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MATERIAL DAMPING IN DYNAMIC ANALYSIS OF STRUCTURES (WITH LIRA-SAPR PROGRAM)

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Abstract

The purpose of this paper is to justify that it is necessary to take account of physical and mechanical properties of soil and different materials of erected structure for damping vibrations in dynamic loads; to suggest tools for modelling the damping effect (natural or engineering induced) between foundation and soil. Certain technique is suggested for modelling behaviour of structure in time history analysis with account of material damping. In the software, the damping effect is modelled in two variants: Rayleigh damping (for structure) and finite element of viscous damping. When solving this problem, the following results were obtained: physical meaning of material damping is described; Rayleigh damping coefficients were computed through modal damping coefficients. Numerical analysis is carried out for the structure together with soil in earthquake load using developed FE of viscous damping. Time history analysis was carried out for the problem. Peak values of displacement, speed and acceleration at the floor levels were compared. Analysis results are compared (with and without account of material damping). Significant influence of damping on the stress-strain state of the structure is confirmed. Scientific novelty of the paper is in the following: the damping effect is proved to happen regardless of the presence of installed structural damping equipment; technique for account of damping with Rayleigh damping coefficients is developed; new damping element is developed – FE of viscous damping (FE 62), its behaviour is described as linear mathematical model. Practical implications of the paper: developed technique and new FE enables the user to carry out numerical analysis properly and work out a set of measures on seismic safety for buildings and structures.

Keywords:

Dynamic load;
Numerical modelling;
Computer modelling;
Material damping;
Structural damping.

1 Introduction

Structural dynamics as a science appeared in the 20-ies of the 20th century. This science appeared due to the practical needs of construction, a significant increase in dynamic loads on structures: increased capacity and speed of machines, the speed of moving loads, etc. However, development of structural dynamics in those years lagged significantly behind its theoretical base - the theory of oscillations and building mechanics, and actual information obtained in dynamic tests of structures.

The increase in computer power, development of information technologies and methods of computer modelling along with numerical methods in the last 20 years have given a fresh impetus to the development of the structural dynamics. So, complex problems may be solved with computer modelling and numerical experiments.

The aim of this work is to study the forced vibrations of steel and concrete structures.

2 Description of the approach

Differential equation of motion for the structure is presented as [1]:

$$[K]\{U\}+[C]\{\dot{U}\}+[M]\{\ddot{U}\}=\{P(t)\}, \tag{1}$$

where [*K*] - stiffness matrix of the system, [*C*] - damping matrix, [*M*]- mass matrix, {*U*}, $\{\mathring{U}\}$, $\{\ddot{U}\}$ - unknown vectors of nodal displacements, velocities, accelerations, {*P*(*t*)} - vector of external nodal load at time point *t*.

To solve the system of differential equations of motion, there are two main methods: expansion by mode shapes of natural vibrations and direct (or indirect) integration of the equations of motion. The method of expansion by mode shapes of natural vibrations may be applied only for linear analysis, since the superposition principle is not applied to the nonlinear theory. Direct integration methods such as Runge-Kutta method, Newmark method, Wilson method, method of central differences, etc. may be used to carry out all types of dynamic analysis of structures.

Thus, system of equations of motion solved based on Newmark method [1-4] in the matrix form is as follows:

$$[A]=\frac{1}{\alpha\Delta t^2}[M]+\frac{1}{\gamma\Delta t}[C]+[K], \tag{2}$$

$$\{B\}_{i+1}=F(t_{i+1})+[M]\left(\frac{1}{\alpha\Delta t^2}\{U\}_i+\frac{1}{\alpha\Delta t}\{\dot{U}\}_i+\left(\frac{1}{2\alpha}-1\right)\{\ddot{U}\}_i\right)+$$
$$+[C]\left(\frac{1}{\gamma\Delta}\{U\}_i+\left(\frac{1}{\gamma}-1\right)\{\dot{U}\}_i+\left(\frac{1}{2\gamma}-1\right)\Delta t\{\ddot{U}\}_i\right), \tag{3}$$

$$[A]\{U\}_{i+1}=\{B\}_{i+1} \tag{4}$$

where [*A*] – effective stiffness matrix, {*B*} - effective vector of loads, *α ,β, γ* – integration factors. Speeds and accelerations of nodes in the system are computed by expressions:

