saipem

Effect of Underwater Explosion on Pipeline Integrity

Roberto Bruschi – roberto.bruschi@saipem.com
Lorenzo Marchionni – lorenzo.marchionni@saipem.com
Antonio Parrella – antonio.parrella@saipem.com
Lorenzo Maria Bartolini – lorenzo.bartolini@saipem.com

Pavia, November 21st, 2014

OUTLINE

UNEXPLODED ORDNANCES – WHAT IS IT?

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:

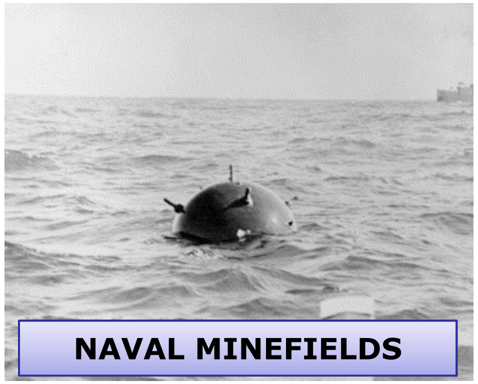
1. **Military training exercises (abandoned gunnery ranges, naval warfare exercises);**
2. **Accidental disposal due to poor working practices during munitions handling and transportation, or other accidental events (shipwreck, crash landing, ecc.);**
3. **Wartime ops during armed conflicts (WWI and 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


AERIAL BOMBING


ANTI-SUB WARFARE


NAVAL MINEFIELDS


WARSHIP ARTILLERY


TORPEDOES


AERIAL BOMBS

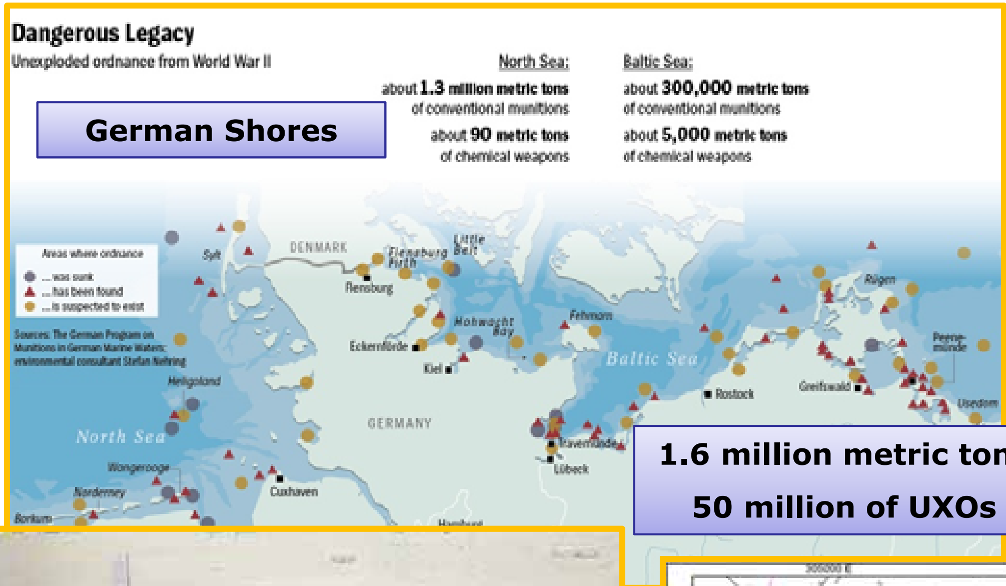

DEPTH CHARGE


MINES


ARTILLERY SHELLS

UNEXPLODED ORDNANCES – WHERE?

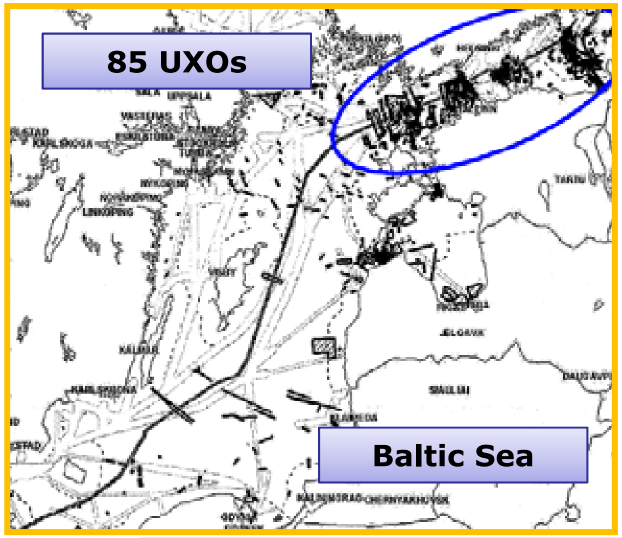
UXO arises from both hostile and defensive MILITARY ACTIVITIES often related to World Wars I and II. Their occurrence is higher in documented WAR THEATRE sea regions (e.g. Baltic Sea, North Sea, shores of Northern Germany, English Channel, Mediterranean Sea, Western Areas of Pacific Ocean, ecc.), or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



German Shores

1.6 million metric tons

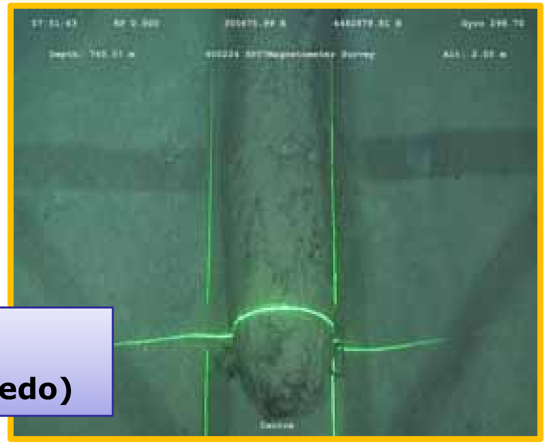
50 million of UXOs



85 UXOs

Baltic Sea

Typical Torpedo used during the WW2



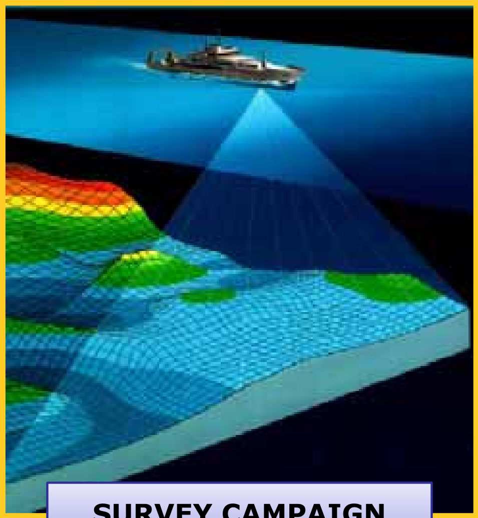
Discovered UXO

(WWII German Torpedo)

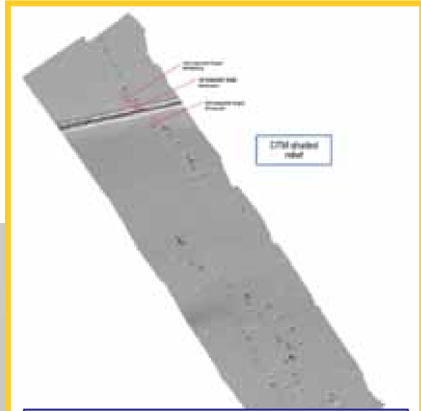
UNEXPLODED ORDNANCES DISCOVERY – SURVEY

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.



