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Determination of Dynamic Deflected Mode of Cylindrical Pipe Under the Impact of a Seismic Type

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Annotation. The article covers the problem of determination of dynamic deflected mode of a cylindrical pipe under the influence of a seismic wave. The design diagram is shown in Fig. 1.
Known from the dynamic theory is solved by the method based on summation theorem. The summation theorem for cylindrical wave functions is derived in the work of elasticity, and the equation of motion in vector form for an isotropic body is obtained in the following form (1).

Introduction.

The article covers the issues of developing a methodology for solving the problem of the dynamic deflected mode of cylindrical pipe under the influence of a seismic wave. This problem is theoretically solved by elasticity summation theorem, when a seismic wave falls perpendicular to the axis of a long pipe laid in a high embankment and filled with an ideal compressible fluid. Let us consider the problem of the dynamic theory of elasticity summation when a seismic wave falls perpendicular to the axis of a long pipe laid in a high embankment and filled with an ideal compressible fluid. The design diagram is shown in Fig. 1.

Equation of motion in vector form known from the dynamic theory of elasticity for an isotropic body is: [1.2].

$$(\vec{\lambda}+\vec{\mu})gradd\ iv\vec{u} - rot\,rot\vec{u} + \vec{f} = \rho\frac{\partial^2\vec{u}}{\partial t^2}, \qquad (1.)$$

where ρ is the density of the medium, and all other designations have the same meaning as in the equation of the static theory of elasticity [8]. Let us make a standard transformation of the equation as follows. We show the displacement vector in the form: [4.5].

$$\vec{u} = grad\varphi + rot(\vec{\psi}) \qquad (2.)$$

Substituting (3.1.2) into (3.1.1) and considering that the motion of the particle has a steady character, as well as neglecting the body forces, i.e. f=01 since in accordance with the principle of superposition, they can be considered separately when solving a static problem, we obtain in the case of a plane deformation the following system of Helmholtz wave equations for potentials: [6.7].

$$\begin{aligned}\Delta\varphi + \alpha^2\varphi = 0;\\ \Delta\psi + \beta^2\psi = 0\end{aligned}, \qquad (3.)$$

where α and β are wave numbers The method is based on the summation theorem. The summation theorem for cylindrical wave functions was derived in [5].

Let there be two (r_g,θ_g) and (r_k,θ_k) different polar coordinate systems (Fig. 4.9), whose polar axes are equally directed. The pole coordinate θ_k in the q system will be R_{kq}, θ_{kq}, so that the following equality is fulfilled.

$$Z_g = R_{kg}e^{i\theta_{kg}} + Z_k \qquad (1.)$$

Then the summation theorem has the form:

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$$b_n(\alpha r_q)e^{in\theta_q} = \sum_{p=-\infty}^{\infty} b_{n-p}(\alpha R_{kq})e^{i(n-p)\theta_{kq}}Tp(\alpha r_k)\exp(ip\theta_k),$$

$$r_k < R_{kq}; \qquad (2.)$$

$$b_n(ar_q)e^{in\theta_q} = \sum_{p=-\infty}^{\infty} J_{n-p}(\alpha R_{kq})e^{i(n-p)\theta_{kq}}b_p(\alpha r_k)\exp(ip\theta_k),$$

$$r_k < R_{kq};$$

Formulas (2) allow transforming the solution of the wave equation (1) from one coordinate system to another.

Let us consider the calculation of an extended underground multi-line pipeline for seismic action in the framework of a plane problem of the dynamic theory of elasticity. In this case, we study the case of stationary diffraction of plane waves on a number of periodically located cavities supported by rings with an ideal compressible fluid inside.

We can solve this problem by the method of potentials in the same way as it is done in other authors. The boundary conditions have the form of a system of linear equations carried out by the Gauss method with the selection of the main element. The form of the incident potential will not change either.

