PAPER • **OPEN ACCESS**

Underground pipelines dynamics problem solution under longitudinal seismic loading

To cite this article: D Bekmirzaev *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **883** 012045

IOP Conf. Series: Materials Science and Engineering **883** (2020) 012045 doi:10.1088/1757-899X/883/1/012045

Underground pipelines dynamics problem solution under longitudinal seismic loading

D Bekmirzaev[2], N Mansurova[2], N Nishonov[2], E Kosimov[2] and A Numonov[1*]

[1]Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, Tashkent, Uzbekistan
[2]Academy of Sciences of the Republic of Uzbekistan Institute of Mechanics and Seismic Stability of Structures named after M.T. Urazbayev, Tashkent, Uzbekistan

diyorbek_84@mail.ru

Abstract. In this article are considered some problems of oscillations of underground pipelines under seismic loading. The resulting system of equations is solved by the finite-difference of the second order of accuracy. The program is based on a computer algorithm implementation on oriented language Borland Delphi 7. Conducted theoretical and computational-experimental studies solve the problem of assessing the stress-strain state of underground pipelines under seismic effect the axes of the pipeline. The Stress-strain state of the underground pipeline is studied at linear and non-linear interaction with the soil. Linear and non-linear solutions are compared. Dangerous points of maximum normal stress occurrence under seismic loading in the underground pipeline are determined to take into account elastic pipe-soil system interaction. The conducted computational and experimental studies allow solving the problems of assessing the stress-strain state of pipelines under seismic loading, which is important for practical calculations.

1. Introduction

At present the transportation of energy resources is one of the most important fields in the economics of many developing countries all over the world. Underground pipelines serve as a primary part of the life-support system of cities and centers of population (water-, gas- and heat supply, sewer system), objects of extraction and transportation of oil and gas; their safe operation, especially in seismic zones, is very important[1-12].

There is no doubt that the development of urbanized territories in cities and villages requires an increase in underground engineering. According to U.N.O. data the expenditure on underground engineering is more than 25% of the overall building volume. At present in domestic and foreign engineering science there exist several systematically validated methods of determination of stress-strain state (SSS) of underground pipelines interacting with surrounding medium under seismic effects.

As is well known, at present more than half of the population of the earth live in towns and large megalopolis. Hence, we may draw a conclusion on the importance of the conditions of the water-, gas-supply, sewer system and other underground structures, especially after the earthquakes; this requires a wide theoretical and practical investigation of their behavior under seismic effect.

At present abroad there have already appeared several scientific research works, which state not only the problems of seismic stability of underground structures but also the formation of normative documents on their calculation and design (Japan, USA, China, Russia, and others). This is facilitated, on the one hand, by active development of urban areas, expansion of support system networks, on the other hand, by a sufficient number of strong earthquakes in the world, which caused damage to underground networks.

Tashkent earthquake (1966) has also caused serious damage and destruction to underground networks of life support – to water supply pipelines, sewer systems, and others. However, as noted in the dissertation, this was observed only in cases when the pipes were laid into the soil with a certain bearing capacity.

Almost always after the earthquakes the accident rate on pipelines is increasing. The damage of one part of underground structures affects the performance of the entire system.

Research on the strength of underground pipelines and buildings under seismic loadings was held by such great scientists of the world, engaged in the problems of seismic resistance of structures as M.J. O'Rourke, L.R. Wang, N.M. Newmark, El. Hmadi, T. Takahashi, T. Tanaka, D. Wijewickreme, K. Yoshizaki, R. Flores-Berrones, X.L. Liu, D.D. Barkan, V.A. Il'ichev, Ya.M. Ayzenberg, Sh.G. Napetvaridze, A.G. Nazarov, A.B. Aynbinder, A.S. Gekhman, M.Sh. Israilov, A.A. Aleksandrov, R.A. Gumerov, E.N. Figarov and others.