SURVEY CAMPAIGN



SUSPECT OBJECTS

UXO IDENTIFICATION

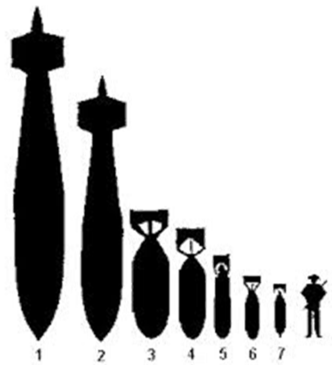
ASSESSMENT OF RISK OF ACCIDENTAL EXPLOSION AND PIPELINE INTEGRITY

UNEXPLODED ORDNANCES – CHARACTERIZATION

MASS OF EXPLOSIVE CHARGE

Mass Range: 15 – 1000 kg

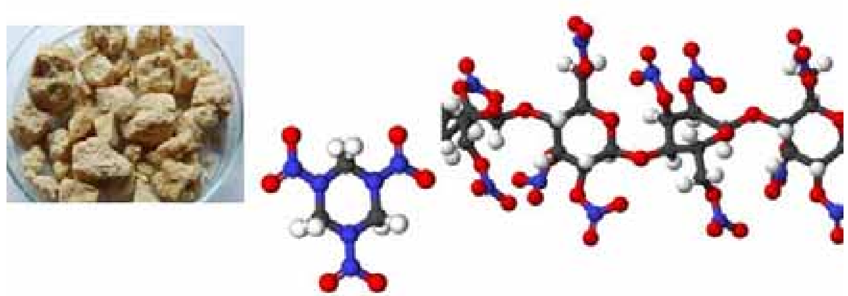
Mass Average: 200 – 300 kg



WARHEAD EXPLOSIVE TYPE

TNT, Hexanite, Nitrocellulose, RDX, Torpex

(Often it is difficult to determine the correct explosive type)



WARHEAD SHAPE AND DIMENSIONS

High variability depending from the UXO type

saipem

RECENT STUDIES

1994 OMAE — Volume V, Pipeline Technology
ASME 1994

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

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

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

Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2011
June 19-24, 2011, Rotterdam, The Netherlands

OMAE2011-49178

STRUCTURAL INTEGRITY ASSESSMENT OF A PIPELINE SUBJECTED TO AN UNDERWATER EXPLOSION

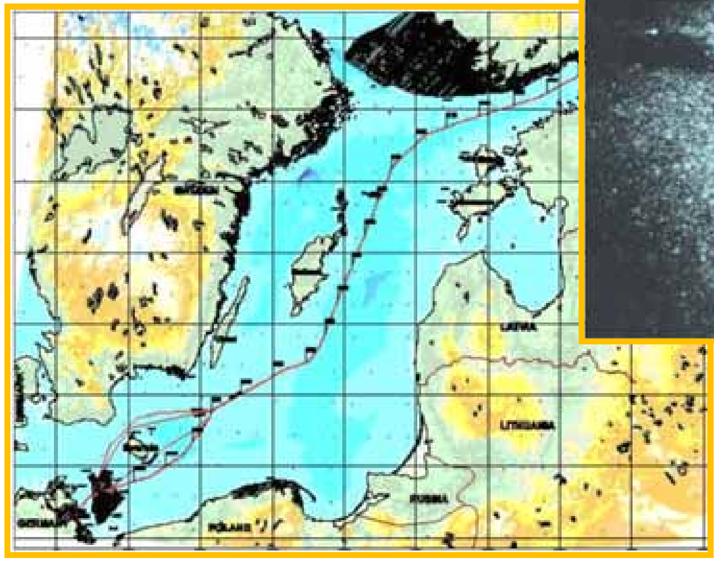
Paolo Monti, Caterina Molinari
Saipem Energy Services S.p.A.
Sealines and Subsea Division
San Donato Milanese (MI), Italy

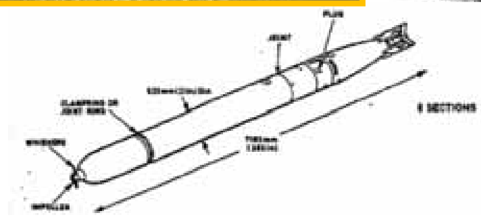
Massimiliano Bocciarelli, Alberto Corigliano, Stefano Mariani
Politecnico di Milano, Department of Structural Engineering
Milan, Italy

TransMed

Nord Stream

Nord Stream Project

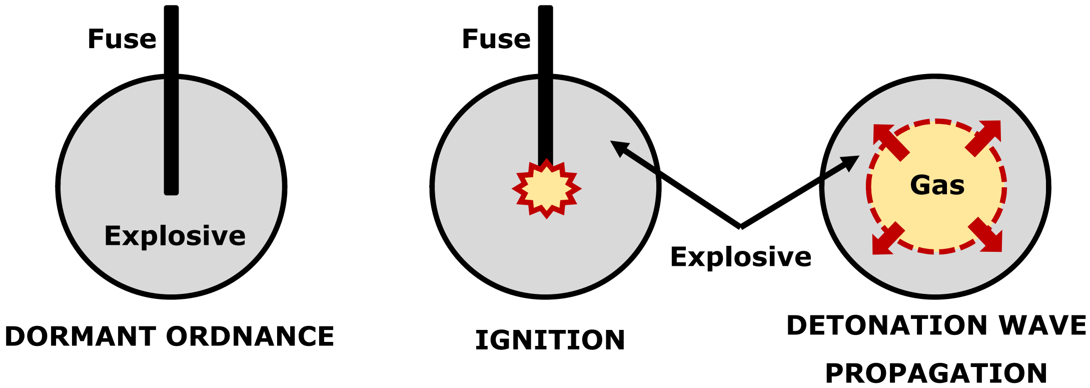


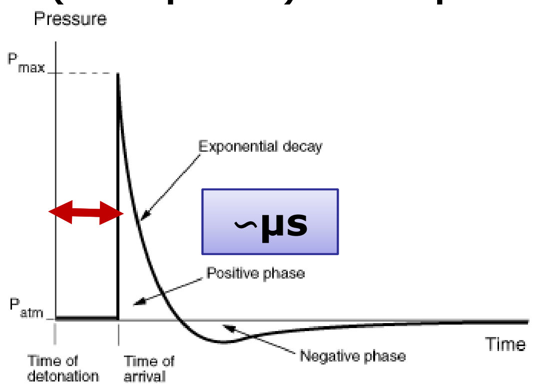


saipem

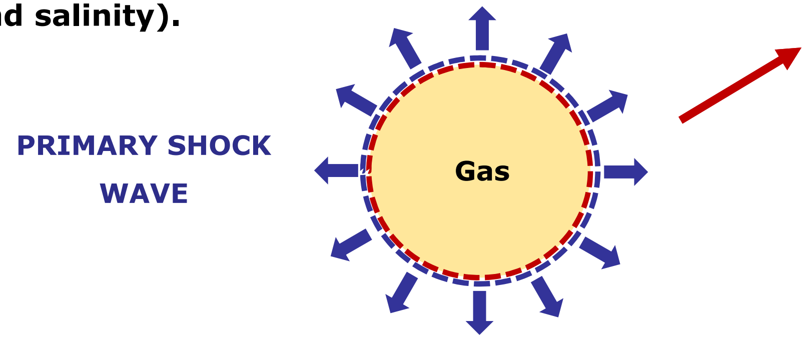
UNDERWATER EXPLOSION – PRIMARY SHOCK WAVE

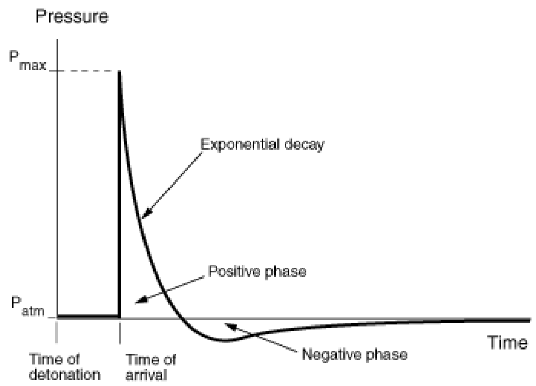
- **The explosion is activated by mean of a fuse (or detonator) giving the initial energy needed to ignite the detonation process.**
- **During the detonation process, a rapid transformation of the initial explosive reagent occurs into an expanding gas mass having high temperature and pressure (3000°C, 10^3 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.**





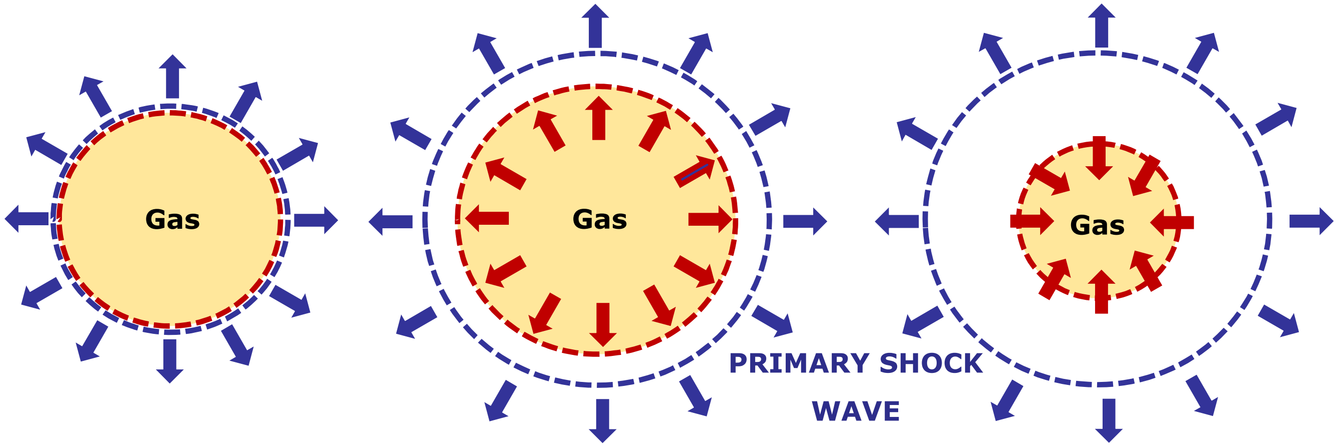
- **Once the detonation wave reaches the limit of the explosive mass domain the explosion energy is transferred to the surrounding medium (seawater), giving rise to a PRIMARY SHOCK WAVE travelling in the water at the SEAWATER SPEED OF SOUND (about 1550 m/s in relation to water depth, temperature and salinity).**

