Effect of Underwater Explosion on Pipeline Integrity

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Pavia, November 21st, 2014
OUTLINE

- UNEXPLODED ORDNANCES
- RECENT STUDIES
- UNDERWATER EXPLOSION
- OBJECTIVE AND SCOPE OF WORK
- ABAQUS FEM MODEL DESCRIPTION AND VALIDATION
- APPLICATION
  - Scenario Description
  - FEM Analysis Results
- CONCLUSIONS
- FUTURE DEVELOPMENTS
Definition of UneXploded Ordnance (UXO) is given by United Nations as follows:

«...explosive ordnance that has been primed, fused, armed, or otherwise prepared for use and used in an armed conflict. It may have been fired, dropped, launched or projected and should have exploded but failed to do so»

Found UXOs originate from three principal sources:

1. **Military training exercises** (abandoned gunnery ranges, naval warfare exercises);
2. **Accidental disposal** due to poor working practices during munitions handling and transportation, or other accidental events (shipwreck, crash landing, ecc.);
3. **Wartime ops** during armed conflicts (WWI and WWII mainly), including:
   - Naval ship bombing and torpedoing events;
   - Anti-submarine warfare;
   - Long range shelling (naval gunnery, coastal artillery);
   - Munitions deliberately placed as means of area denial (naval mine fields);
   - Munitions deliberately sunk by warring armies to avoid enemy appropriation.
UNEXPLODED ORDNANCES – WARTIME ORIGINS
UNEXPLODED ORDNANCES – WHERE?

UXO arises from both hostile and defensive MILITARY ACTIVITIES often related to World Wars I and II. Their occurrence is higher in documented WAR THEATRE sea regions (e.g. Baltic Sea, North Sea, shores of Northern Germany, English Channel, Mediterranean Sea, Western Areas of Pacific Ocean, ecc.), or in disused FIRE RANGES.

Typical Torpedo used during the WW2

Discovered UXO (WWII German Torpedo)

1.6 million metric tons
50 million of UXOs

85 UXOs

Baltic Sea

German Shores

1.6 million metric tons of conventional munitions
90 metric tons of chemical weapons

50 million of UXOs

North Sea

About 1.3 million metric tons of conventional munitions
About 90 metric tons of chemical weapons

Saipem
During survey campaign activities **UNEXPLODED ORDNANCES (UXOs)** are **FREQUENTLY** discovered.

As they are a **HIGH CONSEQUENCE** but **LOW PROBABILITY** event, appropriate allowance should be made for assessing the risk of encountering UXO on-site and for mitigating that risk if significant.
### UNEXPLODED ORDNANCES – CHARACTERIZATION

<table>
<thead>
<tr>
<th>MASS OF EXPLOSIVE CHARGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Range: 15 – 1000 kg</td>
</tr>
<tr>
<td>Mass Average: 200 – 300 kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WARHEAD EXPLOSIVE TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNT, Hexanite, Nitrocellulose, RDX, Torpex</td>
</tr>
<tr>
<td>(Often it is difficult to determine the correct explosive type)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WARHEAD SHAPE AND DIMENSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>High variability depending from the UXO type</td>
</tr>
</tbody>
</table>

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RECENT STUDIES

UNDERWATER EXPLOSION IN THE VICINITY OF A PIPELINE: STRUCTURAL INTEGRITY ASSESSMENT

Roberto Bruschi
Offshore Division
Snamprogetti S.p.A.
Fano, Italy

Fioriano Casola and Paolo Monti
Offshore Division
Snamprogetti S.p.A.
Milan, Italy

PROCEDINGS OF THE ASME 2011 30TH INTERNATIONAL CONFERENCE ON OCEAN, OFFSHORE, AND ARCTIC ENGINEERING
June 19-24, 2011, Rotterdam, The Netherlands
OMAE2011-49178

STRUCTURAL INTEGRITY ASSESSMENT OF A PIPELINE SUBJECTED TO AN UNDERWATER EXPLOSION

Paolo Monti, Caterina Molinari
Saipem Energy Services S.p.A.
Seabed and Subsea Division
San Donato Milanese (MI), Italy

Massimiliano Bochicci, Alberto Corigliano, Stefano Marioli
Politecnico di Milano, Department of Structural Engineering
Milan, Italy

TransMed
Nord Stream Project

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UNDERWATER EXPLOSION – PRIMARY SHOCK WAVE

The explosion is activated by mean of a fuse (or detonator) giving the initial energy needed to ignite the detonation process.