In works of K.S. Sultanov, M. Mirsaidov, T. Mavlyanov, T. Yuldashev, I. Mirzaev, Sh.M. Mamatkulov, A.A. Haldzhigitov, K.D. Salyamova, B.E. Husanov, M.K. Usarov, T.T. Sobirov et al. the use of different mechanical mathematical models was analyzed and several urgent problems of underground and ground structures were solved [1, 12-20]. The model of a box-shaped structure of a building is improved in [17-18] taking into account forces and moments in the contact zones of beam and plate elements interaction. The equations of motion of the box-shaped elements, the boundary conditions in the box base, and the contact conditions between the box elements are given; the graphs of plates and beams displacements are constructed. The problem of forced oscillations of a building of spatial box type is considered in the paper; it composes of rectangular panels and interacting beams under dynamic effect set by base displacement according to a sinusoidal law. The finite difference method was used in the problem solution. Numerical results of stresses, displacements in the hazard areas of the box-like building are obtained.

Solutions to the problem of transverse and longitudinal vibrations of buildings and structures were obtained using a plate model developed in the framework of the bimoment theory of plates [19].

The results of theoretical and practical research in the field of seismic stability of underground pipelines are analyzed in detail in monographs by M.J. O'Rourke and X.L. Liu (1999) [8]. A deep analysis of the results of this monographic study allows us to trace the history of the formation and development of seismodynamics worldwide. Seismodynamic theory of underground structures was developed in Uzbekistan, it is based on actual data of the consequences of Ashgabat (1948) and Tashkent (1966) earthquakes. More than half a century ago, when the dynamic theory of seismic stability of underground pipelines was just beginning to form, the information about the damage and destruction of underground facilities during the earthquakes was practically non-existent.

There were only a few data on the consequences of the earthquake in Japan (Tokyo, 1923), United States (California, 1906), Turkmenistan (Ashgabat), Uzbekistan (Tashkent), and others. This is explained by the fact that the length of underground pipelines in seismically active areas was comparatively short and it was difficult to find the damage.

2. Methods

In seismodynamic theory of underground structures the studies on the problem of interaction in the system «structure-soil» have primary importance. In this connection, various laws of soil-structure interaction are developed; they consider the parameters characterizing the process of contact interaction of rigid deformed bodies with soil.

The main problem of seismodynamics of underground pipelines is a simulation of interaction in the system «pipe-soil». The main parameters determining the stressed state of life support systems (underground pipelines) are the coefficients of the interaction of these structures with the surrounding soil. They include the coefficient of uniform displacement of the pipeline relative to soil k_x, that is, the coefficient of pipeline displacements is:

$$k_x = \left(\alpha \frac{G_B}{100B} + \beta \right) \cdot 10^2 , \tag{1}$$

where α, β are the coefficients depending on soil conditions; G_B is vertical soil pressure on linear length of the pipe; B is the trench width at pipe laying into the trench.

Dynamic coefficient of pipeline interaction with surrounding soil is determined as:

$$k_x^{stat} = \frac{4\pi^2 m}{\pi D_H T^2} \frac{p^2}{\omega^2} \text{ or, } k_x^{stat} = \eta \cdot k_x^{din} \tag{2}$$

where

$$\eta = \frac{p^2}{\omega^2} . \tag{3}$$

Both in domestic and foreign literature the dependence between interaction coefficients under static and dynamic loading is within the range of

$$k_x^{din} = (0{,}7 \div 0{,}8) \cdot k_x^{stat} .$$

This formula is used when calculating pipeline systems in the process of solution of dynamics problems.

A simplified method of study of seismodynamics of complex underground systems reduces a general problem to independent problems of longitudinal motion of main pipelines with complicated conditions of joining in the units and brings it to a fairly well-studied problem of longitudinal oscillation of underground pipeline [1-3].

The dependence of tangent force τ_a on soil-structure surface contact on the value of relative displacement $u - u_0$ and velocity of relative displacement $\dot{u} - \dot{u}_0$ in a general form is written as:

$$\tau_a = k_x (u - u_0)[1 - \omega(u - u_0)] + \mu(\dot{u} - \dot{u}_0)[1 - \omega_1(\dot{u} - \dot{u}_0)] + \ldots \quad , \tag{4}$$

where $k_x, \mu, \omega, \omega_1$ – are the parameters characterizing elastic, viscous, and plastic properties of interacting with soil, depending on characteristics of soil, structure, and the mode of loading defined experimentally; $\omega(u - u_0)$ – may be taken as Ilyushin's function of plasticity, characterizing non-linear properties of interaction.