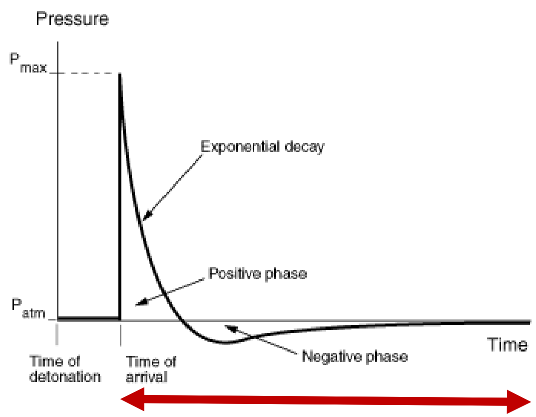




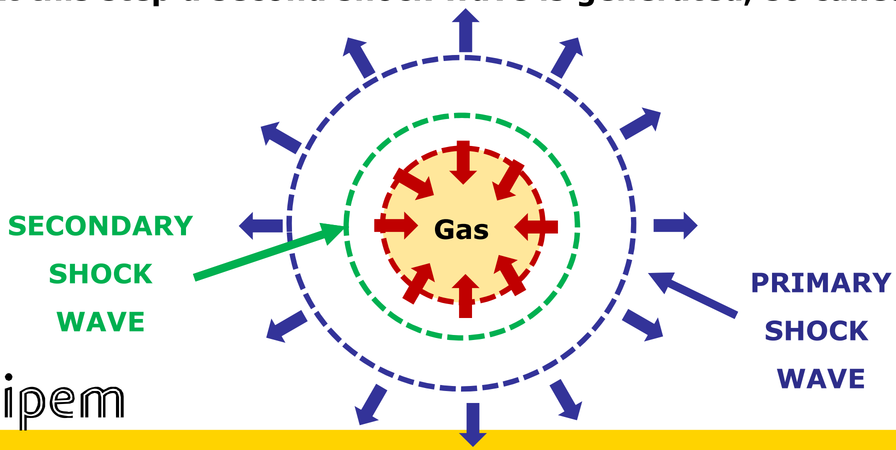
UNDERWATER EXPLOSION – SECONDARY SHOCK WAVE

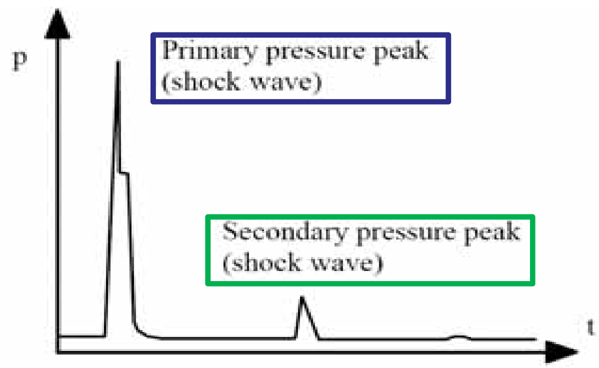
- **The initial pressure inside the gas sphere is much higher than the water hydrostatic pressure, causing the surrounding water to be subjected to a large outward acceleration due to the rapid EXPANSION OF THE GAS BUBBLE continuing also when the internal pressure is in equilibrium with the external 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.**





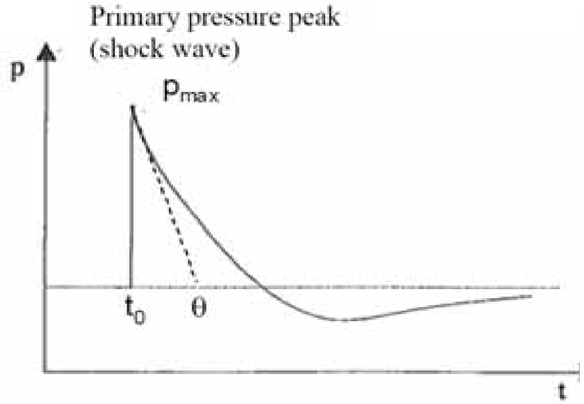
saipem

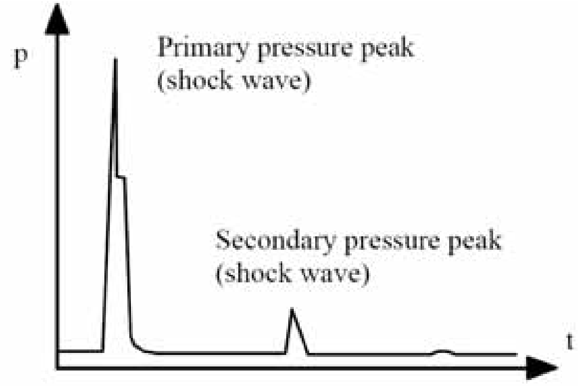
UNDERWATER EXPLOSION – SHOCK WAVE

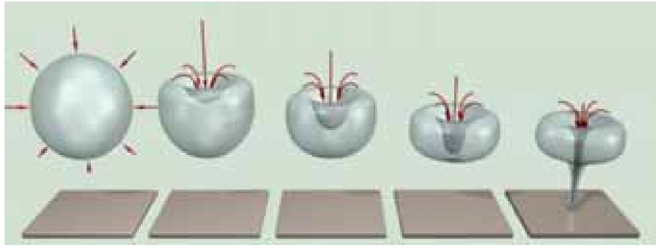
- **The viscoelasticity of the water and the behavior of the gas bubble give rise to a series of contraction and expansion cycles. At each cycle a pressure wave is released in the surrounding water. The entity of these waves is such negligible with respect to the INITIAL SHOCK WAVE and the 1st BUBBLE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

UNDERWATER EXPLOSION – EXPLOSION EFFECT

CHARGE FAR FROM THE STRUCTURE	CHARGE CLOSE TO THE STRUCTURE	CHARGE VERY CLOSE TO THE STRUCTURE
Distance >> Rbubble	Distance > Rbubble	Distance < Rbubble
PRIMARY SHOCK WAVE	PRIMARY SHOCK WAVE + SECONDARY SHOCK WAVES	PRIMARY SHOCK WAVE + SECONDARY SHOCK WAVES + WATER JETTING







BJERKNES FORCE

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.

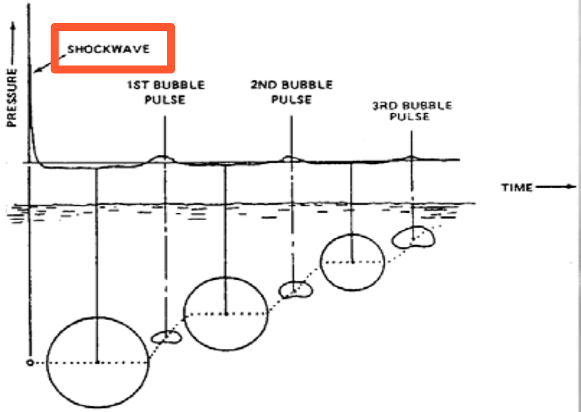
UNDERWATER EXPLOSION – SURFACES INTERACTION

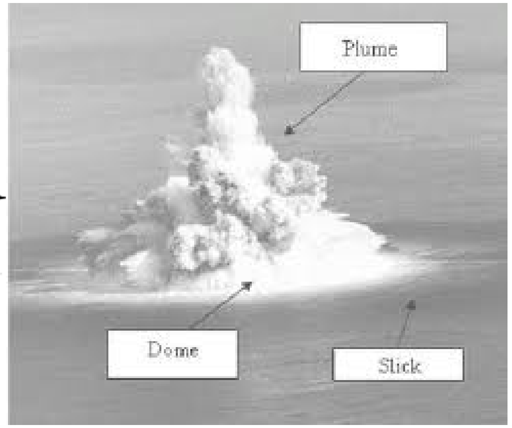
FREE WATER EXPLOSION

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.