$$\{\dot{U}\}_{i+1}=\frac{1}{\gamma\Delta t}\left(\{U\}_{i+1}-\{U\}_i\right)+\left(1-\frac{1}{\gamma}\right)\{\dot{U}\}_i+\left(1-\frac{1}{2\gamma}\right)\Delta t\{\ddot{U}\}_i, \tag{5}$$

$$\{\ddot{U}\}_{i+1}=\frac{1}{\alpha\Delta t^2}\left(\{U\}_{i+1}-\{U\}_i\right)-\frac{1}{\alpha\Delta t}\{\dot{U}\}_i+\left(1-\frac{1}{2\alpha}\right)\{\ddot{U}\}_i \tag{6}$$

To obtain complete and reliable description of the stress-strain state of a structure, it is necessary not only to take into account any and all factors that describe the real object, such as its geometric properties, physical and mechanical properties of material, to take into account initial stress and strain during erection of the structure, but with high accuracy to determine external loads and their character. Typical examples of interaction between load and an object include many modes of dynamic load.

In the active building codes, it is accepted that earthquake acceleration of foundations (and the entire structure) and the base coincide [5]. However, experimental data indicates that the accelerations of foundations may be several times different from the accelerations of the soil base. This can be explained by the fact that not all energy of the earthquake load from the soil is transmitted to the foundation, i.e. part of load is transmitted because of peculiarities of interaction between the foundation and the base. The "loss" (leakage) of part of this energy may occur for a number of reasons:

- the damping effect (natural or engineering simulated) in elements between foundation and soil base (including due to seismic isolation);
- the ‘sliding’ of horizontal seismic wave under the foundation (in case of frictional forces and the specific character of one-way springs between the foundation and the soil base);
- the scatter of stiffnesses and mass values in the building models (altitude and stylobate parts) [6].

Let’s consider the damping effect. If dynamic load is acting on the structure, there is always a damping factor. Damping is provided by structural devices - dampers (vibration dampers). But even if the dampers are not installed, then the damping factor is still present and it is caused by material damping. The structure itself has the property of damping vibrations, especially if the structure is rather massive. During severe earthquake, deformations of such structure will go beyond the elasticity limit and the structure will not be destroyed only due to its ability to deform inelastically. Inelastic deformations assume a shape of localized plastic hinges, it causes an increase in compliance and energy absorption. In this case, major part of the earthquake energy is absorbed by the structure through local damage. A soil body under the structure is also a powerful damper.

An accurate description of the damping forces associated with energy dissipation presents significant challenge. These forces may depend on displacements, velocities, stresses or other factors. Most of the energy dissipation mechanisms in oscillating systems are nonlinear and cannot be reduced to either linear viscous damping or linear hysteresis damping.

Nevertheless, idealized damping models should be considered in analysis since they often give a satisfactory approximation to real behaviour of the structure.

If material damping is considered in simulation of behaviour of the structure, it allows the user to obtain more adequate picture of the stress strain state in comparison with the same calculation without damping.

Different materials with different properties contribute differently to vibration damping. The physical meaning of material damping is caused by transferring mechanical energy into thermal energy. It takes place due to microplasticity, rather than viscosity, both in liquids and gases. Viscous damping may be used for any form of excitation. Matrix of viscous damping coefficients [C] in the Rayleigh model [6, 7] is defined as a linear combination of the stiffness matrix of the system [K] and the mass matrix of the system [M] with coefficients α and β presented as:

$$[C] = \beta[K] + \alpha[M], \tag{7}$$

where α and β – Rayleigh damping coefficients.

To take into account different materials in the parts of structure for each element, we specify certain Rayleigh coefficients (Fig. 1), and, thus, compose a combined dissipation matrix. Mass matrix of the structure corresponds to mass matrix of the whole system, but the stiffness matrix does not: stiffness of the soil spring is not included into this matrix [6].

