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Numerical analyses of underwater pipe sections under falling objects

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ABSTRACT

Underwater and land pipelines are generally modelled under the environmental loads. In addition to these mentioned loads, pipelines are subjected to destructive sudden loads due to accidental drops, ship anchors, rock falls, trawlers fishing and military attacks. In this study, numeric analysis of the same pipe section has been carried out according to the sudden loads caused by falling objects both underwater and on land. Abaqus finite elements analysis software is used in the analysis. While the interaction of pipe-falling object is modelled in the analysis of the pipeline on land, the interaction of pipe-falling object-water is modelled in the underwater pipeline. Bidirectional fluid-structure interaction (FSI) analysis is utilized in the water-pipe-falling object interaction modelling. A fully nonlinear free surface simulation is performed by Coupled Eulerian Lagrangian (CEL) technique in the FSI analysis. Impact parameters such as accelerations, velocities, displacements and impact forces, are determined for both land and underwater pipe sections at the end. Thus, while determining the effect of water on the impact behaviour, the free surface movement of the water in the course of impact is also obtained.

1. Introduction.

Pipelines are important structures built at sea and on land, formed by the combination of multiple pipe sections. The importance of pipelines is due to the fact that that they carry out vital activities such as clean-waste water, oil, natural gas transmission, energy and communication lines.

During their service life, the pipelines are faced with environmental loads such as earthquakes, waves, currents, as well as damage threats that may occur due to storms, landslides, soil liquefaction and accidental impact loads. Ship collisions on marine pipelines (Yu et al. 2016), and rock falls on land pipelines (Pichler et al. 2006) can be given as examples of impact loads.

Impact effect from sudden falling objects changes mechanical properties of structural members due to dynamic effects. Stress values change because of these effects at the strike moment. Damage expands beyond the impact point during such crushing events. For this reason, extensive damage and losses may be observed. Various experimental (Kishi et al. 2002: Zhu et al. 2018: Erdem, 2014:) and numerical studies (Erdem and Gücüyen, 2017: Odina, Hardjanto and Walker, 2018: Zhou and Zhang, 2022: Kawsar et al 2015: Zhang, Liang, and Han, 2014) have recently been developed by many scientists to facilitate better understanding of these complex impact-related situations. On the other hand, similar computer simulations have been performed to compare the experimental and the numerical studies (Zeinoddini et al. 2013: Zhou and Zhang, 2023: Gau et al 2020).

As different from the pipelines on land, investigation of marine pipelines under falling impact loads is performed by considering fluid-structure interaction (FSI) analysis. FSI analysis is unidirectional when the force transfer occurs from the fluid to the structure only. However, bidirectional analysis is when the force is transferred from the fluid and the displacement is transferred from the structure. Finite element analysis is applied for both analyses. Finite elements supported FSI analysis can be generated by either Eulerian technique (Martínez, 2009) or Lagragian technique (Gücüyen, Erdem and Gökkuş, 2016). On the other hand, both techniques can also be used in Arbitrary Lagragian Eulerian (ALE) (Korobenko et al. 2017)

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and Coupled Eulerian Lagrangian (CEL) analyses (Gücüyen et al. 2018). Abaqus finite element software is widely used in the interaction modelling (ABAQUS User's Manual, 2015). In ALE and CEL analyses, the structure and the fluid are modelled by Lagrangian and Eulerian techniques respectively. The CEL technique which is implemented in the software Abaqus and uses an explicit time integration scheme is a large deformation finite element method coping with the deficiencies of the pure Lagrangian and Eulerian techniques.

