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Computer simulations of deformations and tensions in the pipelines of hydraulic lifting systems

Tadeusz Szelangiewicz[1], Katarzyna Żelazny[1] ✉, Ryszard Buczkowski[2]

[1] Maritime University of Szczecin, Faculty of Navigation
1-2 Wały Chrobrego St., 70-500 Szczecin, Poland
e-mail: {t.szelangiewicz; k.zelazny}@am.szczecin.pl
[2] West Pomeranian University of Technology
✉ corresponding author

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Abstract

One of the methods of collecting polymetallic nodules from the sea floor is a hydraulic system using a single or double vertical pipeline. While mining, collecting pipelines suspended from a mining support vessel (MSV) move together. As a result of both the MSV's motion with a suspended pipe system and water action (including deep-water currents) a vertical deflection and deformation occur along the pipeline. Simultaneously, stretching and bending tensions emerge along the pipeline. The article presents computer simulation results of vertical deflection and tensions within single and double vertical pipelines with fixed force from the ship's movement (linear movement at constant speed) and regular force from the waves.

Introduction

The concept of a hydraulic system for collecting polymetallic nodules from the seafloor has been presented in numerous publications (Chung, Cheng, & Huttelmaier, 1994; Chung, 1996; Deepak et al., 2001; Halkyard, 2008). While mining, a seafloor vehicle should move with a linear movement over a designated area collecting seafloor nodules with the highest possible accuracy. The mining vehicle velocity depends on its assumed efficiency per year, the width of mining (the width of a mining vehicle), and the density of polymetallic nodules on the seafloor. A mining support vessel (MSV) will have to follow the location of a seafloor vehicle and maneuver in such a way as to position the lower end of a vertical collecting pipeline close to a mining vehicle. Mining vehicle movement will shape the collecting pipeline, resulting in a vertical deflection of the lower end of the collecting pipeline. This lower end is connected to a seafloor miner with an elastic pipeline with zero or minimal positive buoyancy. The length of this pipeline must never be smaller than a maximum distance between a temporary position of the pipeline's lower end and a seafloor miner (Figure 2). Any contact between the pipeline's lower end and a seafloor miner must be prevented. The reaction force of any such contact would lead to damage of the elastic pipeline, the seafloor miner, or both (Szelangiewicz, 2006). Therefore, basic issues to be examined when evaluating the reliability of a hydraulic with vertical pipe system, apart from tensions present along the vertical pipeline, are shape deformations and the vertical deflation of the collecting pipeline's lower end.

Under actual conditions, due to the formation of the ocean floor, the aggregate collecting the conclusions will have to perform various maneuvers – changing speed, stopping, bypassing areas where no conclusions can be gathered. Therefore, the vessel floating on the ocean surface will also have to make various maneuvers so that the lower end of the extraction pipeline is near the aggregate (Figure 2). Due to the need to precisely control the movement of the mining vessel, and in real time, approximate and accurate methods of calculating deformations from the vertical of the lower end of the extraction pipeline are necessary. In the literature on this subject there are various publications containing mathematical models which allow the prediction of the deformations of the pipeline from the vertical at the assumed constraint, e.g. (Yu, 2007), a 3D nonlinear model based on the finite element method; (Hong, Kim, & Choi, 2003), a model of the extractive pipeline dynamics based on the Euler equation; (Li et al., 2011), a model of discrete elements; and (Wang & Liu, 2005; Yoon et al., 2003), a finite element model. In these publications, there are no algorithms or information about the time of numerical calculations or the accuracy of calculations with respect to known values.

The purpose of the research was to perform the calculations of stresses and deformations (deviations from the vertical) of the pipeline system of the recognized Abaqus computer program. The resulting calculation results will be used to develop a simplified calculation model, whose calculation accuracy and calculation time will be accepted to control the ship's movement during the lifting nodules.

The movement of a seafloor mining vehicle and MSV on the ocean surface

It is assumed in numerous research publications on mining systems dynamics, including hydraulic suction systems (Figure 1), that a sea miner travels with a linear movement and reverses at the end of an exploited area. Such a trajectory will also shape the trajectory of a MSV on the surface of the ocean. Since the ocean floor is not flat, being more similar to the surface of the moon, the mining vehicle will not move with a linear motion only: its velocity will change, while movement trajectory will depend on the surface of the ocean floor. Therefore, a MSV will have to adjust its trajectory according to the movement of a sea miner. A MSV will also be affected by the action of the marine environment (wind and wave action; possibly also surface ocean currents) interfering with its trajectory. A complex movement of a MSV, which consists of a slowly varying movement resulting from maneuvering and a high frequency movement resulting from motions (Figure 3), will bring about a kinematic forcing on the vertical pipeline's upper end.