The values of Rayleigh coefficients (α and β) are not generally known. To determine Rayleigh coefficients, it is necessary to carry out modal analysis of the structure, define empirical damping coefficients for material at the two lowest eigenfrequencies and calculate the coefficients through the modal damping powers:

$$\alpha = \frac{2\xi_i \xi_j \omega_i \omega_j}{\xi_i \omega_i + \xi_j \omega_j}, \beta = \frac{2\xi_i \xi_j}{\xi_i \omega_i + \xi_j \omega_j}, \tag{8}$$

where $\omega_{i.}$ ω_{j} – eigenfrequencies, ξ_i, ξ_i –modal degrees of damping (the ratio of the actual damping to the critical damping for a certain mode shape).

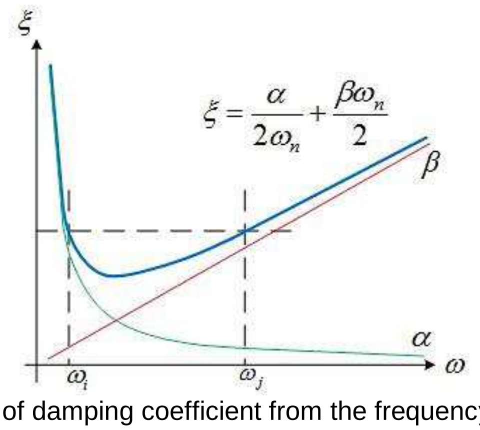

Fig.1: Dependence of damping coefficient from the frequency by Rayleigh damping.

To consider effect of engineering and structural damping, in LIRA-SAPR program there is a special damping element - FE of viscous damping (FE 62). Schematic presentation of this element is shown in Fig. 2.

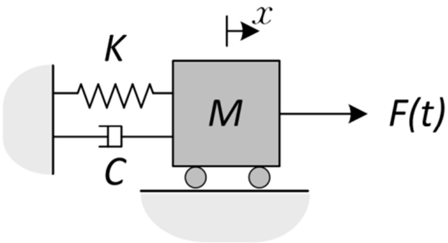

Fig. 2: Spring-damper system.

Let's examine behaviour of this element. The loss of energy in one cycle of vibrations in such element may be determined as

$$W_d = \int F_d \mathrm{d}x \,, \tag{9}$$

where F_d - damping force.

In linear mathematical model, the force of viscous damping is $F_d = C \cdot \dot{x}$. The equation of harmonic vibrations

$$x = X \cdot \sin(\omega t - \varphi) \,, \tag{10}$$

the speed of motion is determined by expression

$$\dot{x} = \omega X \cdot \cos(\omega t - \varphi) \,. \tag{11}$$

In view of the fact that $dx = \dot{x}dt$, we could write

$$W_d = \int C\dot{x}\mathrm{d}x = \int C\dot{x}^2 \mathrm{d}t \,. \tag{12}$$

Then loss of energy in one cycle of vibrations is equal to

$$W_d = C\omega^2 \cdot X^2 \int_0^{2\pi/\omega} \cos^2(\omega t - \varphi)\mathrm{d}t = \pi C \omega X^2 \,. \tag{13}$$

With resonance, $\omega = \omega_n = \sqrt{\frac{K}{M}}$ and $C = 2\varsigma\sqrt{KM}$

$$W_d = 2\varsigma\pi K X^2 \,. \tag{14}$$

Equation (11) may be displayed as

$$\dot{x} = \pm\omega X \sqrt{1 - \sin^2(\omega t - \varphi)} = \pm\omega\sqrt{X^2 - x^2} \,. \tag{15}$$

Damping force

$$F_d = C \cdot \dot{x} = \pm C\omega\sqrt{X^2 - x^2} \,. \tag{16}$$

Expression (14) may be displayed as

$$\left(\frac{F_d}{C\omega X}\right)^2 + \left(\frac{x}{X}\right)^2 = 1. \tag{17}$$

Energy dissipation in a cycle may be also represented as

$$W_d = \pi C_{eq} \omega X^2. \tag{18}$$

Thus, equivalent damping coefficient is determined as

$$C_{eq} = \frac{W_d}{\pi \omega X^2}. \tag{19}$$

Thus, this method leads to separate differential equations (15) and (16), each of which describes vibrations of a system with one degree of freedom.