However, in the case of dynamic (in particular, seismic) effects characterized by a quick switch in loading-unloading, more essential is a component which takes into account elastic-plastic properties of interaction

$$\tau_a = k_x (u - u_0)[1 - \omega(u - u_0)] . \tag{5}$$

Here τ_a – is a tangent pressure, u – absolute displacement of the pipe, u_0 – a law of soil motion during the earthquake.

In the case of bilinear law of interaction for the plasticity function $\omega(u - u_0)$ we have:

In loading mode

$$\omega(u - u_0) = 0 \text{ at } u - u_0 \le u_s ,$$

$$\omega(u - u_0) = \lambda \left(1 - \frac{u_s}{u - u_0} \right) \text{ at } u_s \le u - u_0 \le u_p ,$$

In unloading mode

$$\omega(u-u_0)=\lambda\frac{u_p-u_s}{u-u_0} \text{ at } u-u_0\ge u_p,$$

where $\lambda=(k_x-k'_x)/k_x$, k_x, k'_x are coefficients of instant shear in elastic and plastic stages of interaction, respectively, u_s, u_p are displacements of pipeline relative to the soil at the beginning of plastic loading and unloading, respectively.

If to consider tangent pressure (5), differential equation of oscillations of the underground pipeline has the form

$$\frac{\partial^2 u}{\partial t^2}-a_T^2\frac{\partial^2 u}{\partial x^2}+b^2(u-u_0)[1-\omega(u-u_0)]=0. \quad (6)$$

To solve equations (6), Finite difference method of the second order of accuracy is used. As an example consider the following problem. The solutions of equations (6) are found in the following form

$$u_i^{j+1}=\alpha_{i+1}u_{i+1}^{j+1}+\beta_{i+1} \quad (7)$$

3. Results and Discussion

Problem 1. Consider the stress-strain state of the cast-iron pipeline with compliant ends under longitudinal seismic effect taking into account non-linearity of interaction.

Mechanical geometrical parameters of a pipeline and soil are given as: D_H=0.5 m; D_B=0.49 m; l=100 m; k_x=1·104 kN/m^3; the law of soil motion has the form: $u_0=a_0\cdot\sin\omega(t-x/C_p)$; a_0=0.001 m; $\omega=2\pi/T$; T=0.3 s; C_p=800 m/s; u_s=0.0001 m; λ=0.2; coefficient of a joint rigidity is $K_N=29\cdot10^4$ kN/m.

Based on the developed algorithm, computer realization of the problem has been conducted; its results are given in Fig.1, where the values of the changes in longitudinal displacement and normal stress along the pipeline axis at a given time are shown.

