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Underground pipeline damping from the action of rayleigh waves

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Abstract. The question of the depth of laying occupies a special place in the seismic protection of underground structures. With a seismic shock, different waves appear in the ground. Upon impact on the surface of the half-space, surface waves arise that have a destructive force for underground structures. Waves with longitudinal and transverse components of displacement, called Rayleigh waves, can occur on the surface. Rayleigh waves have a maximum effect on the surface and quickly fade with depth. To protect against the action of such waves, underground structures are laid deep on the ground. Reducing the depth of laying allows you to reduce costs and facilitates the maintenance of the structure. It will be possible to reduce the influence of Rayleigh waves at a shallower depth using dynamic dampers installed on the structure. The analysis of the work of a dynamic damper to reduce the displacement of an underground cylindrical structure allows us to conclude that the damping effect can be achieved both in terms of displacement amplitude and in the frequency zone width.

1. Introduction

Studying the behavior of underground structures involves studying the behavior of the passage of waves both in the ground environment and in the structure, as well as considering their joint interaction as a medium-structure system. The dynamics of the soil medium was evaluated in [1], the linear theory of hereditary viscoelasticity for the dynamic analysis of soil structures was studied in [2]. The behavior of land dams as surface objects of wave action is of interest for studying the state of hydraulic structures. In [3], the strength of soil dams under various dynamic influences was studied; in [4,5], the stress-strain state of soil dams was estimated taking into account the nonlinear deformation of the material and taking into account large deformations. The spatial stress state and dynamic characteristics of earthen dams were considered in [6], and in [7] wave processes in determining the mechanical characteristics of the soil medium were studied.

Studying the behavior of the structure under wave action will allow us to assess the state and dynamic characteristics of the object. The dynamics of physically nonlinear structures was considered in [8, 9], body vibrations taking into account the viscoelastic properties of the material were studied in [10, 11], and in [12] non-linear vibrations of an axisymmetric body under the action of a pulsating load were studied. The dynamic behavior of the “medium - foundation” system was estimated taking into account wave energy removal in [13].

The patterns of interaction of the contact surface between solids and soil were studied in [14].

The laying depth for underground structures is an important parameter, especially when exposed to surface waves. Surface waves, which carry the main destructive force for underground structures, quickly decay with increasing depth of the structure.

In [15], the oscillation of an elastic half-space with a cylindrical cavity under the influence of Rayleigh waves was considered. The work [16] is devoted to the study of the earthquake resistance of a structure during the propagation of Rayleigh waves in elastic half-space.

The issue of damping vibrations of underground structures is important in ensuring their safety. In practice, dynamic vibration dampers are widely used [17, 18, 19, 20]. So the efficiency of using a single-mass absorber was studied in [17], in [18] an analysis of the damping of vibrations of a pipeline was carried out, in [19] the vibration protection of high-rise buildings was studied using dynamic vibration dampers built into typical floors under seismic and wind influences. In [20], the effectiveness of multi-mass dynamic vibration dampers was evaluated, and in [21], the durability of building structures and structures equipped with multi-mass dynamic vibration dampers was evaluated. The effectiveness of the shock absorber during bending vibrations of rectilinear rods and the efficiency of a two-mass dynamic vibration damper with periodic impulsive action in [22,23]. The damping of oscillations of the hard disk in elastic space from wave diffraction using multi-mass dampers was considered in [24].

2. Methods

This article considers the problem of damping vibrations of a cylindrical structure located in an elastic half-space. The dynamic load is a Rayleigh wave passing in the elastic half-space. The purpose of the review is the possibility of reducing the displacements of the cylindrical structure. In fig. 1 presents the design scheme of the problem.

In [1], the displacements of a cylindrical cavity in a half-space from the action of Rayleigh waves were obtained by summing up two solutions: the problem of half-space oscillations when a Rayleigh wave passes along its surface and the problem of oscillations of an infinite medium with a cylindrical cavity:

$$u = u^{I} + u^{II}. \tag{1}$$

Displacements and stresses are expressed in the coordinate system replaced by z with $(z' + H + r_0)$, where $(H + r_0)$ is the distance from the half-space surface to the center of the cavity section. The underground structure is examined with a rigid undeformable section.

