Mechanics of contact interaction and deformation of main pipelines in the conditions of extreme external actions

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Abstract: Formulation and solution of a task for the composite engineering-geological interaction of a pipeline and a soil are considered. Finite element method is used for numerical analysis of the task, accounting for large displacements and corresponding strains under changing boundary conditions. The capability of the limit state reaching in the pipeline with loss of form stability is shown depending on pad layer and the pipe properties. It is demonstrated also that safety maintenance could be provided by usage of ribs, formed on a pipe by a cyclic thermomechanical actions.

Keywords: structural material; deformation; strength; contact interaction; pipeline integrity; seismic steadiness; modelling; finite element method.

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1 Introduction

Fracture of pipes of main oil and gas pipelines occurs more often under normal service conditions owing to damages accumulation, first of all corrosion or stress-corrosion. However in certain cases pipes are exposed to loads which considerably exceed loads at normal service. Such cases include, in particular, earthquakes.

Earthquake resistance of structures, including pipelines and pressure vessels, is analysed in a large number of scientific publications. A number of normative documents are also devoted to the problem in power engineering, oil and gas industry – Russian PNAE G-7-002-86 (1989), American ASME BPVC (2015, Sec. III App. N) and ANSI/API Recommended Practice 2EQ (2004), etc. However, the schemes considered there are primarily oriented to unconstrained (not buried) pipelines that have large possible displacements under dynamic action and produce considerable forces on attached vessels – see, for example, article of Shang et al. (2017). Alexandrov et al. (2011) show that stresses, calculated for buried pipelines using the methods of above-mentioned codes, appears to be relatively small. Murzakhanov and Ryabtsev (2009) and Denisov and Lalin (2013) obtain analogous results by numerical simulation. It is easy to see, for example, that maximum amplitude of the ground accelerations given in PNAE G-7-002-86 (1989) for 9-point earthquake corresponds (accounting the frequency) to displacements of up to 40 mm. Calculating the wave speed using a soil density and stiffness, it is easy to obtain wavelength, corresponding to the frequency: from 60 m for sandy soil of medium moisture up to 500 m for rocky soil. If we assume (obviously significantly overestimating the stresses) that the pipe deforms exactly as the soil free from the pipe deforms, then the bending with such wave parameters will correspond to stresses from 1 to 50 MPa. The greater value corresponds to the sandy soil and, taking into account the assumption made, is strongly overestimated. Thus, the seismic waves in the ground should not lead to dangerous consequences for the pipeline from the point of view of static fracture. An exception could be zones of high local stresses – vicinity of defects, bends and tees.

Significantly more dangerous is the movement of the soil, which may occur in places of tectonic faults, seismic ruptures and landslides. Three-dimensional displacements in these cases can be in metres, which should lead to high stresses. For example, tectonic faults on Island of Sakhalin have possible vertical and horizontal displacements up to 3 m with a total displacement vector up to 4–5 m. This task closely adjoins the problems of extreme displacements of soils during their erosion by water streams or thawing of permafrost zones. It is obvious that such displacements make conditionally elastic calculations inapplicable.

A series of publications, devoted to the updated calculating methods of strength of under seismic impact, appeared recently. Psyrras and Sextos (2018) make detailed enough survey of such publications, including up-to-date. Some works uses analytical approach or semi-analytical approach – see, for example, Sarvanis and Karamanos (2017). Such approaches demand an introduction of some the guessworks (simplifications) which reasonableness is difficultly to verify. Trifonov (2015), Banushi and Squeglia (2018) and a number of other researchers tried to use numerical finite-element analysis, but faced significant difficulties in ensuring convergence of the numerical solution. Therefore, despite the achieved progress, developing of a computational model with sufficient effectiveness and small number of simplifying assumptions remains necessary.

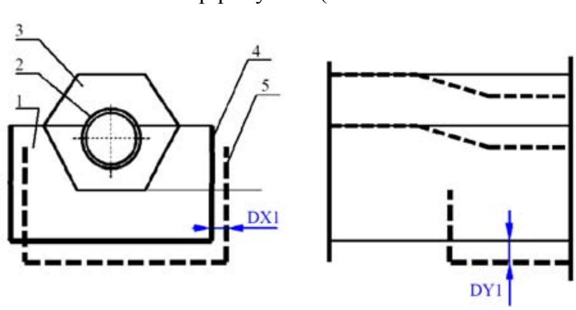
The wide-known LS-DYNA finite element code was used here as a tool for such modelling, taking into account characteristic features of this software, aimed to the solution of highly-nonlinear dynamic tasks.

