The vibration amplitude dependence of the construction elements on soil-structure interaction parameters

Comment l'amplitude de la vibration des éléments de la construction dépend de paramètres d'action réciproque sol-structure

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ABSTRACT: The soil conditions influence on vibration level of the construction elements is analyzed. It has been established that the damping of the structure vibrations is defined by energy radiation of vibrations into the basis by elastic waves for certain ratios between stiffness and inertia characteristics of the structure and the soil. The methods applied and calculation results of the vibration parameters of the soil-structure system for different kinds of constructions and soil conditions have been described.

RESUME: On analyse l' influence des conditions des terrains sur les vibrations des constructions. On presente les resultats des calculs des vibrations des pont en coditions differentes du terrain.

1 INTRODUCTION

The question of the soil conditions influence on damping level and vibration amplitudes of the constructions (Ilyitchov 1981, Uzdin 1990 and etc.) has been discussed in scientific literature for a long time. In particular, this problem is very urgent for the theory of earthquake stability. However, at present soil conditions are not evidently taken into account in Russian and foreign instructive literature on dynamic calculation of the constructions. In addition, the number of works devoted to the problem of quantity estimation of the soil conditions influence on vibration amplitudes of the structures is quite limited.

As a rule, the calculations of dynamic coefficients of the structures subjected to dynamic loads are carried out according to empirical formulae, obtained for the constructions of the same class under medium soil conditions. In this situation it is possible at best to take into consideration the basis flexibility and to estimate the system frequency spectrum. The determination of vibration amplitudes depending on system damping spectrum (damping parameters for each mode) is completely impossible.

The methods and some calculation results of the constructions in the conditions of their interaction with the basis are presented in the paper.

2 DESIGN MODEL OF THE SYSTEM UNDER CONSIDERATION.

We have investigated two types of constructions. The first one is modeled by bend-shift clamped rod and has only one contact point with the basis. The other type of structures is presented by an extended frame model with point supporting on the soil; in this case the influence of the piers on one another through the ground is supposed to be absent.

The first design model is used to describe the vibrations of buildings, towers, separately working bridge piers etc. The second one (Figure 1) permits to calculate bridges, pipelines and other extended structures, if the distance between the piers is more than five typical sizes of the foundation.

For the design models under consideration the soil under each pier is modeled independently. Different design models with big and small number of freedom degrees are well known to be used for modeling the soil basis (Uzdin 1992, Uzdin 1993). Simple models with a small number of degrees of freedom are the most convenient for the engi-

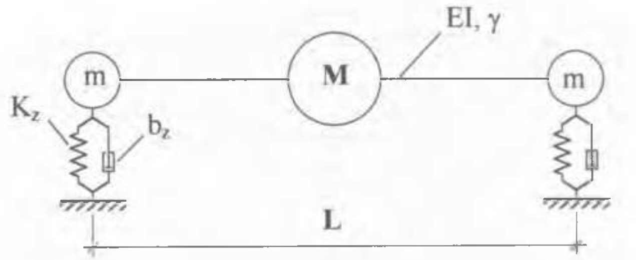

Figure 1. Design model of the extended structures.

neering practice. The theoretical evidence of those models is to be found in famous works by V.A. Ilyitchov (1971), John P. Wolf (1994) and in a number of other investigations (Uzdin 1993).

For mass calculations we used the simplest model of the soil basis. It consists of spring and damper, with the damper dissipating the energy, equal to hysteresis losses in soil and energy radiation into the basis by elastic waves. This model is regulated by Russian design standards of foundations under machines with dynamic loads. The parameters of more complicated basis models are shown described in works (Uzdin 1992, Uzdin 1993, John p.Wolf 1994).

3 THE CALCULATION METHOD OF A SOIL-STRUCTURE SYSTEM.

The accepted design model of a soil-structure system is characterized by heterogeneity of damping. In general, this heterogeneity is caused by both various value of damping parameters in the construction and basis elements and different nature of this process. In the construction elements the damping is frequency-independent (hysterestic), but in the basis elements it is viscous. Having expressed hysterestic damping through viscous one, we can write down the following system of the dynamic equilibrium equations:

$$\mathbf{M}\ddot{\mathbf{Y}} + \mathbf{B}\dot{\mathbf{Y}} + \mathbf{R}\mathbf{Y} = \mathbf{P}, \quad (1)$$

where **M**, **B**, **R** are the mass matrix, the damping matrix and the stiffness matrix of the system respectively; **Y** is the column of generalized displacements; **P** is the impact vector.