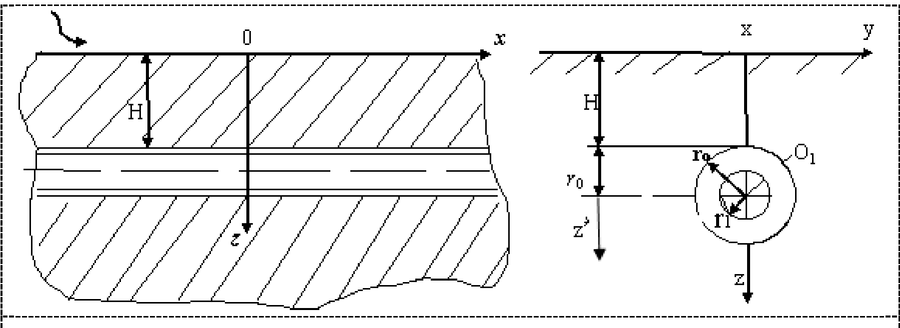

Figure1.Oscillations of a cylindrical structure in half-space.

In [1], the expression of radial displacements of a half-space with a cylindrical cavity at $r = r_0$ is presented, which was used to calculate and plot the amplitude-frequency characteristics (Fig. 2-3) [1]. The Poisson's ratio for an elastic medium is taken to be $\vartheta = 0.25$, and the ratio of the velocities of the longitudinal and transverse waves in the medium is equal to $R_0 = \sqrt{3}$. To identify the nature of the oscillation with a change in the frequency of exposure for different values of the quantities $R_v = \mu_2 / \mu_1$, $h = r_0 / H$, the radial displacements are studied.

The resonant frequency depends on the parameters λ_2, μ_2, ρ_2, r_0 and the velocity of the Rayleigh wave C_R. Since surface waves exist only on the boundary region of the half-space, for $h = 0$, i.e. when the depth H is infinite, the Rayleigh waves disappear.

The graphs of the amplitude-frequency characteristic (AFC) (Figure 2-3) show that the depth of the cavity strongly affects its amplitude of oscillations - with decreasing depth, the amplitude increases sharply. The amplitude reaches the maximum value at $h = 1$, when the laying depth is equal to the diameter of the cavity. In this case, for a deeply embedded cavity (Fig. 2a), the maximum amplitude of displacements falls on the low-frequency section. For a shallow cavity (Fig. 2b), the maximum displacement corresponds to the high-frequency region, while the resonance occupies a wide frequency region. For $\alpha < 1$, the cavity undergoes strong and rather dangerous movements. The low-frequency region is dangerous for underground structures since most of the dynamic impacts are low-frequency.

Since the movement of the pipeline strongly depends on the depth of its laying in the soil, it is important to ensure a decrease in the movement of the pipeline when it is not deeply embedded in the soil - this would reduce the cost of construction and maintenance. Previously, damping of vibrations of an underground structure using a dynamic damper was considered [3].

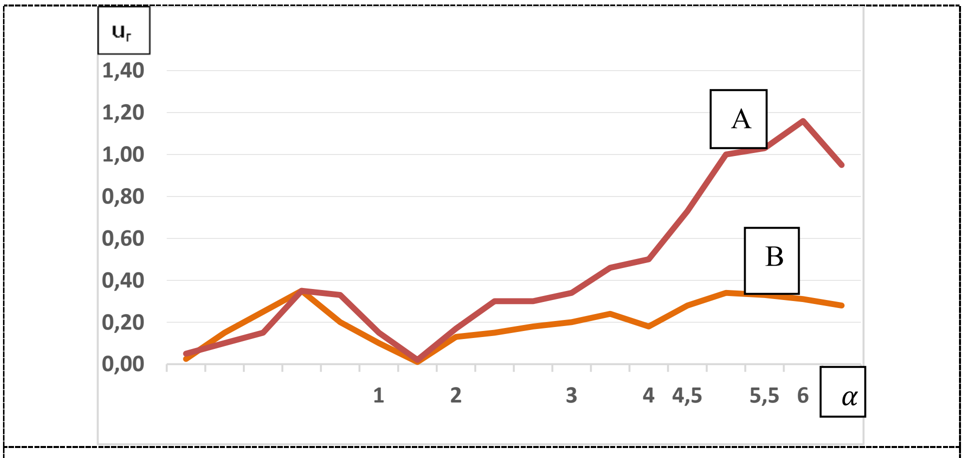

Figure 2. Frequency response characteristic. $R_v = 0.5$; A - $h=0.25$; B – $h=0.5$.

