Advanced Finite Element Analysis to Tackle Challenging Problems in Pipeline Geotechnics

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Abstract: Offshore pipeline design is a multidisciplinary field of engineering that covers route optimization, mechanical wall thickness design, fracture mechanics, flow assurance, stress analysis, geotechnics, … For decades, pipelines have been designed pursuing a stress based approach, based on analytical methods and semi-empirical rules of thumb. However, the challenging conditions in oil and gas exploration and production (remote locations, seismic risks, ultra deep water developments, arctic conditions…) dictate the use of sophisticated numerical tools to assist the pipeline design engineer. In particular, pipe-soil interaction is a complicated phenomenon that governs the response of the offshore pipeline to operational load patterns. Interaction of the subsea pipeline with the seabed can give rise to buckling, pipeline walking or self-burial and berm formation. Analytical approximations and simplified numerical models fail to capture those complex interactions, and are hence no longer suitable to predict the offshore pipeline behavior. Solving such challenging problems in pipeline geotechnics requires more advanced finite element analysis tools, which are demonstrated in this paper.

Keywords: Geotechnics, Pipelines, Offshore Technology, Soil Mechanics, Pipe-Soil Interaction

1. Introduction

The fitness for purpose of the Abaqus Unified Finite Element Analysis (FEA) product suite to conduct high performance simulations in soil mechanics has been proven by (Hügel, 2003) and was recently re-confirmed by (Pichler, 2012). These authors use the Abaqus built-in features for soil mechanics to tackle a wide range of geotechnical issues like soil compaction, quay wall construction, pile driving and spudcan penetration.

In this paper, we demonstrate the enhanced capabilities that Abaqus offers to tackle challenging problems in pipeline geotechnics:

- First, the Coupled Eulerian Lagrangian (CEL) method is introduced to simulate the large deformations during subsequent pipeline embedment, berm formation and break-out. The constitutive models to describe the behaviour of different types of seabed soils are briefly reviewed.

- Then, the CEL approach is used to predict the impact forces on a pipeline when subjected to a debris flow. Abaqus 6.12 offers the use of Non Newtonian liquids that can capture the rheology of a slurry and hence simulate the run-out velocities of a mudslide.
- At the end of the paper, the added value of dedicated pipe elements and pipe soil interaction elements is demonstrated by evaluating buckling susceptibility for offshore pipelines installed on an uneven seabed.

2. Simulation of pipeline embedment, berm formation and break-out

The interaction of a subsea pipeline with the seabed is a complex phenomenon, which is governed by the pipe properties, the soil properties, the initial pipeline embedment, the break-out resistance, the axial friction between the seabed and the pipe and the formation of new soil berms when the pipe moves laterally. When the subsea pipeline is subjected to operational temperature and pressure profiles, the pipe-soil interaction can give rise to ratcheting, pipeline walking or lateral buckling.

The pipe-soil interaction behavior at the large displacements that correspond to lateral buckling has received a lot of attention from the SAFEBUCK Joint Industry Project (Bruton, 2005). The SAFEBUCK JIP intends to develop more enhanced pipe-soil interaction models to replace the use of Coulomb friction approximations, which are unrealistic for the large lateral displacements that occur upon buckle formation and inappropriate for modeling the development of soil berms that occur during lateral cyclic displacements in operation.

The SAFEBUCK models are based on small-scale and full-scale tests (Cheuk, 2007) on deepwater soils from the Gulf of Mexico and West-Africa. Four stages of pipe-soil interaction are considered (Bruton, 2006):

1. Initial pipeline embedment at installation
2. Break-out during buckle formation
3. Large amplitude displacement during buckle formation
4. Repeated cyclic behavior, influenced by berm formation

Accurate modeling of these aspects would require three-dimensional models that include soil plasticity in a large strain setting. This requirement leads to computationally expensive models, and the large plastic deformations of the soil necessitate repetitive re-meshing during berm formation. (Chatterjee, 2012) has developed such a large deformation finite element (LDFE) method involving subsequent re-meshing steps. The method is based on the re-meshing and interpolation technique with small strain (RITTS) approach described by (Hu, 1998). The RITTS approach is a form of the arbitrary Lagrangian-Eulerian (ALE) method, where Lagrangian calculations are performed in each step, but where a new mesh is generated before each Eulerian step. In between steps, the boundary of the domain is updated and the whole model is re-meshed.

In this section, the use of the Coupled Eulerian Lagrangian (CEL) method is introduced to simulate the large deformations during subsequent pipeline embedment, berm formation and break-out. The pipeline is modeled as a Lagrangian body, whereas the soil is simulated in an Eulerian framework. In an Eulerian formulation, the nodes stay fixed, while the subsea soil flows through the mesh. Although this approach makes it more difficult to track the material boundaries, it has the distinct advantage of completely eliminating mesh distortion due to material deformation.

In (Qiu, 2009), the application of the CEL method to geotechnical problems involving large deformations (like subsoil pile penetration) is presented in detail. Gütz has recently presented the use of CEL techniques to model spudcan footing penetration in sand (Gütz, 2013). In (Shi, 2011), the CEL approach is applied to predict offshore pipeline embedment in cohesive soils. In the analysis, presented here, the CEL approach is used to simulate pipeline embedment, berm formation and break-out.

For this analysis, a rigid pipe with diameter D = 400 mm and thickness t = 20 mm has been modeled. The reference point is defined at the centre of the pipe. The Eulerian domain, shown in Figure 1, is 7.5 m long and 1.2 m deep. Initial soil properties and geostatic stress conditions are assigned to the lower half of the Eulerian domain. In order to perform a three dimensional analysis that is close to a plane strain condition, only a small length of the pipeline (50 mm) is simulated to obtain an indication of the lateral soil resistance.