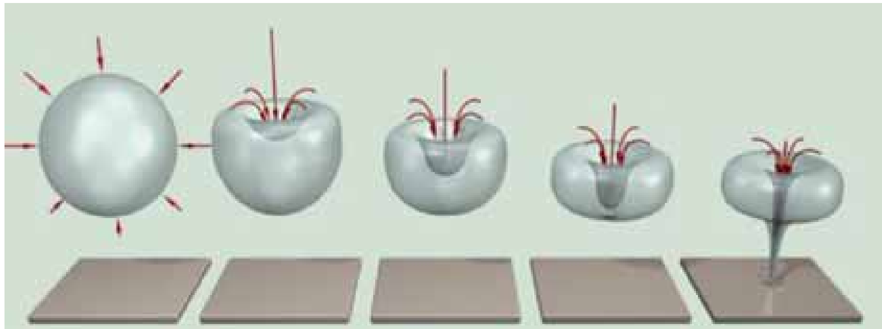
During the pulsation the bubble travels toward the sea surface. Surface SPRAY DOME can be observed in relation to the initial water depth of the charge.

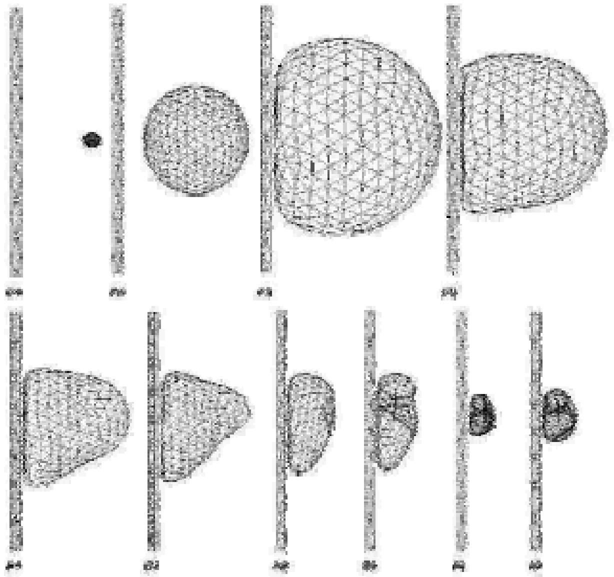




CLOSE SURFACES INTERACTION

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.





saipem

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)**

Explosion Energy (1–3)

Bubble Dynamics (3–4)

Interaction with Structures (1–5)

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_{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.**

saipem

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).

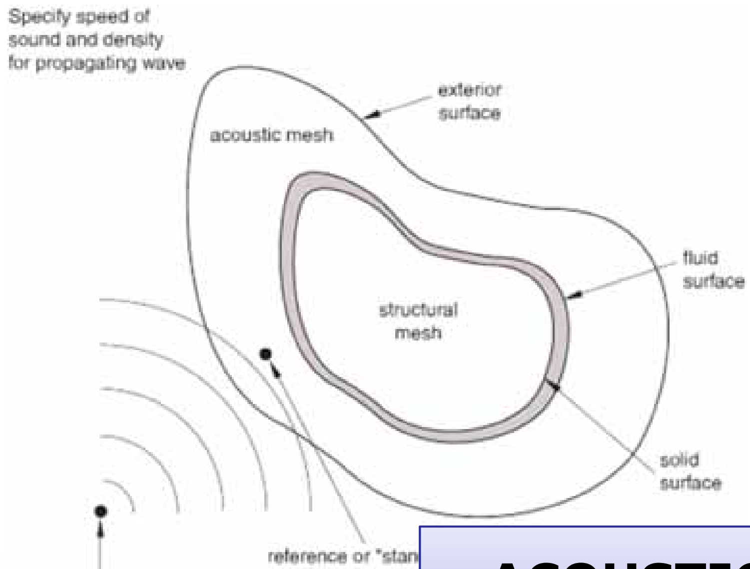
SERVICEABILITY LIMIT STATES (SLS)

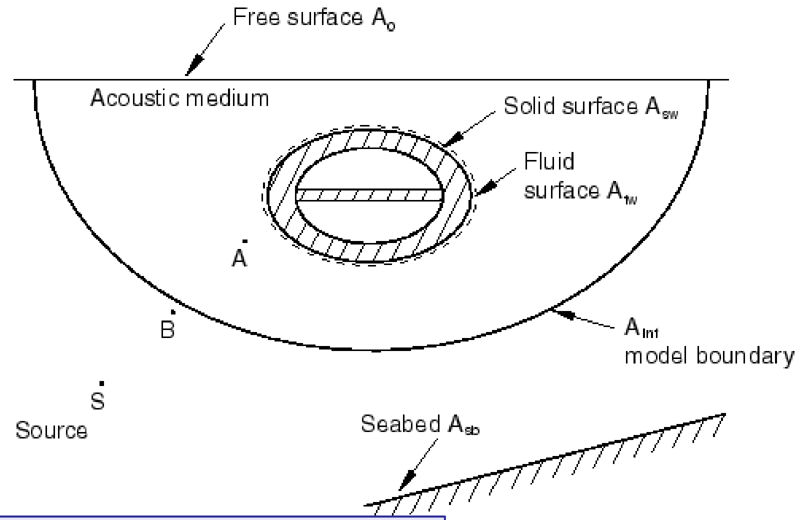
- **OVALIZATION BASED CRITERION**: in accordance to DNV OS-F101, the pipeline shall not be subject to excessive ovalization. The residual **FLATTENING** is not to exceed **3.0%**.
- **DENT BASED CRITERION**: in accordance to DNV-RP-F107 **DENT** to diameter ratio shall be limited to **5.0%.**

ULTIMATE LIMIT STATE (ULS)

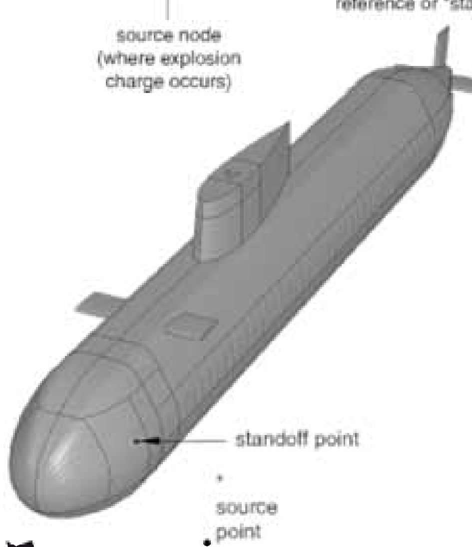
The pipe wall may experience **SIGNIFICANT PLASTIC STRAINS**, but the pipe wall tearing or a gas leakage shall not appear (corresponding to a **MAXIMUM EQUIVALENT PLASTIC STRAIN** equal to the uniform elongation limit = **10%**).

