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Formation of Bending Waves in Underground Extended Pipelines under the Action of Seismic Wave

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ABSTRACT: Non-stationary processes of long pulse effect on an underground pipeline under various conditions at its ends and the elastic interaction coefficients are studied in the paper. An analysis of the results obtained from the action of a seismogram of a real earthquake is carried out.

KEY WORDS: underground pipeline, seismo-dynamics, seismic effect, interaction, soil, elastic constants, parameters of the viscosity, model, seismic load.

I.INTRODUCTION

At the initial stage of formation of a dynamic theory of earthquake resistance of underground pipelines, there was practically no information about damage and destruction of underground structures during earthquakes. There were only single data on the consequences of earthquakes in Japan (Tokyo, 1923), the USA (California, 1906), Turkmenistan (Ashgabat, 1948), Uzbekistan (Tashkent, 1966) and several others.

The main attention in the earthquake resistance of underground structures [1-7] is given to modeling the interaction in the pipe-soil system. The key parameters that determine the stress state of life support systems (underground pipelines) are the interaction coefficients of these structures with surrounding soil. These include the elastic interaction coefficient k_x.

Analysis of the effect of strong ground motion shows that the earthquake resistance of underground structures depends on ground conditions and the direction of seismic wave propagation, therefore, the assessment of the stability and stress-strain state of underground pipelines under longitudinal, torsional and transverse vibrations is an urgent problem [3-7].

II. LITERATURE SURVEY

In 1968, V. Bykhovsky, K. Zavriev and S.V. Medvedev [8] emphasized the need to take into account the effect of the load transfer velocity in soil on underground structure, as well as the changes in rheological properties of soil. The models discussed in that paper most fully reflected various properties of soils. Several examples of negative consequences of neglecting such properties of soils as viscosity, dynamic and relaxation properties were given. The team of authors considered the problems of earthquake-resistant engineering and soil-structure interaction under seismic (dynamic) effect.

In1973, T.R. Rashidov has proposed the “seismo-dynamic” theory of earthquake resistance to calculate complex systems of underground pipelines with branches and inclusions [1]. The pipe-soil interaction outside the tectonic fault zone under the influence of seismic waves was discussed in the monograph, as well as the soil effect on the stress-strain state (SSS) of the pipeline under seismic influences. T.R. Rashidov did not consider the problem of pipe-soil interaction in zones of tectonic faults under transverse velocity displacements of soil.

The problems similar to the ones in soil-pipeline interaction arise in tunnels calculation. In 1974, V.M. Lvovsky [9] examined the tunnel vibrations in ground and indicated the need to account for viscoelastic interaction. It was shown that ignoring this interaction in structure calculation led to accidents in the underground tunnels of Boston.

A.A. Samarin in [10] presented vibration calculations of power plants pipelines, the sources of pipelines vibration, and the ways to reduce pipeline oscillations to acceptable values. In his book it was noted that due to the high-speed propagation of waves through the structure, individual sections of the pipeline that are more susceptible to vibrations could act as a vibration generator.

In 1980, in the monograph by Sh.G. Napetvaridze, A.S. Gekhman and V.V. Spiridonov [11], the data on the consequences of a number of earthquakes was summarized and analyzed. The influence of ground conditions and capital character of the construction project on the choice of calculated seismicity was considered, information on the mechanism of oscillations initiation in the structures under consideration was given. At the same time, the cases of such structures construction in tectonic fault zones were not considered in that paper.

Information on seismic effect on the SSS of pipelines located outside the zones of tectonic faults was presented in the study by A.S. Gekhman, Kh.Kh. Zaynetdinov [12] (1988). There, it was noted that the transverse loads acting on the pipeline presented the greatest danger when the pipeline crossed tectonic fault lines.

In the second half of the 20th century, the problems of seismic stability were dealt with by T.R. Rashidov, G.Kh. Khozhmetov [1, 13, 14], A.S. Gekhman [15], V.V. Bolotin, Sh.G. Napetvaridze, B. Mardonov, R.M. Mukurdumov, V.V. Spiridonov, V.P. Ilyin and other scientists. According to the analytical calculation method, based on the “frozen wave” hypothesis [15], the main underground and surface pipelines were presented as rods, immovable with respect to the ground, perceiving seismic waves in the ground medium under dynamic influences.

III. METHODOLOGY

The equations of motion of spatial system of underground pipelines were given in [1-5]. A numerical study by the finite element method (FEM) (in spatial coordinates) and the finite difference method (FDM) (over time) of seismo-dynamics problems of spatial system of underground pipelines under seismic waves was given in [6] based on the records of a real seismogram. An analysis of the process of longitudinal wave formation in a pipeline interacting with soil under the effect of a pulse in the form of a half wave of a sine was presented in [7]. A study of the bending wave propagation in a rod is given in [16], the bending waves have an unlimited velocity of propagation, basic part of energy propagates at a variable velocity.