2 Numerical simulation

To perform the simulation, a parameterised geometric model of the 'main soil – backfill (pad layer) – pipeline' system was prepared (Figure 1). The model includes the main soil – 1 (with a trench excavated), a pipe – 2, a backfill soil – 3 and two rigid 'containers' – 4 and 5, in which the main soil is located. The mutual displacement of these 'containers' corresponds to the mutual displacement of the soil on different sides of the tectonic fault. Interactions of all elements of the system (soil with the pipe, soil layers with each other and with 'containers') are described as one-way connections that transmit compressive and shear (friction) forces. External action is specified in the form of the dependence of the containers displacements on time, the displacement components (vertical DY1 and horizontal DX1) are set separately. The LS-DYNA software provides consideration of this system in dynamics - taking into account the inertial forces of the soil layers and the pipe that interacts with it.

Sizes and positions of all parts of the model, as well as mechanical properties of all materials, are given in the form of parameters. A sufficiently large number of parameters (14 geometric ones + material properties) ensure a good fit of the model to a real system. Parameterisation makes it possible to almost completely automate the preparation of variants of the structure – for example, for a comparative analysis of the effect of trench geometry on the result.

Figure 1 Parametric model of the soil-pipe system (see online version for colours)



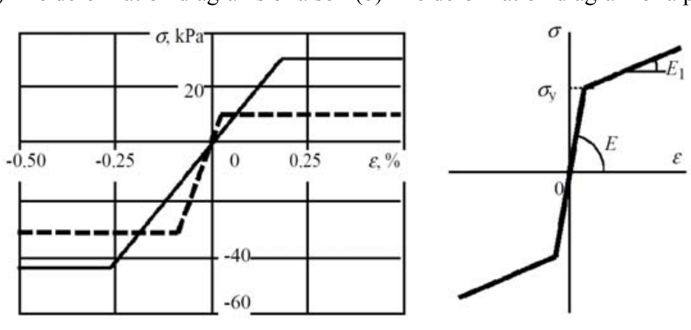
Notes: 1 – main soil; 2 – a pipe section; 3 – a backfill soil; 4 and 5 – two rigid 'containers'.

The elastic-plastic properties of the pipe material in the model can be specified by having the results of specimens testing and passing from the conditional diagram of deformation to the true one-for example, using the known Ramberg-Osgood relations. Soil properties are traditionally described by the known Drucker-Prager model, parameters of the model for a number of soils is easy to find in national standards. Interaction between a soil and a pipe is described using contact algorithm: absence of soil penetration through a pipe wall and a friction. Specific features of implementation of this description depend on the chosen type of modelling and are discussed below.

The length of a modelled section is restricted by computational cost. If the length is not large then modelling results depend on axial boundary conditions for a pipe. Banushi and Squeglia (2018), for example, discuss this dependence. Let us note here only that free axial displacements of the pipe ends leads to a conservative evaluation: local buckling of the pipe appears in this case at the least soil displacement. Accurate information of axial boundary conditions demands the knowledge of soils properties, frictions coefficient, and also the pipeline wiring diagram (curvature in horizontal and vertical planes, presence of offtakes and T-connectors); in the absence of the complete information it seems to be natural to use the scheme that gives lower estimation of the safety.

Examples of calculations were made using demonstrative properties of the soil, backfill and the pipe (at presence of detailed data all calculations can be easily repeated without change of the method and the parametric model). As the basic soil the loam has been accepted with the next parameters of the Druker-Prager model (in accordance with Russian standard SNiP 2.02.01-83): adhesion of 17 kPa, angle of internal friction of 14 degrees, strain modulus of 12 MPa. The backfill – a dusty soil with a porosity of 0.45, corresponding model parameters are 8 kPa, 36 deg, 39 MPa. For the pipe material the elastoplastic model with bi-linear diagram was used with elastic modulus of 2.105 MPa, a 'yield point' 300 MPa and a hardening modulus 600 MPa (usage of a model with nonlinear hardening, for example power law plasticity, also does not meet any difficulties). The Druker-Prager model has yield points depending on the stress state (different yield stresses at tension and compression), uniaxial diagrams corresponding to the above-mentioned parameters are shown in Figure 2(a). Figure 2(b) illustrates true stress-strain diagram for the pipe steel (deformations and geometric nonlinearities were taken into consideration at calculation of 'engineering' behaviour). The pipe diameter in examples shown in the figure is 1,200 mm and the wall thickness is 30 mm.