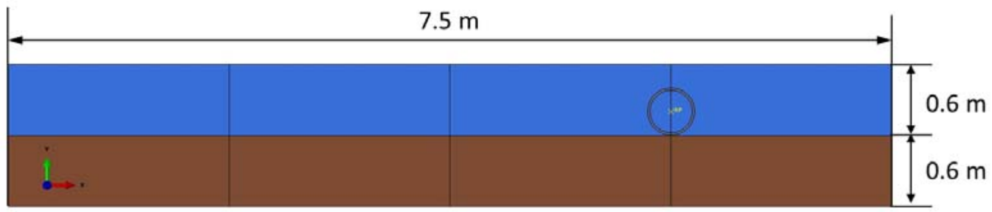

Figure 1. Definition of the Eulerian domain: rigid subsea pipeline on seabed soil

For the seabed soil, a dense sand with submerged unit weight γ_s = 11 kN/m³, Young's modulus E = 50 000 kPa and Poisson's ratio ν = 0.25 is considered. The constitutive behavior of frictional materials like sand can be modeled by the Mohr-Coulomb criterion, which assumes that failure occurs when the shear stress at any point in the material reaches a value that depends linearly on the normal stress in the same plane. Like explained in Figure 2, the Mohr-Coulomb model is based on plotting Mohr's circle for stress states at failure in the plane of maximum and minimum principal stress. The failure line is the straight line that is tangent to these Mohr's circles. For the soil properties, a cohesionless sand with friction angle ϕ = 38° and a dilatation angle ψ = 8° is selected, which is similar to the measurements reported by (Qiu, 2011). The friction angle ϕ controls the shape of the yield surface in the deviatoric plane.

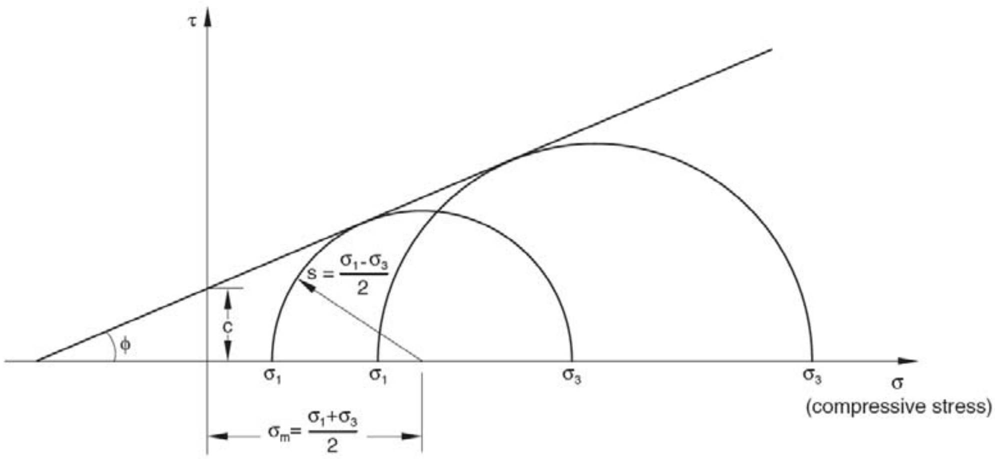

Figure 2. Mohr-Coulomb constitutive model for frictional materials

The finite element simulations require a fine mesh density in the vicinity of the rigid pipe. However, the size of the stable time increment for the explicit solver is dictated by the smallest element. To increase the accuracy of the results, whilst limiting the computational cost, a biased mesh strategy was pursued. The corresponding finite element mesh is shown in Figure 3. This strategy allows capturing the detailed pipe-soil interaction with high accuracy, while keeping the simulation runtime manageable by gradually increasing element size for the far field soil reactions.

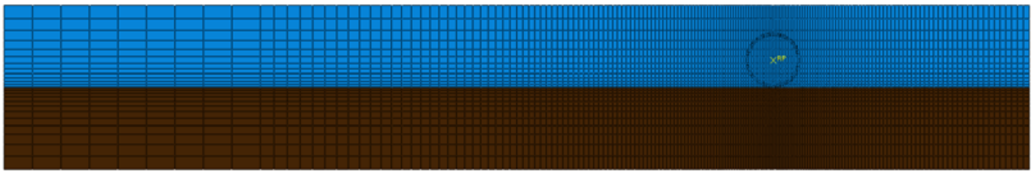

Figure 3. Mesh strategy for CEL simulations

In the first step of the CEL analysis, gravity is smoothly ramped in to allow the pipe to come to rest on the seabed. The gravity loading induces the initial pipeline embedment, like shown in Figure 3. In the analysis at hand, the initial embedment of a light pipe on a dense sand is fairly small, but (Shi, 2011) has shown that the CEL technique allows predicting the embedment of offshore pipelines in soft clays, taking into account dynamic installation effects and undrained shear strength profiles of cohesive soils as well.

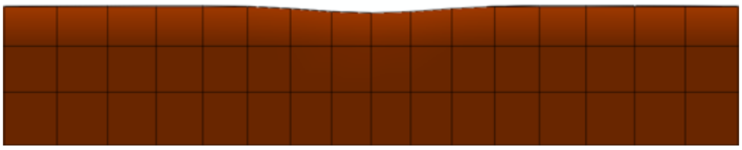

Figure 3. Initial pipeline embedment under gravity loading

In the next step, a cyclic lateral movement of the pipe is imposed, which leads to self-burial and berm formation. The creation of new soil berms increases the lateral resistance. In the last step, a large lateral pipe displacement is imposed to simulate the response of the pipe during lateral buckling.The pipe response during cyclic lateral loading and subsequent break-out is shown on Figure 4. The berm formation induced by the cyclic lateral displacement of the partially embedded pipe is clearly visible. In the last step, the pipe is forced to push the entire soil berm, which leads to a significantly increased lateral resistance.

