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TRANSLATION

INVESTIGATION OF CONDITIONS OF SERVICE OF UNDERGROUND PIPE LINES DURING EARTHQUAKES

By

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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

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INVESTIGATION OF CONDITIONS OF SERVICE OF UNDERGROUND PIPE LINES DURING EARTHQUAKES

T. Rashidov

Earthquake resistance of underground pipe lines has been little investigated

Authors of works [1] and [2] proceed from the static theory of the earthquake resistance of constructions; in this respect it is assumed that a pipe line and the ground surrounding it are deformed identically. The relative dislocations are not considered. As a result there have been obtained formulas for determining stresses on a pipe line during the propagation of longitudinal seismic wave in a direction along the axis of the pipe line. Author of work [2] takes into consideration the creep of particles of ground from pipe line by means of a certain coefficient, which for an evaluation of the magnitude of stresses is assumed to be equal to unity

In our work [17] the creeping of a pipe line from particles of ground have been considered depending upon volume of ground, participating in the joint movement of the cited medium "ground—pipe line". On the basis of several examples we came to the conclusion about large reserve in strength of ordinary steel pipe lines during earthquakes of average and high intensities.

In the indicated work [17] terminal conditions were not taken into account. In this work on the basis of dynamic theory of earthquake resistance of an hydroelastic system [3, 4] we propose a dynamic theory of earthquake resistancy of underground pipe lines. In assuming that the law of movement of soil during an earthquake is subject to a harmonic sinusoidal law, we will show the influence of a harmonic force on underground pipe lines.

Differential Equations of an Oscillation of an Underground Pipe line during Earthquakes

From actual data on the effect of an earthquake on underground pipe lines, it follows that pipes during earthquakes basically are damaged as a result of axial extension (compression), which becomes especially intense with the direction of pipe line axis the same as that of the propagation of the seismic wave.

Experimental investigations of service conditions of underground pipe lines during ordinary conditions [5--8] show that there is observed a relative dislocation of the pipe line. In indicated investigations the force of the interaction of pipe with surrounding ground is assumed to be a proportional dependence on displacement. The proportionality factor has been the given name coefficient of uniform heave of pipe line. In work [18] there was obtained a formula for the dependence of this coefficient on the depth of pipe line.

During the propagation of seismic wave along the direction of axis of the pipe line there generates a certain force of interaction, apparently which is the main cause of the destruction of the pipeline during earthquakes.

We shall isolate from the pipe line an element of length Δx. If we designate the relative dislocation of isolated element Δx with the coordinate x at moment of time t by $u(x, t)$, then tangential force of interaction between surface of pipe and the ground, in general case, will be function of the displacement and speed, i. e.

$$\tau = -\Phi\left(u, \frac{\partial u}{\partial t}\right)\Delta x.$$

In addition to this, onto the element isolated from pipe line with our assumptions there will act stresses, resultant of which applied along the direction of the axis of pipe line, will be

$$\sigma = E\frac{\partial}{\partial x}\left[F(x)\frac{\partial u}{\partial x}\right]\Delta x,$$

where F(x) is area of cross section of pipe;

E is elastic modulus of material of pipe.

According to D'Alembert's principle these forces will be balanced by the force of inertia of pipe line, equal to

$$I = -m(x)\frac{\partial^2(u_0+u)}{\partial t^2}\Delta x;$$

here m(x) is mass of element of pipe;

$u_0(t)$ is the dislocation of ground, occurring during earthquake, which is a given function of time.