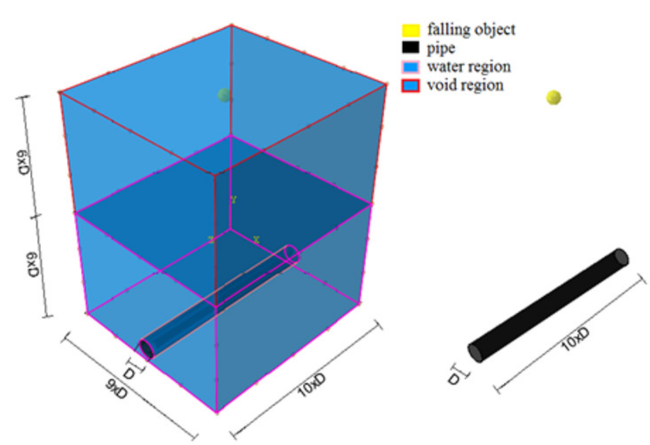
In the literature survey, it is seen that the CEL technique has been used in a few studies in modeling the behavior of underwater pipes under the effect of sudden falling objects (Jiang and Dong 2020: Jiang et al. 2019: Jiang and Dong 2022). In these studies, while CEL technique has been utilized in soil-structure interaction modeling, the submerged unit weight of soil is used to consider the seawater pressure. In the study in which bidirectional fluid structure interaction is generated under the effect of a sudden falling object (Kristoffersen et al. 2014), the behavior of the water in the pipe under the impact effect is modeled. The origin point of this study is the limited number of studies in which the free surface movement of the water surrounding the pipe under the impact of impact is modeled and the bidirectional fluid structure interaction is carried out.

This paper aims to numerically investigate the dynamic behaviour of underwater and land pipes impressed by falling objects. CEL technique is utilized by Abaqus software in the numerical analysis. While the pipe and falling object are modelled by Lagrangian procedure, water environment is modelled by Eularian procedure. Impact parameters such as accelerations, velocities, displacements and impact forces, are determined for both land and underwater pipe sections in the end.

1.1. Numerical Models.

In this study, the effect of the environment of the pipes under sudden falling objects on the behaviour of the pipe has been investigated. For this purpose, above ground pipe models seen on the right of Fig. 1 and underwater pipe models on the left have been created. The situation only under the effect of free falling where the pipe is not in use is modelled in the software.

Figure 1: Numerical models and dimensions.



Source: Authors.

The numerical model belongs to underwater pipe, has 4.5 x 5 m base dimensions with a height of 6 m. While width of the water part is determined as nine times of the diameter (D) of the pipe (9 x D), length of the region is taken as equal to ten times of pipe diameter (10 x D). In addition, the height value is twelve times of pipe diameter (12 x D). While the drop height is 5 m, the mass of the striker is taken to be 140 kg in the analyses. Void region with the height of 3 m is set above the water region, which is used to describe the potential water flow on the free surface during the simulation process.

Properties of the fixed supported pipe which is used to model both land and underwater pipe under falling object effect are seen in Table 1. While the underwater pipe model has three parts; pipe, water and falling object, the land pipe model has two parts; pipe and falling object.

Table 1: Geometric and material properties of the pipe and water parts.

Parts	Geometric Properties		Material Properties	
Pipe part	Length (m)	5	Yield Stress (MPa)	240
	Diameter (m)	0.50	Young's modulus (GPa)	210
	Thickness (m)	0.016	Mass density (kg/m^3)	7850
Water part	Length (m)	10	Density (kg/m^3)	998
	Width (m)	4.5	Dynamic viscosity (Ns/m^2)	0.0010
	Height (m)	6	Velocity of sound (m/s)	1480

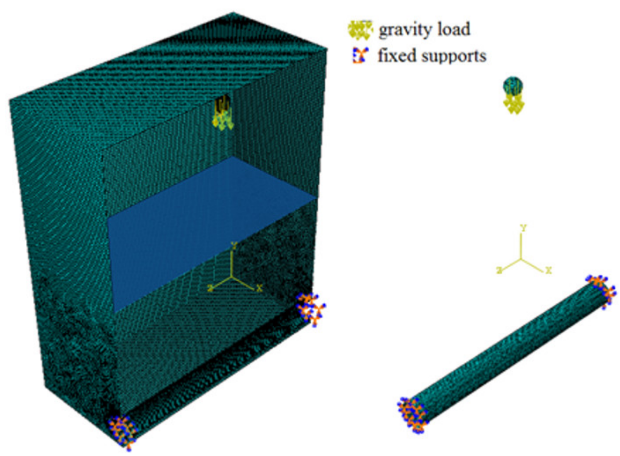
Source: Authors.