Figure 2 (a) The deformation diagrams of a soil (b) The deformation diagram of a pipe metal



(a) (b)

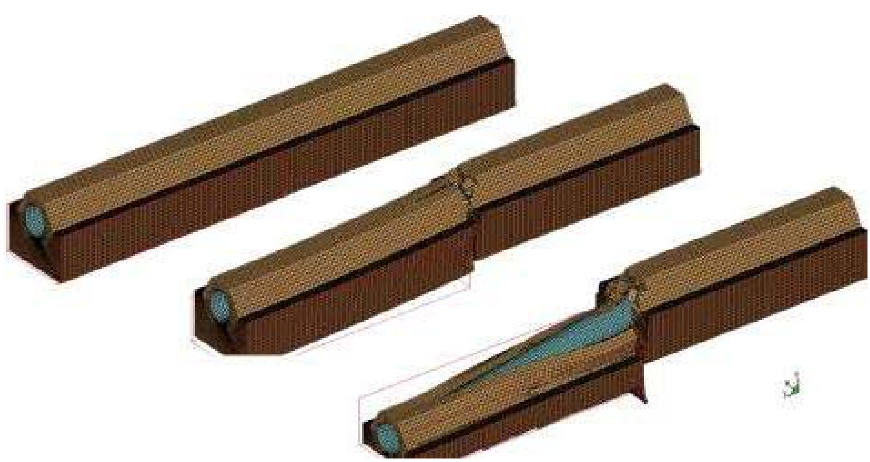
Note: Full line – the main soil; dotted line – the dusty soil.

Computational modelling of the behaviour of the system is complicated by large displacements and large strains, which in FEM (finite-element) formulation often leads to problems with convergence, loss of accuracy or even a complete inability to continue the calculation. In addition, in the deformation of the soil at the kinks, tensioned areas are formed. The Drucker-Prager model predicts a very low (sometimes even negative) yield point in such places, which also leads to instability or stopping of the calculations. This instability can be overcome in two ways.

The first method relates to the Lagrange formulation of finite-elements, in which the mesh nodes are connected with material points, and the finite elements are distorted with the deformation of the material. The soil and a pipe are modelled as separate bodies with a contact conditions – absence of soil penetration through a pipe wall with a possibility of gap appearance at tension. This algorithm uses penalty functions method for calculation of normal components of pipe-soil reactions. The tangential component caused by a friction is computed by multiplication of a normal component to friction coefficient. Value of this coefficient depends on loading type (speed, repeated character of action – see, for example, Russian standard SP 41-105-2002). LS-DYNA code allows to consider the friction coefficient as a function of relative velocity.

To overcome the problems associated with large deformations at use of the Lagrange approach, highly distorted finite elements could be removed from the calculation process. Practice shows that strain equal to approximately 200% can be treated as leading to instable calculations and demanding to eliminate the element. Such removal is like the destruction of a material (crumbling soil – see the example in Figure 3). However, such 'destruction' is not completely physical – eliminating elements from the calculation leads to violation of the laws of conservation of mass and energy, since part of the mass and energy disappears along with the removed elements. Therefore, the error associated with this approach underestimates the stresses in the pipe wall and overestimates the safety.

Figure 3 Sequential phases of the deformation process (from left to right), calculation using the Lagrange scheme (see online version for colours)



Another way is usage of the Euler finite element scheme, in which the deformed soil ‘flows’ through a mesh of finite elements fixed in the space. Thus contact interacting between a soil and a pipe looks like of the exclusion of ‘leakage’ of a soil through a pipe wall that is implemented through the ratios bundling velocity of a wall and a component of soil velocity in a direction of a normal line to a wall (as well as at use of the Lagrange approach, the description of occurrence of a spacing between a pipe and a soil is possible). The friction coefficient in this statement can be set only as constant values, but it does not lead to essential limitation of a computational accuracy. The matter is that the tangential component of interacting forces of a soil and a pipe is restricted not only by a friction coefficient, but also by a soil yield point on shear. At small or, in particular, tensile stresses the Druker-Prager model forecasts low meanings of this yield point that automatically restricts a friction force between a pipe and a soil.

The use of a mixed formulation (the soil in Euler’s formulation, the pipe in Lagrange’s formulation) allows solving the problem of large displacements without artificial methods (Figures 4 and 5). Verification of this model can be performed, for example, by comparing the calculated results for the pipe shear in the trench (Figure 6) with experimental ones (similar results were obtained, for example, in the Sakhalin-2 project).