The system of equations (1) may be presented as the sum of vibration mode shapes. In the process of the investigation exact and approximate solutions are considered and the interaction parameters influence on the damping parameters for each mode (damping spectrum) is analyzed.

The approximate method does not take into account the damping influence on mode shapes. In this case the displacements **Y** are presented as the sum of vibration mode shapes **X** of undamped system:

$$\mathbf{Y} = \mathbf{X}\Xi, \tag{2}$$

where **X** is the eigenvectors matrix of matrix $\mathbf{M}^{-1}\mathbf{R}$, Ξ is the vector column of main coordinates.

After the substitution of (2) into (1) and the following approximate presentation

$$\mathbf{X}^{-1}\mathbf{M}^{-1}\mathbf{B}\mathbf{X} \approx \Gamma\Lambda^{1/2}, \tag{3}$$

where Λ is the eigenvalues matrix of matrix $\mathbf{M}^{-1}\mathbf{R}$, the independent equations system for main coordinates is obtained

$$\ddot{\xi}_j + \gamma_j \lambda_j^{1/2} \dot{\xi}_j + \lambda_j \xi_j = \sum d_{ji} p_i, \tag{4}$$

where γ_j are coefficients of inelastic resistance per each mode shape. These coefficients are the elements of diagonal matrix Γ; d_{ji} are the elements of matrix $(\mathbf{MX})^{-1}$.

The exact method takes into consideration the damping influence on the vibration modes. This influence is essential for massive constructions on soft soils, when for the first mode shape $\gamma_1 > 0.3$ and also essential for the systems with additional damping devices, for example, for seismoisolating foundations with dampers. In this case the presentation identical to (2) may be written down as follows:

$$\mathbf{Y} = \mathbf{X_1}\Xi + \mathbf{X_2}\mathrm{H} + \mathbf{T}\mathbf{Y} \tag{5}$$

Here $\Xi = \{\xi_1, \xi_2, \ldots, \xi_k\}$, $\mathrm{H} = \{\eta_1, \eta_2, \ldots \eta_k\}$, $\mathrm{Y} = \{\upsilon_1, \upsilon_2, \ldots \upsilon_m\}$ are the main coordinates, from which ξ_j and η_j are pair ones, satisfying the equations:

$$\ddot{\xi}_j + \gamma_j k_j \dot{\xi}_j + k_j^2 \xi_j = \sum d_{ji}^{(1)} p_i,$$

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and υ_j satisfying the following expression:

$$\dot{\upsilon}_j + \nu_j \upsilon_j = \sum d_{ij}^{(3)} p_i.$$

The definition of parameters γ_j, κ_j, ν_j and matrixes $\mathbf{X_1 X_2}, \mathbf{T}$ is described in detail by Uzdin (1986).

4 EXAMPLES AND CALCULATION RESULTS

As examples of calculations we considered vertical and horizontal vibrations of bridges. Vertical vibrations of frameworks modeled by beam have been investigated by authors in previous works (Uzdin 1980). The main results of vertical vibrations calculations in the form of dependences of inelastic resistance coefficient γ on the span length of the bridge are illustrated in Figure 2. It is clearly shown that the value of inelastic resistance coefficient is sharply decreasing with the span length increasing according to calculating and experimental data. This phenomenon may be explained as follows. The bridges of small spans possess high stiffness, and on non-rock basis the vertical displacements of these constructions are firstly determined by soil deformation. On the contrary, large-spanned bridges do not practically involve the basis in joint work because of their flexibility, and energy dissipation into the soil basis is insignificant.