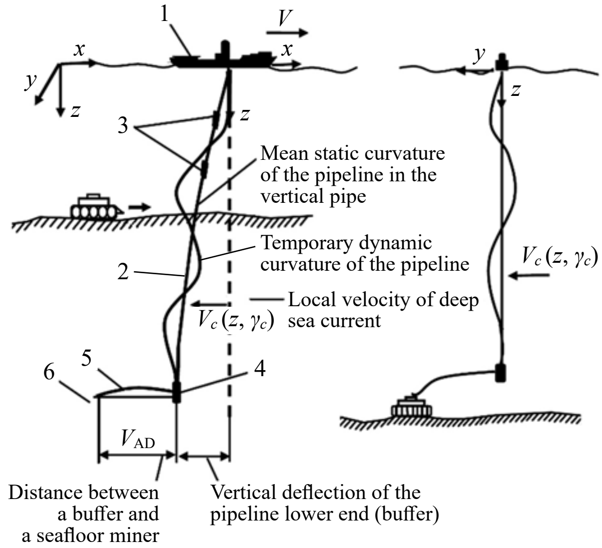

Figure 1. Vertical deflection and pipeline deformation: 1 – a MSV, 2 – a vertical collecting pipeline, 3 – deep-sea pumps, 4 – a buffer, 5 – a horizontal elastic transporting pipeline, 6 – a seafloor mining vehicle, V – velocity of a MSV, V_{AD} – velocity of a seafloor mining vehicle collecting nodules, $V_C(z,\gamma_C)$ – velocity of a deep-water current whose value depends on water depth „z" and geographical current direction γ_C

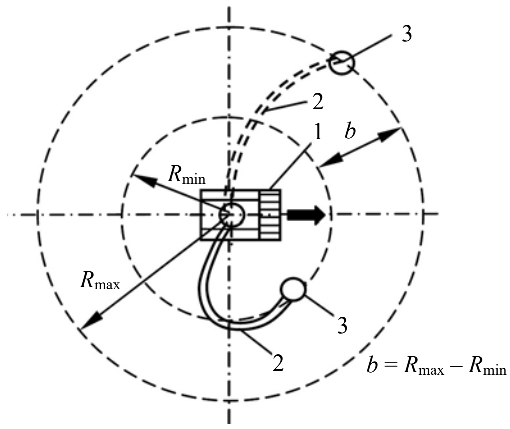

Figure 2. Reciprocal position of the pipeline's lower end (buffer) and a sea miner: 1 – a seafloor miner, 2 – elastic, horizontal pipeline, 3 – lower end of the vertical pipeline (buffer), R_{max} – maximum distance between a buffer and a seafloor miner, R_{min} – minimal distance between a buffer and a seafloor miner

Such kinematic forcing, together with deep-ocean current action, will cause vertical deflection (shape deformation: twisting) of a collecting pipeline. There will be a significant delay/time lag between the forcing of a 5000-meter-long pipeline's upper end and the reaction to this at its lower end. Therefore, monitoring the position of a collecting pipeline against the seafloor miner is one of the basic design issues for hydraulic suction systems.

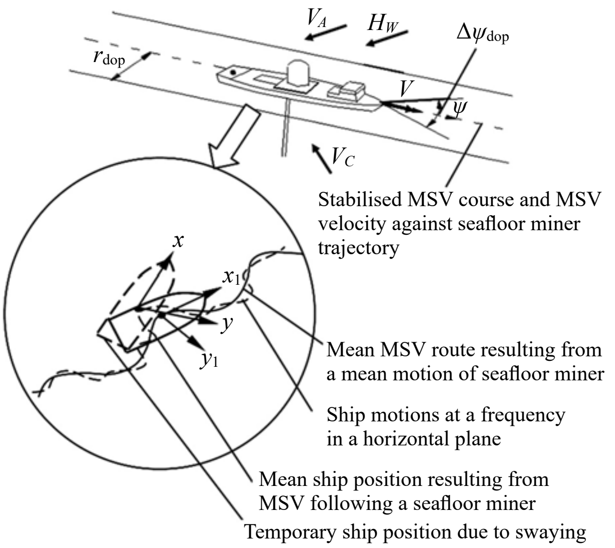

Figure 3. An example of a trajectory and stabilized parameters of MSV movement over an area with polymetallic nodules: V – MSV velocity over an area with nodules maintained at ΔV, accuracy ΔV, ψ – MSV course, maintained at ΔV_{dop} accuracy, r_{dop} – acceptable deviation from a set MSV trajectory, V_A – wind speed, V_C – surface current velocity, H_W – wave height

Computer simulations of deformation in the pipelines of the vertical pipe

Carrying out an extensive simulation of the movement of a seafloor miner and MSV, as well as deformations along the pipeline in time domain, requires the creation of a specialized computer program and a bathymetric map of the ocean floor where the nodules will be collected. Such a computer system must contain a module to calculate – with sufficient accuracy – a temporary position of the individual parts of the collecting pipeline suspended in water at random, changeable kinematic forcing. Thus, as a first step, computer simulations of the collecting pipeline dynamics have been performed for a given, set kinematic forcing without analyzing the motion of a seafloor miner. These computations have been performed using ABAQUS (ABAQUS/CAE).