If fractions in right part (15) and (16) denote through P_1 and P_2 respectively, the stationary part of solution will took a form:

$$f_1 = \frac{P_1}{\omega_1^2 - p^2} \sin pt; \tag{20}$$

$$f_2 = \frac{P_2}{\omega_2^2 - p^2} \sin pt. \tag{21}$$

After substitution (17) and (18) into (9), we will get generalized coordinates of forced vibrations of considered system of two fibrous concrete beams:

$$\begin{cases} x_1 = \dfrac{a_{11}P_1}{\omega_1^2 - p^2} \sin pt + \dfrac{a_{12}P_2}{\omega_2^2 - p^2} \sin pt; \\ x_2 = \left(\dfrac{a_{21}P_1}{\omega_1^2 - p^2} + \dfrac{a_{22}P_2}{\omega_2^2 - p^2}\right) \sin pt. \end{cases} \tag{22}$$

It follows from the above arguments that such separate differential equations can be obtained at any number of beams, joining each other.

3 Numerical solution

The paper presents analysis of the building together with the soil and taking account of shallow subway.

To aid the visualization of damping effect, parameters of the stress-strain state (displacements, moments, internal forces) are compared at different storey levels. Analysis is carried out with LIRA-SAPR program where time history analysis is realized based on Newmark method. The problem is solved in the plane statement with defined real soil properties. The computational model is introduced in Fig. 3.

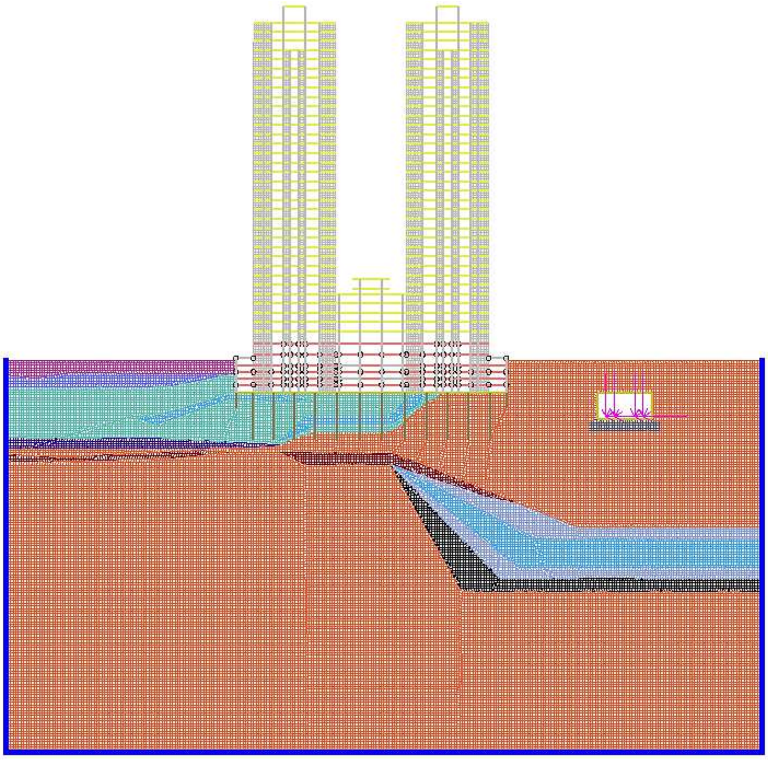

Fig. 3: Test problem in LIRA-SAPR.

The building structures take the load from the subway located at the distance of 40 m from the bearing framework. This is sinusoidal load: $P(t) = P \cdot \sin(\omega \cdot t)$, where P = 490 kN along the X-axis and 294 kN along the Y-axis, frequency ω = 395 rad/s.

To consider absorbing properties of soil, damping coefficient is used. It is determind by formulas described in [8].

In LIRA-SAPR program, matrix of damping coefficients is determined from the stiffness matrix and mass matrix (7) with Rayleigh damping coefficients α and β which in turn determined from dependence (8) [9,10].

To do the above-mentioned, system of two equations is composed for the fundamental and the first modes for every soil layer and required coefficients are determined [11].

4 Results

Some results of calculations are presented in Fig. 4, Fig. 5 and Table 1.