The analysis of calculation results has allowed the authors to explain the cases of apparent dropping out of

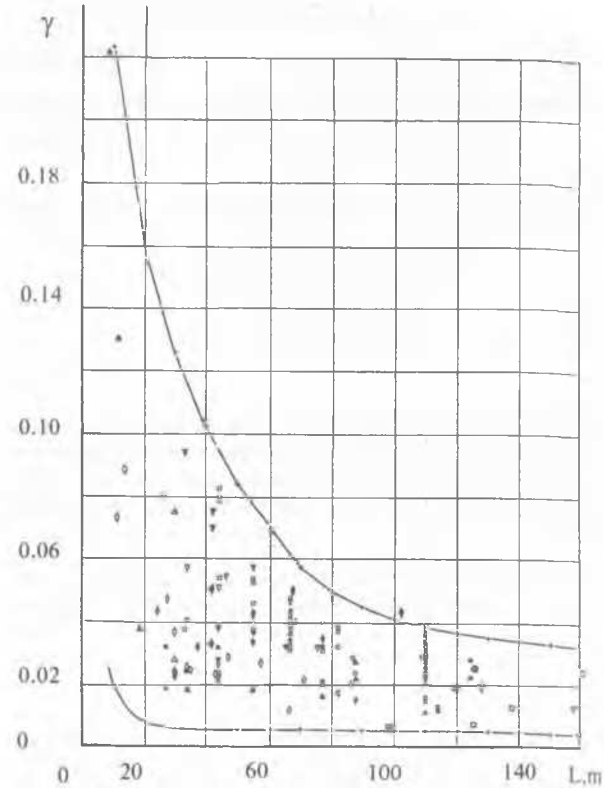


Figure 2. Dependences of inelastic resistance coefficient on the span length for vertical bridge vibrations.

some experiments from general dependence as well. In these experiments beam bridges 9-11m long on weak soils had small vibration damping. This is connected with the presence of three vibration mode shapes given in Figure 3 for the framework-piers-basis system under consideration.

The first mode shape is characterized by the absence of framework deformation. The second and the third vibration modes represent nearly the same character of deformations. However, there is some difference between them: in the second one the framework and piers are moving in phase, but in the third mode - in antiphase (Figure 3). Besides, these mode shapes are characterized by different damping change (Figure 4). The second one demonstrates the decrease of inelastic resistance coefficient γ_2 with the increase of the span length - from the value of inelastic resistance coefficient γ_s to analogous value γ_f in the framework. On the contrary, the third mode shows the increase of γ_3 from γ_f to γ_s.

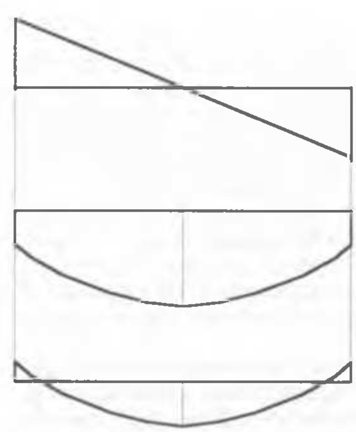


Figure 3. The first, second and third vibration modes.

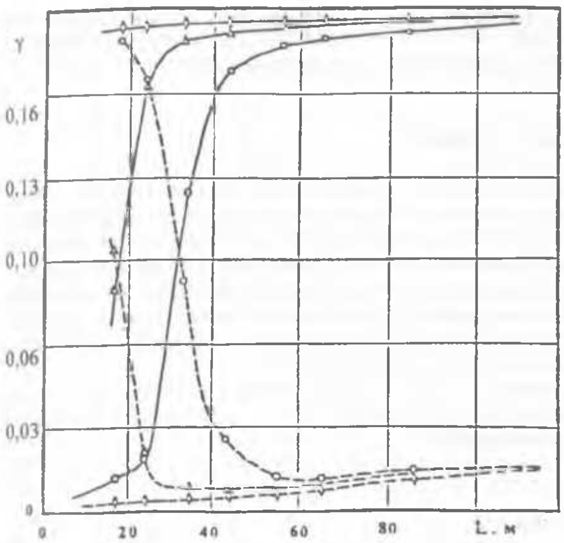


Figure 4. Dependences of inelastic resistance coefficient on the span length for second and third vibration modes. (for E_0=500 MPa - ◊, E_0=60 MPa - Δ, E_0=20 MPa - •.

It is practically impossible to distinguish between the second and the third mode shapes, if sensing elements are fixed in the middle of the span. As a rule, the strongly damped second vibration mode damps quickly and only the third mode may be clearly seen on the record. Consequently, for the correct investigation the sensing elements should be fixed both in the middle of the span and on piers.