Due to a very large number of parameters influencing the pipeline dynamics within a hydraulic suction system, and thus their possible combinations, simulations were performed for the most representative cases:

- A MSV with a suspended collecting pipeline system will sail at a set speed V and drift angle β;
- MSVs sail at a constant speed simultaneously motions (in relation to water plane) at constant amplitude and frequency;
- Deep-water current velocity:
  - at the depth 0–600 m $V_C = 1$ m/s,
  - at the depth 600–4600 m $V_C = 0.3$ m/s

  any deep-water current in relation to the vessel (MSV) displacement;
- Hydraulic system:
  - single pipeline,
  - double pipeline;
- Hydraulic system – dimensions:
  - pipe length $L_R = 4600$ m,
  - external diameter $D_Z = 0.28$ m,
  - internal diameter $D_w = 0.25$ m;
- Pipeline material: steel:
  - pipeline unit weight in air $\rho_{RP} = 0.923$ kN/m,
  - pipeline unit weight in water $\rho_{RW} = 0.835$ kN/m,
  - Young's modulus $E = 210$ Gpa.

During the calculation of the Abaqus program, the 4600-meter-long lifting pipe was divided into 4600 sections (finite elements). The normal and shear forces and the bending moment were calculated at each node.

To obtain the forces on the nodes of the finite element we need to know the stiffness matrix and node displacements of the frame element used after introducing the boundary conditions.

The stiffness matrix for a 2D frame element in the local coordinate system is given as:

$$\mathbf{k} = \begin{bmatrix} \frac{AE}{2a} & 0 & 0 & -\frac{AE}{2a} & 0 & 0 \\ & \frac{3EI}{2a^3} & \frac{3EI}{2a^2} & 0 & -\frac{3EI}{2a^3} & \frac{3EI}{2a^2} \\ & & \frac{2EI}{a} & 0 & -\frac{3EI}{2a^3} & \frac{EI}{a} \\ & & & \frac{AE}{2a} & 0 & 0 \\ & & & & \frac{3EI}{2a^3} & -\frac{3EI}{2a^2} \\ & & & & & \frac{2EI}{a} \end{bmatrix} \quad (1)$$

where A is the area of the cross-section of the frame element; I is the second moment of area of the cross-section of the element; a is the length of the element; and E denotes the Young modulus.

The vectors of displacements and force corresponding to the order of the degrees of the freedom of the element are:

$$\mathbf{u} = \begin{Bmatrix} u_1 \\ v_1 \\ \theta_1 \\ u_2 \\ v_2 \\ \theta_2 \end{Bmatrix}, \quad \mathbf{P} = \begin{Bmatrix} N_1 \\ S_1 \\ M_1 \\ N_2 \\ S_2 \\ M_2 \end{Bmatrix} \quad (2)$$

where N_1, S_1, M_1 and N_2, S_2, M_2 are the normal force, shear force, and bending moment at node 1 and 2, respectively. So, the force vector in the finite element is obtained from the following system of equation:

$$\mathbf{P} = \mathbf{k} \cdot \mathbf{u} \tag{3}$$

Results of computer simulations of deformations and tensions in the pipelines of the hydraulic lifting system

All computer simulations have been performed in the time domain, while their results have been presented graphically for each computational case in the time domain (that is, a condition of a pipeline at chosen time steps has been shown) or for a set condition (for the pictures pertaining to the set conditions, the relevant parameters, such as pipeline design, kinematic forcing from the MSV, and marine environment, have been shown).

Computer simulations of deformations have been performed for single and double hydraulic suction systems (in this case the pipes were joined by a rigid connection – in the Abaqus program the pipe connection was modeled with PIPE31H beams).

Hydraulic System: Single Pipeline

Computer simulations of collecting pipeline deformations and tensions have been performed for MSV velocity range 0.257–1.285 m/s, various amplitudes and frequencies (in water plane), vessel swaying, and various deep-water current directions in relation to the direction of the vessel's motion. Example computational results have been given in Figures 4–9, while complete simulation results are in (Szelangiewicz, 2006).