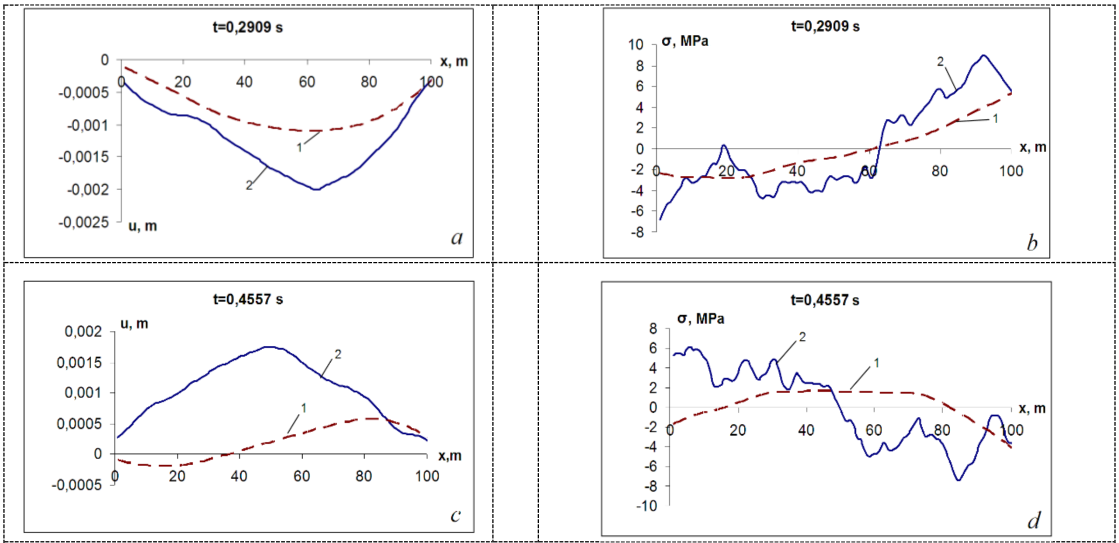

Figure 1. Change in longitudinal displacements and stresses along the pipeline axes at a given time: 1–linear interaction; 2–non-linear interaction

Table 1 gives the absolute maximum values of longitudinal stresses in a pipeline under the effect of various types of waves on steel and cast-iron pipelines.

As stated, absolute maximum values of stresses at non-linear soil interaction with soil are always greater than at elastic interaction (Fig.1, Table 1).

Comparative analysis shows that consideration of non-linearity of soil interaction with a pipeline, generally, leads to an increase in the value of the normal pressure of a pipeline.

IOP Conf. Series: Materials Science and Engineering **883** (2020) 012045 doi:10.1088/1757-899X/883/1/012045

Table 1. Maximum stresses in underground pipelines, MPa.

Point	Wave type	Steel		Cast-iron	
		Linear interaction	Non-linear interaction	Linear interaction	Non-linear interaction
7	Sinusoid waves	43.65895	44.8284	35.28842	39.3207
	Travelling waves	65.85012	70.14736	51.79212	64.481
8	Sinusoid waves	76.4068	81.9358	63.94046	70.4899
	Travelling waves	115.2249	122.7579	82.24973	118.531

Fig.2 shows the graphs of changes in normal stresses along the pipeline axis at set points of time; this allows us to observe the wave propagation in the underground pipeline at set points of time.

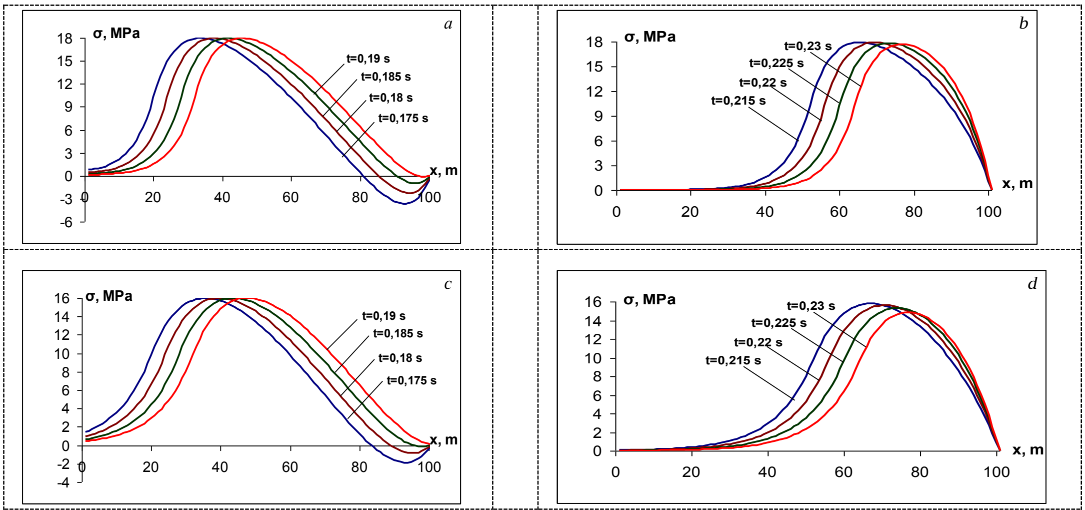

Figure 2. Change in normal stresses along the pipeline at set points of time
a, b – D_H=0.2 m, D_B=0.192 m, δ=0.004 m; *c, d* – D_H=0.5 m, D_B=0.48 m, δ=0.01 m.