During the detonation process, a rapid transformation of the initial explosive reagent occurs into an expanding gas mass having high temperature and pressure (3000°C, 10³ MPa). The spherical front of chemical reaction represents the DETONATION WAVE, travelling at high speed (6000-9000 m/s) in the explosive mass domain. Detonation speed is HIGHER than the medium (i.e. explosive) sound speed.

Once the detonation wave reaches the limit of the explosive mass domain the explosion energy is transferred to the surrounding medium (seawater), giving rise to a PRIMARY SHOCK WAVE travelling in the water at the SEAWATER SPEED OF SOUND (about 1550 m/s in relation to water depth, temperature and salinity).
The initial pressure inside the gas sphere is much higher than the water hydrostatic pressure, causing the surrounding water to be subjected to a large outward acceleration due to the rapid *expansion of the gas bubble* continuing also when the internal pressure is in equilibrium with the external hydrostatic one, due to the inertia of the accelerated water.

When the outward movement of the gas bubble stops, the water viscoelasticity gives rise to an inward motion of the gas bubble spherical front, until the increasing pressure in the bubble reverses the motion. At this step a second shock wave is generated, so called *1st bubble pulse shock wave*. 

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UNDERWATER EXPLOSION – SHOCK WAVE

• The viscoelasticity of the water and the behavior of the gas bubble give rise to a series of contraction and expansion cycles. At each cycle a pressure wave is released in the surrounding water. The entity of these waves is such negligible with respect to the INITIAL SHOCK WAVE and the 1st BUBBLE PULSE SHOCK WAVE.

Movie_UNDEX.avi
UNDERWATER EXPLOSION – EXPLOSION EFFECT

**CHARGE FAR FROM THE STRUCTURE**

Distance >> \( R_{\text{bubble}} \)

PRIMARY SHOCK WAVE

---

**CHARGE CLOSE TO THE STRUCTURE**

Distance > \( R_{\text{bubble}} \)

PRIMARY SHOCK WAVE + SECONDARY SHOCK WAVES

---

**CHARGE VERY CLOSE TO THE STRUCTURE**

Distance < \( R_{\text{bubble}} \)

PRIMARY SHOCK WAVE + SECONDARY SHOCK WAVES + WATER JETTING

---

Target is far from the UXO, it interacts only with the first pressure wave. No secondary effects are experienced by the structure.

Target is close to the UXO and both primary and secondary pressure waves are experienced by the structure.

Target is very close to the UXO. It experiences all consequences of UNDEX and influences the bubble dynamics. Water jetting phenomena are experienced.
UNDERWATER EXPLOSION – SURFACES INTERACTION

FREE WATER UNDEX occurs when structure surfaces and other walls (seabed, sea surface, hulls, pipelines) are far from the explosive charge.

In this case no surface interactions arise, and the bubble evolves following the described process.

During the pulsation the bubble travels toward the sea surface. Surface SPRAY DOME can be observed in relation to the initial water depth of the charge.

CLOSE SURFACES INTERACTION

The presence of a near wall deeply affects the bubble dynamics. The bubble is “attracted” by near surfaces. The pulsating bubble moves toward the surface and slams into it. A HIGH SPEED WATER JETTING hits the surface. This effect is also known as BJERKNES FORCE.
UNDERWATER EXPLOSION – PARAMETER EFFECT

UNDerwater EXplosion (UNDEX) is strictly affected by the following physical and geometrical parameters:

1. Mass of Explosive Charge
2. Type of Explosive Material
3. Shape of Explosive Charge
4. Water Depth of the Charge
5. Distance from Interacting Surfaces (Structure and Seabed)

The previous parameters have influence on:

1. Peak Pressure of Primary Shock Wave
2. Pressure of Secondary Shock Wave (1st Bubble Pulse)
3. Time History
4. Bubble Radius ($R_{\text{bubble}}$)
5. Jetting Phenomena
OBJECTIVE AND SCOPE OF WORK

The main objective of this study is to verify the structural integrity of a pipeline subject to the effects of the potential underwater explosion (UNDEX) of unexploded ordnances found in proximity of the pipeline.