We shall obtain

$$-m(x)\frac{\partial^2(u_0+u)}{\partial t^2}\cdot\Delta x + E\frac{\partial}{\partial x}\left[F(x)\frac{\partial u}{\partial x}\right]\Delta x - \Phi\left(u,\frac{\partial u}{\partial t}\right)\Delta x = 0 \qquad (1)$$

or

$$\frac{\partial^2 u}{\partial t^2} - \frac{E}{m(x)}\frac{\partial}{\partial x}\left[F(x)\frac{\partial u}{\partial x}\right] + \frac{1}{m(x)}\Phi\left(u,\frac{\partial u}{\partial t}\right) = -\frac{\partial^2 u_0}{\partial t^2}. \qquad (1')$$

From equation (1') it is evident that the possibility of dynamic design of underground pipe lines under seismic loads requires knowledge of laws of dislocation of soil during earthquake, i. e. a knowledge of function $u_o(t)$ with the known function $\Phi\left(u, \frac{\partial u}{\partial t}\right)$.

If we assume that the ground, surrounding pipe line, is uniform and elastic, material of pipe uniform longitudinally and the area of cross section does not vary longitudinally, and also the force of interaction is proportional to the relative displacement, then from equation (1') we will obtain

$$\frac{\partial^2 u}{\partial t^2} - a_\tau^2 \frac{\partial^2 u}{\partial x^2} + bu = -\frac{\partial^2 u_0}{\partial t^2}, \qquad (2)$$

where

$$a_\tau^2 = \frac{EF}{m}, \qquad b = \frac{\pi D_n\, k_x}{m}; \qquad (3)$$

D_n --external diameter of pipe;

k_x --coefficient of uniform heave of pipe line.

This different equation was derived from work [19].

Reaction of a Harmonic Force On Pipe lines With Closed Ends

The generating (during earthquake) dislocations of soil bear a confused character, revealing not in any distinct types of mathematical laws, and therefore certain authors call them "wild".

A complexity of the phenomenon, is on one hand, its short duration (fractions at a second) and comparatively rare frequency--on the other; investigation on question, have been made difficult and construction of a well-grounded theory of designing structure against seismic effects in all countries has been founded on the so-called static theory, proposed by the Japanese scientist F. Omori [9] .

According to this theory, constructions are assumed to be absolutely rigid bodies, which during earthquakes are displaced collectively with the soil, in addition to this, it is assumed that, at the same time in them are observed rotational dislocations [10] . The pipe line also is assumed to be a rigid body, being displaced jointly with the ground. Then the force of inertia, generating in any element of construction (including that in pipe line), is determined by the formula

$$S = k_c Q, \qquad (4)$$

where Q--weight of element of construction;

k_c--is the coefficient of seismicity, characterizing intensity of earthquake, and magnitude of it is set depending upon the seismicity of the region. In norms of USSR values of the coefficient of seismicity are 0.1; 0.05; and 0.025, in American norms are introduced certain corrections.

All above-mentioned corrections to static theory of design for a seismic event could not even tentatively reflect the actual distribution of stresses, forming in buildings during an earthquake which is especially evident in application to pipe lines. All this required and requires tests of new, more contemporary prerequisites for a design, based on a consideration of elastic properties of constructions and forming in their vibrations. There was developed a dynamic theory of earthquake resistance of constructions. Devoted to the development of dynamic theory of earthquake resistance of constructions were the investigation by K. S. Zavriev, M. T. Urazbaev, A. G. Nazarov, I. V. Goldenblat, I. A. Korchinskiy, V. K. Kabulov, Sh. G. Napetvaridze, V. T. Rasskazovskiy, G. V. Tishchenko, Yu. R. Leyderman et al.

For the solution of the main problem on theory of earthquake resistance, American specialists Bayon, G. V. Khauzner, R. R. Martel, Joule. Alphard et al. constructed spectrum curves of the cited seismic accelerations of linear oscillator, by using an integration of recordings of strong earthquakes.

According to investigations by I. A. Korchinskiy [11, 12] , seismic movements of soil occur according to law of attenuating sinusoids

$$u_0(t) = a_0 e^{-\varepsilon_0 \tau} \sin^{\omega \tau}, \qquad (5)$$

If we assume $\varepsilon_0 = 0$, then for seismic movement of soil we have

$$u_0(t) = a_0 \sin^{\omega \tau},$$

Thus, we shall assume that the vibration of soil occurs according to a sinisoidal law. If period of first mode of vibrations we designate by T, then for law of vibration of soil, we may assume

$$u_0(\tau) = A \sin \frac{2\pi}{T} t, \qquad (6)$$

where A --amplitude of vibrations.