Once the models are created, the element types, material properties of related sections, proper step and mesh sizes, connection between surfaces of elements, correct boundary, and initial conditions are provided. Time steps have an important effect on the results of impact analyses. For this purpose, both step and total time spans are checked consistently. Time steps are determined from beginning to the end of the drop movement of the falling object. While the time increments have been defined as 0.060 seconds before the contact point, they have been set to $2x10^{-8}$ seconds when the contact between the falling object and the pipe has started.

Finite elements models should be separated into small pieces, known as meshing, so that the analyses can be performed correctly. Mesh structure and load-support conditions of the models are seen in the

Fig. 2. While the left side of the figure belongs to underwater pipe, right side belongs to land pipe. C3D8R (three dimensional, 8-node linear brick, hexahedron) typed elements are used in pipe parts, C3D10M (10-node modified tetrahedron) typed elements are used in falling object parts so the element assignment of the Lagrangian parts is realized. Element assignment of the Eulerian part is realized by assigning EC3D8R (8-node linear eulerian brick, reduced integration, hourglass control) typed elements to water part. Distance between nodes in pipes and falling object is 0.016 m, same as thickness of the pipe. In water part, the node distance is 0.016 m on the contact regions with pipe and on the rest of geometry the node distance is 0.025 m. Thus, the whole finite elements model is constituted by 87144 nodes and 49840 elements in Lagrangian part and 10314717 node and 10169600 elements in Eulerian part.

Figure 2: Mesh structure and load-boundary conditions of the models.



Source: Authors.

As the problem is related to the free falling movement, only gravity load is applied to the system. Pipes are fixed supported in both ends. In the underwater pipe model, pipe and dropped object are interacting with water. Due to this interaction, fluid structure interaction (FSI) analysis shoud be performed in underwater model.

2. FSI Analysis.

Fluid-structure interaction analysis of the underwater pipe under dropped object effects is performed by Abaqus finite element analysis software (ABAQUS User's Manual, 2015). Lagrange and Eularian procedures are followed through CEL technique in the numerical analysis. Mathematical definition of this technique is presented in the following sections.

2.1. Mathematical Definition of CEL Technique.

Formulation of CEL technique that is used by Abaqus is described by the equations below. Eqs (1-3) are the mass, momentum and energy Lagrangian conservation equations respectively.

$$\frac{D\rho}{Dt} + \rho\nabla \cdot v = 0 \tag{1}$$

$$\rho\frac{Dv}{Dt} = \nabla \cdot \sigma + \rho b \tag{2}$$

$$\frac{De}{Dt} = \sigma : D \tag{3}$$

In the Eqs (1-3), material velocity, density, the Cauchy stress, the body force and the internal energy per unit volume are represented by v, ρ, σ, b and e respectively.

$$\frac{D\varphi}{Dt} = \frac{\partial\varphi}{\partial t} + v \cdot (\nabla\varphi) \tag{4}$$

By using the Eq. (4), governing equations for Lagrangian technique are determined in the general conservation form for Eularian procedure as follows.

$$\frac{\partial\varphi}{\partial t} + \nabla \cdot \Phi = S \tag{5}$$

φ is the arbitrary solution variable, Φ is the flux function and S is the source term in the Eq. (5). This equation can be written as two separate equations as follows.

$$\frac{\partial\varphi}{\partial t} = S \tag{6}$$

$$\frac{\partial\varphi}{\partial t} + \nabla \cdot \Phi = 0 \tag{7}$$

Eq. (6) is hence identical to the standard Lagrangian formulation if the spatial time derivative is replaced by the material time derivative on the fixed mesh. The deformed mesh is moved to the original fixed mesh, and volume of material transported between adjacent elements is calculated to solve the Eq. (7). The Lagrangian formulation variables such as the mass, energy, momentum, stress and others are then adjusted to account for the flow of the material between adjacent elements by the transport algorithms.