The potentials of the waves reflected from the pipes after applying the addition theorem and, taking into account the periodicity of the problem, according to [22] will have the form

$$\varphi_1^{(r)} = e^{-iwt}\sum_{n=0}^{\infty}\left[A_nH_n^{(1)}(\alpha_1 r) + S_nJ_n(\alpha_1 r)\right]e^{in(\theta-\gamma)},$$

$$\psi_1^{(r)} = e^{-iwt}\sum_{n=0}^{\infty}\left[B_nH_n^{(1)}(\beta_1 r) + \sigma_nJ_n(\beta_1 r)\right]e^{in(\theta-\gamma)},$$

$$S_n = \sum_{p=0}^{\infty}\sum_{m=1}^{\infty}A_pE_p\left[e^{im\xi}H_{n-p}^{(1)}(\alpha_1 m\delta) + e^{-im\xi}H_{n-p}^{(1)}(\alpha_1 m\delta)\right], \qquad (3.)$$

$$Q_n = \sum_{p=0}^{\infty}\sum_{m=1}^{\infty}B_pE_p\left[e^{im\xi}H_{n-p}^{(1)}(\beta_1 m\delta) + e^{-im\xi}H_{n-p}^{(1)}(\beta_1 m\delta)\right],$$

where: $\xi = k\delta\cos\gamma$, δ is the distance between the pipe centers.

The potentials of refracted waves in pipes are written in the form

$$\varphi_2 = e^{i(m\xi - w\xi)}\sum_{n=0}^{\infty}E_n\left[C_nH_n^{(1)}(\alpha_1 r) + D_nH_n^{(2)}(\alpha_2 r)\right]e^{in(\theta-\gamma)},$$

$$\psi_2 = e^{i(m\xi - w\xi)}\sum_{n=0}^{\infty}E_n\left[E_nH_n^{(1)}(\beta_1 r) + F_nH_n^{(2)}(\beta_2 r)\right]e^{in(\theta-\gamma)}, \qquad (4.)$$

and the potential of speed in the ideal form of a compressible fluid is

$$\varphi_3 = e^{i(m\xi - w\xi)}\sum_{n=0}^{\infty}E_nG_nJ_n(\alpha_3 r)e^{in(\theta-\gamma)}, \qquad (5.)$$

Unknown coefficients A_n-G_n are determined from the boundary conditions. As a result, an infinite system of linear equations is obtained, which is solved by an approximate reduction method, provided that the relation is not satisfied

$$k\delta(1 \mp \cos\gamma) = 2\pi n \qquad (6.)$$

The incidence of P, SV or SH-waves on multi-line pipes is taken into account in the same way as it was done in paragraph 4.1 and 4.2.

The general characteristic of the program is intended for multi-strand pipes in an embankment for the case of seismic wave’s incident perpendicular to the axis passing through the centers of the pipes.

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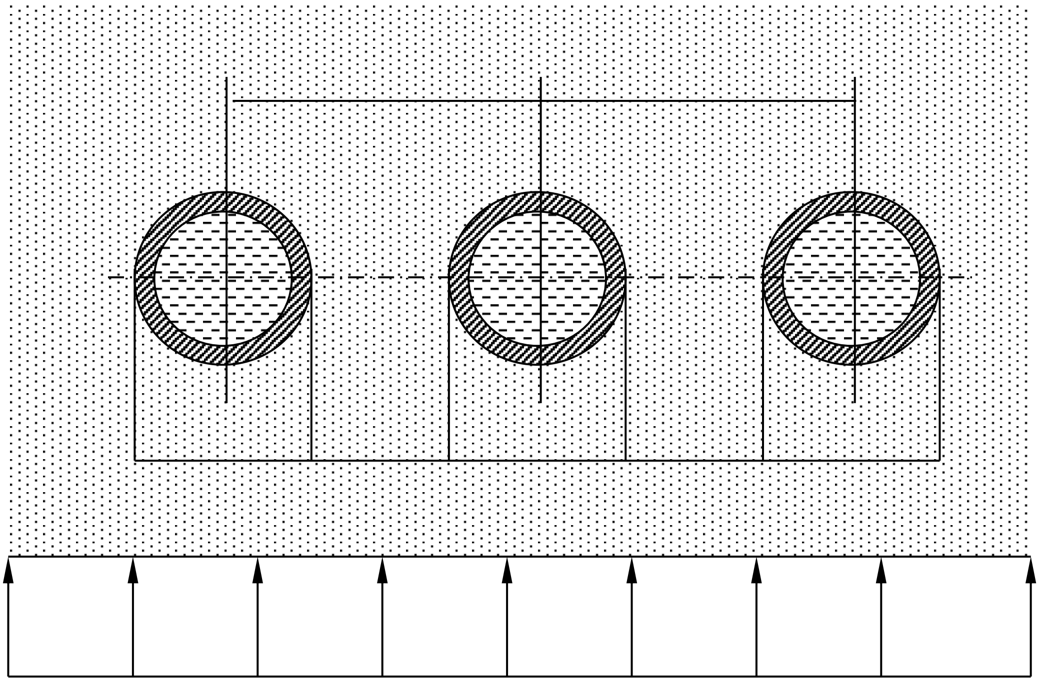

Fig. 1. Design diagram.