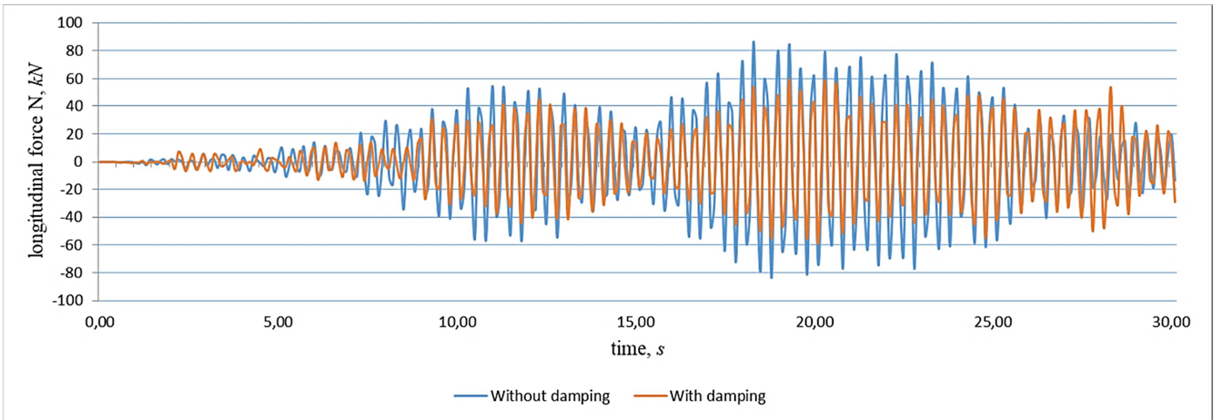

Fig. 4: N values compared in the column of the upper storey.

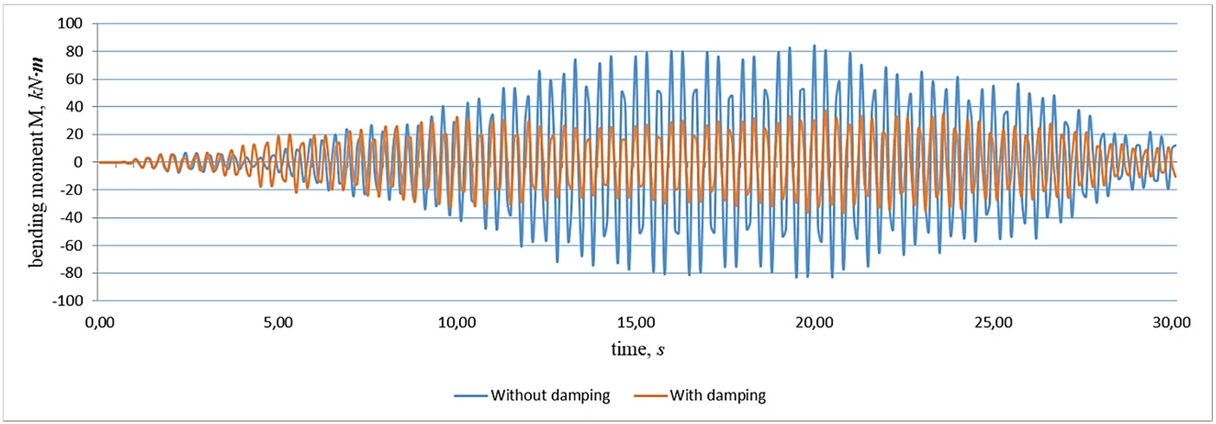

Fig. 5: M values compared in the column of the first storey.

Table 1: Comparison of output data.

The value of the parameters of the strass-strain state	Without damping		With damping	
	N, [kN]	M, [kNm]	N, [kN]	M, [kNm]
Storey 1	106	15.3	42.2	7.34
Storey 35	86.2	23.9	59.5	21.4

5 Conclusions

From an interpretation of the output data, the following conclusions can be drawn:

• There is no real impact of subway, mostly because of small value of dynamic load; though the trend toward negative impact to the building structures is apparent and in case of prolonged influence it may cause the unintended effect.

• Damping properties of soil has more important effect. Results of numerical simulation show that account of damping in soil has significant impact on the stress-strain state of the structure (30 – 65 %).

New methods of numerical simulation with account of advanced methods of dynamic analysis (such as nonlinear properties of materials, material damping) enable the user to perform numerical experiments and develop a number of activities to provide seismic safety of buildings and structures.

6 References

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