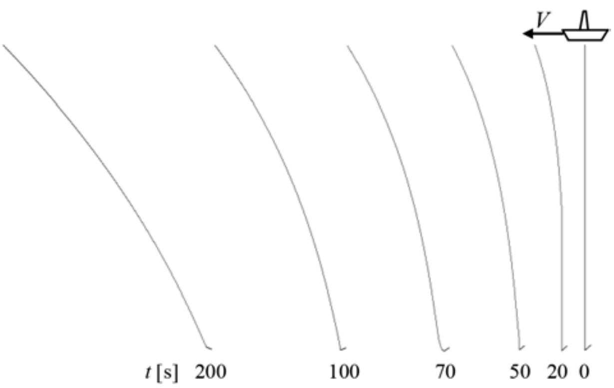

Figure 4. Simulation of pipeline deformation in a hydraulic system: pipeline horizontal displacement [m], MSV velocity V = 1.285 m/s, deep-water current in the same direction

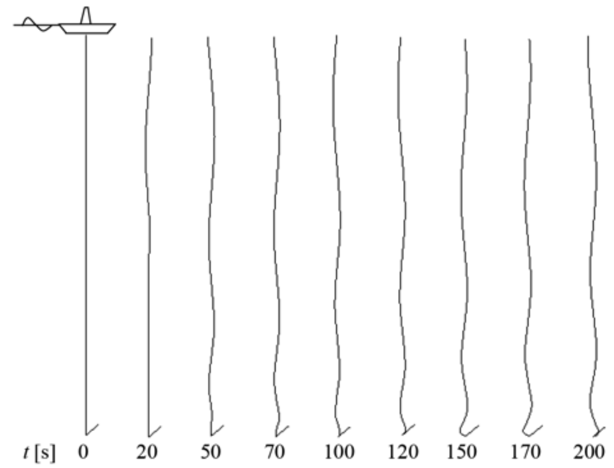

Figure 5. Simulation of pipeline deformation in a hydraulic system: pipeline horizontal displacement [m], MSV velocity V = 0 m/s, kinematic oscillatory forcing on the pipeline upper end at amplitude S_{AX} = 1 m, forcing frequency ω = 0.3 1/s

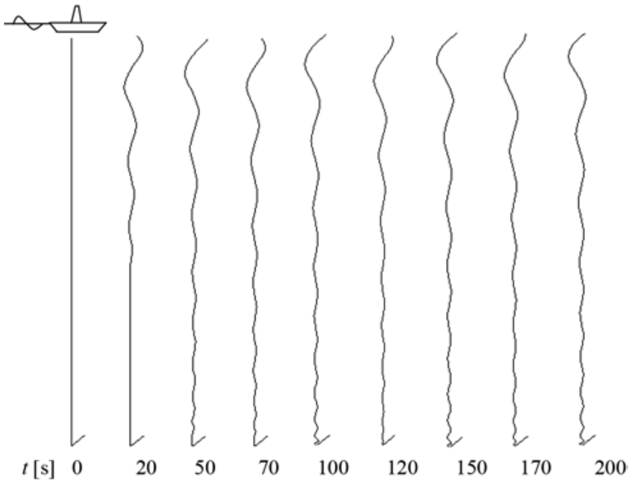

Figure 6. Simulation of pipeline deformation in a hydraulic system: pipeline horizontal displacement [m], MSV velocity V = 0 m/s, kinematic oscillatory forcing on the pipeline upper end at amplitude S_{AX} = 4 m, forcing frequency ω = 1.0 1/s

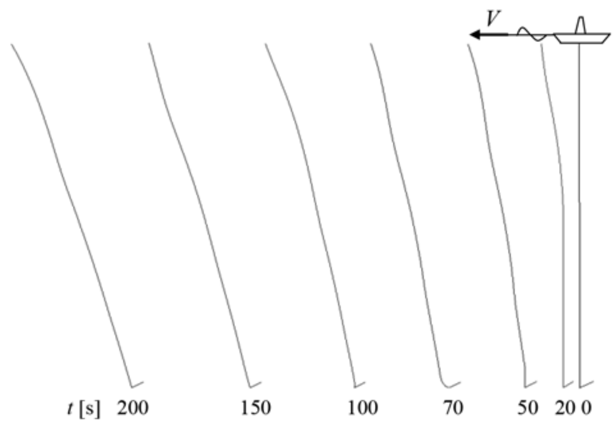

Figure 7. Simulation of pipeline deformation in a hydraulic system: pipeline horizontal displacement [m], MSV velocity V = 0.514 m/s, kinematic oscillatory forcing on the pipeline upper end in the same direction as MSV motion at amplitude S_{AX} = 2 m, forcing frequency ω = 0.3 1/s