The program is written in FORTRAN language and has a modular structure. This allows further expanding it by adding new modules.

The input information for calculating the deflected mode is the elastic characteristics (E и ν) of the soil of the embankment and pipes, the density of the soil, the pipe and the liquid that fills it, the inner and outer radii of the pipes, the prevailing period of oscillation of the soil particles, the coordinates of the point at which the deflected mode is searched, and seismicity coefficient. With the help of a special mark, it is possible to calculate both pipes filled with ideal compressible liquid and empty ones.

The cylindrical Bessel and Hankel functions are calculated according to the well-known formulas [5, 16]. The solution of the system of linear equations is carried out by the Gauss method with the selection of the main element.

The output information contains the deflected mode along the pipe contour (contact), in the pipe wall, and in the lintel between the pipes. The counting time on a PC does not exceed 10-15 minutes.

The program for calculating parallel pipelines is easy to use and is designed for use in design organizations. It allows determining the dynamic pressure of the soil both on empty multi-line pipes equidistant from each other and on pipes filled with an ideal compressible fluid.

With the help of the DIFR program, the influence of the following factors on the distribution of the dynamic soil pressure of the embankment around the round reinforced concrete pipes under seismic impact was studied: distance between the pipes; type of impact (P-, SV or SH-wave); the length of the seismic wave incident in the ground (or its speed); pipe concrete class (E и ν) and its wall thickness; the influence of the liquid filling the pipe.

Impact of distance between pipes. Table 1 shows the values of the coefficient $\eta_{\max}(\eta_{\max} = |\sigma_{rr}|/(\lambda + 2\mu)\alpha^2$ of the maximum radial pressure of the soil on the pipes at different clear distance d between them in the case of a falling P-wave. In this case, the wave number of P-wave α_r=1.0 was taken: the inner and outer radius of the pipes R_0=018 m and R=1.0 m: the prevailing period of oscillations of soil particles T=0.12 sec. Embankment soil characteristics: Lame constants λ_1=8.9-MPa; μ_1`=4.34MPa; density ρ_1=1.74 kn sec/m^4, characteristics of the pipe material λ_2=86.90MPa; μ_2=12.930MPa; ρ_2=2.55 kn sec/m^4.

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Table 1.

The value of the coefficient of dynamic concentration at different distances between the pipes for the case of P-waves falling

D/d	015	1.0	2.0	4.0
η_{max}	1.68	1.76	1.61	1.60

It follows from Table 1 that at first, with an increase in the distance between the pipes 015≤d/D≤1.0, the coefficient η_{max} slightly increases (by 5%), and with a further increase in d/D>1.0, it decreases more sharply (by 10%). At d/D>2.0, the value of η_{max} stabilizes, i.e. practically does not change, at l≤4.0 it is close to the value of η_{max} for a single pipe according to calculations.

Therefore, the mutual influence of reinforced concrete pipes of multi-strand laying takes place at a clear distance between them of d≤4.0D and leads to an increase in the maximum dynamic soil pressure on them compared to a single pipe. This effect of increasing the coefficient η_{max} is associated with the superposition of waves reflected by several surfaces of multifilament pipes, and is called “local resonance” in [13]. In this case, the nonmonotonic increase in the coefficient η_{max} with a decrease in the distance between the pipes d/D is connected, in our opinion, with the phenomenon of interference of waves superimposed after reflection.

This phenomenon is extremely important for the practice of designing seismic underground multi-line pipelines, since allows choosing the optimal distance between the pipes, at which the dynamic pressure during seismic action is minimal. For example in Table 1 such distance is d=015D.

It is known to note for comparison that in the case of a static impact, the opposite picture is observed: the soil pressure on multi-strand pipes is less than on a single one.

In addition to the above, when analyzing the influence of the distance between pipes on their deflected mode, it is necessary to consider the relation (6), (the so-called “slip points”), at which there is a significant increase in dynamic stresses approximately the pipe - resonance. This phenomenon is known from optics under the name anomaly.