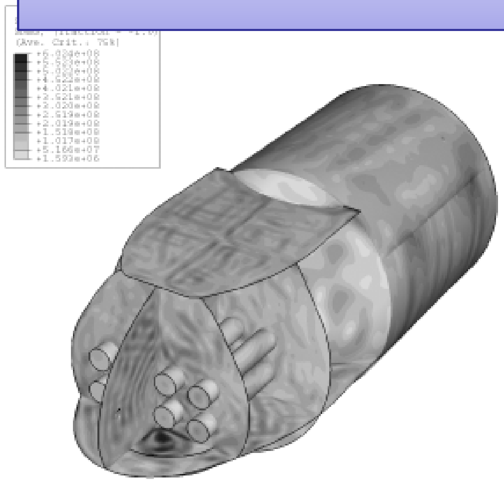
UNDEX MODELING IN ABAQUS

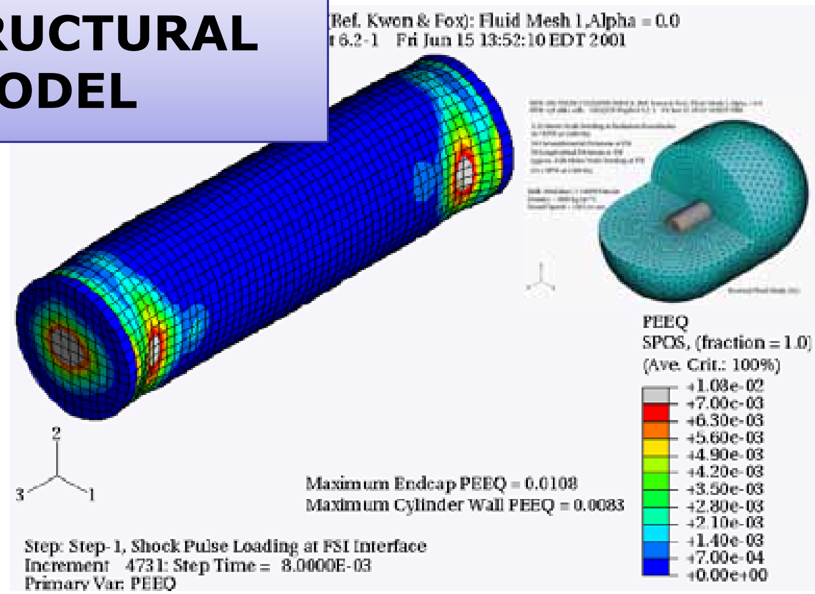




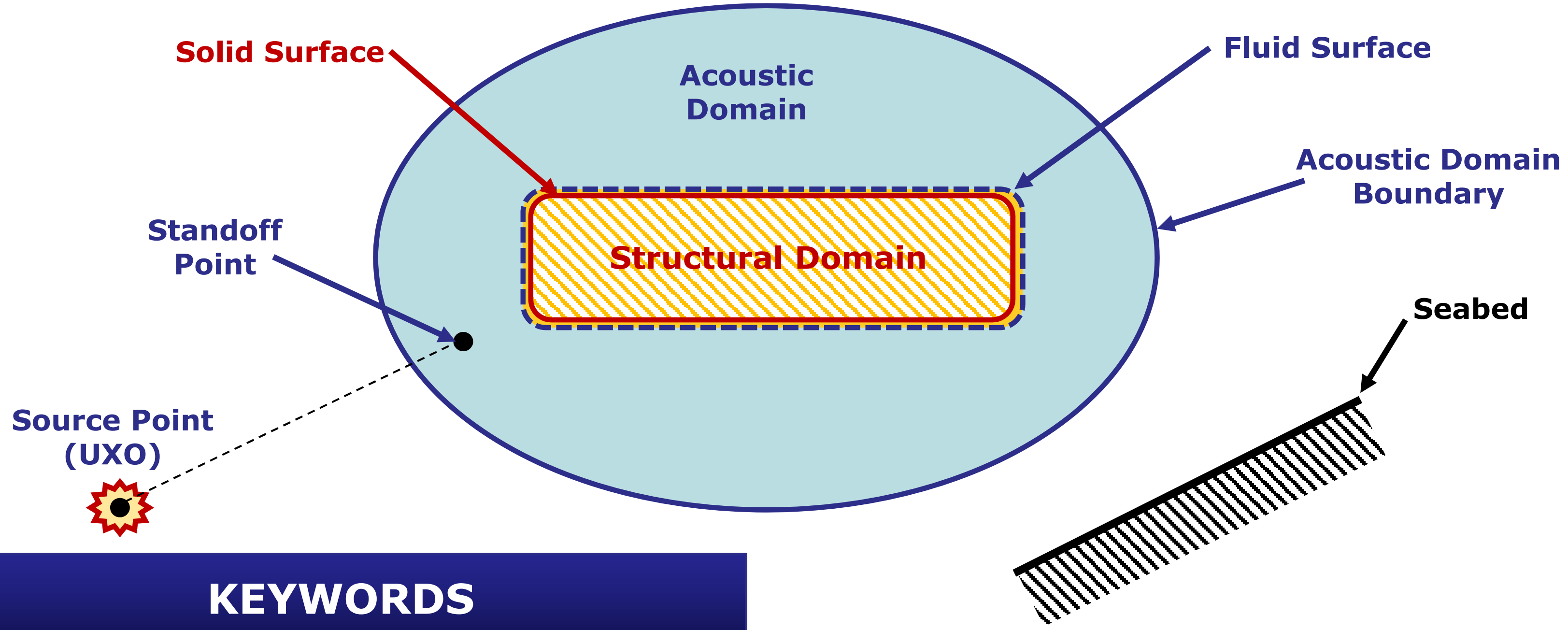
ACOUSTIC – STRUCTURAL COUPLED MODEL





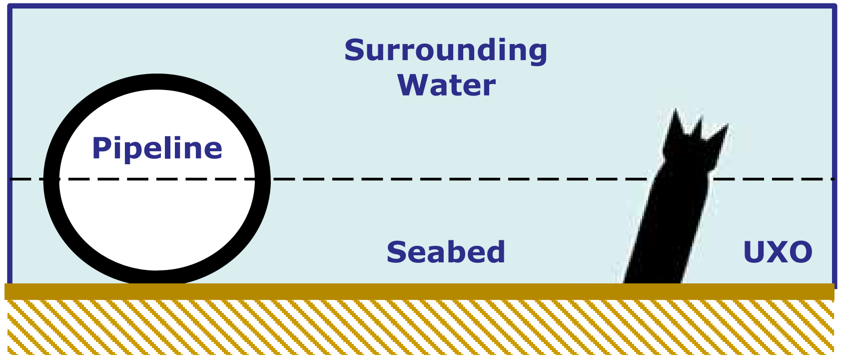


ABAQUS UNDEX MODELING – ACOUSTIC-STRUCTURAL COUPLING



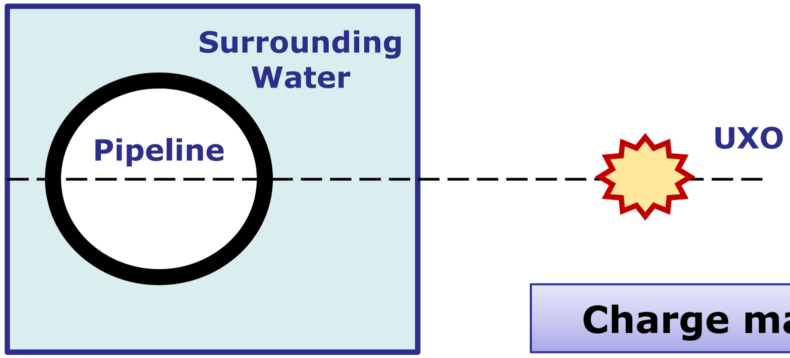
KEYWORDS	
*INCIDENT WAVE INTERACTION PROPERTY	Definition of fluid properties for ACOUSTIC DECAY calculation of incident wave.
*INCIDENT WAVE INTERACTION	Definition of incident wave loading, hit surface and SOURCE and STANDOFF points.
*UNDEX CHARGE PROPERTY	Definition of UXO charge PROPERTIES.
*SIMPEDANCE	Definition of surface reflection properties.