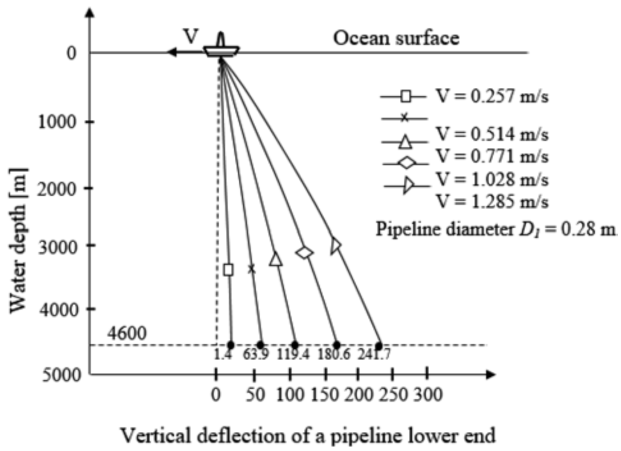

Figure 8. Vertical deflection of a pipeline's lower end in the constant MSV velocity function

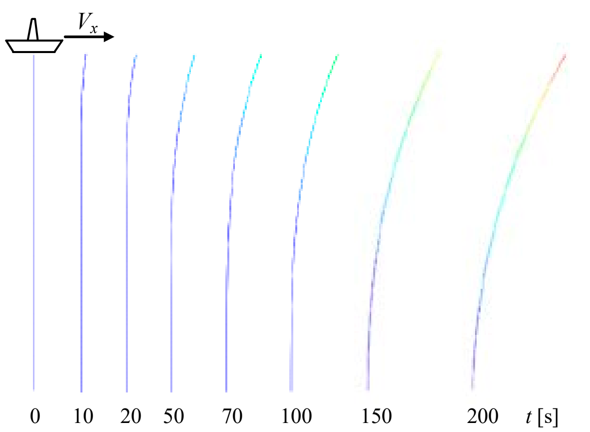

Figure 10. Simulation of a pipeline deformation in a double pipeline hydraulic system: MSV velocity V_x = 1.285 m/s

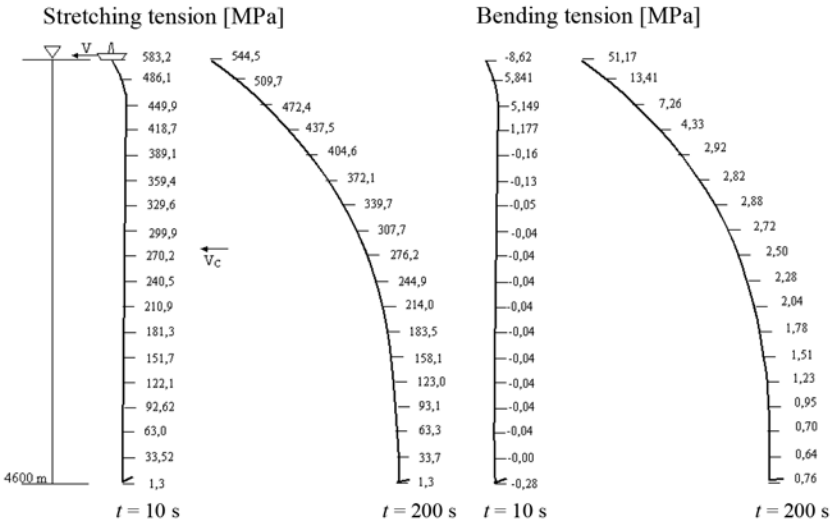

Figure 9. Simulation of stretching and bending tensions along the pipeline of the hydraulic system for two time steps (tensions correspond to individual pipeline parts for a shape in a given time moment): MSV velocity *V* = 0.771 m/s, deep water direction the same as the MSV motion