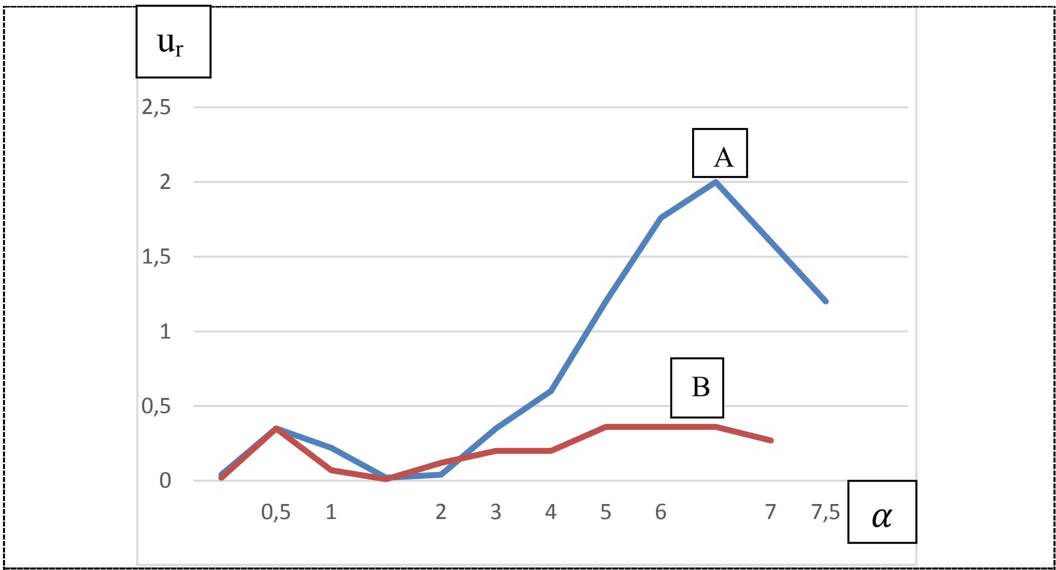

Figure 3. Frequency response characteristic. A - $R_v = 0.5$, $h=1$; B – $R_v = 1$, $h=0.25$.

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Radial displacements [3] includes two directions of displacements — longitudinal and transverse, corresponding to members of the series with *cos2nθ* and *sin(2n + 1)θ*. Vibration dampers work effectively when used for one of the displacement directions. To reduce lateral vibrations in the direction of the z-axis, we consider the operation of a dynamic damper and install it in the pipeline section at a point with an angular coordinate $\theta = \frac{3\pi}{2}$.
The equation of motion of the pipeline with the vibration damper installed in the section has the following form:

$$\int_0^{2\pi}(\sigma_r sin\theta - \tau_{r\theta} cos\theta) r_0 d\theta = m_o \frac{d^2u^*}{dt^2} + m_d \frac{d^2u_d^*}{dt^2}, \quad (2)$$

where $\sigma_r, \tau_{r\theta}$ - are the stress components on the line of contact of the pipeline with the environment (at $r=r_0$); $u^*, u_d^* -$ the displacement of the pipeline and the relative displacement of the damper;
$m_o,\ m_d -$ linear masses of the pipeline and the damper, respectively.
Stresses $\sigma_r,\ \tau_{r\theta}$ are defined in [1], and the displacements of the pipeline and damper can be represented as

$$u \cdot \exp[i(kx\text{-}\omega t)] = u_r\left(r_{0,}\ \frac{3\pi}{2}\right)\exp[i(kx-\omega t)],$$

$$u_d \cdot \exp[i(kx\text{-}\omega t)] = u \cdot \exp[i(kx-\omega t)] \cdot (L - iQ). \quad (3)$$