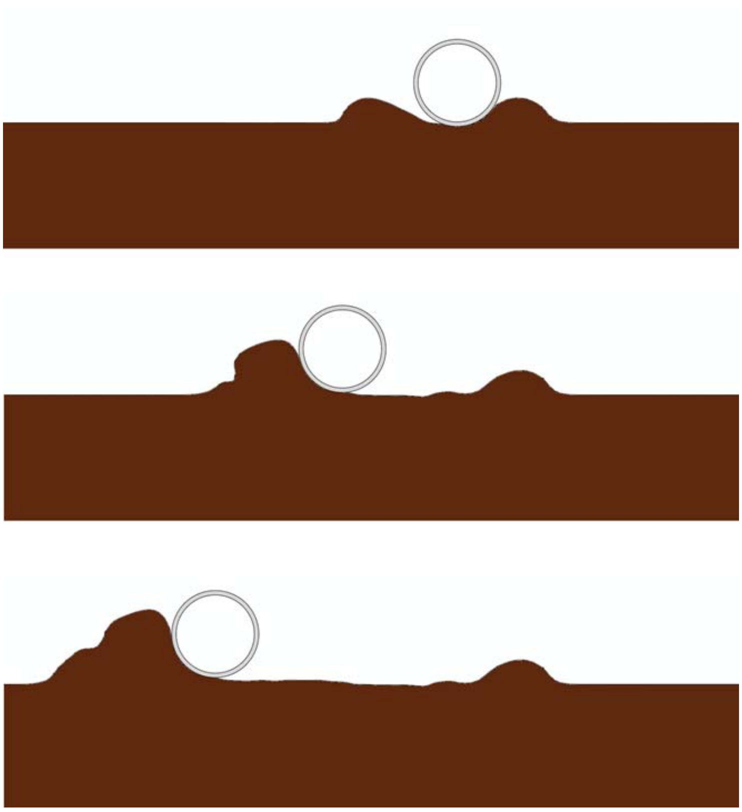

Figure 4. Cyclic lateral movement, berm formation and break-out

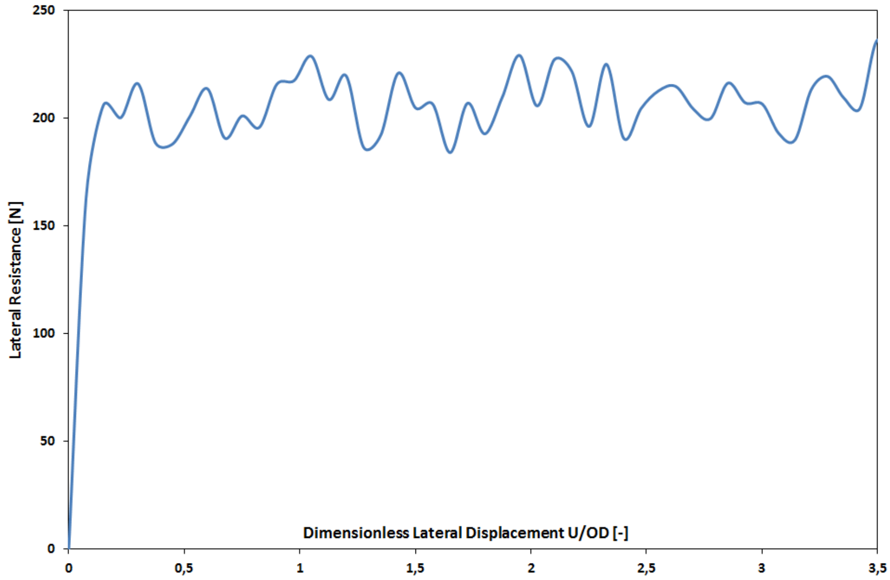

Figure 5. Lateral resistance during pipeline break-out

On Figure 5, the lateral resistance experience by the pipe during this break-out step is shown. The reaction forces, predicted by a well-conditioned CEL model, can be used to derive design recommendations when selection pipe soil interaction parameters for offshore pipelines susceptible to lateral buckling (Bruton, 2008).

3. A numerical model for submarine debris flow impact on pipelines

The CEL approach, introduced in the previous section, can be applied to tackle yet another challenge in pipeline geotechnics: finite element simulation of debris flow impact on pipelines. Indeed, fast moving, flow-like submarine landslides are among the most destructive and frequently occurring geohazards with the potential to compromise the integrity of offshore pipelines and subsea structures.

A comprehensive review on the geohazards associated with debris flows, the impact forces induced on subsea pipelines and possible control and mitigation measures can be found in (Zakeri, 2008a). Recently, (Clare, 2013) has presented a finite cloud approach to model the run-out and velocity for slide-induced submarine density flows. The numerical model is presented as a building block of an integrated geohazards assessment for deepwater developments (Spinewine, 2013), accounting for the cumulative probabilities of subsequent slope failure, transition to sediment density flow, pipeline impact and loss of integrity.

In this section, the CEL approach is pursued to simulate debris flow impact on pipelines, to assess the impact-induced forces and to evaluate the stressed induced in the pipeline. Benchmarks on run-out velocities of debris flows and the associated turbidity currents have been published by (Mohrig, 1998) and (Mohrig, 1999). Zakeri et. al. have published experimental investigations (Zakeri, 2008b) and numerical analysis (Zakeri, 2009) to obtain impact forces exerted by submarine debris flows on offshore pipelines.

In this paper, we have used the dimensions of the Zakeri experimental setup to simulate debris flow impact on pipelines using the CEL method. For their experiments, Zakeri et. al. used a 10 m long, 3 m high and 0.6 m wide tank. A 0.2 m wide and 9.5 m long flume with adjustable slope angle was suspended inside this tank. The head tank with a height of 0.85 meter and an 0.2 m² cross sectional area was used to release the slurry inside the flume. For each experiment, 190 liters of slurry was prepared in a mixing tank in an attempt to model about 2 seconds of continuous flow, ideally under constant head conditions (Zakeri, 2008b). Copper pipes with 28.6 mm outer diameter were mounted 6 meter downstream of the head tank and connected to a load cell to monitor the impact forces during the experiments.