2.2. CEL application to mentioned model.

While water region constitutes the Eularian part, pipe region constitutes the Lagrangian part in the underwater pipe model. Eularian part is composed of void parts with and without assigning material as it can be seen in the figure. The CEL approach assists various materials (with the inclusion of voids) in the single element. The fowing material along the mesh is followed by the Eulerian Volume Fractions (EVF) symbolizing the ratio as the material is filled with the Eulerian elements. If a material entirely fills the element, the EVF is equal to 1; if there is no material in the element, the EVF is considered as 0.

After generating Eularian and Lagrangian parts in the software, material characteristics are defined to these parts. Material properties of Eularian and Lagrangian parts have been given in Table 1. The environment of the pipe is modelled as EOS materials with the velocity of sound in water. Boundary conditions are defined in the next step of the numerical analysis. Velocity components are set to zero at Bottom of water part is set to wall boundary condition where all of the velocity components equal to zero. Velocity component in the related axis are set to zero on the lateral surfaces. Horizontal movement of the falling object is restrained. It can only move vertically.

3. Results.

Acceleration values from 100 mm distance from the impact point, maximum displacements and impact load values are obtained after performing numerical analyses. The results are given in Table 2 for the land and underwater pipes.

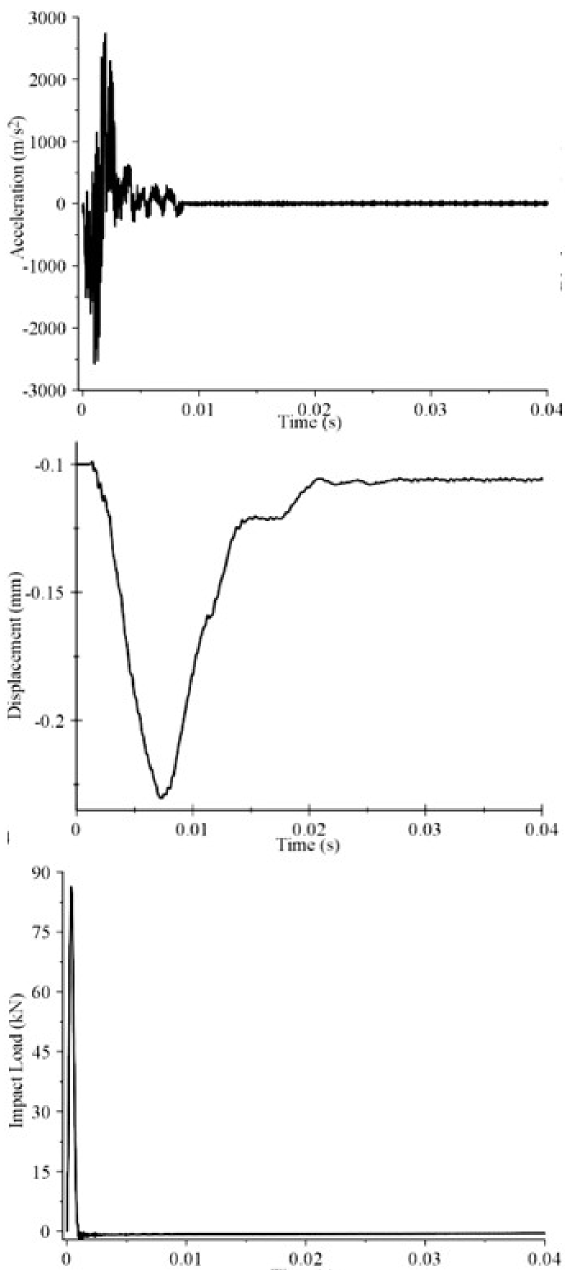
Table 2: Numerical results.

Pipe model	Acceleration (g)	Displacement (mm)	Impact Load (kN)
land	-5638,6243	2,9866	198,7
underwater	-2574,2975	0,2302	86,4

Source: Authors.