From the point of view of design practice, it is necessary to know at what distance pipes can be laid so that the dangerous phenomenon of resonance does not occur.

Relation (6) gives the answer to this question. Let us analyze this ratio for the case of the impact of P- and SV- seismic waves on an underground pipeline. Table 2 shows the dependence of the maximum distance in the light between the centers of the pipes d_{max}, at which resonance does not occur, on the angle of incidence of seismic waves γ.

Table 2

Dependence of the distance D_{max} on the angle of incidence γ.

γ, degree	0	30	45	60	70	80	90
D_{max}, m	5.0	5.36	5.86	6.66	7.45	8.52	1010

From Table 2 it follows that the smaller the angle of incidence of a seismic wave on the pipeline, the closer to each other it is necessary to lay the pipes. Thus, the occurrence of resonance in multi-strand pipes can be avoided by choosing an appropriate distance between them and, thereby, ensure the seismic resistance of the pipeline. Influence of the type of seismic action (P-, SV- or SH-wave). Table 3 shows the values η_{max} of the maximum radial pressure of the soil on the pipes in the case of falling P- and SV - seismic waves at different distances d in the light between the pipes. In this case, β_r=2 was taken.

Analysis of the data in Table 4.3.3 shows that at d/D<4.0, the values of the coefficient η_{max} for the P- and SV-waves are, as it were, in antiphase, i.e. at l/D=1.0, the maximum seismic impact of the P-wave is 27% higher than that of the SV-wave, at d/D=2.0 it is 7% lower, and at d/D=4.0 it is again higher, but only by 1 %.

At the same time, with an increase in the distance between the pipes, the difference in these effects decreases and at d/D=4.0 it practically disappears altogether. In addition, we note that when exposed to the SV - wave, the values of η_{max} at different distances between the pipes have a 2.5 times greater spread (up to

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25%) than when exposed to the P - wave (up to 10%). Therefore, the phenomenon of "local resonance" manifests itself more strongly for seismic action in the form of an SV-wave.

Table 3

The value of the coefficient η_{max} under seismic effects in the form of P - and SV - waves at various distances d between pipes

d/D	η_{max}	
	P – wave	SV – wave
1.0	1.76	1.29
2.0	1.61	1.72
4.0	1.60	1.51

Influence of liquid filling pipes. Table 4 shows the values of the coefficient η_{max} in the case of the incidence of the P-wave on empty and water-filled pipes at various distances d in the light between the pipes. The liquid density was assumed to be ρ_3=01102 kn sec/m^4.

From Table 4 it follows that the presence of water in the pipes increases the seismic effects on them compared to empty pipes. Obviously, this is due to an increase in the mass of the pipeline. The maximum dynamic soil pressure on the pipes is increased. For example, at d/D=1.0 the difference in the values of the coefficient d/D=2.0-10%, at d/D=4.0-19%.

Table 4

The value of the coefficient η_{max} for the case of falling P - waves on empty and water-filled pipes

d/D	η_{max}	
	P – wave	SV – wave
1.0	1.76	1.89
2.0	1.61	1.78
4.0	1.60	1.90

Moreover, we note that the spread in the values of the coefficient η_{max} at different distances d for pipes filled with water is less (7%) than for empty pipes (10%).

Influence of the length of the incident seismic wave. Table 4 shows the values of the coefficient η_{max} of various lengths l_0/l_0-$2\pi/\alpha$, p is the wave incident on empty pipes located at a distance l=1.0D from each other.

Table 5

Coefficient η_{max} values for different lengths l_0 of P -wave

l_0/D	3.0	5.0	1010
η_{max}	1.76	1.52	1.20

From Table 5 it follows that the greater the length of the incident seismic wave, i.e. the denser the soil of the embankment, the lower the coefficient η_{max}. For reference, we note that the ratio l_0/D=5.0 refers to not bulk sandy, sandy loamy and loamy soils; l_0/D=10 refers to clay soils.

Thus, the type of soil, and especially its density, has a significant impact on its dynamic pressure on pipes during seismic action.

It follows that when building an embankment above the pipes, it is necessary to compact the bulk soil. It is interesting to note that good soil compaction also reduces its static pressure on pipes. In addition, calculations show that for l_0>1010D the dynamic problem is reduced to a quasi-static one, which greatly simplifies its solution. This leads to an important conclusion that the quasi-static approach is not applicable to the calculation of the seismic action of pipes under embankments.

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