Carrying out intermediate calculations, we present an expression for the displacements of a pipeline equipped with a dynamic vibration damper in the form

$$u=\{\frac{[\aleph_4\Delta-(\aleph_3+F_2\varkappa_1)]\aleph_5}{[\aleph_2-F_1\aleph_1-\Delta\aleph_5]} + \aleph_4\}exp[i(kx-\omega t)], \quad (4)$$

where,

$$\aleph_1 = \left[\frac{T_2}{T_1}(L_1' - T_1') + (L_2' + T_2')\right],$$

$$\aleph_2 = \left[\frac{T_3}{T_1}(\mu_2 T_1' - L_1') + (L_3' - \mu_2 T_3')\right],$$

$$\aleph_3 = \left[\frac{2B_{p1}^I}{T_1\mu_2}(T_1'\mu_2 - 1) - \frac{1}{4}B_{p1}^{II}\right],$$

$$\aleph_4 = \left\{A_{p1}^{II} - K_1'(q_1r_1)\frac{2B_{p1}^I}{T_1\mu_2} + F_2\left[K_1'(q_1r_1)\frac{T_2}{T_1} + \frac{1}{s_1r_1}K_1(s_1r_1)\right]\right\},$$

$$\aleph_5 = \left\{K_1'(s_1r_1) - K_1'(q_1r_1)\frac{T_3}{T_1} - F_1\left[K_1'(q_1r_1)\frac{T_2}{T_1} + \frac{1}{s_1r_1}K_1(s_1r_1)\right]\right\},$$

$$\Delta = m_0[1 + \vartheta_r(L - iQ)], \qquad \vartheta_r = \frac{m_d}{m_0},$$

$T_1', T_2', T_3', L_1', L_2', L_3'$ - have the same form as in [1], only Bessel functions of the third kind must be written in the form $K_1(q_1r_1),\ K_1(s_1r_1)$;

$$L=(l f^2+t^2)/(l^2+t^2),\ \ Q=(tf^2 - lt)/(l^2+t^2),$$

$$l= [(f^2 - q^2)],\ \ \ t= (\chi q), f = \frac{k_d}{m_d\omega_0^2},\ \chi = \frac{\gamma_d}{m_d\omega_0},$$

$\omega_0 -$ the natural frequency of vibrations of the structure;
$k_d,\ \gamma_d -$accordingly, the stiffness and viscous friction coefficients of the absorber. The constants in (4) are expressed in terms of modified Bessel functions of the third kind $K_1(z)$ at $r=r_1$.
For calculations, expression (4) is reduced to a dimensionless form using the following notation:

$$\Omega = \frac{m_0}{\rho_1 r_0^2},\ \delta = \frac{r_0}{r_1}, R_V^2 = \frac{\mu_2}{\mu_1},\ \alpha = kr_0,\ h = \frac{r_0}{h}, \gamma_p = q_1r_0, \gamma_s = s_1r_0,$$

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$$\varepsilon = \frac{C_2}{C_R}, R_c^2 = \frac{(\lambda_2+2\mu_2)}{\mu_2},$$

where, μ_2, λ_2 are permanent lame for construction;
ρ_1, μ_1 are density and shear modulus for the environment;
C_R is the speed of Rayleigh waves.

3. Results

To establish the effectiveness of the vibration damper, the system parameters were optimized, while optimization was carried out for f = 0.8 - 1.2 and χ = 0.02 - 0.2 for several values of the relative mass of the vibration damper ϑ_d = 0.01; 0.05; 0.10.
During the calculations, the following values of the system parameters were also taken: R_V = 0.5; h = 0.25; Poisson's ratio is 0.25. The results of the calculation are presented in Fig. 4-7.