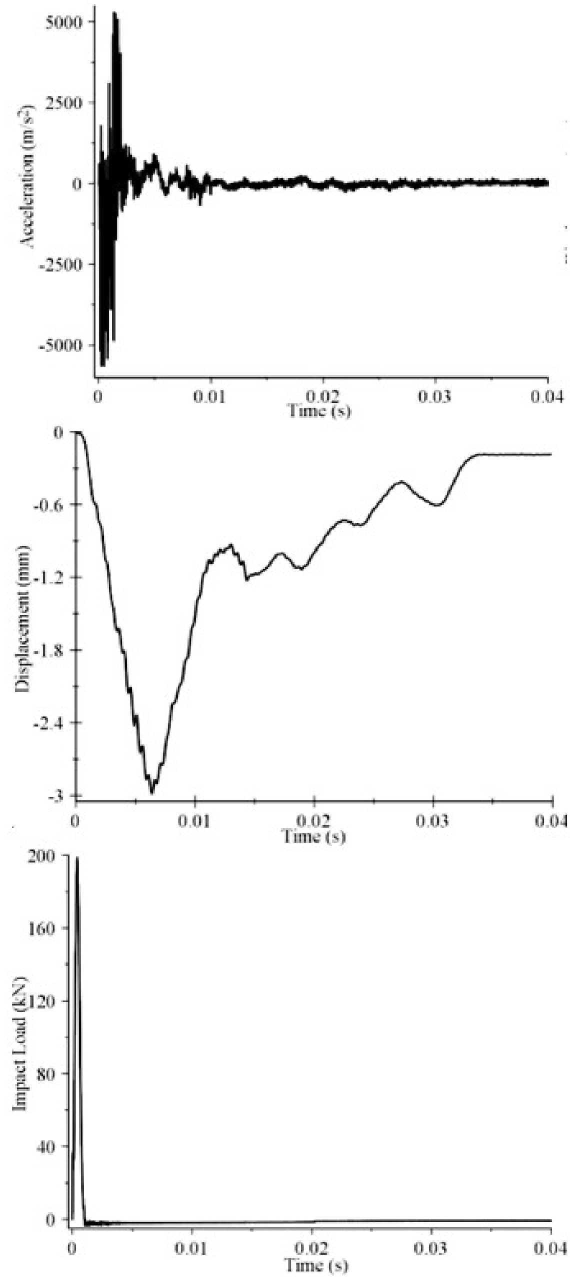
Time histories of acceleration, displacement and impact load values are obtained from the software. Graphs of these outputs are visually presented in the Figs. 3 and 4.

Figure 3: The graphs for underwater pipe model.



Source: Authors.

Figure 4: The graphs for land pipe model.



Source: Authors.

After performing finite element simulations, Von-Mises stress distributions are determined when impact loading is completely applied on the pipes. In addition, the variation of the pipe external pressure over time from the moment the falling object contacts with the water is given in Fig. 6 for the contact area.

The variation of the time varying external pressure of the above-ground pipeline for the same time interval is also seen in the same figure.

Figure 5: Stress distributions for the pipes.