PIPELINE-UXO INTERACTION – MODEL ASSUMPTIONS



Charge mass = M

- **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.**

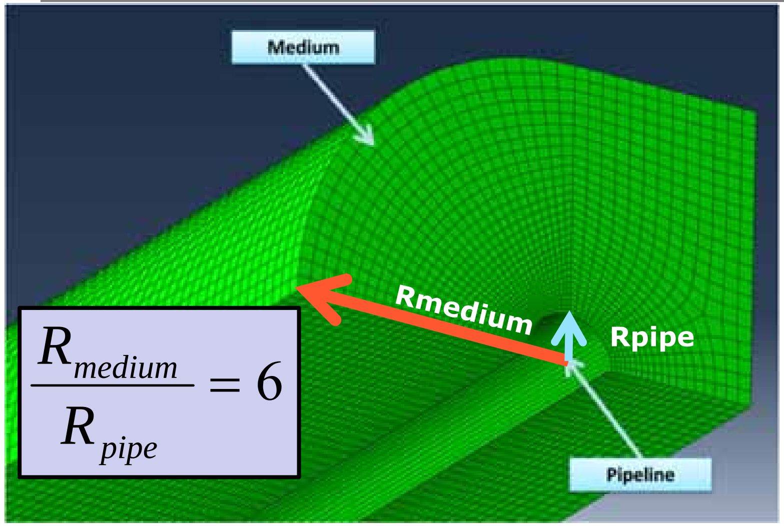


Charge mass = 2M

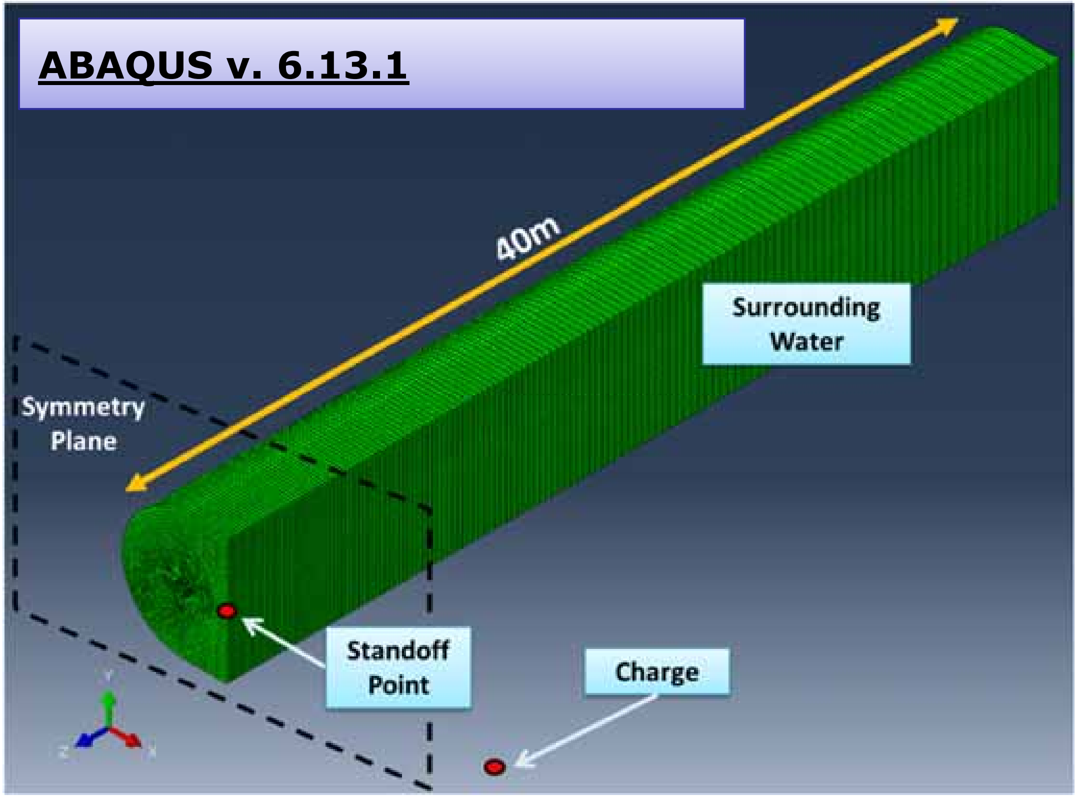
Geers-Hunter model	
Charge constant *K*	5.97e+07
Charge constant *k*	8.83e-05
Similitude spatial exponent *A*	0.13
Similitude temporal exponent *B*	0.18
Charge constant K_c	1.05e+09
Ratio of specific heats for explosion gas	1.27
Charge material density	1654

saipem

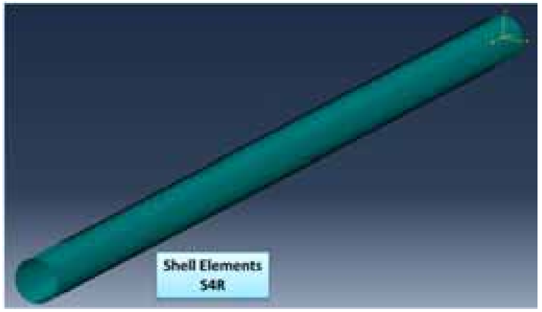
PIPELINE-UXO INTERACTION – FE MODEL



Added Mass for N=1 Translation Mode of an Infinite Cylinder (Fluid Between Concentric Cylinders – Blevins[1])	
Cylinder Radius Ratio (R_o/R_I)	Added Mass Ratio (External Boundary/Infinite Domain)
1.5	2.600
2.0	1.667
4.0	1.133
6.0	1.057
8.0	1.032
16.0	1.008
24.0	1.004



- **PIPELINE – S4R SHELL ELEMENTS**
- **WATER – AC3D8R ACOUSTIC BRICK ELEMENTS**



MODEL VALIDATION – ANALYTICAL APPROACH

- **INITIAL SHOCK WAVE (due to Detonation wave)**

Cole, R.H.: "Underwater Explosions", Dover Publications Inc., N.Y. , 1965

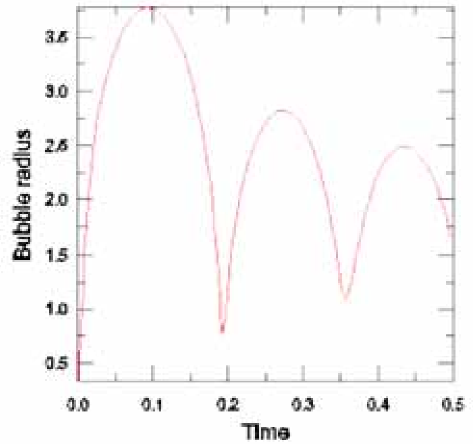
$$P = P_{max}(D,W)\exp\left[-\frac{t-t_0}{\vartheta(D,W)}\right]$$

D = Charge Distance

W = Charge Weight

- **BUBBLE MOTION EQUATION (Rayleigh-Plesset)**

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



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

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

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

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

D = Charge Distance

W = Charge Weight

wd = water depth

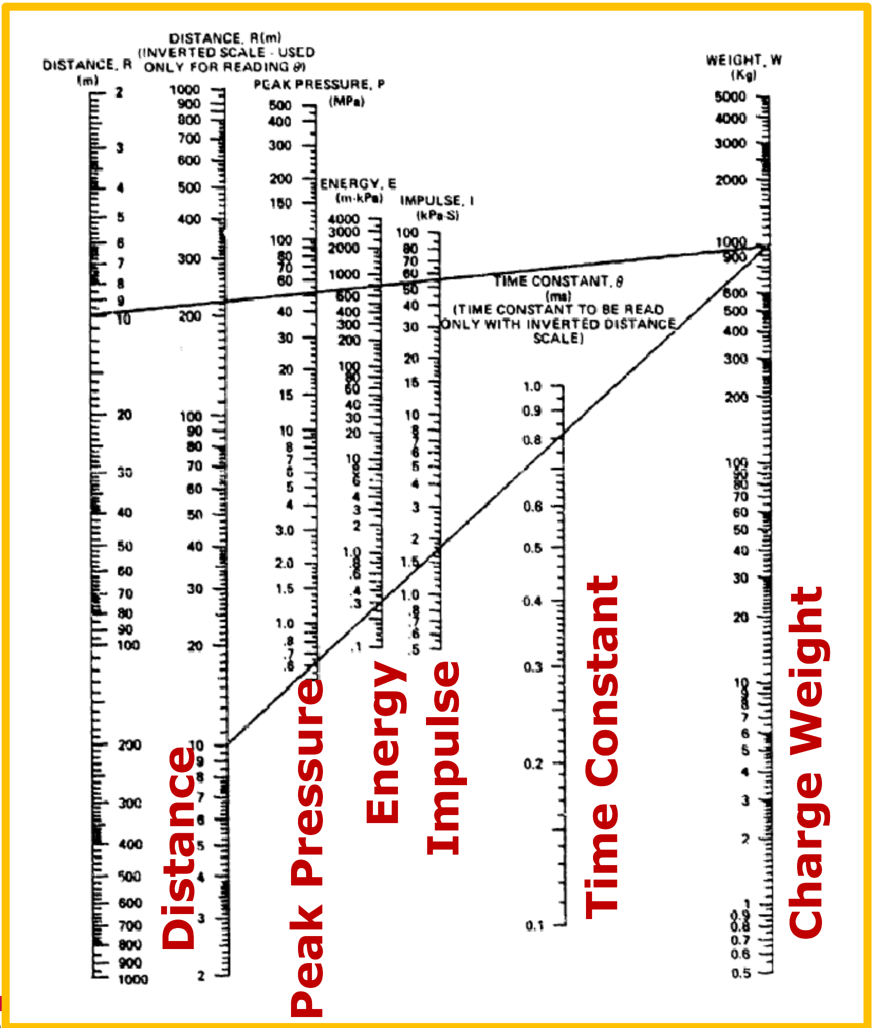
M.M. Swisdak Jr, "Explosion effects and Properties: Part II – Explosion Effects in Water", Naval Surface Weapon Center, 1978.

Petralia S., 2000, Explosivistic Compendium, Mariperman La Spezia.