Figure 4 Sequential phases of the deformation process (left to right), calculated using Euler-Lagrange schemes (see online version for colours)

Figure 5 Stress state of the pipe in the zone of the ground displacement (see online version for colours)

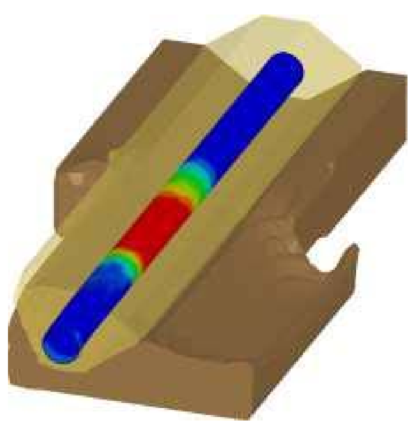
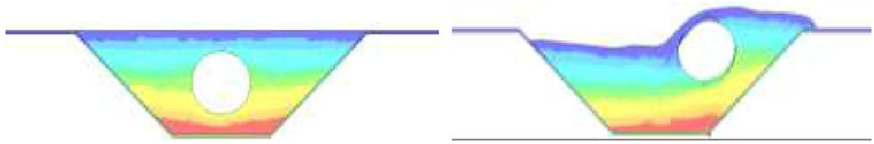
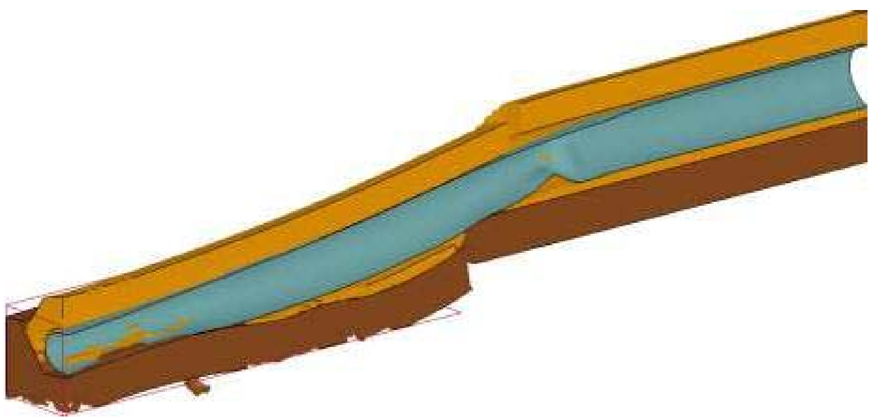


Figure 6 Evolution of the pressure field when the pipe is loaded with a horizontal force (example calculation) (see online version for colours)



Simulation shows that the vertical displacement of the ground, caused by the sudden dropping of one 'container' by 2 m, leads to a local buckling of the pipe wall with the possibility of forming corrugated folds (Figure 7). The specific values of strains in the vicinity of folds depend on the initial imperfections of the shape of the pipe, however, in any case, strains near the fold can be large enough comparing to the plasticity resource and can cause fracture.

Figure 7 Local loss of pipe wall steadiness (see online version for colours)

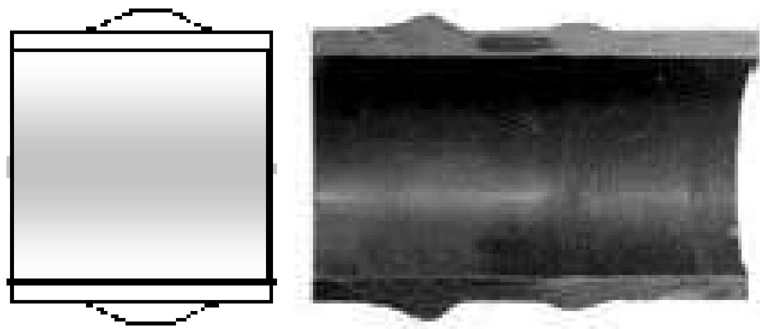


3 Possibility of a danger decrease of wall pipe buckling

The considered approach allows analysing the comparative effectiveness of various measures to ensure strength of a pipeline: changes in the trench profile (which is especially important for horizontal displacements), properties and thickness of the backfill layer, properties and wall thickness of the pipe material. As one of the non-standard techniques can be considered, for example, the use of pipes with ribs – Figure 8.