The objective was achieved by using FEM code ABAQUS, and its specific capabilities/features for blasting and underwater explosion simulation.

The SoW includes:

• Pipeline **INTEGRITY CRITERIA** definition;

• Assessment of the **PROPAGATION IN WATER OF PRESSURE WAVES** induced by the underwater explosion of a spherical TNT charge, equivalent to the expected unexploded ordnance;

• Definition of **RELEVANT PIPELINE LOAD SCENARIOS** induced by the interaction between the pressure wave and the pipeline shell;

• Characterisation of the **PIPELINE DYNAMIC RESPONSE**, in terms of activated local and global deformation modes;

• Pipeline response analysis and integrity assessment: definition of a relationship between the weight of the spherical TNT charge and the **MINIMUM DISTANCE** from the pipeline.
PIPELINE INTEGRITY CRITERIA

**STRESS BASED CRITERION**
No damage experienced by pipeline wall due to the underwater explosion. The **MAXIMUM VON MISES STRESS** shall be less than 96% SMYS (namely 432MPa).

**SERVICEABILITY LIMIT STATES (SLS)**
- **OVALIZATION BASED CRITERION**: in accordance to DNV OS-F101, the pipeline shall not be subject to excessive ovalization. The residual **FLATTENING** is not to exceed 3.0%.
- **DENT BASED CRITERION**: in accordance to DNV-RP-F107 DENT to diameter ratio shall be limited to 5.0%.

**ULTIMATE LIMIT STATE (ULS)**
The pipe wall may experience **SIGNIFICANT PLASTIC STRAINS**, but the pipe wall tearing or a gas leakage shall not appear (corresponding to a **MAXIMUM EQUIVALENT PLASTIC STRAIN** equal to the uniform elongation limit = 10%).
UNDEX MODELING IN ABAQUS

ACOUSTIC – STRUCTURAL COUPLED MODEL
**ABAQUS UNDEX MODELING – ACOUSTIC-STRUCTURAL COUPLING**

**KEYWORDS**

- ***INCIDENT WAVE INTERACTION PROPERTY**
  - Definition of fluid properties for **ACOUSTIC DECAY** calculation of incident wave.

- ***INCIDENT WAVE INTERACTION**
  - Definition of incident wave loading, hit surface and **SOURCE** and **STANDOFF** points.

- ***UNDEX CHARGE PROPERTY**
  - Definition of **UXO** charge **PROPERTIES**.

- ***SIMPEDANCE**
  - Definition of surface reflection properties.
PIPELINE-UXO INTERACTION – MODEL ASSUMPTIONS

- Seabed surface has been considered **PERFECTLY REFLECTIVE**. This is a **CONSERVATIVE** assumption since no explosion energy amount is absorbed by soil (e.g. for a crater formation). All explosive power diffuses through the acoustic medium and hits the pipeline.

- For this reason in the FEM model the assumed mass charge has been **DOUBLED** with respect to the real mass of explosive charge.

- The explosive mass has been assumed as a **POINT SOURCE**, and the wave propagation has been modeled as **SPHERICAL**.

- The TNT charge has been modelled considering the **GEERS-HUNTER model**.

<table>
<thead>
<tr>
<th>Geers-Hunter model</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge constant $K$</td>
<td>5.97e+07</td>
</tr>
<tr>
<td>Charge constant $k$</td>
<td>8.83e-05</td>
</tr>
<tr>
<td>Similitude spatial exponent $A$</td>
<td>0.13</td>
</tr>
<tr>
<td>Similitude temporal exponent $B$</td>
<td>0.18</td>
</tr>
<tr>
<td>Charge constant $K_{c}$</td>
<td>1.05e+09</td>
</tr>
<tr>
<td>Ratio of specific heats for explosion gas</td>
<td>1.27</td>
</tr>
<tr>
<td>Charge material density</td>
<td>1654</td>
</tr>
</tbody>
</table>
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**PIPELINE-UXO INTERACTION – FE MODEL**

\[
\frac{R_{\text{medium}}}{R_{\text{pipe}}} = 6
\]