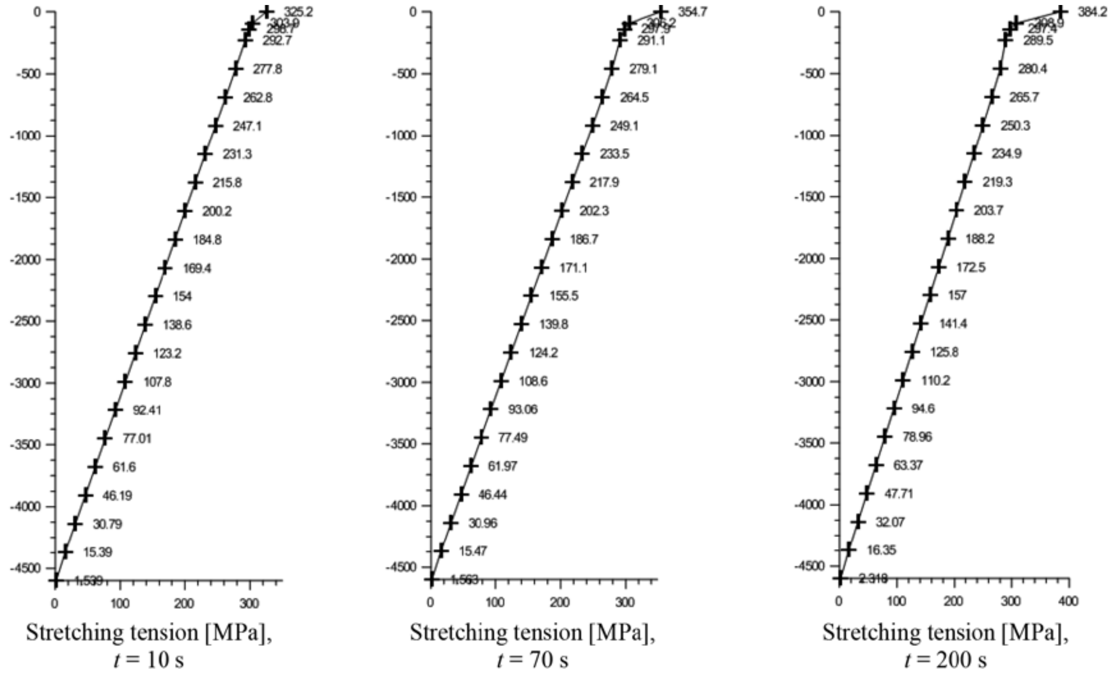

Figure 11. Numerical tension values for individual compute nodes

Hydraulic System: Double Pipeline

The range of computer simulations of pipeline deformations and tensions for a double pipeline system was the same as for a single pipeline system. Additionally, an oblique motion of MSV and oblique directions of deep-water currents relative to the MSV motion were simulated. Since in the case of a double pipeline system the water flow may be asymmetrical, a torsional moment twisting the pipelines against the vertical axis has been examined, together with tensions tangent to twisting and the value of twisting angle. Example calculation results are given in Figures 10–16, with complete results in (Szelangiewicz, 2006).

A full set of calculation results for all kinematic constraints is presented in (Szelangiewicz, 2006).

Initial conclusions from research performed

The calculation time for the simulations of stresses and deformations (vertical deviations) of the lifting pipeline is too long to allow the Abaqus calculation to be used in real time.

Also, during the simulation of the Abaqus program it was not possible to change the initial conditions,

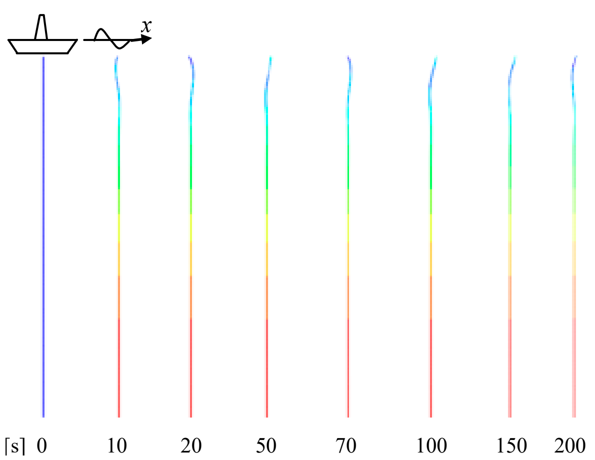

Figure 12. Simulation of a pipeline deformation in a double pipeline: MSV with null velocity, motions against the *x* axis, amplitude S_{Ax} = 1 m, frequency ω = 1 m/s

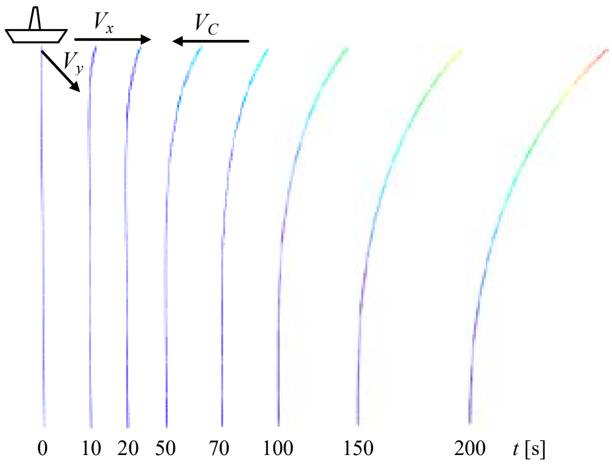

Figure 14. Simulation of a pipeline deformation in a double pipeline system: oblique MSV movement with velocity of $V_x = V_y = 0.908$ m/s (net velocity value $V = 1.285$ m/s), deep-water current with velocity against the direction of *x* axis