As seen from Fig.2, *b*, the wave effect is observed in the cross-section of the pipeline x=35 m at pipeline diameter D_H=0.2 m, and from Figure 2, *d* - in the cross-section of the pipeline x=15 m at D_H=0.5 m. Thus, the greater the pipeline diameter, the earlier the wave effect on the pipeline is observed.

In the second half of the twentieth century to calculate the complex system of underground pipelines with a large number of branches and inclusions (water supply, drainage systems, etc.) T.R. Rashidov has proposed «Dynamic theory of seismic stability of complex systems of underground structures», based on the presentation of the linear part of the pipeline by core elements of finite length and joint connections (structural inclusion) – by absolutely rigid bodies.

Here all the relevant elements and units are in interaction with the surrounding soil medium. In the future, the work has been carried out to improve this technique in terms of taking into account different kinds of nonlinearities (joints deformation, slip on the ground, etc.).

In particular case at I_y=I_z=0 (I_y=I_z=0 inertia in the joint),

IOP Conf. Series: Materials Science and Engineering **883** (2020) 012045 doi:10.1088/1757-899X/883/1/012045

$$\begin{cases} -\rho F \dfrac{\partial^2 u'}{\partial t^2} + EF \dfrac{\partial^2 u'}{\partial x^2} - 2\pi R k_x \left(u' - u_0\right) = 0, \\ -\rho_1 F_1 \dfrac{\partial^2 u^0}{\partial t^2} + EF \dfrac{\partial u'}{\partial x} - EF \dfrac{\partial u''}{\partial x} - 2\pi R_{uz} H_{uz} k_x^{uz} \left(u^0 - u_0\right) = 0, \\ -\rho F \dfrac{\partial^2 u''}{\partial t^2} + EF \dfrac{\partial^2 u''}{\partial x^2} - 2\pi R k_x \left(u'' - u_0\right) = 0. \end{cases} \tag{7}$$

The system of differential equations (7) with consideration of boundary conditions is solved by the Finite difference method. As an example consider the following problem.

Problem 2. Consider the cast-iron underground pipeline with fixed ends. Mechanical and geometrical parameters of underground pipelines and soil are taken in the following form: D_H=0.4 m; D_B=0.39 m; l=20 m; k_x=1·10^4 kN/m^3. For the well: E=2.5·10^4 MPa; $D_{H\ uz}$=1.2 m; $D_{B\ uz}$=1.1 m; H_{uz}=1 m; k_x^{uz} =2·10^4 kN/m^3; $u_0=a_0\cdot\sin\omega t$; a_0=0.002 m; $\omega=2\pi/T$; T=0.3 s.

Fig.3, a shows the results of longitudinal displacement of the joint under seismic load changing according to sinusoid law along the pipeline axis, and Fig.3, *b* is the change in displacements of the pipelines along coordinate axis x at a given time. Based on Fig.3, *a*, *b*, the maximum displacements of the pipelines correspond to maximum displacements of the joint.

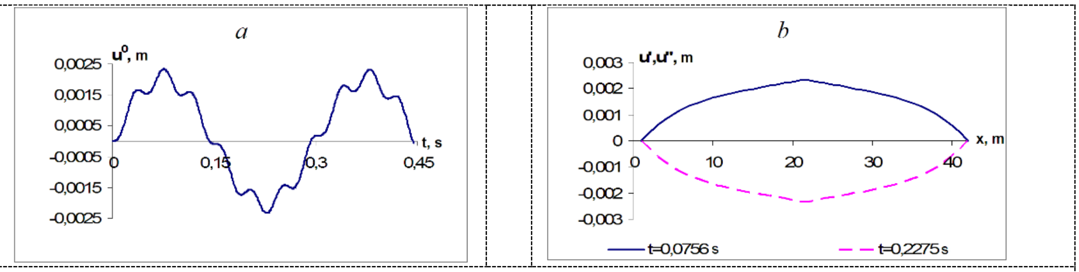

Figure 3. Change in displacements of the joint in time (a) and along coordinate axis x under sinusoid loading (b)

Figure4, *a* gives the change in pipeline stresses near the joint. According to Figure 4, *a* stresses in the pipelines have opposite signs, that is, if the first pipeline works on tension, the second works on compression (Fig.4, *a*). This case is verified by Fig.4, *b*: at a given time maximum values of stresses are observed on fixed ends of the pipelines.