**ABAQUS v. 6.13.1**

<table>
<thead>
<tr>
<th>Cylinder Radius Ratio ((R_c/R_b))</th>
<th>Added Mass Ratio ((\text{External Boundary}/\text{Infinite Domain}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>2.600</td>
</tr>
<tr>
<td>2.0</td>
<td>1.667</td>
</tr>
<tr>
<td>4.0</td>
<td>1.133</td>
</tr>
<tr>
<td>6.0</td>
<td>1.057</td>
</tr>
<tr>
<td>8.0</td>
<td>1.032</td>
</tr>
<tr>
<td>16.0</td>
<td>1.008</td>
</tr>
<tr>
<td>24.0</td>
<td>1.004</td>
</tr>
</tbody>
</table>

- **PIPELINE** – **S4R SHELL ELEMENTS**
- **WATER** – **AC3D8R ACOUSTIC BRICK ELEMENTS**
MODEL VALIDATION – ANALYTICAL APPROACH

- INITIAL SHOCK WAVE (due to Detonation wave)

\[ P = P_{\text{max}}(D, W)\exp \left[ -\frac{t - t_0}{g(D, W)} \right] \]

**D** = Charge Distance
**W** = Charge Weight

- BUBBLE MOTION EQUATION (Rayleigh-Plesset)

\[ \rho \left[ R\ddot{R} + \frac{3}{2} \dot{R}^2 \right] = P_B(t) - P_\infty \]

\[ R_{\text{min}} = 8.24 \frac{W^{5/9}}{(wd + 10.3)^{11/9}} + 0.007 \cdot W^{5/16} \]

\[ R_{\text{max}} = 3.36 \sqrt[3]{\frac{W}{wd + 10}} \]

**D** = Charge Distance
**W** = Charge Weight
\( wd \) = water depth

\[ T_{\text{bubble}} = 2.11 \frac{W^{1/3}}{(wd + 10)^{5/6}} \]

\[ P_{\text{bubble,max}} = 1.9 \frac{3}{4\pi} \frac{1}{D} \frac{W}{R_{\text{max}}^2} \left( 1 - \frac{0.1581 \cdot W^{0.25}}{R_{\text{max}}^{0.75}} \right) \]

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Petralia S., 2000, Explosivistic Compendium, Mariperman La Spezia.
MODEL VALIDATION – NOMOGRAPH

NOMOGRAPH FOR INITIAL SHOCK WAVE EVALUATION

NOMOGRAPH FOR BUBBLE DYNAMICS CHARACTERIZATION

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UNDEX CHARACTERIZATION AND FE MODEL VALIDATION

Pressure vs. Charge Distance

Bubble Shock Wave

\[ P_{\text{bubble, max}} = 7084 \frac{W^{0.33}}{D} \]

Primary Shock Wave

\[ P_{\text{max}}(D, W) = 20.5 \left( \frac{W^{1/3}}{D} \right)^{0.55} \text{ if } \frac{D}{W^{1/3}} < 0.32 \]
\[ P_{\text{max}}(D, W) = 52.5 \left( \frac{W^{1/3}}{D} \right)^{1.13} \text{ if } \frac{D}{W^{1/3}} > 0.32 \]
UNDEX CHARACTERIZATION AND FE MODEL VALIDATION

Shock Pressure Time History

\[ P = P_{\text{max}}(D,W) \exp \left[-\frac{t-t_0}{\Theta(D,W)}\right] \]

Charge Weight = 300 kg

\[
\begin{align*}
P_{\text{max}}(D,W) &= 20.5 \left(\frac{W^{1/3}}{D^{1/3}}\right)^{0.95} \quad \text{if} \quad D/W^{1/3} < 0.32 \\
&= 52.5 \left(\frac{W^{1/3}}{D^{1/3}}\right)^{1.13} \quad \text{if} \quad D/W^{1/3} > 0.32 \\
\Theta(D,W) &= 0.0001048 \cdot W^{1/3} \left(\frac{D}{D/W^{1/3}}\right)^{1.33} \quad \text{if} \quad D/W^{1/3} < 2.70 \\
&= 0.0001163 \cdot W^{1/3} \left(\frac{D}{D/W^{1/3}}\right)^{1.25} \quad \text{if} \quad D/W^{1/3} > 2.70
\end{align*}
\]