With these assumptions, equation (2) is written out as:

$$\frac{\partial^2 u}{\partial t^2} - a_\tau^2 \frac{\partial^2 u}{\partial x^2} + bu = \frac{4\pi^2 A}{T^2} \sin \frac{2\pi}{T} t. \qquad (7)$$

We then solve the problem under the following initial and boundary conditions:

$$u(x, 0) = \dot{u}(x, 0) = 0 \qquad (8)$$

and

$$u(0, t) = u(l, t) = 0, \qquad (9)$$

i. e. examined portion of the pipe line at both ends is closed. Such an assumption will be valid, if the examined part of pipe line is located between wells or between cisterns, or from one sharp turn to other, or from a well to sharp turn etc. We shall seek the solution in the form of expansion into series of Fourier by

$$u(x, t) = \sum_{n=1}^{\infty} u_n(t) \sin \frac{\pi n}{l} x. \qquad (10)$$

We put the right side of equation (7) in the form of Fourier series

$$f(t)=\sum_{n=1}^{\infty} f_n(t)\sin\frac{\pi n}{l}x,$$

where

$$f_n(t)=\begin{cases} 0, & \text{если } n \text{ четный}, \quad \text{if n is even,} \\ \frac{16\pi A}{T^2 n}\sin\frac{2\pi}{T}t, & \text{если } n \text{ нечетный}. \quad \text{if n is odd,} \end{cases}$$

Thus,

$$f(t)=\frac{16\pi A}{T^2}\sin\frac{2\pi}{T}t\cdot\sum_{n=1,3,5,\ldots}^{\infty}\frac{\sin\frac{\pi n}{l}x}{n}.$$

By substituting the form of solution (10) in original equation (7)

$$\sum_{n=1}^{\infty}\sin\frac{\pi n}{l}x\left\{a_n(t)+\left[\left(\frac{\pi a_T n}{l}\right)^2+b\right]u_n(t)-f_n(t)\right\}=0.$$

We see that it will be satisfactory, if all coefficients of the expansion are equal to zero, i. e.

$$a_n(t)+\left[\left(\frac{\pi a_T n}{l}\right)^2+b\right]u_n(t)=f_n(t). \tag{11}$$

Suppose n is even. Then, equation (11) acquires the form

$$a_n(t)+\left[\left(\frac{\pi a_T n}{l}\right)^2+b\right]u_n(t)=0.$$

Since initial conditions for $u_n(0) = u_n(0) = 0$, then hence, these will be obtained trivial solutions. Thus, $u_n(t) = 0$ at all even n.

At odd n, equation (11) has a nontrivial solution.

We now introduce the designations.

$$c_n^2=a_T^2+b\left(\frac{l}{\pi n}\right)^2. \tag{12}$$

Then equation (11) will be rewritten as

$$a_n(t)+\left(\frac{\pi n}{l}\right)^2 c_n^2 u_n(t)=f_n(t).$$

The solution of this equation during zero initial conditions will be

$$u_n(t) = \frac{l}{\pi n c_n} \int_0^t \sin \frac{\pi n}{l} c_n (t-\tau) \cdot f_n(\tau) d\tau. \qquad (13)$$

By substituting the value $f_n(t)$ after integration we then obtain

$$u_n(t) = \frac{16Al}{n^2 T^2 c_n} \cdot \frac{1}{\frac{\pi^2 n^2 c_n^2}{l^2} - \frac{4\pi^2}{T^2}} \left(\frac{\pi n c_n}{l} \sin \frac{2\pi}{T} t - \frac{2\pi}{T} \sin \frac{\pi n c_n}{l} t \right). \qquad (13')$$