Such ribs can be produced by means of cyclical thermal actions on a pipe without usage of any mechanical load. Change of pipe geometry is gained due to the plastic deformation arising under the influence of thermal stresses not simultaneously in different points of a pipe. The augmentation of a wall thickness (rib forming) is accompanied by some reduction of a pipe length (taking into account incompressibility of a material at a plastic deformation). This techniques uses phenomenon called 'progressing accumulation of strains and displacements' (also 'incremental collapse' or 'ratcheting', though the term 'ratcheting' is used in other senses also). The theory can be found in a work of Gokhfeld and Cherniavsky (1980).

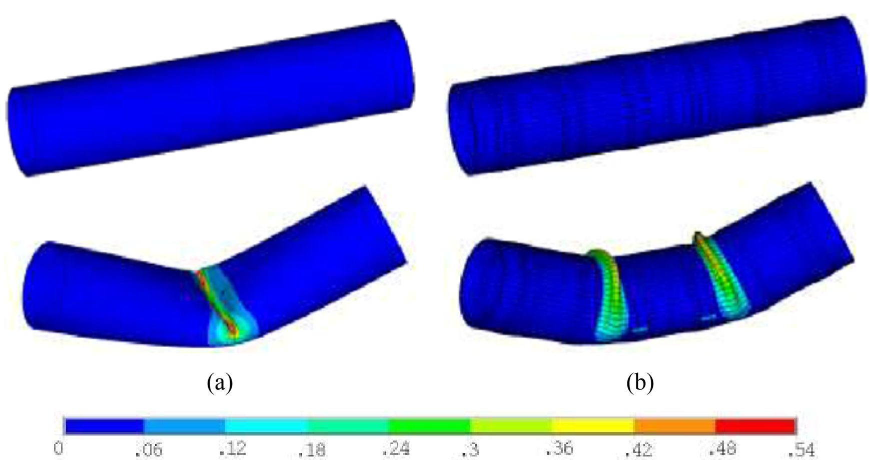
Figure 8 Ribs on a tube blank (scheme, laboratory specimen)



Making of such ribs in laboratories is described in the work of Gokhfeld et al. (1989). Industrially this technique can be implemented by use of only those equipments that are already available on pipe plants: induction heaters and water spray coolers. Let us note, however, that use of pipes with ribs for main pipelines is not stipulated by existent standards.

Buckling of a plane pipe at bending proceeds in the form of a single fold with significant values of plastic deformations [Figure 9(a)]. The presence of ribs changes the deformation mechanism, creating several zones of buckling instead of one [Figure 9(b)]. At the same time, deformations in each of the zones turn out to be less – the risk of depletion of the plasticity resource with the formation of a crack, respectively, also decreases.

Figure 9 Buckling at bending of (a) smooth and (b) ribbed pipes (see online version for colours)



Note: Colour scale – levels of plastic deformation.

4 Conclusions

Seismic action on main buried pipelines is connected with seismic wave propagation and possible ground displacements near tectonic faults. Calculations show that the bending stresses induced in a pipeline by propagation of a seismic wave are usually small and should not lead to hazardous consequences for the pipeline, excluding zones with high local stresses – in the vicinity of defects, bends and tees. The ground displacements near tectonic faults (or similar displacements due to landslide) are much more dangerous because of large values of displacements, strains, possible depletion of the plasticity resource with the formation of cracks.

Numerical simulation of the pipe dynamical stress-strain state with account of elastoplastic properties of the pipe and soil, internal pressure in the pipe, inertia forces, contact interaction of soil and pipe could be done using finite-element method, and, in particular, LS-DYNA software, realising this method. It is shown that usage of purely Lagrange formulation demands elimination of highly distorted elements, otherwise calculation process became instable. However this elimination leads to overestimation of the safety of the pipeline. Combined approach (Lagrange's for a pipe modelling and Euler's for the modelling of the soil) is free of this shortcoming and allows analysing the consequences of large ground displacements. The developed fully parameterised model allows calculations with a minimum of developer labour to compare the effectiveness of various measures: changes in the profile of the trench (which is particularly important for horizontal displacements), properties and thickness of the backfill layer, properties and wall thickness of the pipe material.

Reducing the risk of local buckling, folding, crack formation and loss of tightness can be achieved by using of ribbed pipes, produced using special technology based on cyclic thermal actions.

The considered method of the numerical analysis of pipelines behaviour at extreme combinations of mechanical and geological actions has been used in the implementation of unique project (described in the 'Safety of Russia' monograph, 2013) of a pipeline on Sakhalin island with its high seismic activity and the presence of about 20 tectonic faults.

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