Charge Weight = 600 kg
Time History of the Bubble Radius as a Function of the Water Depth and Charge Weight

\[ R \ddot{R} + \frac{3}{2} \dot{R}^2 = \frac{P_B(t) - P_\infty}{\rho} \]
UNDEX CHARACTERIZATION AND FE MODEL VALIDATION

Shock Wave Pressure vs. Charge Distance from the Pipe

\[ P_{\text{max}} (D, W) = \begin{cases} \frac{W^{1/3}}{D} & \text{if } \frac{D}{W^{1/3}} < 0.32 \\ \frac{W^{1/3}}{D} & \text{if } \frac{D}{W^{1/3}} > 0.32 \end{cases} \]

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Charge Weight = 300 kg

Maximum Pressure of First Bubble vs. Charge Distance from the Pipe

Cole Eq.

OMAE 2011 – Petralia Eq.
PIPELINE DYNAMIC RESPONSE – FEM VS. ANALYTICAL RESULTS

\[
\begin{align*}
T_{ij} [s] & \quad 1,1 & 1,3 & 1,5 & 1,7 \\
\text{FEM} & \quad 2.16 & 0.36 & 0.14 & 0.07 \\
\text{Analytic} & \quad 2.39 & 0.26 & 0.10 & 0.05 \\
\end{align*}
\]

R.D. Blevins: “Formulas for Natural Frequency and Mode Shape”

\[
\begin{align*}
\lambda_{0,j} &= 1 \quad (i = 0 \text{ and } L/jR > 8) \\
\lambda_{n,j} &= \frac{i^2 \pi^2 (1-\nu^2)^{1/2}}{2} \frac{R^2}{E} \quad (i = 1 \text{ and } L/jR > 8) \\
\hat{\lambda}_{n,j} &= \sqrt{\left(1-\nu^2\right) \left(\frac{j\pi R}{L}\right)^4 + \left(\frac{\rho h k^2}{12 R^2}\right) i^2 + \left(\frac{j\pi R}{L}\right)^2} \quad (i > 1) \\
\end{align*}
\]

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PIPELINE DYNAMIC RESPONSE – EXCITED NATURAL MODES

FREQUENCY SPECTRUM OF SHOCK WAVE (FFT)

PIPELINE RESPONSE

EXCITED PIPELINE NATURAL MODES

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### APPLICATION – PIPELINE BASIC DATA

**Pipeline Water Depth**
- WD = 744 m

Two scenarios have been analysed:
- Pint = 0
- Pint = Pdes = 145 barg

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Offshore 36” Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Diameter (Constant)</td>
<td>mm</td>
<td>871.0</td>
</tr>
<tr>
<td>Steel Wall Thickness</td>
<td>mm</td>
<td>34.0</td>
</tr>
<tr>
<td>Internal Coating</td>
<td>μm</td>
<td>60 to 110</td>
</tr>
<tr>
<td>Corrosion Allowance</td>
<td>mm</td>
<td>0.0</td>
</tr>
<tr>
<td>Manufacturing Method</td>
<td></td>
<td>UOE</td>
</tr>
<tr>
<td>Welding process</td>
<td></td>
<td>SAW</td>
</tr>
<tr>
<td>Fabrication Thickness Tolerance (body)</td>
<td>mm</td>
<td>+1.0 -1.0</td>
</tr>
<tr>
<td>Out of Roundness (body)</td>
<td>%/mm</td>
<td>1.0/10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Offshore 36” Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Grade</td>
<td>-</td>
<td>L450</td>
</tr>
<tr>
<td>Specified Minimum Yield Stress at 20°C</td>
<td>MPa</td>
<td>450</td>
</tr>
<tr>
<td>Specified Minimum Tensile Stress at 20°C</td>
<td>MPa</td>
<td>535</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>7850</td>
</tr>
<tr>
<td>Coefficient of linear thermal expansion</td>
<td>°C⁻¹</td>
<td>1.16 x 10⁻⁵</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>MPa</td>
<td>207 x 10³</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>-</td>
<td>0.3</td>
</tr>
</tbody>
</table>
APPLICATION – ORDNANCE BASIC DATA