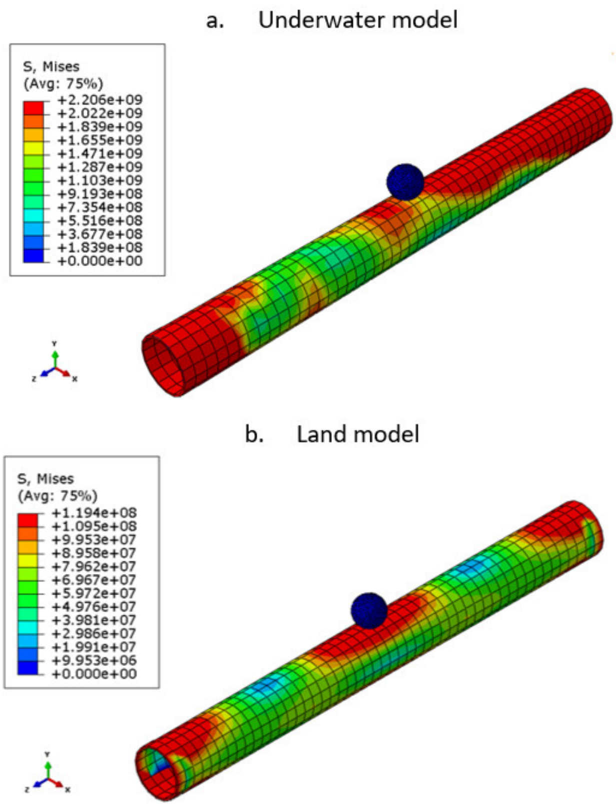


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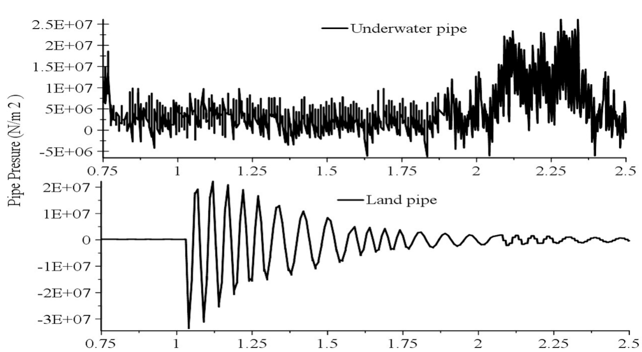
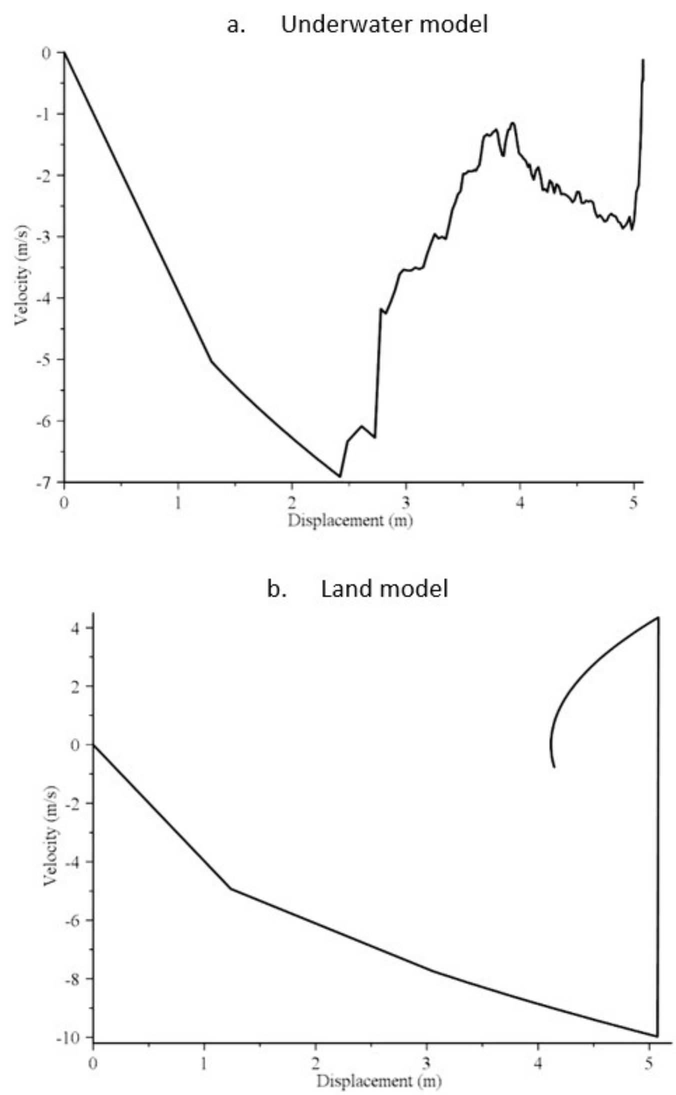
Figure 6: Time varying external pressure values of pipes.