In addition to the described calculations, the dynamic analysis of a through truss has been carried out. (Figure 5). It has been established that the soil-structure interaction is essential only for the first 3-5 vibration mode shapes. For the higher modes the effect of energy dissipation into the soil basis is not significant. Therefore, in the conditions of truss elements calculations as separate rods it is possible to neglect energy dissipation into the soil and take into account only the energy dissipation in the material of the rod.

To analyze bridges transversal vibrations, more complicated design models have to be used. One of these models is presented in Figure 6. It simulates the space vibrations of one of the beam bridge spans and is characterized by 15 degrees of freedom. Two of them describe the vertical vibrations of the beam, two others - horizontal ones and other two - torsion vibrations, another one - the displacement of a rolling-stock, still two others - the displacement of piers top, and each pier has three generalized displacement.

Three dependences of inelastic resistance coefficient for the first mode shape of the bridges with the piers H=3 m, H=10 m and H=20 m height, respectively, are indicated in Figure 7. The cases H=3 m and H=20 m are considered for the weak soil with the deformation modulus of E_0=12 MPa and case 2 (H=10) - with E_0=40 MPa. The calculation results for weak soils, when the piers are not practically deformed and the energy losses are distributed between the dissipation into the framework and the basis, are demonstrated in Figure 7a.

This dependence γ (L) is much more complicated, if the soil rigidity is comparable to the stiffness of piers. It is shown in Figure 7b. On the rock basis the damping is determined by losses ratio in piers and frameworks.

It is interesting to connect the system damping parameters, which determine the vibration amplitudes of its elements, with the parameters of soil-structure interaction. We accepted the following parameters:

$a_o = \frac{\omega r}{v}$ - dimensionless resonance frequency of the construction vibrations;

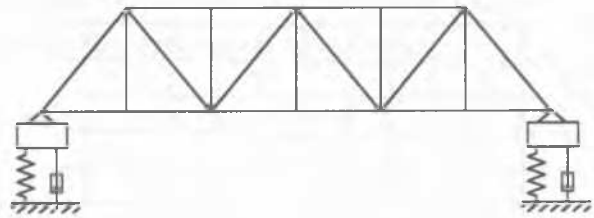


Figure 5. Design model of the through truss.

$m_o = \frac{m}{\rho r^3}$ - dimensionless mass of the construction;

$\aleph = \frac{K_x}{K_\varphi} h^2$ - dimensionless rotating stiffness of the foundation.

In the given expressions the following values are used: ω - the main frequency of the construction vibrations on the rock basis; $r = \sqrt{\frac{F}{\pi}}$ - radius of the circle, the area of which is equal to the foundation bottom; F - the area of the foundation bottom; v - the shift waves velocity in the basis; m - mass of the construction per a pier; ρ - density of the basis soil; K_x, K_φ - rotating and shift stiffness of the foundation; h - the distance between the foundation bottom and the construction gravity center.

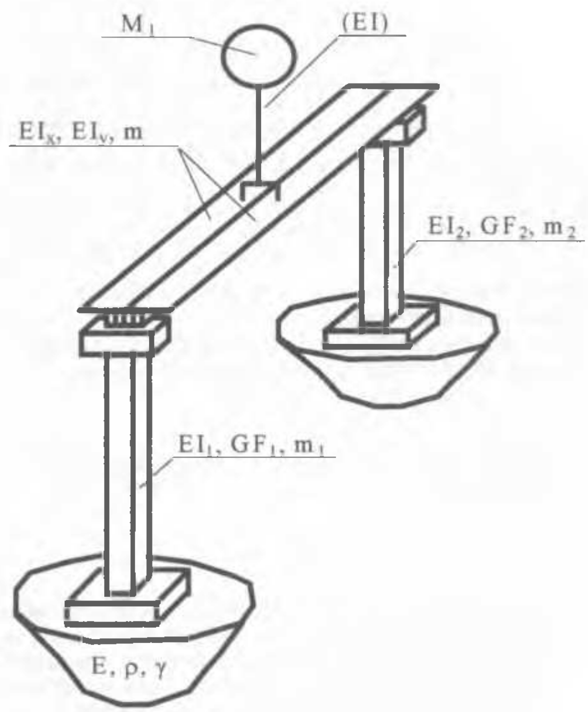
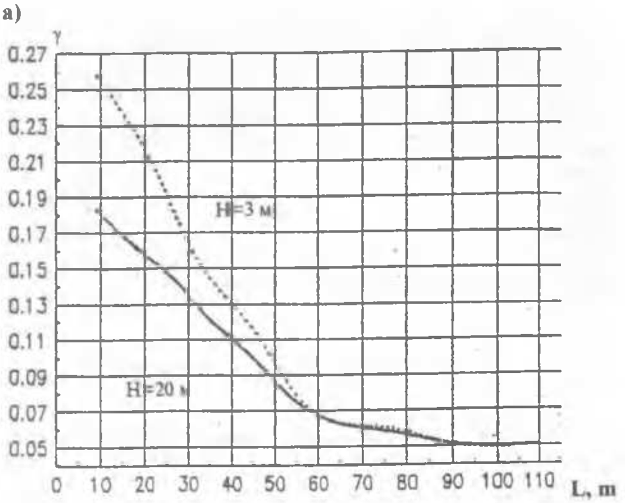