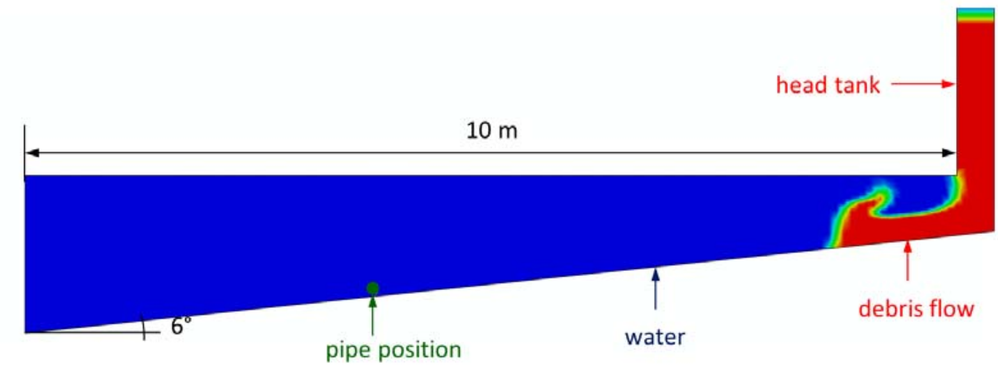

Figure 6. CEL model to simulate submarine debris flow impact on pipelines

In Figure 6, the CEL model to simulate the Zakeri flume experiments is schematically shown. The pipe is modeled as a rigid body, and the degrees of freedom of the reference point are constrained. Again, a fine mesh density is necessary t capture the detailed slurry response and the free surface effects. As a trade-off between accuracy and runtime, a fairly coarse mesh is used upstream of the pipe position, whereas a refined mesh is used in the vicinity of the pipe and in the downstream wake. This approach allows keeping the computational cost within reasonable limits, whilst ensuring a high level of accuracy of the results in the vicinity of the pipe, which is the zone of interest. Given the high number of iterations involved, solving with double precision is highly recommended – if not a prerequisite for large-scale CEL simulations.

The water is modeled with an Equation of State, using a density $\rho_w = 1000$ kg/m³, a dynamic viscosity $\mu = 0.001$ Pa*s and a sound velocity $c_0 = 1483$ m/s. For the debris flow, a clay-rich slurry with density $\rho_s = 1690$ kg/m³ is used.

The rheology of a subaqueous debris flow, however, cannot be described using merely the dynamic viscosity of a Newtonian liquid. Instead, the shear-thinning, non-Newtonian slurry can be described by a power-law (Zakeri, 2010) or Herschel-Bulkley (Locat, 1997) rheological model.

Abaqus 6.12 offers extended capabilities to capture the shear viscosity of non-Newtonian fluids, e.g. using a power law model

$$\eta = k\,\dot{\gamma}^{n-1} \qquad (1)$$

connecting the shear viscosity η to the shear strain rate $\dot{\gamma}$, where k is the flow consistency index and n is the flow behavior index ($n < 1$ for shear-thinning fluids).

It is well documented (Locat, 1997) that the behavior of most clay-rich debris flows can be described by the Herschel-Bulkley model

$$\tau = \begin{cases} \eta_0 & \text{if} \quad \tau < \tau_0 \\ \frac{1}{\dot{\gamma}}\left(\tau_0 + k(\dot{\gamma}^n - [\tau_0/\eta_0]^n)\right) & \text{if} \quad \tau \geq \tau_0 \end{cases} \qquad (2)$$

Here, τ_0 is the yield sress, and η_0 is a penalty viscosity to model the rigid-like behavior for very low strain rates. With increasing strain rates, the viscosity transitions into a power law model once the yield threshold is reached. For $n = 1$, the Herschel-Bulkley formulation translates into Bingham plasticity. Abaqus 6.12 offers both the power law and Herschel-Bulkley model to describe the shear viscosity of non-Newtonian slurries. In this analysis at hand, a power law

$$\eta = 91.5\,\dot{\gamma}^{0.11} \qquad (3)$$

is used to capture the rheology of a 25% clay slurry (Zakeri, 2008).

In Figure 7, the predicted debris flow run-out is shown just prior to impact, by visualizing the distribution of the soil volume fraction (EVF). A detailed comparison between the simulated debris flow impact and high camera footage published in (Zakeri, 2008) is given on Figure 8, indicating a good correlation between the experiments and the CEL model.

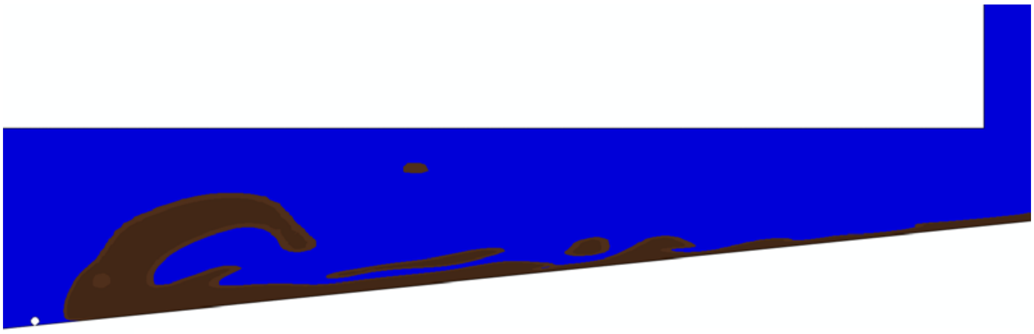

Figure 7. Submarine debris flow run-out prior to impact

In (Zakeri, 2008), the impact forces during the experiments are reported, and these signals can be used as a dynamic load pattern to predict the damage induced in a deformable pipeline when subjected to debris flow impact. However, the CEL approach allows to model the pipeline as an elastoplastic Lagrangian body, and hence coupling the debris flow impact and the impact induced stresses in one numerical framework.