Source: Authors.

Decelerating effect of water on the falling object can be seen in the Fig. 7 by velocity-displacement graph. Simultaneously, values of velocity varying with displacement are obtained for land pipe model to reveal water effect. The sudden decrease in the velocity of the object that passes 2.69 m, which is the vertical distance between the lower point of the falling object and the water surface, is seen in Figure 7.a. In the above-ground pipe model, where the water is not considered, the sudden decrease in the velocity of the falling object occurs only after passing as far as the drop height. The distortion in linearity seen after the first meter in both graphs occurs at the time of passing from the first step to the second step.

Figure 7: Velocity-displacement graph of falling object.



Source: Authors.

Numerical values of velocity varying with displacement for land and underwater models are given in Table 3. Negative sign represents the movement of the falling object in the –y direction. The slowing effect of water started to be seen after -2.5m.

Interaction of falling object, pipe and water is seen in the Fig. 8 from the moment the falling object touches the water until it strikes the pipe.

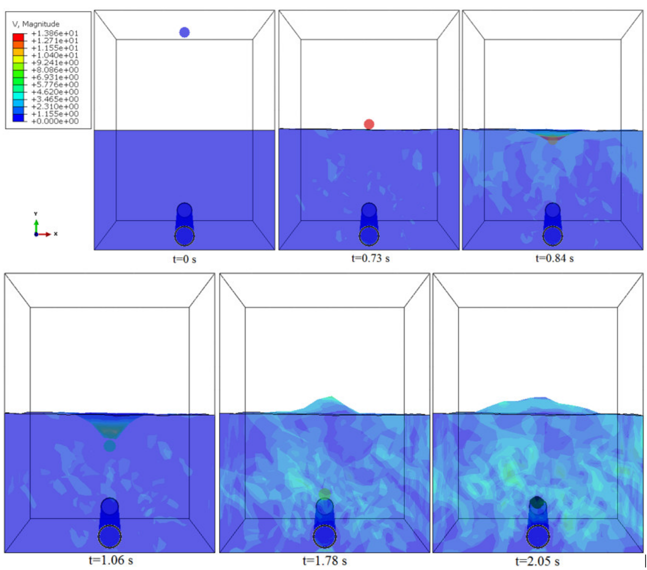
Surface movement of the water under falling object is seen in Fig. 9. ABAQUS post processing using Eulerian Volume Fraction (EVF) is used to visualize the position of the water during the analysis. If EVF is equal to 1, means that the elements are filled with Eulerian material (water). Isosurface option of contour plots is used to achieve the surface movement. Elements with no results are in black color.

Table 3: Velocity-displacement values of falling object for land and underwater models.

Displacement (m)		y=0	y=-0.5	y=-1.0	y=-1.5	y=-2.0	y=-2.5	y=-3.0	y=-3.5	y=-4.0	y=-4.5	y=-5.07
Velocity (m/s)	Land	0	-1.95	-3.96	-5.43	-6.31	-6.89	-7.73	-8.32	-8.91	-9.39	4.35
	Under water	0	-1.95	-3.96	-5.43	-6.31	-6.33	-3.55	-1.97	-1.66	-2.26	-0.12

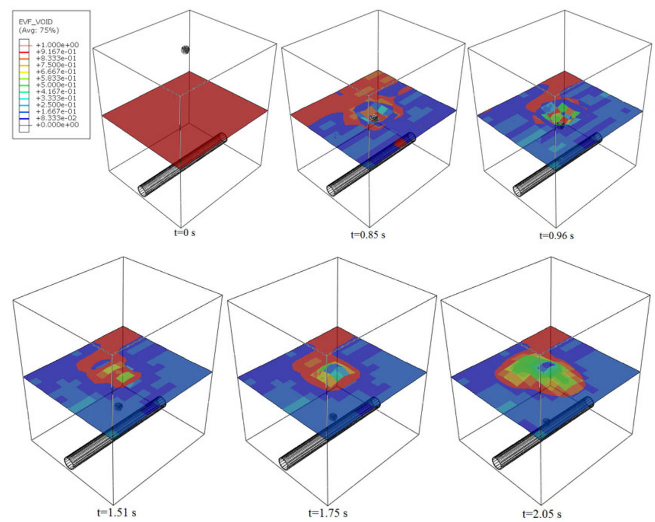
Source: Authors.