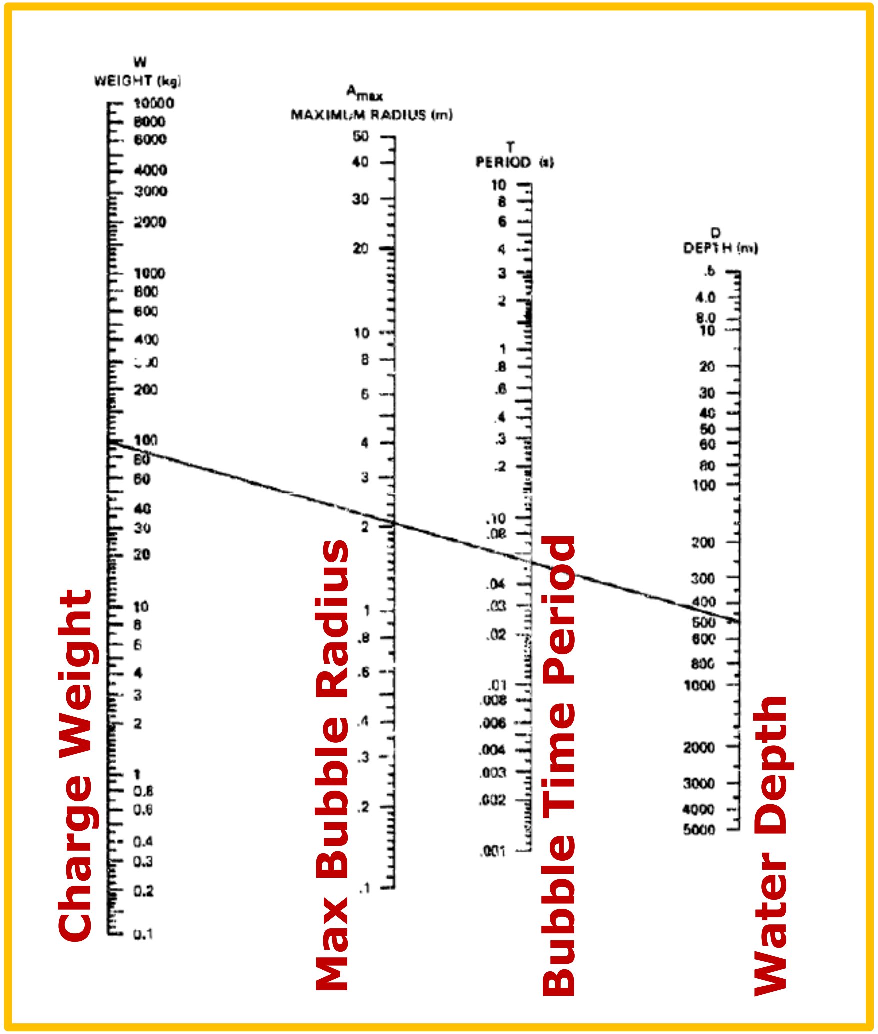
saipem

MODEL VALIDATION – NOMOGRAPH

NOMOGRAPH FOR INITIAL SHOCK WAVE EVALUATION

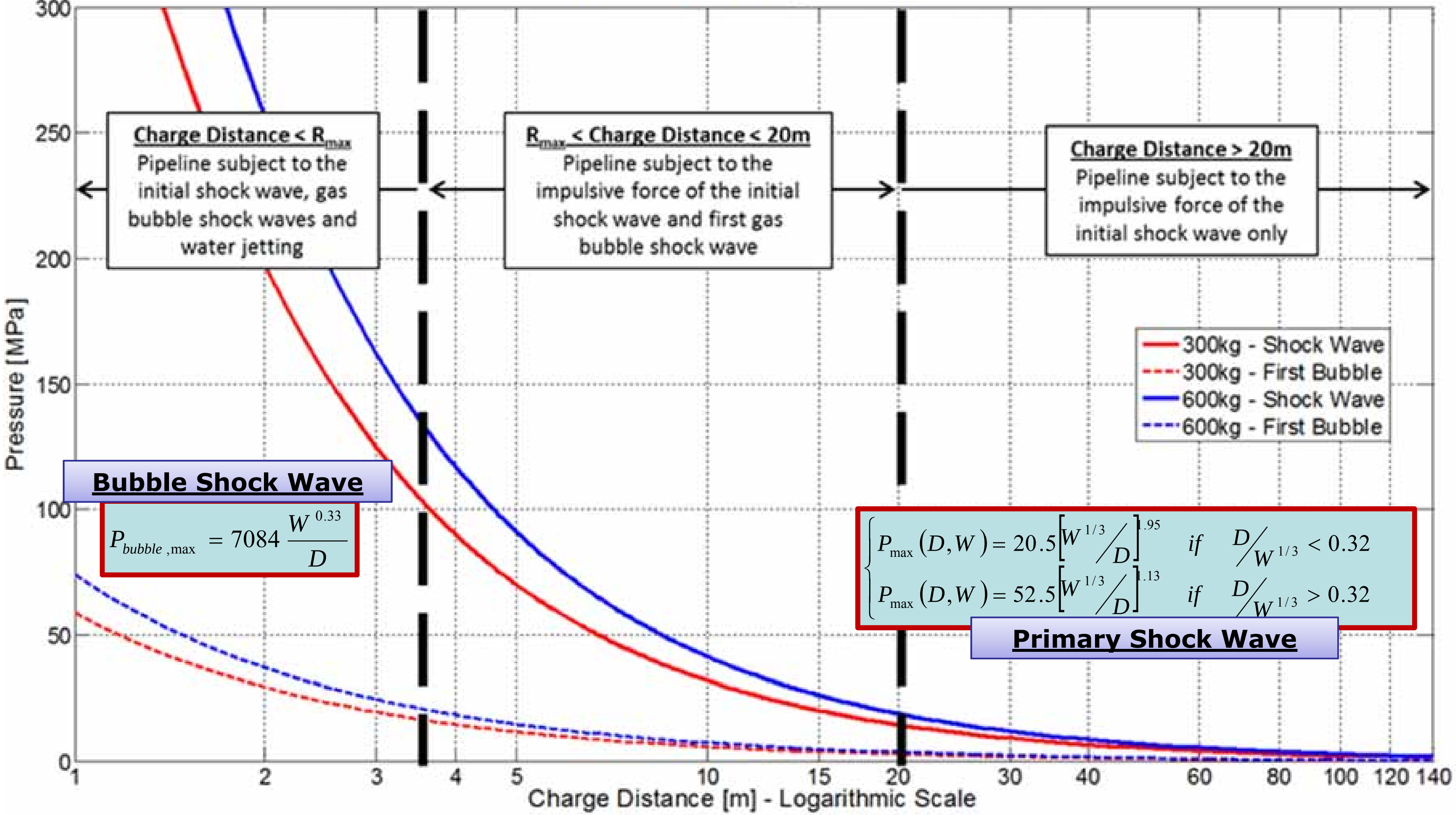


NOMOGRAPH FOR BUBBLE DYNAMICS CHARACTERIZATION



UNDEX CHARACTERIZATION AND FE MODEL VALIDATION

Pressure vs. Charge Distance



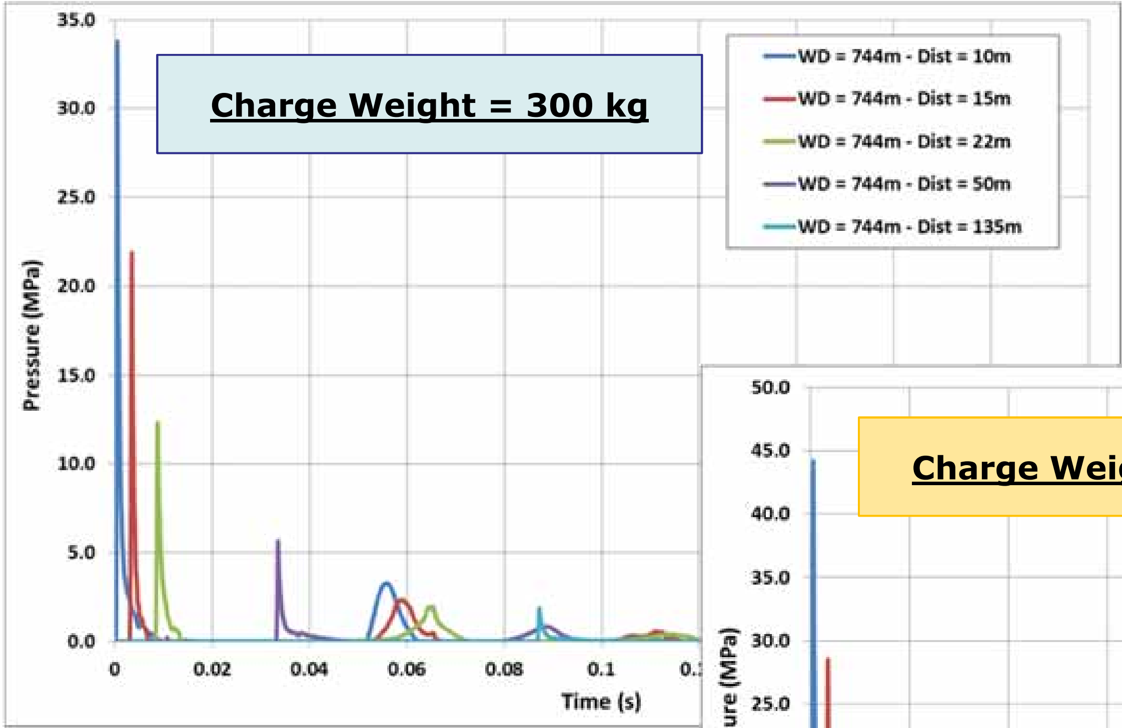
Bubble Shock Wave

$$P_{bubble,max} = 7084 \frac{W^{0.33}}{D}$$

Primary Shock Wave

$$\begin{cases} P_{max}(D,W) = 20.5\left[\frac{W^{1/3}}{D}\right]^{1.95} & \text{if } \frac{D}{W^{1/3}} < 0.32 \\ P_{max}(D,W) = 52.5\left[\frac{W^{1/3}}{D}\right]^{1.13} & \text{if } \frac{D}{W^{1/3}} > 0.32 \end{cases}$$