Thus, the being sought solution will be written in the form

$$u(x, t) = \frac{16\pi A}{T^2} \sum_{n=1,3,5}^{\infty} \frac{\sin \frac{2\pi}{T} t - \frac{2l}{T \cdot n c_n} \sin \frac{\pi n c_n}{l} t}{n \left(\frac{\pi^2 n^2 c_n^2}{l^2} - \frac{4\pi^2}{T^2} \right)} \sin \frac{\pi n}{l} x. \qquad (14)$$

The stress, forming in body of pipe line, will be

$$\sigma = \frac{16\pi^2 EA}{T^2 l} \sum_{n=1,3,5,\ldots}^{\infty} \frac{\sin \frac{2\pi}{T} t - \frac{2l}{T \cdot n c_n} \sin \frac{\pi n c_n}{l} t}{\frac{\pi^2 n^2 c_n^2}{l^2} - \frac{4\pi^2}{T^2}} \cos \frac{\pi n}{l} x. \qquad (15)$$

As can be seen, the vibration consist of two parts: 1) forced vibrations, proportional to $\sin \frac{2\pi}{T} t$ and having the same period as the excitation force, and 2) free vibrations, proportional to $\sin \frac{\pi n c_n}{l} t$ (usually under free oscillat... are implied as oscillations, not generated by zero initial conditions, but in ... given case it is a question of vibrations caused by the excitation force, but occurring with its own frequencies; as is noted in [13] , in this case the term "freedom vibrations" it is impossible to assume fully successful).

In considering that $\frac{4\pi^2 A}{T^2} = k_c g$, where k_c is the coefficient of seismicity, and by introducing the designations $\omega = \frac{2\pi}{T}$, $\omega_n = \frac{\pi n c_n}{l}$, expression (15) can be written as

$$\sigma = \frac{4 k_c g E}{l} \sum_{n=1,3,5,\ldots}^{\infty} \frac{\sin \omega t - \frac{\omega}{\omega_n} \sin \omega_n t}{\omega_n^2 - \omega^2} \cos \frac{\pi n}{l} x. \qquad (15')$$

Let us consider now several cases, characteristic for different ratios at $\frac{\omega}{\omega_n}$.

1. ω is significantly less than ω_n . This corresponds to the case of a gradual change in the movement of soil during earthquakes. Then we obtain what the relative displacement of underground pipe line under the assumptions made will be,

$$u(x, t) = \frac{4k_c g}{\pi}\left(\sum_{n=1,3,5,\ldots}^{\infty} \frac{\sin\frac{\pi n}{l}x}{n\omega_n^2}\right)\sin\omega t \tag{16}$$

and longitudinal stress--

$$\sigma = \frac{4k_c gE}{l}\left(\sum_{n=1,3,5,\ldots}^{\infty} \frac{\cos\frac{\pi n}{l}x}{\omega_n^2}\right)\sin\omega t. \tag{17}$$

By applying summation method of A. N. Krylov [14] , we obtain

$$\sigma = \frac{k_c gE}{a_r\sqrt{b}} \cdot \frac{\operatorname{sh}\alpha\pi\left(\frac{1}{2}-\frac{x}{l}\right)}{\operatorname{ch}\frac{\alpha\pi}{2}}\sin\omega t, \tag{17'}$$

where

$$\alpha^2 = \frac{b}{\left(\frac{\pi a_r}{l}\right)^2}. \tag{18}$$

For x = 0 and x = 1 we have

$$\sigma_{max} = \pm\frac{k_c gE}{a_r\sqrt{b}}\operatorname{th}\frac{\alpha\pi}{2}. \tag{19}$$