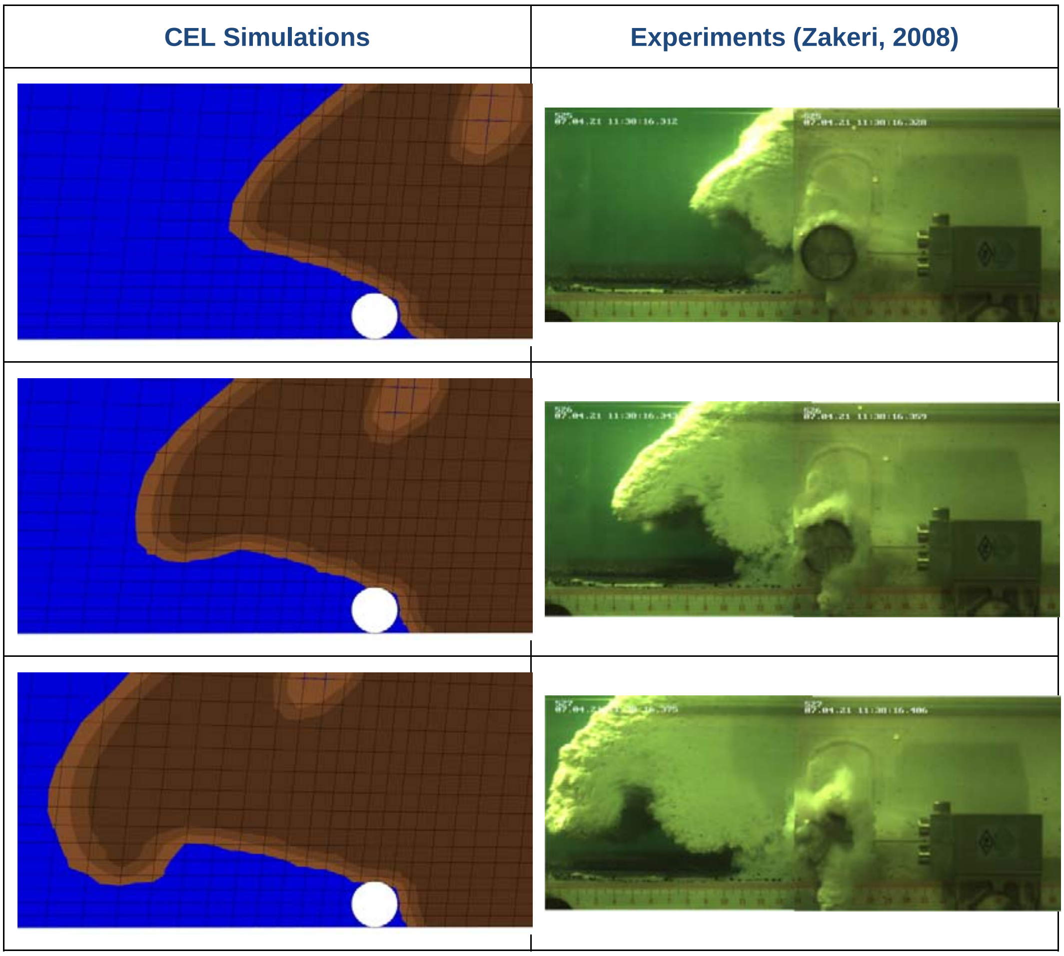

Figure 8. Submarine debris flow impact: CEL simulations vs. experiments

In Figures 9 and 10, such a full-scale CEL simulation is shown. A large-diameter, high pressure gas pipeline, installed in water depths exceeding 2000 meters, is subjected to a slide-induced submarine density flow.