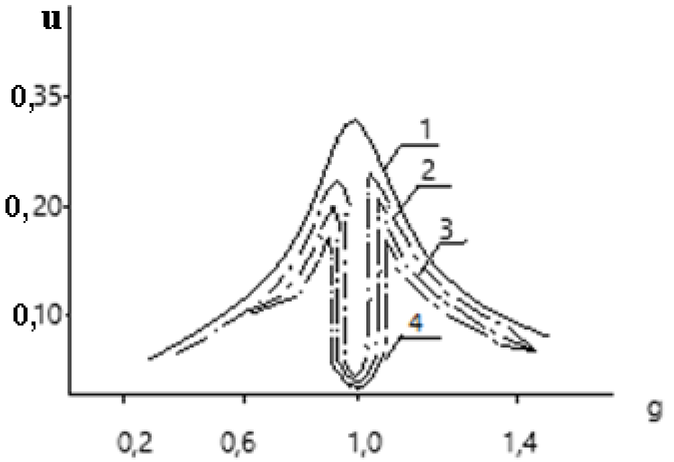

Figure 4. Frequency response of a pipeline with a vibration damper Ω=10, 1 - $\vartheta_d = 0$; 2 - $\vartheta_d = 0.01$; 3 - $\vartheta_d = 0.05$; 4 - $\vartheta_d = 0.10$.

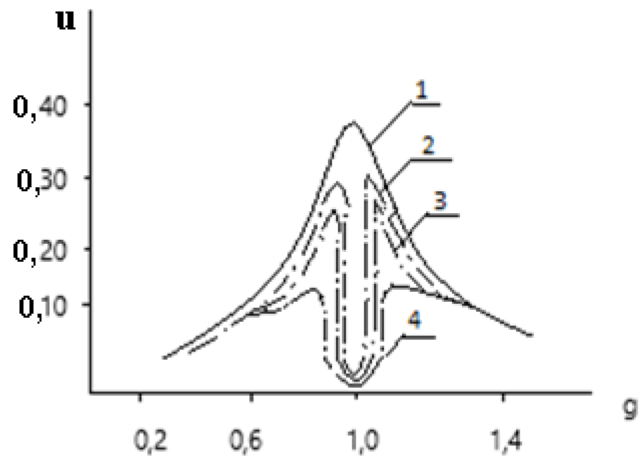

Figure 5. Frequency response of a pipeline with a vibration damper Ω=5, 1 - $\vartheta_r = 0$; 2 - $\vartheta_r = 0.01$; 3 - $\vartheta_r = 0.05$; 4 - $\vartheta_r = 0.10$.

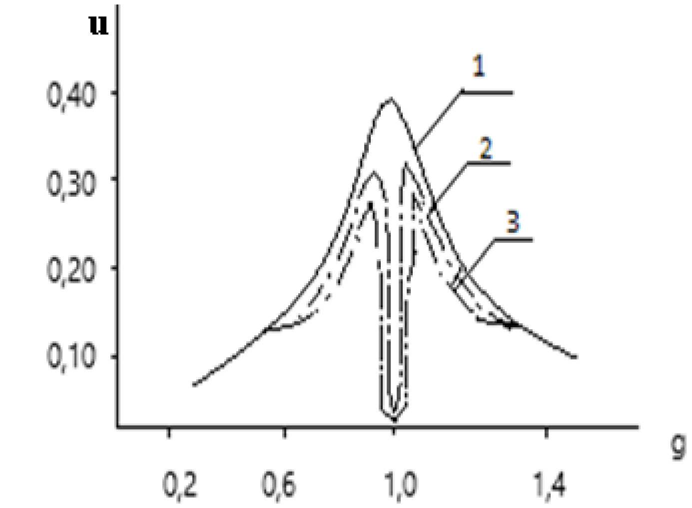

Figure 6. Frequency response of a pipeline with a vibration damper. Ω=10, χ =0, 1 - $\vartheta_r = 0$; 2 - $\vartheta_r = 0.01$; 3 - $\vartheta_r = 0.05$.