In this paper we consider the process of bending wave initiation in an extended underground pipeline under the action of transverse shear wave SH in the form of a half wave of a sine and a sine squared, propagating at a velocity of c_g in the direction parallel to the pipeline axis, under various conditions at the ends of the pipeline. Next, the process of reaching the stationary mode under the action of a sinusoidal wave is analyzed. Then the patterns of the process of real seismic wave effect are given. When considering a bending wave only, in one plane, the process is described by the equation of bending vibrations of the pipeline interacting with soil [1]. For long (as compared to the pipeline diameter) and sufficiently smooth waves acting on the pipeline, dynamic processes are described with reasonable accuracy by the Bernoulli–Euler or Timoshenko equations [16] with additional terms responsible for the wave-soil interaction [17].

IV. ANALYSIS OF THE RESULTS OF NUMERICAL RESEARCH

The FEM [18], taken as a numerical method for solving the equation of motion, is used to discretize the problem along the pipeline length and the FDM of Newmark type [19, 20] - over time. Then the problem is reduced to solving the system of algebraic equations at each time step using the values of displacements and rotation angles of the pipeline cross sections at the previous two steps.

Consider a steel pipe with characteristics: outer diameter D=0.61 m; thickness s=0.01 m; elastic modulus $E=2.1\cdot10^5$ MPa; Poisson's ratio ν=0.25; material density ρ=7800 kg/m^3; pipe length l=500 m; moment of inertia of the cross section $J=8.48\cdot10^4$m^4. Soil characteristics are taken from [1-5]: the coefficient of transverse interaction $k_y=1.0\cdot10^4$kN /m^3; wave interaction coefficient η_y=200 kN·f/m^2; transverse wave propagation velocity in soil c_g=500m/s; pulse action time T= 0.1s; pulse amplitude A=0.004 m.

In calculations, equations of bending vibrations of the Timoshenko type are used. Figures 1-4 show the calculations results of the moment of inertia and shear forces at points of 0.5 m, 19.5 m, and 199.5 m over time under the wave in the form of a half wave sine squared (the pulse length is 50 m) acting on a pipeline fixed in soil. Calculations were carried out at a length of each finite element of 1 m with a time step of 0.001 s. At the left end, the

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values of the moment and the shear forces are greater (by 17.15 and 1.16 times, respectively) than at a distance of 20 m from the left end, then the waveform is set and does not change until the right end is reached.

When the wave reaches the right end of the pipeline, the moment and shear forces reach the maximum (2000 Nm and 63,900 N, respectively) at this point. The influence of the ends on the values of the moment and shear forces is local in nature, i.e. at a distance of 15-20 m from the left or right end of the pipeline, the influence of the processes occurring at the ends is not observed.

An 8 times increase in elastic interaction coefficient leads to the following changes: the moments at the left and right ends, and in the region of the formed wave are 42600 Nm, 1500 Nm and 2300 Nm, respectively, the shear forces at the left and right ends, and in the region of the formed wave are 76,300 N, 77,000 N and 57,500 N, respectively.

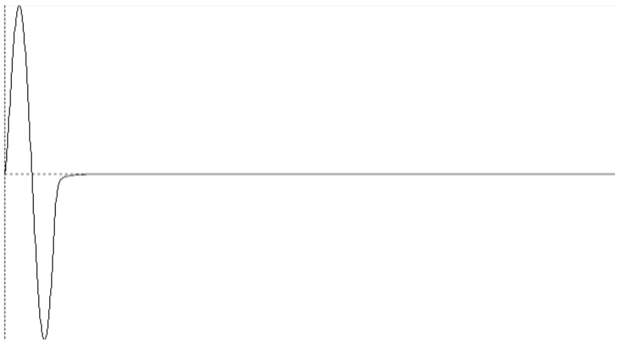

Figure 1. Change in moments at point x=0.5 m over time, the maximum value is 34300 Nm

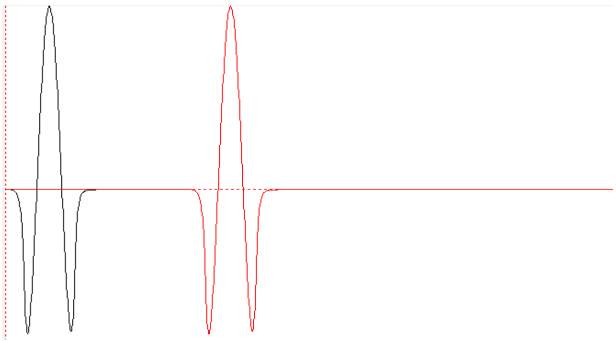

Figure 2. Change in moments at points x=19.5 m and x=199.5 m over time, the maximum value is 2000 Nm