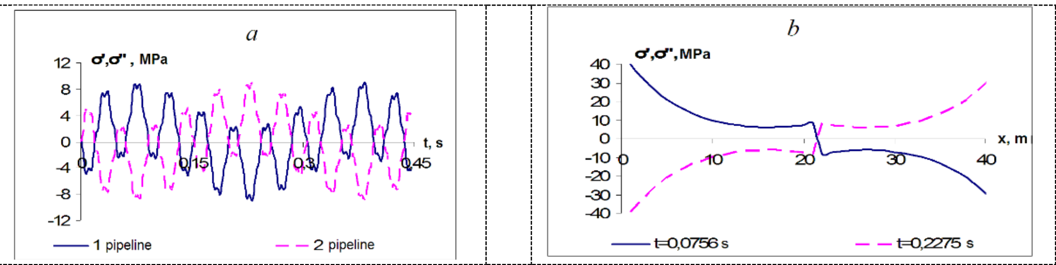

Figure 4. Change in stresses of the pipelines near the joints in time and coordinate axis x under sinusoid loading

In discussed problems the values of maximum displacements of the pipelines occur near the joints and are equal to joint displacements. The maximum effect of interaction with soil is concentrated in joint (nodal) sections of the pipelines.

Developed applied program for PC allows to obtain several numerical results depending on the parameters of the pipeline, joint, ground conditions, and various fixing of the ends under different seismic effects. Here a possibility arises to automatize the studies of stress-strain state of the pipeline in a joint when the seismic effect is directed along the pipeline axis.

4. Conclusions

1. Universal bases for the design of underground rectilinear pipelines laid in natural soils on seismic effects are developed with the Finite difference method. Algorithm and design programs are built; they allow to study the stress-strain state of underground rectilinear pipelines, considering ground conditions, including the depth of bedding, the geometry of fixing of pipeline ends under different seismic effect. The universal character of the design algorithm and program allows to obtain new results presented in the dissertation in the form of graphs.

2. The Stress-strain state of the underground pipeline is studied at linear and non-linear interaction with the soil. Mathematical models and algorithms for computer realization of these problems fit for engineering practice are given. Each concrete case is solved to its numerical values; weak sections of the underground pipeline with maximum normal stresses are determined under the effect of seismic loads. Linear and non-linear solutions are compared. A comparative analysis of results obtained with the ones obtained earlier was conducted to prove the reliability of the selected numerical method.

3. Several numerical results were obtained depending on the angle of incidence of the seismic load. As seen from the results of numerical experiments, based on the hypothesis taken in calculations concerning the forces of interaction between long underground structures (pipelines) and soil, a good agreement is stated with actual data obtained from the analysis of earthquake aftermath. It should be noted that this hypothesis has shown its effectiveness in different ground conditions.

4. Results obtained present a new contribution into seismodynamic theory; they open wide possibilities for their use in optimal design of the complex of life support in seismic zones.

