(t) \tag{12}$$

ε – the damping coefficient of the system

$$\varepsilon = \frac{\beta}{2m} \tag{13}$$

If y(t)=y˙(t)=0, then by calculating expression (12), we obtain the system's acceleration as a function of the ground acceleration:

$$\ddot{z}(t) = \omega \int_0^t \ddot{y}_0(\tau)\, e^{-\varepsilon(t-\xi)} \sin\big(\omega(t-\tau)\big)\, d\tau \tag{14}$$

The seismic load is given by the following expression:

$$S(t) = m\ddot{y}(t) = m\omega \int_0^t \ddot{y}_0(\tau)\, e^{-\varepsilon(t-\xi)} \sin\big(\omega(t-\tau)\big)\, d\tau \tag{15}$$

Based on this expression, it is possible to calculate the acceleration spectra of systems with different damping coefficients (Figure 2).

In 1958, the California Engineers Association proposed using a uniform standard spectrum for practical calculations, expressed in terms of $\ddot{z}_{max}(T)$. At the same time, the magnitude of the maximum seismic force can be expressed as follows:

$$S=S_{max}(T)=m\ddot{z}_{max}(T) \qquad (16)$$

To account for the system's resistance, Ye.S. Sorokin proposed his hypothesis. According to this hypothesis, the dependency is expressed not through the velocity $\dot{y}(t)$, but in the complex form of displacements y(t):

$$(1+i\gamma)K\bar{Z}(t)=\bar{\Phi}(t) \qquad (17)$$

The vibration equation is expressed in the following form:

$$m\ddot{y}(t)+(1+i\gamma)Ky(t)=-m\ddot{y}_0(t) \qquad (18)$$

American scientists such as K. Arnold and R. Reyterman highlighted that the weight and dimensions of a building are the primary factors affecting its seismic resistance. They also noted that as the weight and size of a building increase, seismic impacts can lead to structural failure. In practice, most buildings are large and heavy. In such cases, they recommended designing buildings in simple forms, considering the mutual arrangement of structures, applying seismic joints, minimizing building weight where possible, and using rigid cores along with horizontal and vertical diaphragms throughout the building's full height.

The scientists emphasized that, for buildings and structures to be seismically resilient, it is necessary to prevent the main weight from concentrating on the upper floors, ensure that the height of the first floor does not differ sharply from other floors, and design the building plan to be symmetrical along orthogonal directions.

Moreover, the literature presents analyses of damage caused by earthquakes in various cities, concluding that among L-shaped, T-shaped, G-shaped, and simple rectangular buildings, those with a rectangular plan are more resistant to seismic effects.

Conclusion. The scientific works of the aforementioned researchers and their results have laid the foundation for subsequent studies. From the simple expressions developed by F. Omori to the present, the advancement of science has led to the emergence of more complex equations. In conclusion, it should be noted that, according to the current design regulations in our country, dynamic and spectral methods can be applied to calculate the seismic effects on buildings and structures, taking into account the requirements specified in the relevant documents.

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