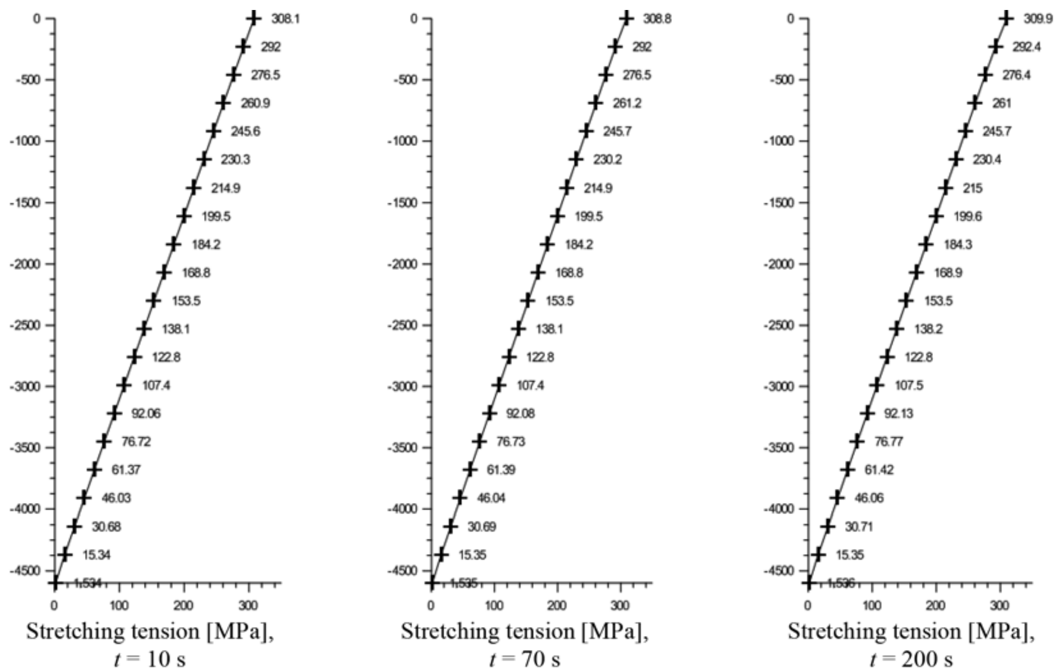

Figure 13. Numerical tension values for individual compute nodes

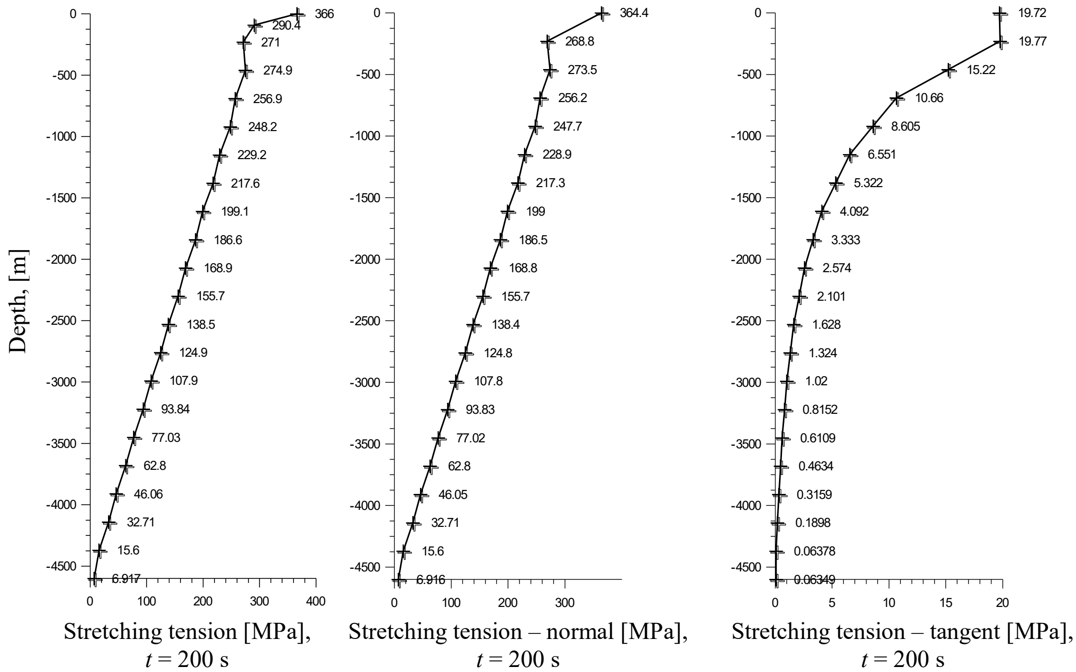

Figure 15. Numerical net values (Misesa reduced) of normal and tangent tensions for individual compute nodes, simulation time $t = 200$ s