References

[1] Rashidov T R Yuldashev T Bekmirzaev D A 2018 Seismodynamics of Underground Pipelines with Arbitrary Direction of Seismic Loading. *Soil Mech. Found. Eng*. **55** pp 243–248 https://doi.org/10.1007/s11204-018-9533-1
[2] Rashidov T R Bekmirzaev D A 2015 Seismodynamics of Pipelines Interacting with the Soil. *Soil Mech. Found. Eng*. **52** pp 149–154 https://doi.org/10.1007/s11204-015-9321-0
[3] Bekmirzaev D A Rashidov T R 2015 Mathematical Simulation and Solution of the Problem of Dynamics of Underground Pipelines *J. Sib. Fed. Univ. Eng. Technol.* **8** pp 1046–1055 https://doi.org/10.17516/1999-494X-2015-8-8-1046-1055
[4] Bekmirzaev D A Kishanov R U 2020 Assessment of the Effect of Inertia Forces in Problems of Underground Pipeline Seismodynamics *Int. J. Innov. Technol. Explor. Eng*. **9** pp 500–503 https://doi.org/10.35940/ijitee.C8526.019320
[5] Bekmirzaev D A Mirzaev I 2020 Dynamic Processes in Underground Pipelines of Complex Orthogonal Configuration at Different Incidence Angles of Seismic Effect *Int. J. Sci. Technol. Res*. **9** pp 2449–2453
[6] Rashidov T R Nishonov N A 2016 Seismic Behavior of Underground Polymer Piping with Variable Interaction Coefficients *Soil Mech. Found. Eng*. **53** pp 196–201 https://doi.org/10.1007/s11204-016-9385-5
[7] Rashidov T R An E V Geometrically nonlinear buckling stability analysis of axially loaded underground pipelines *Soil Mech. Found. Eng*. **54** pp 76–80 https://doi.org/10.1007/s11204-017-9437-5
[8] O'Rourke M Liu X 1999 Response of buried pipelines subject to earthquake effects *MCEER, Univ. at Buffalo*
[9] Corrado V D'Acunto B Fontana N Giugni M 2012 Inertial effects on finite length pipe seismic response 2012, **1–14** https://doi.org/10.1155/2012/824578
[10] Chian S C Madabhushi S P G 2012 Effect of buried depth and diameter on uplift of underground structures in liquefied soils. *Soil Dyn. Earthq. Eng.* **41** pp 181–190

https://doi.org/10.1016/j.soildyn.2012.05.020
[11] Vazouras P Karamanos S A Dakoulas P 2010 Finite element analysis of buried steel pipelines under strike-slip fault displacements *Soil Dyn. Earthq. Eng*. **30** pp 1361–1376 https://doi.org/10.1016/j.soildyn.2010.06.011
[12] Sultanov K S Kumakov J Loginov P Rikhsieva B 2020 Strength of underground pipelines under seismic effects *Mag. Civ. Eng*. **1** pp 73–82 https://doi.org/10.18720/MCE.93.9
[13] Khusanov B Rikhsieva B 2019 Thickness dimensions of the contact layer of soil-rigid body interaction. *E3S Web of Conferences* https://doi.org/10.1051/e3sconf/20199704040
[14] Mirsaidov M M Sultanov T Z Assessment of stress-strain state of earth dams with allowance for non-linear strain of material and large strains *Mag. Civ. Eng.* **49** pp 73–82 https://doi.org/10.5862/MCE.49.8
[15] Koltunov M A Mirsaidov M Troyanovskii I E 1978 Transient vibrations of axissymmetric viscoelastic shells *Polym. Mech*. **14** pp 233–238 https://doi.org/10.1007/BF00857468
[16] Mirsaidov M Sultanov T Yarashov J Toshmatov E 2019 Assessment of dynamic behaviour of earth dams taking into account large strains. *E3S Web of Conferences* https://doi.org/10.1051/e3sconf/20199705019
[17] Usarov D Turajonov K Khamidov S Simulation of free vibrations of a thick plate without simplifying hypotheses *Journal of Physics: Conference Series* https://doi.org/10.1088/1742-6596/1425/1/012115
[18] Usarov M Mamatisaev G Yarashov J Toshmatov E 2020 Non-stationary oscillations of a box-like structure of a building. *Journal of Physics: Conference Series* https://doi.org/10.1088/1742-6596/1425/1/012003
[19] Usarov M Mamatisaev G Toshmatov E Yarashov J 2020 Forced vibrations of a box-like structure of a multi-storey building under dynamic effect *Journal of Physics: Conference Series* https://doi.org/10.1088/1742-6596/1425/1/012004
[20] Mirzaev I et al. 2019 Formation of Bending Waves in Underground Extended Pipelines under the Action of Seismic Wave. *Int. J. Adv. Res. Sci. Eng. Technol*. **6** pp 10553–10557