Figure 6. Design models to analyze bridges transversal vibrations.

Besides the indicated parameters, the relative stiffness of the construction can be introduced :

$$C_o = \frac{C}{G_r},$$

where C is the construction stiffness; G is the shear modulus of the basis.



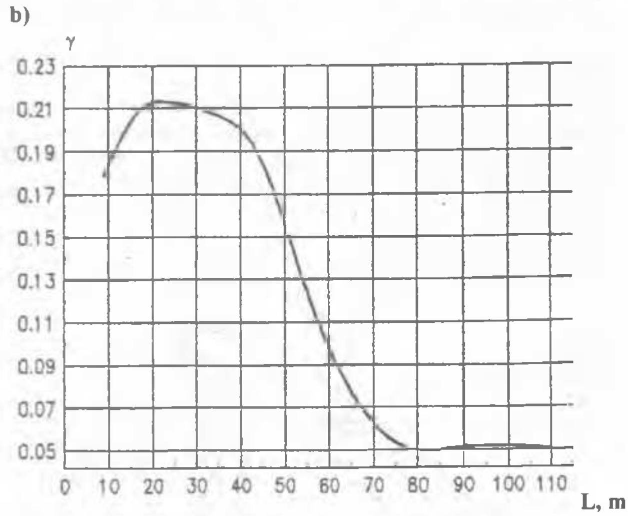


Figure 7. Dependences of inelastic resistance coefficient for the first mode of vibrations.
a) for the bridge with the piers H=3 m, H=20 m, E_0=12 MPa;
b) for the bridge with the piers H=10 m and E_0=40 MPa

There exists the following ratio between a_0, m_0 and C_0:

$$a_0^2 = \frac{C_0}{m_0}$$

For massive structures with dimensionless resonance frequency $a_0<0.25$ and parameter $\aleph<1$ the system shift vibrations resulting from the soil basis deformations are the most important. In this case there occurs considerable energy dissipation into the basis, which leads to the reduction of the construction vibration amplitudes.

For the high massive structures with $a_0<0.25$ and $\aleph>1$ the rotating vibrations are the most essential, its importance increasing with the growth of parameter $\aleph$. In this case the vibrations damping of structure is defined by both energy radiation into the basis by elastic waves and hysteresis in the ground. It should be noted that in this situation hysterestic losses in the soil are quite essential, because the energy radiation into the basis is negligible under the foundation rotating vibrations.

For flexible high structures with $a_0>1$ damping and vibration amplitude are defined by the value of relative stiffness parameter C_0. When the values of C_0 are large, the rotating vibrations of structure as the rigid whole predominate, and energy losses are determined by hysteresis in the soil.

In the conditions of small value of C_0 the structure bending vibrations predominate and energy losses are defined by hysteresis in the material of structure.

5 CONCLUSION

Consideration of the soil-structure interaction is very important to estimate the structure vibrations amplitudes, as it is the energy dissipation into the soil, that predicts the damping parameters according to the fundamental mode shape.

In analyzing general dynamic deformations of the construction, especially under seismic, wind, explosion and impact loads, the soil-structure interaction predetermines the calculation results.

When the level of local vibrations of the construction elements is being estimated, the soil-structure interaction may be neglected.

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