Figure 3. Change in shear forces at x=0.5 m over time, the maximum value is 61000 N

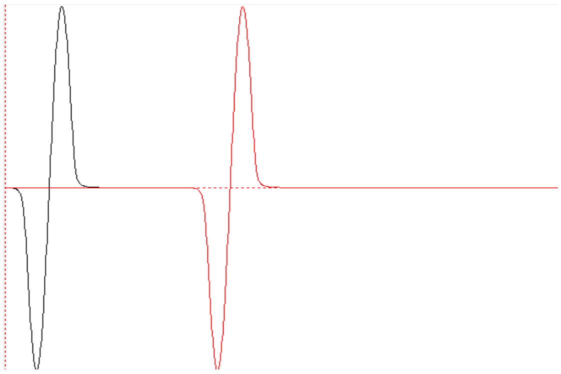

Figure 4. Change in shear forces at points x=19.5 m and x=199.5 m over time, the maximum value is 52500 N

If the ends of the pipeline are free, then the following pattern is observed. At k_y=1.0·10^{4}kN/m^3 the values of the moments of inertia and shear forces are: at a distance of 0.5 m from the left and right ends of the pipeline:1600 Nm, 4470 Nm and 8500 N, 9000 N, in the region of the formed wave 2080 Nm, 52500 N, respectively. At k=8.0·10^{4}kN/m^{3}the moments and shear forces are: at a distance of 0.5 m from the left and right ends of the pipeline: 3300 Nm, 7650 Nm and 21500 N, 22500 N, in the region of the formed wave 2260 Nm, 57600 N, respectively. An 8 times increase in k_y leads to a sharp increase in shear forces in the region close to the pipeline ends and to a slight increase in the region of the formed wave. If the acting wave has the shape of a half wave of a sine, then the following pattern is observed. At k_y=8.0·10^{4}kN/m^{3}the values of the moments and shear forces are: at a distance of 0.5 m from the left and right ends of the pipeline: 3170 Nm, 8100 Nm and 22500 N, 25770 N, in the region of the formed wave 8160 Nm, 56600 N, respectively. In this case, the difference of wave action in the form of a half wave of a sine squared is significant for the moment of inertia in the region of the formed wave. At k_y=1.0·10^{4}kN/m^{3}the values of the moment and shear forces are: at a distance of 0.5 m from the left and right ends of the pipeline 1290 Nm, 4810 Nm and 8212 N, 10700 N, in the region of the formed wave 3250 Nm, 50,000 N, respectively. An 8 times increase in the value of k_y, in this case, leads to a sharp increase in shear forces in the region close to the ends of the pipeline and to an insignificant

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increase in the region of the formed wave. If the wave is a sinusoid, then the process goes to the stationary mode after the first period.

The mode of the acting wave mainly affects the mode and values of the moments in coordinate and time. The phenomena described above are linked by non-stationary character of the process.

Now consider the effect of a sinusoidal wave. Figures 5 and 6 show the graphs of changes in the moments of inertia and shear forces at the point x=19.5 m at k_y=1.0·10^{4}kN/m^3. From these figures it is seen that the process after the first period of the sinusoidal wave goes to the stationary mode. The maximum values of the moments of inertia in the first half-period are: at the point x=0.5 m 1210 Nm, at the point x=19.5 m 3220 Nm, at the point x=499.5 m 4810 Nm.

Accordingly, the maximum shear forces are: 8300 N, 50300 N and 10600N. The maximum values of the moments of force in a stationary wave are: at a point x=0.5 m 1300 Nm, at a point x=19.5 m 1100 Nm, at a point x=499.5m 4190 Nm. Accordingly, the maximum shear forces are 8300 N, 56200 N and 8500 N. An 8 times increase in the value of k_y, in this case, leads to a sharp increase in shear forces in the region close to the ends of the pipeline and to insignificant increase in the region of the formed wave.

When both ends of the pipeline are fixed to the ground, only the maximum value of the moments of force of the stationary mode decreases by almost 3 times.