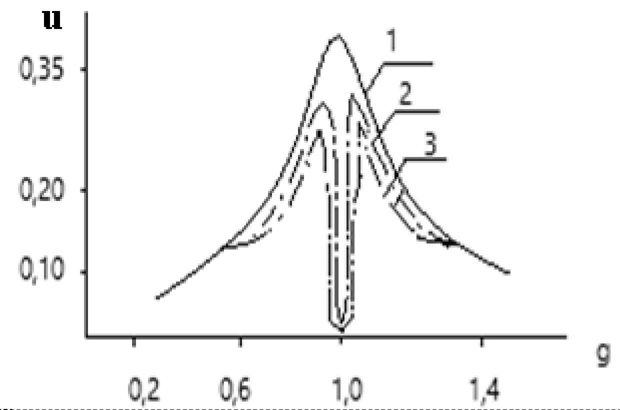

Figure 7. Frequency response of a pipeline with a vibration damper. Ω=5, χ=0; 1 - $\vartheta_r = 0$; 2 - $\vartheta_r = 0.01$; 3 - $\vartheta_r = 0.05$.

4. Discussions

As can be seen from the frequency response graph (Fig. 4), the use of a dynamic vibration damper (DVD) gives a large effect of damping the amplitude of movement of the structure. The effect increases with the increasing mass of the damper ϑ_d. So for $\vartheta_d = 0.01$, the maximum amplitude of the oscillations decreases 1.20 times, and for $\vartheta_d = 0.10$- 1.56 times. Interestingly, at a relatively high density of the building material (Ω = 10), the effective absorber operation zone is larger than at a lower density (Ω = 5). In the case where Ω = 5, the optimal result is f = 1, i.e. the absorber tuned to the natural frequency of the structure gives the greatest effect, while the frequency response graph is almost symmetrical with respect to $q = 1$. It should be noted that the relatively small mass of the absorber ($\vartheta_d = 0.01$) gives a fairly significant quenching effect. And with less dense soil (Ω = 10), the damper works effectively with a frequency of $f = 1.08 - 1.12$. Some optimization results are presented in Table 1.

Table 1. Optimum damper parameters.

b	R_V	H	ϑ_d	f	χ	K_e, effectiveness
5	0.5	0.25	0.01	1.02	0.02	1.16
5	0.5	0.25	0.05	1.02	0.02	1.30
5	0.5	0.25	0.10	1.04	0.02	1.44
10	0.5	0.25	0.01	1.04	0.08	1.20
10	0.5	0.25	0.05	1.08	0.14	1.35
10	0.5	0.25	0.10	1.12	0.17	1.56

The calculation results for $\chi = 0$ are shown in Fig. 6-7. If for Ω = 10 at $\chi \neq 0$ (Fig. 4) the frequency response has two small peaks, then at $\chi = 0$ (Fig. 6) the frequency response has two sharp peaks. The maximum amplitude U_{max} for both cases is almost the same. With an increase in the relative mass of the damper ϑ_d (0.01 → 0.10), it almost completely damps the vibrations of the structure at the resonant frequency.

Note that in optimal cases, the frequency response graphs with the absorber do not intersect with the frequency response graphs without the absorber in the resonance zone, i.e. the amplitude for any frequency at $\vartheta_d \neq 0$ does not exceed the amplitude for the corresponding frequency at $\vartheta_d = 0$.

5. Conclusions

The use of a dynamic vibration damper (DVD) makes it possible to reduce the amplitude of vibrations of an underground structure - the damping effect increases with increasing damper mass $\boldsymbol{\vartheta_D}$. With a relative mass of the damper $\boldsymbol{\vartheta_D}$= 0.10, the amplitude of movement of the structure can be reduced by more than 50%, two times more than when $\boldsymbol{\vartheta_D = 0,10}$. The density of the material of the structure is directly proportional to the efficiency of the quenching - at a relative density of the structure *Ω = 10*, the effective quencher zone is greater than at a density of *Ω = 5*. For cases of the low density of the structure, the absorber works effectively in the resonance zone. For heavy construction, a quencher even with a small relative mass gives a good quenching effect in a wide frequency zone. The presence of viscous friction in the design of the absorber allows it to have small displacements outside the resonance zone of oscillation.

The performed calculations suggest that the amplitude of displacements of underground structures, when exposed to surface waves of Rayleigh, can be reduced with the installation of a vibration damper on it. Since Rayleigh waves amplify near the surface of the half-space, reducing the amplitude of the displacements can be achieved reducing the laying depth, which facilitates the operation of underground structures

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