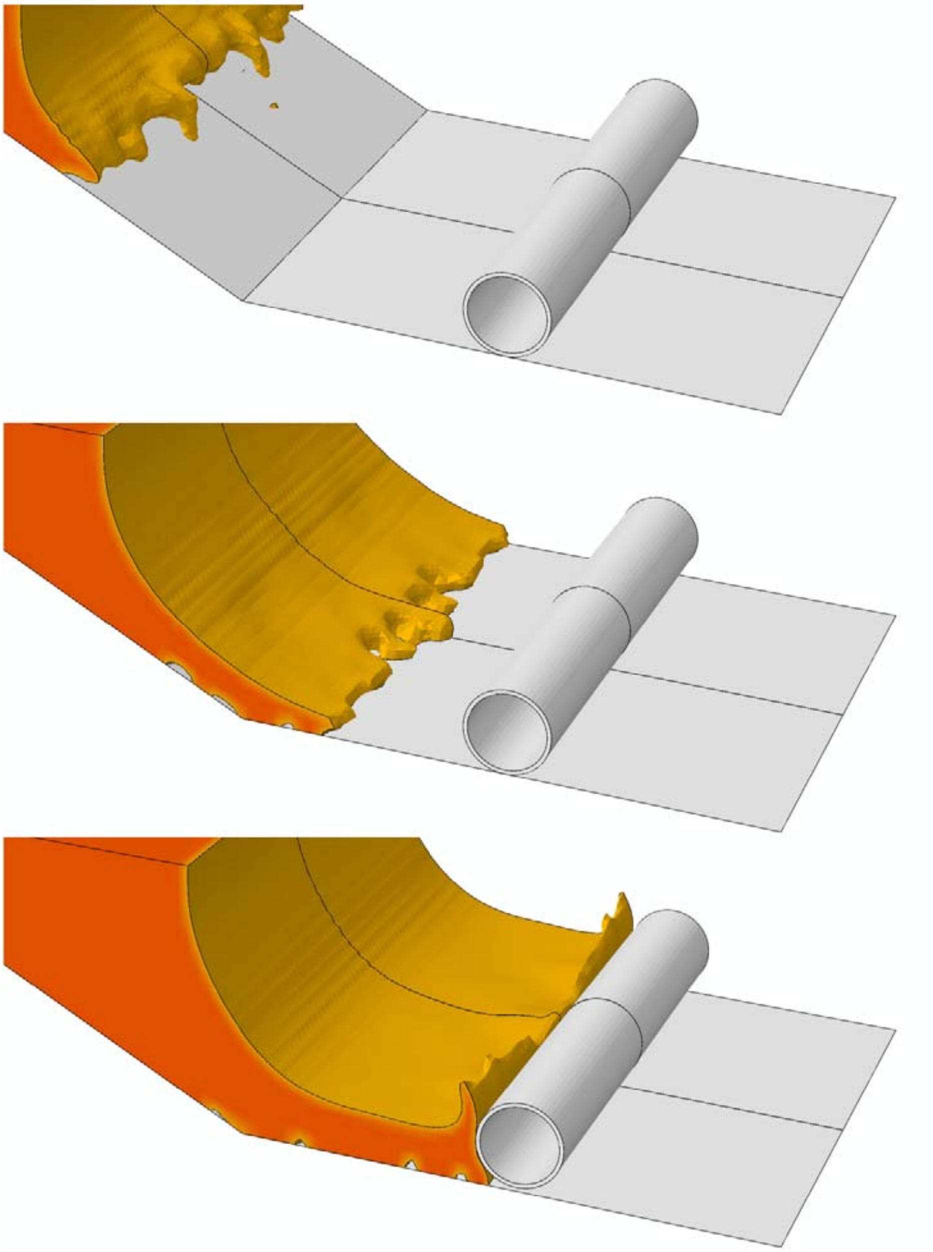

Figure 10. Submarine debris flow impact on large diameter pipeline

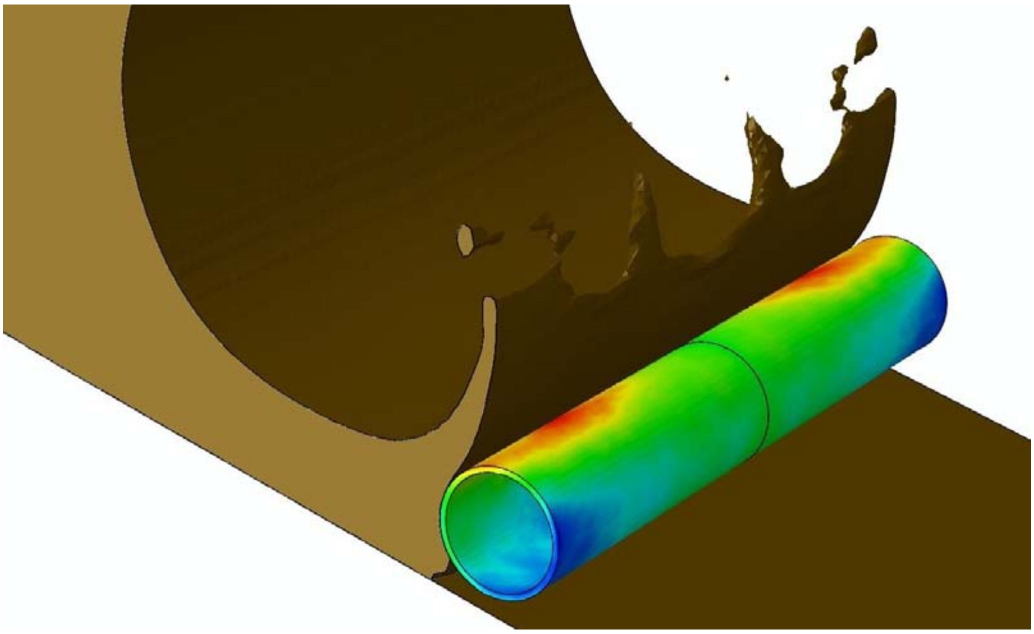

Figure 11. Impact induced stresses during full-scale submarine debris flow impact

The evolution of the debris flow at different time frames is shown on Figure 9. The steel pipe is modeled using solid elements, and with an elastoplastic constitutive law to describe the properties of the X65 steel grade. The integrated CEL approach allows simulating displacements and impact induced stresses on the pipe joint during the debris flow impact, like shown in Figure 10.

4. Prediction of buckling susceptibility

The PIPE31H element is particularly suitable to model long, slender pipelines with a thin-walled circular cross section. For offshore pipelines installed on an uneven seabed, a simplified laydown analysis can be performed by lowering a dummy flat rigid surface (containing the initially straight pipeline) under gravity loading to establish contact between the pipeline and the 3D seabed. Although this simplified laydown procedure does not account for the effects of lay tension, it can provide an indication of on bottom roughness and susceptibility to free spanning pipes.

A more powerful alternative, which is up to five times faster, is to perform an implicit dynamics simulation by invoking *Dynamic, APPLICATION=QUASI-STATIC in the step definition. With this technique the pipeline is slowly dropped onto the seabed though the application of gravity and any kinetic energy is quickly absorbed. As a result, contact with a separate dummy rigid surface is no longer required. Figure 12 shows an offshore pipeline installed on an uneven seabed using this implicit dynamics calculation scheme.

Abaqus offers a library of Pipe Soil Interaction (PSI) elements to capture the interaction between the pipeline and the surrounding soil. The user can define the constitutive behavior of the PSI elements. For instance, the bearing capacity is reflected by the vertical soil reaction. For sands, DNV-RP-F105 recommends

$$Q_u(z_p) = \left(\frac{\gamma_s\, N_\gamma}{2} B(z_p) + \ \gamma_s z_p N_q\right)\ B(z_p) \tag{4}$$

where γ_s is the submerged unit weight,

$$N_q = \ \exp(\pi \tan\varphi)\ \tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) \tag{5}$$

with φ the friction angle, and

$$N_\gamma = \frac{3}{2}\left(N_q - 1\right)\tan\varphi \tag{6}$$

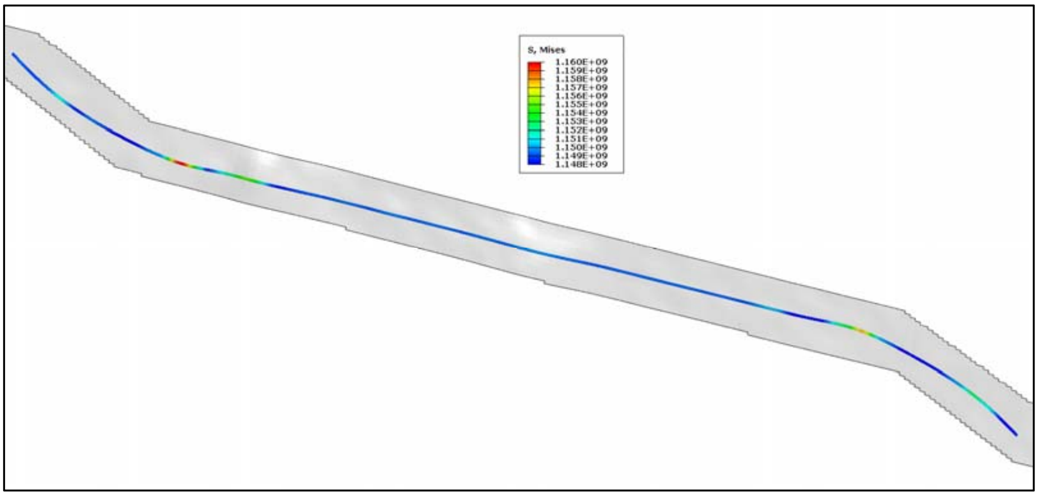

Figure 12. Offshore pipeline installed on an uneven seabed

The bearing width B depends on the pipe penetration z_p, and can be calculated as

$$(z_p) = \begin{cases} 2\sqrt{z_p(D_o - z_p)} & 0\ \le z_p \le\ D_o/2 \\ D_o & \text{otherwise} \end{cases} \tag{7}$$