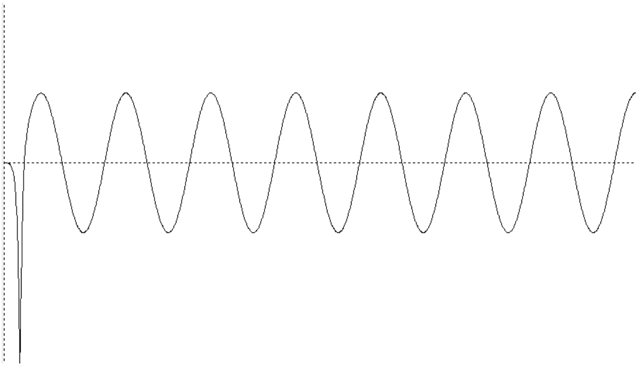

Figure 5. Change in moments of force at the point x=19.5 m over time, the maximum value is 3220 Nm, the stationary maximum value is 1100 Nm

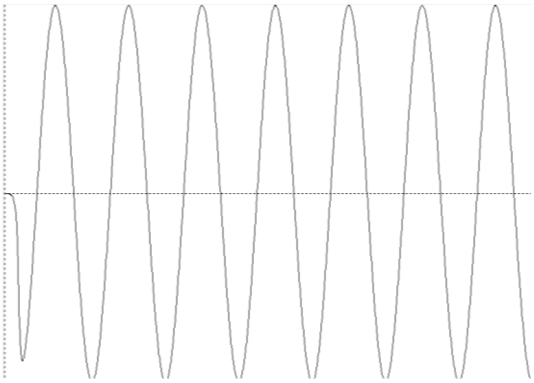

Figure 6. Change in shear forces at x=19.5 m over time, the maximum value is 50300 N, the stationary maximum value is 56200 N

So, under the action of a wave in the form of a pulse or a harmonic wave, the conditions at the ends of long pipelines have little effect on the formed wave in the pipeline. At a distance of about 15-20 m from the end, a wave in the pipeline is formed completely and then propagates without change.

Now consider the results of calculations when a seismic wave acts on an underground pipeline; the wave is given by digitized record of seismograms in three directions; the earthquake in Chile, on February 27, 2010 with magnitude 8.8 (the University of Chile). Let the seismic wave propagate in the NS direction with the Rayleigh wave velocity ofc_R=c_g=500 m/s.

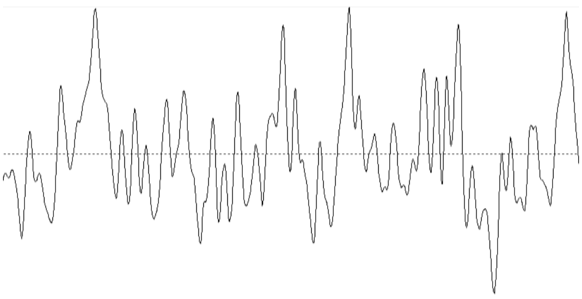

Figure 7. Change in shear forces at the point x=0.5 m in time interval 43s-54s, the maximum value is 224000 N

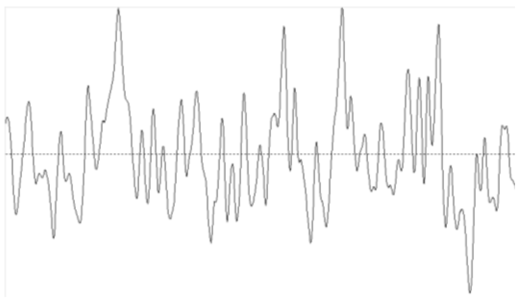

Figure 8. Change in shear forces at x=249.5 m in time interval43s-54s, the maximum value is 172000 N

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Figures 7-8 show the graphs of changes in time interval 43 s - 54 s, where the maximum values of the moments and forces, shear forces in the *OXY* plane occur near the ends and in the pipeline midpoint when its ends are fixed to the ground (the displacements and torques are the same as near the ground), at k_y=8.0·10^{4}kN/m^3. In the *OXZ* plane, the values of shear forces are 3 times less than in the *OXY* plane. To ensure the accuracy of calculations, they were carried out at time steps of 0.001 s, 0.005 s, 0.01 s. Comparison of results showed that the calculations at a time step of 0.005 s gave sufficient accuracy in shear forces.

V. CONCLUSION

The case considered in the paper illustrated that an influence of a very strong earthquake on underground steel pipeline with the above characteristics does not present any danger to a pipeline.

Calculations and plotted graphs were performed by the ShARK-PT software package for studying the seismo-dynamics of spatial systems of underground pipelines. The program package contains the finite elements of various models of underground pipelines, nodes and joints.

The developed algorithm and computing program allow us to study the pipeline vibrations at various types of ends fixing and soil parameters. The results of solving the problems under consideration are presented in the form of graphs; their analysis shows that the intensive changes in longitudinal and transverse displacements, normal and tangential stresses, longitudinal and transverse forces occur near the fixed end of the underground pipeline.

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