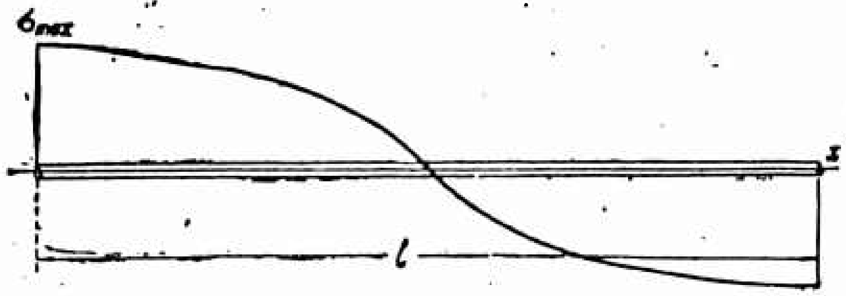
2. Let us assume that ω approaches $K\omega_n$. Then for the expression σ from expression (15') we have an indetermination. By solving this indetermination we obtain

$$\sigma = \frac{2k_c gE}{\omega^2 l}\left(\sin\omega t - \omega t\cos\omega t\right)\cos\frac{\pi n}{l}x,$$

where $n = \frac{\sqrt{\omega^2 - b}}{\pi a_r} \cdot l$ is a whole, odd number. In the opposite case, problem has no meaning.

The maximum by time is obtained at $\omega t = \pi$, then

$$\sigma'_{max} = \frac{2\pi k_c gE}{\omega^2 l} \cos \frac{\pi n}{l} x. \qquad (20)$$



The obtained formula (20) gives the distribution of stresses longitudinally of investigated section of pipe line. In this respect maximum stresses form in places of connection of pipe line to any massive construction or to a well, reservoir, and also in sharp turns there appear significant stresses, equal σ^{τ}_{max}. Graph of distribution of the stress is shown in the figure.

In expression (20), after assuming x = 0 and x = 1, we obtain

$$\sigma'_{max} = \pm \frac{2\pi k_c gE}{\omega^2 l}. \qquad (21)$$

From expression (21) it is clear that the smaller l, the larger σ will be. If it is considered that length of considered section of pipe line is equal to length of longitudinal waves in the ground, then formula (21) acquires the form

$$\sigma_{max} = \pm \frac{g}{2\pi} k_c \frac{E}{C_p} T,$$

where C_p --speed of propagation of longitudinal waves in the ground.

The given formula is obtained in work [1] and for a band foundation [15] with the assumption of continuity of deformations of ground and body of pipe (foundation) in which it does not give a distribution of the stresses along the length of pipe line. Formula (20) gives distribution of stresses directly in the body of pipe line. If we take into consideration that the ends of pipe line are not completly secure, then one should to introduce into the formula (20) certain coeficient , smaller than unity, after writing it in such a form:

$$\sigma_1 = \frac{2k_c gE}{\omega^2 l} \eta \cos \frac{\pi n}{l} x. \qquad (20')$$

However, if we restrict ourselves to the problem of determining the order of magnitude of the stresses, then the indicated modification becomes unnecessary, moreover the experimental value is unknown.

For any material, at any values of period of vibrations of ground it is possible to calculate the magnitude of stress by the formula (20).

3. ω is significantly larger then ω_n, then

$$\sigma = \frac{4k_c gE}{l} \sum_{n=1,3,5,\ldots}^{\infty} \frac{\sin \omega t \cos \frac{\pi n}{l} x}{\omega_n} . \qquad (21')$$

As can be seen from expressions (14)--(21), stress is symmetric relative to middle of pipe line (fig.1). The stresses will attain own maximum value, σ_{max} in places of fastening of pipe line to a well, reservoir or at sharp turns of the pipe line. Expressions (15), (17), (20) and (21) give us a distribution of the stresses along the length of the pipe line. Dangerous sections during earthquakes are place of connection of pipe line to a well, or reservoir. On sharp turns als there form large stresses. At these places it is necessary to anticipate fre dislocations of pipe line (as is done usually for a compensation of the temperature stresses [16]).

Conclusions

Usually, pipe lines have great reserve of strength during earthquakes of average and high intensities. In places of connection of underground pipe lines to reservoirs, well, and also there, where pipe lines have sharp turns there form significant stresses, therefore it is necessary to anticipate dislocation in these places.

In laying pipe lines in seismic regions special attention must be given to the place of connecting pipe line to wells, reservoirs and to compensation of stresses at sharp turns.

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