MASS OF EXPLOSIVE CHARGE
- Warhead Mass (by survey) = 300 kg
- Warhead Mass (Safety Factor 2) = 600 kg

WARHEAD EXPLOSIVE TYPE
- Trinitrotoluene (TNT)

WARHEAD SHAPE AND DIMENSIONS
- Torpedo – Spherical Warhead
  - Assumed as Point Source in FE Model

Geers-Hunter model
- Charge constant $K$ = 5.97e+07
- Charge constant $k$ = 8.83e-05
- Similitude spatial exponent $A$ = 0.13
- Similitude temporal exponent $B$ = 0.18
- Charge constant $K_c$ = 1.05e+09
- Ratio of specific heats for explosion gas = 1.27
- Charge material density = 1654
FEM STUDY RESULTS – UNDERWATER EXPLOSION

Charge Weight = 600 kg
Water Depth = 744 m
Charge Distance = 4 m

Primary Shock Wave
Wave Propagation
Shock Wave Tail
Secondary Bubble Pulse
Primary Shock Wave

Charge Weight = 600 kg
Water Depth = 744 m
Charge Distance = 4 m
FEM STUDY RESULTS – UNDERWATER EXPLOSION

Charge Weight = 600 kg
Water Depth = 744 m
Charge Distance = 4 m

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FEM STUDY RESULTS – UNDERWATER EXPLOSION

Charge Weight = 600 kg
Water Depth = 744 m
Charge Distance = 4 m

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FEM STUDY RESULTS – UNDERWATER EXPLOSION

Charge Weight = 600 kg
Water Depth = 744 m
Charge Distance = 4 m

Pressure Time History

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FEM STUDY RESULTS – PIPELINE DEFORMATION

Charge Weight = 600 kg
Water Depth = 744 m
Charge Distance = 4 m

Internal Pressure = 14.5 MPa
Primary Shock Wave

Internal Pressure = 0 MPa

Wave Propagation
FEM STUDY RESULTS – PIPELINE DEFORMATION

Internal Pressure = 14.5 MPa

Secondary Bubble Pulse

Internal Pressure = 0 MPa

Charge Weight = 600 kg
Water Depth = 744 m
Charge Distance = 4 m

UNDEX End
FEM STUDY RESULTS – PIPELINE DEFORMATION

No Internal Pressure

- Peak Pressure: 132 MPa
- Charge Weight = 600 kg
- Water Depth = 744 m
- Charge Distance = 4 m
- Internal Pressure = 0 MPa
FEM STUDY RESULTS – PIPELINE DEFORMATION

No Internal Pressure

- Charge Weight = 600 kg
- Water Depth = 744 m
- Charge Distance = 4 m
- Internal Pressure = 0 MPa

Wave Propagation
FEM STUDY RESULTS – PIPELINE DEFORMATION

No Internal Pressure

Peak Pressure
12 MPa

Charge Weight = 600 kg
Water Depth = 744 m
Charge Distance = 4 m
Internal Pressure = 0 MPa

Secondary Bubble Pulse
FEM STUDY RESULTS – PIPELINE DEFORMATION

No Internal Pressure

Buckle Propagation

Charge Weight = 600 kg
Water Depth = 744 m
Charge Distance = 4 m
Internal Pressure = 0 MPa

UNDEX End
FEM STUDY RESULTS – PIPELINE DEFORMATION

No Internal Pressure

Primary Shock Wave

Charge Weight = 600 kg
Water Depth = 400 m
Charge Distance = 4 m
Internal Pressure = 0 MPa

UNDEX End
FEM STUDY RESULTS – PIPELINE DEFORMATION

No Internal Pressure

Charge Weight = 600 kg
Water Depth = 400 m
Charge Distance = 4 m
Internal Pressure = 0 MPa

After Primary Shock Wave

Pressure Time History

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FEM STUDY RESULTS – PIPELINE DEFORMATION