For clays, DNV-RP-F105 recommends

$$Q_u(z_p) = \left(5.14\, C_u + \gamma_s\, z_p\right) B(z_p) \tag{8}$$

where C_u is the undrained shear strength. Figure 13 compares the vertical soil spring reaction forces for a medium dense sand (with a friction angle $\varphi = 33°$ and a submerged unit weight $\gamma_s = 8.5$ kN/m³) with the soil reaction of a soft clay (with un-drained shear strength C_u = 30 kPa and a submerged unit weight $\gamma_s = 7.5$ kN/m³).

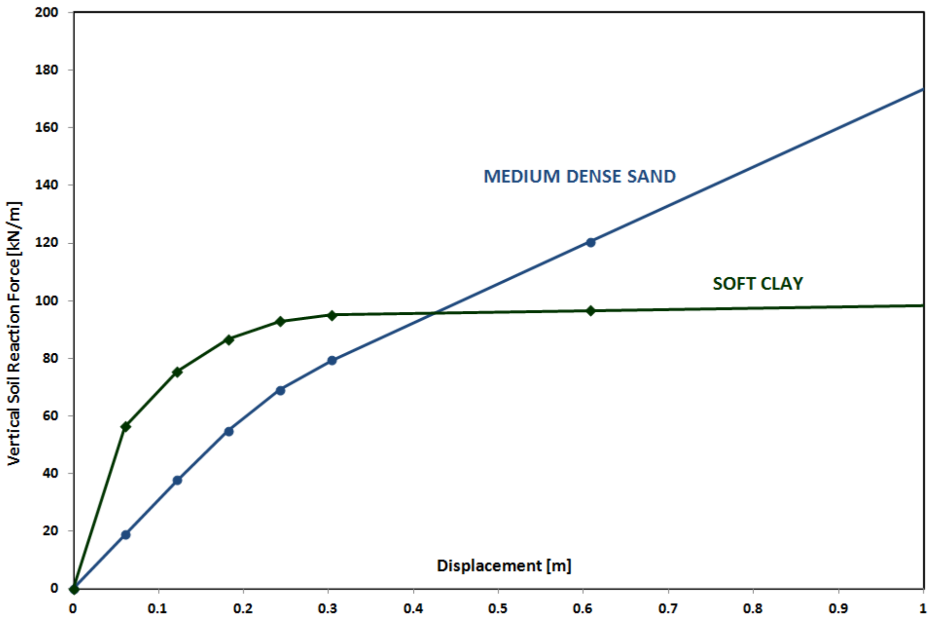

Figure 13. Vertical soil reaction for sand and clay

In addition to the vertical soil spring, reflecting the bearing capacity of the seabed, axial and lateral springs are included in the formulation of pipe soil interaction. Abaqus offers analytical models described in the ASCE Guidelines for the Seismic Design of Oil and Gas Pipeline Systems. Moreover, a dedicated FRIC user subroutine is available to capture more complex pipe soil interaction phenomena (cyclic lateral displacement, berm formation, break-out), like described in section 2 of this paper.

The pipe soil interaction governs to a very large extent the response of the offshore pipeline to operational load patterns (like hydrodynamic loading, pressure and temperature profiles). End expansion, pipeline walking or lateral buckling are all intimately related to the pipe soil interaction parameters.

Pipelines operating at high temperature are susceptible to global buckling. The basics of buckling were first developed by Euler, who established the critical load for a long, slender structures under compression. In pipeline engineering, (Hobbs, 1981) was one of the first to develop a semi-empirical method to calculate buckling. His approach was based on solving the linear differential equation for the deflected shape of a spring-supported beam-column under axial load. The most important limitations of this method are the assumptions on linear elastic material and small rotations, and the idealized straight pipeline. It is recognized (Carr, 2003) that lateral buckling modes tend to occur at lower compressive forces than the vertical (upheaval) buckling mode.

Hence, unless horizontal displacements are restrained (like for buried pipelines) or a prevailing vertical imperfection is present, pipelines tend to buckle laterally. It has even been argued to use lateral buckling as a design tool (Kaye, 1995) to relieve and control axial compression in the pipeline.

Abaqus allows to easily import operational temperature and pressure profiles from flow assurance calculations. On Figure 14, lateral buckling of a subsea pipeline occurs under operational loading (i.e. when the pipe was filled with a hot pressurized fluid).