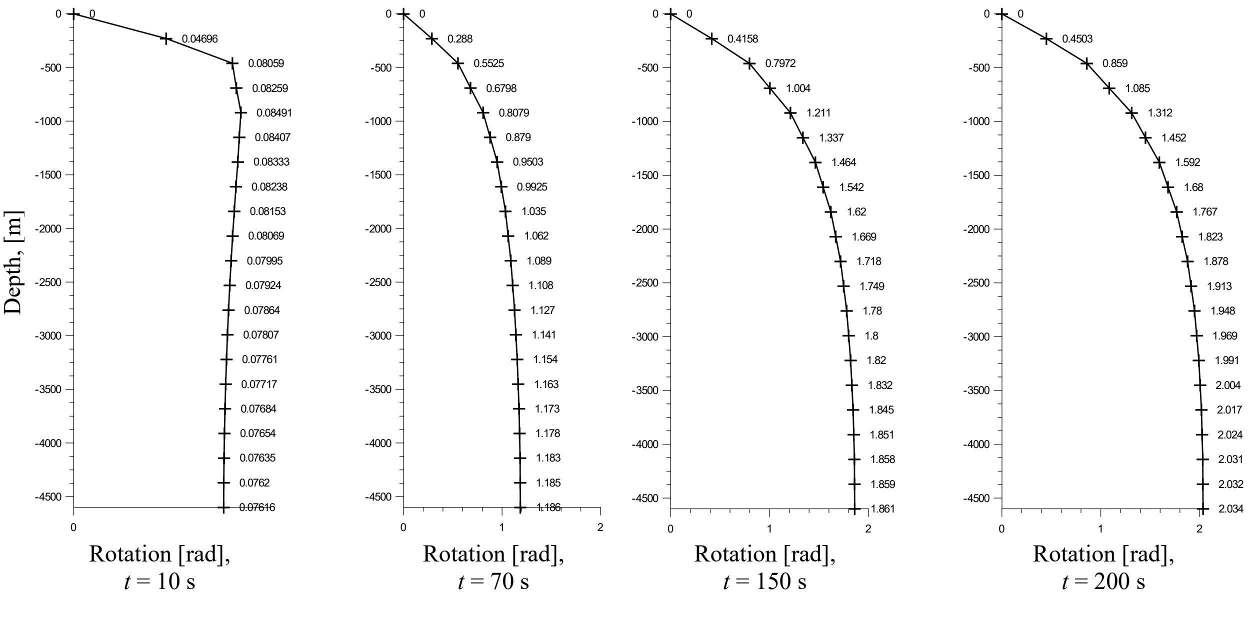

Figure 16. Numerical values of twisting angle for a double pipeline of a hydraulic system at oblique ship motion

e.g. changing the speed and direction movement of the mining vessel. Hence the results of the simulation calculations will be used as benchmark results for the development and testing of a simplified model describing the deformation of the lifting pipeline.

Detailed conclusions from the calculations are as follows:

Hydraulic System – Single Pipeline

1. The vertical deflation of a pipeline in a vertical pipe depends above all on a set vessel velocity while mining, from the deep-water currents' velocity and motions. The bigger the vessel velocity, the bigger the deflation of the collecting pipeline's lower end. Deflation values have a decisive role in the cooperation between a sea miner and a collecting pipeline system.
2. MSV motions give rise to horizontal oscillations of the collecting pipeline, which quickly decrease their amplitude with an increasing depth of water. Kinematic pipeline forcing from motions plays

little role in the total displacement (vertical deflation) of the collecting pipeline's lower end.

3. Possible ways of limiting the deformation of a collecting pipeline system have been examined, taking into account changes in material rigidity and additional damping elements in compute nodes. These actions have not decreased quasi-statistical deformations; however, it was possible to suppress these elements' resonances occurring in the pipelines of hydraulic systems at some frequencies of kinematic forcing at the pipeline's upper end.
4. Increasing the buffer weight has not resulted in a significant decrease in the deflation of the collecting pipeline's lower end.
5. One of the ways to decrease the vertical deflation of the collecting pipeline's lower end is to consequently decrease the velocity of the MSV. In order to ensure a projected mining efficiency, the sea miner must be wide enough; however, its width is restricted by the proper operation of a sea miner and ocean floor features.
6. Tension analysis has shown that stretching tensions from the pipeline weight are decisive for the pipeline's resilience. Bending tensions (from vertical deflation) are very small in relation to the stretching tensions. Reduction in stretching tensions can be achieved by the use of buoyancy modules.

Hydraulic System – Double Pipeline

7. The influence of such parameters as MSV motion and deep-water currents on the deformation (vertical deflation) of a double pipeline system is similar to that on a single pipeline system.
8. In the case of oblique MSV movement or oblique direction of deep-sea currents, pipeline twisting against the vertical axis occurred. The maximum turn value was 10° (lower end turn in relation to the upper end).
9. For the double pipeline systems, tensions tangent to hydrodynamic twisting moment were also present; however, in the case of a single pipeline system, only stretching tensions play a decisive role in resilience.
10. Elimination of double pipeline twisting and tangent tensions, as well as reduction of stretching tensions, is made possible with buoyancy modules with an external circular section.

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