No Internal Pressure

Charge Weight = 600 kg
Water Depth = 400 m
Charge Distance = 4 m
Internal Pressure = 0 MPa

Secondary Bubble Pulse

Secondary Shock Wave
FEM STUDY RESULTS – PIPELINE DEFORMATION

No Internal Pressure

Charge Weight = 600 kg
Water Depth = 400 m
Charge Distance = 4 m
Internal Pressure = 0 MPa
FEM STUDY RESULTS – PIPELINE DEFORMATION
<table>
<thead>
<tr>
<th>Charge Distance (m)</th>
<th>Ovalisat. (%)</th>
<th>Dent (mm)</th>
<th>Dent / Diameter (%)</th>
<th>Longit. Strain (%)</th>
<th>Hoop Strain (%)</th>
<th>Eq. Plastic Strain (%)</th>
<th>Von Mises Stress (MPa)</th>
<th>Max Displ. (m)</th>
</tr>
</thead>
</table>
### UNDEX – FEM STUDY RESULTS – SUMMARY

#### Charge Weight = 600 kg  
**Internal Pressure = 0 barg**

<table>
<thead>
<tr>
<th>Charge Distance (m)</th>
<th>Ovalisat. (%)</th>
<th>Dent (mm)</th>
<th>Dent / Diameter (%)</th>
<th>Longit. Strain (%)</th>
<th>Hoop Strain (%)</th>
<th>Eq. Plastic Strain (%)</th>
<th>Von Mises Stress (MPa)</th>
<th>Max Displ. (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>NA</td>
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#### Charge Weight = 600 kg  
**Internal Pressure = 145 barg**

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<th>Charge Distance (m)</th>
<th>Ovalisat. (%)</th>
<th>Dent (mm)</th>
<th>Dent / Diameter (%)</th>
<th>Longit. Strain (%)</th>
<th>Hoop Strain (%)</th>
<th>Eq. Plastic Strain (%)</th>
<th>Von Mises Stress (MPa)</th>
<th>Max Displ. (m)</th>
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**SLS Oval.**  
**SLS Dent**  
**ULS**  
**96% SMYS**
### UNDEX – FEM Study – Conclusions

<table>
<thead>
<tr>
<th>Distance from Structure</th>
<th>Risk Assessment</th>
<th>Description</th>
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<tr>
<td>Distance &gt;&gt; 20 m</td>
<td>LOW or UNEXISTENT RISK</td>
<td>CHARGE FAR FROM THE STRUCTURE</td>
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<td>20 m &gt; Distance &gt; R\text{bubble}</td>
<td>NEED OF INTEGRITY ASSESSMENT</td>
<td>PRIMARY SHOCK WAVE + SECONDARY SHOCK WAVES (No Interaction with Gas Bubble)</td>
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<tr>
<td>Distance &lt; R\text{bubble}</td>
<td>HIGH RISK</td>
<td>PRIMARY SHOCK WAVE + SECONDARY SHOCK WAVES + WATER JETTING (Interaction with Gas Bubble)</td>
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**Analytic**

- UNDAMAGED PIPE
- DENTED PIPE (SERVICEABILITY OK)
- DENTED PIPE (SERVICEABILITY TO BE ASSESSED)

**Detail FEM Analysis**

- BROKEN/HEAVY DAMAGED/FLATTENED
  - UXO Removal
  - UXO Neutralization
  - Pipeline Route Modification

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Effects of Underwater Explosion on Pipeline Integrity - Pavia, November 21st, 2014
FUTURE DEVELOPMENTS

• Refinement of FE Model by considering the EFFECT OF SEABED on:
  • Shock Wave Propagation (absorption and reflection of shock waves, crater formation);
  • Effect of actual pipeline embedment.

• Characterization of effect of EXPLOSIVE CHARGE SHAPE on explosion behaviour (oriented explosion, shaped charges and Munroe Effect).

• Enhanced modelling of close to pipeline explosion, by considering the interaction between pipeline and GAS BUBBLE and the simulation of occurring WATER JETTING phenomena. Application of Coupled Eulerian-Lagrangian ABAQUS methodology for an enhanced analysis of FLUID-STRUCTURE INTERACTION.
THANKS