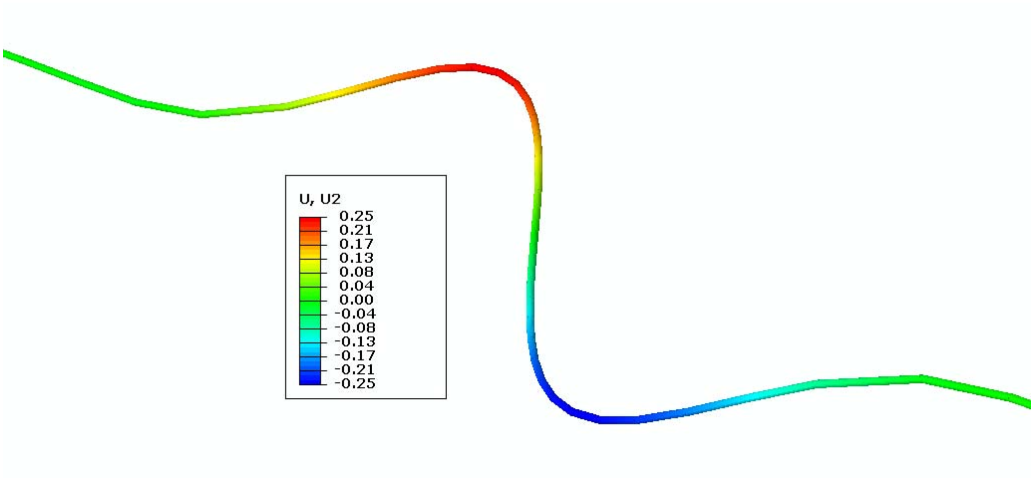

Figure 14. Lateral buckling of subsea pipeline during operation

5. References

1. Bruton D., Carr M., Crawford M. and Poiate E., "The Safe Design of Hot On-Bottom Pipelines with Lateral Buckling using the Design Guideline Developed by the SAFEBUCK Joint Industry Project", Proceedings of the Deep Offshore Technology Conference, Brazil (2005)
2. Bruton D., White D.J., Cheuk D.Y., Bolton M.D. and Carr M., "Pipe Soil Interaction Behaviour During Lateral Buckling, Including Large Amplitude Cyclic Displacement Tests by the SAFEBUCK JIP", Proceedings of the Offshore Technology Conference, OTC-17944 (2006)
3. Bruton A.S., White D.J., Carr M. and Cheuk J.C., "Pipe Soil Interaction During Lateral Buckling and Pipeline Walking – The SAFEBUCK JIP," Proceedings of the Offshore Technology Conference, OTC-19589 (2008)
4. Carr M., Bruton D. And Leslie D., "Lateral Buckling and Pipeline Walking: A Challenge for Hot Pipelines", Proceedings of the Offshore Pipeline Technology Conference OPT (2003)
5. Chatterjee S., White D.J. and Randolph F., "Numerical Simulations of Pipe Soil Interaction During Large Lateral Movements on Clay", Géotechnique vol. 62(8), pp. 693-705 (2012)
6. Cheuk D.Y., White D.J. and Bolton M.D., "Large Scale Modelling of Soil Piper Interaction During Large Amplitude Cyclic Movements of Partially Embedded Pipelines", Canadian Geotechnics Journal, vol. 44, pp. 877-996 (2007)
7. Clare M., Thoms S., SHreeve J. and Spinewine B., "Density Flow Impact Assessment and Mitigation Studies for Deepwater Developments: Challenge on Mulitple Scales", Offshore Technology Conference (2013)
8. Gütz P., Abel-Rahman K. and Achmus M., "Numerical Modeling of Spudcan Footing Penetration in Sand," SIMULIA Community Conference (2013)
9. Hobbs R.E., "Pipeline Buckling Caused by Axial Loads", Journal of Constructional Steel Research, vol. 1(2), (1981)
10. Hu Y. and Randolph M.F., "A Practical Numerical Approach for Large Deformation Problems in Soil," International Journal of Numerical and Analytical Methods in Geo-mechanics, vol. 22(5), pp. 327-350 (1998) Locat J., "Normalized Rheological Behaviour of Fine Muds and Their Flow Properties in a Pseudoplastic Regime, Debris Flow Hazards Mitigation: Mechanics, Prediction and Assessment," American Society of Civil Engineers (ASCE), pp. 260-269 (1997)
11. Hügel H.M., Henke S. and Kinzler S., "High Performance Abaqus Simulations in Soil Mechanics," Proceedings of the Abaqus Users' Conference (2008)
12. Kaye D., LeMarchand D., Blondin P. And Carr M., "Lateral Buckling Design of the Dunbar-North Alwyn Double Wall Insulated Pipeline", Offshore Pipeline Technology Conference (1995)
13. Mohrig D., Ellis C., Parker G. And Kelin X., "Hydroplaning of Subaqeous Debris Flows," Geological Society of America Bulletin, vol. 110, pp. 387-394 (1998)
14. Mohrig D., Elverhoi A. and Parker G., "Experiments on the Relative Mobility of Muddy Subaqueous and Subaerial Debris Flows, and Their Capacity to Remobilize Antecedent Deposits," Marine Geology, vol. 154, pp. 117-129 (1999)

15. Pichler T., Pucker T., Hamann T., Henke S. And Qiu G., "High Performance Abaqus Simulations in Soil Mechanics Reloaded – Chances and Frontiers", Proceedings of the Simulia Community Conference (2012)
16. Qiu G., Henke S. and Grabe J., "Applications of Coupled Eulerian Lagrangian Method to Geotechnical Problems with Large Deformations," SIMULIA Customer Conference (2009)
17. Qiu G., Henke S. and Grabe J., "Application of Coupled Eulerian Lagrangian Approach on Geomechanical Problems involving Large Deformations," Computers and Geotechnics, vol. 38(1), pp. 30-39 (2011)
18. Spinewine B., Rensonnet D., De Their T., Clare M., Unterseh G. and Capart H., "Numerical Modeling of Run-out and Velocity for Slide-Induced Submarine Density Flows: Building Block of an Integrated Geohazards Assessment for Deepwater Developments,", Offshore Technology Conference, OTC13-1270 (2013)
19. Shi H., Sun J., Hossain K., Eltaher A. and Jukes P., "Offshore Pipeline Embedment in Cohesive Soil – Comparison between Existing and CEL Solutions", Proceedings of the 30th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2011-50230 (2011)
20. Zakeri A., Hoeg K. and Nadim F., "Submarine Debris Flow Impact on Pipelines: Drag Forces, Mitigation and Control", Proceedings of the Offshore Technology Conference, OTC-19173 (2008).
21. Zakeri A., Hoeg K. and Nadim F., "Submarine Debris Flow Impact on Pipelines: Experimental Investigation," Coastal Engineering, vol. 55, pp. 1209-1218 (2008)
22. Zakeri A., Hoeg K. and Nadim F., "Submarine Debris Flow Impact on Pipelines: Numerical Analysis," Coastal Engineering, vol. 56, pp. 1-10 (2009)
23. Zakeri A., Si G., Marr J.D. and Hoeg K, "Experimental Investigation of Subaqueous Clay-Rich Debris Flows, Turbidity Generation and Sediment Deposition," in Submarine Mass Movements and Their Consequences, Advances in Natural and Technological Hazards Research, vol. 28, pp. 105-115 (2010)