Figure 8: Velocity distribution of underwater pipe model.



Source: Authors.

Figure 9: Velocity distribution of underwater pipe model.



Source: Authors.

Conclusions.

Pipe systems are used for various purposes in practice. The most significant assignment of these systems is transferring the materials through different geographies. However, pipe systems may be subjected to impact loads that are not considered in design phase. So, investigating the pipes under sudden impact loading due to several reasons is an important issue. In this paper, non-linear dynamic analyses are performed to determine behaviour of both under water and land pipelines under falling object effects. For this purpose, the single 5 m long span of the pipeline is modelled for both above ground and underwater in Abaqus. The drop height and striker mass are adopted as constant values in the simulations. Impact parameters, such as acceleration, velocity, displacement, impact load and pipe pressure are obtained for both models with stress distributions after the analysis. Along with these, surface movement of water is visually presented for underwater pipe model.

When the analysis results are examined, it is seen that water is effective on the impact response of the pipe due to its damping effect. When the acceleration values are investigated, the biggest values are obtained from the land pipe model. The same situation is also observed for the values of displacement and impact load. According to the displacement time graph in Figure 3, it is seen that the pipe is displaced before the moment of impact. This is due to the fact that the pipe is underwater.

Contrary to the above outputs, when stress values are examined, it is seen that the stress values are higher in the underwater pipe model. While the stress distribution in the aboveground pipe model is symmetrical, the stress distribution behaves unsymmetrically in the underwater pipe model as seen in Fig. 5. According to Fig. 5, it is seen that maximum stress values are accumulated around impact point for land pipe model.

The effect of water on the pipe is also seen in the external pressure values. When the external pressure values changing over time in Fig. 6 are investigated, it is seen that there is a pressure fluctuation in the underwater pipe due to the effect of the falling object before the impact. Thus, it can be said that the effect of the turbulent movement of the water is taken into account in the outputs. On the other hand, there is no pressure in the pipe before the moment of impact in the above-ground pipe model.

In order to examine the effect of water on the falling object, the velocity-displacement graph of the falling object has been determined for both the underwater pipe and the aboveground pipe models. This effect is presented in Fig. 7. Therefore, it can be said that CEL supported fluid structure interaction works effectively. The velocity values of the falling object, which are given both graphically and as a table, are also obtained visually with Fig. 8. The values in the colour scale of Fig. 8 and the values given in Table 3 and Fig. 7 are compatible with each other. While the falling object in the pipe on land is rebounded, no rebound motion has been observed in the pipe in the water. The displacement behaviour is shown in the velocity graph. The movement of the falling object is limited only vertically. After the moment of impact, the falling object does not move in other directions and sets its velocity to zero.

The CEL technique allows modelling the free surface movement of water as well as the fluid structure interaction. Since the water surface is also activated by the effect of the sudden falling object, water surface movement is also obtained as seen in Figs 8 and 9. The effect of the changes in the water surface on the behaviour of the pipe can be seen both in the visual and the numerical outputs. The use of CEL technique in cases where fluid motion is examined as well as structural behaviour, interaction modelling is suggested due to its convenience and analysis period. If the underwater pipe model was modelled by a one-way fluid-structure interaction or a pure Lagrangian approximation, the water fluctuation effect would be ignored.

There are several difficulties in the experimental studies such as design of test setups, high costs of materials and calibration of test devices. Therefore, computer simulation has been a strong alternative way to investigate the behaviour of several test elements under various load conditions. This study exhibits that accurate finite element models could be utilized in impact behaviour of land and underwater pipelines. Finally, it is thought that this study will contribute to the literature in terms of proper analysis steps for pipe sections under impact loading.

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