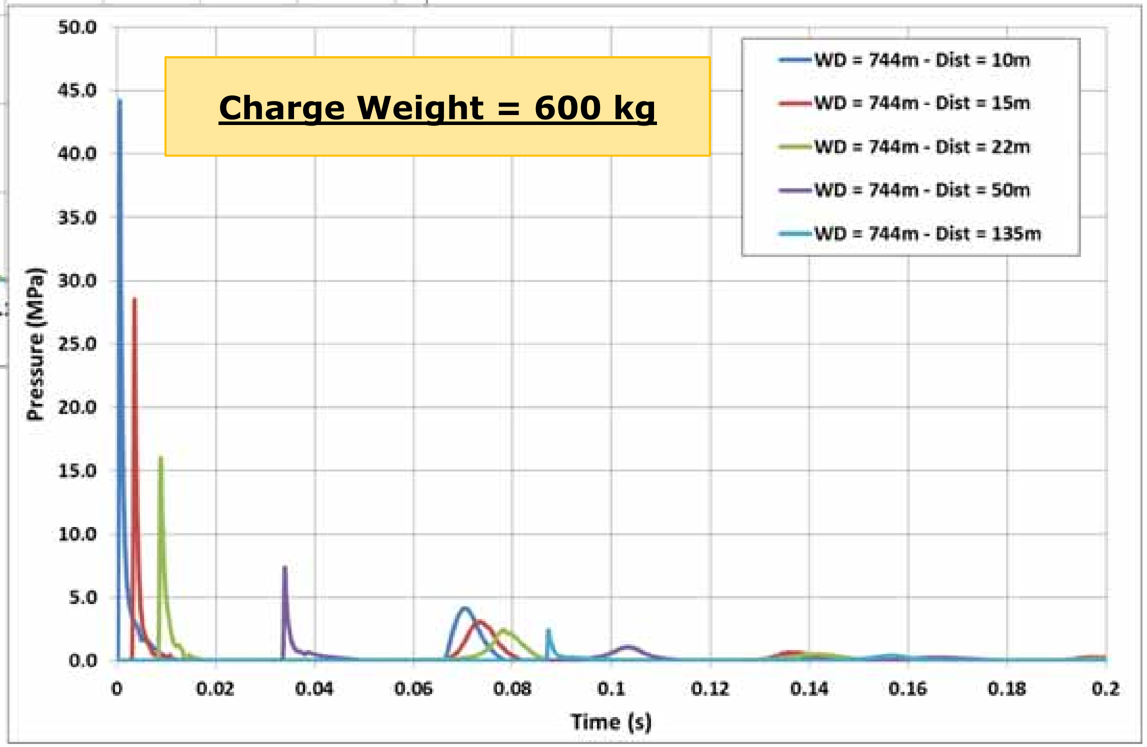
saipem



Shock Pressure Time History

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

Cole



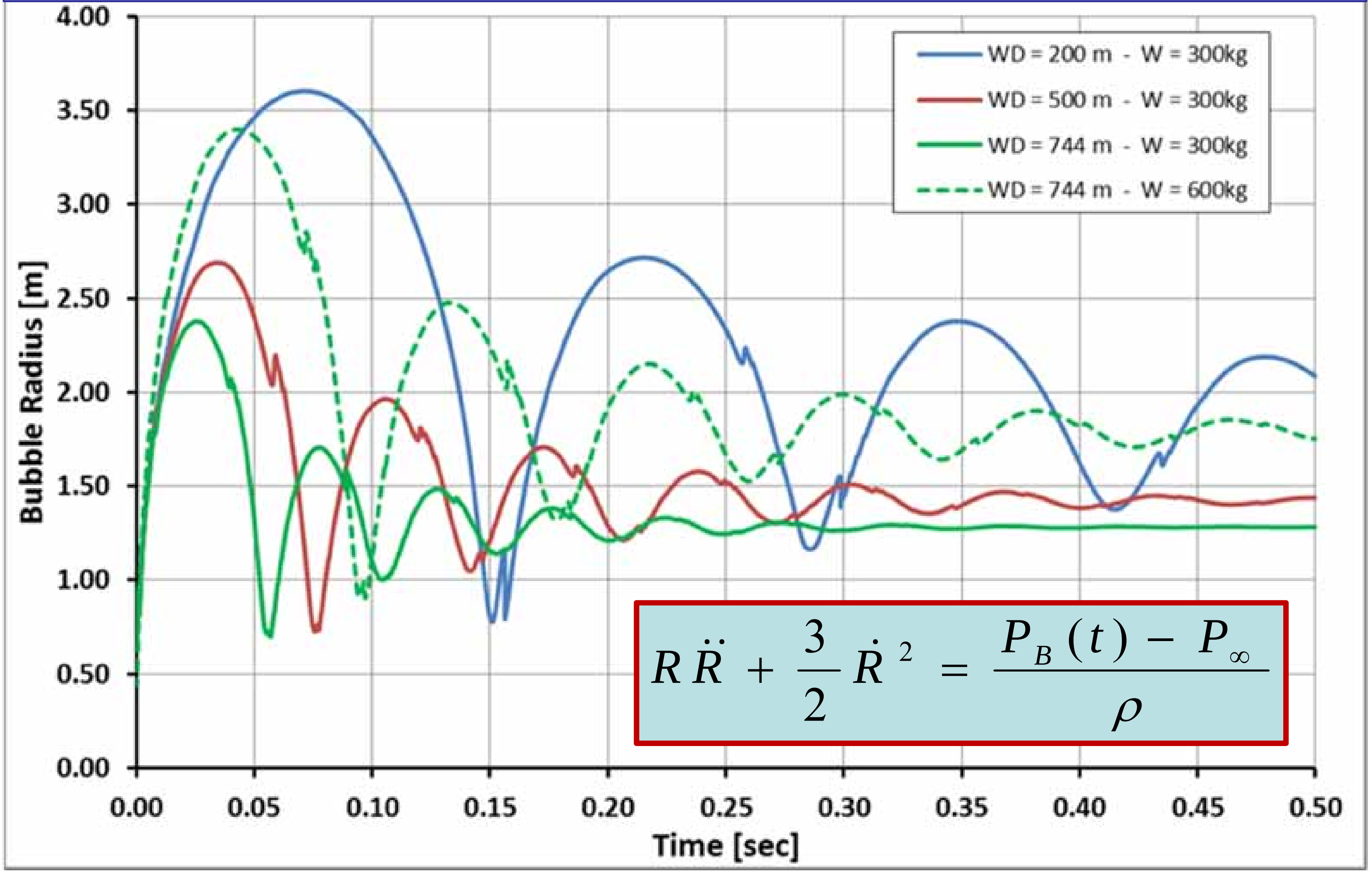
$$\begin{cases} P_{max}(D,W) = 20.5\left[W^{1/3}/D\right]^{.95} & if \quad D/W^{1/3} < 0.32 \\ P_{max}(D,W) = 52.5\left[W^{1/3}/D\right]^{1.13} & if \quad D/W^{1/3} > 0.32 \end{cases}$$

$$\begin{cases} \vartheta(D,W) = 0.0001048 \cdot W^{1/3}\left[D/W^{1/3}\right]^{0.35} & if \quad D/W^{1/3} < 2.70 \\ \vartheta(D,W) = 0.0001163 \cdot W^{1/3}\left[D/W^{1/3}\right]^{0.25} & if \quad D/W^{1/3} > 2.70 \end{cases}$$

saipem

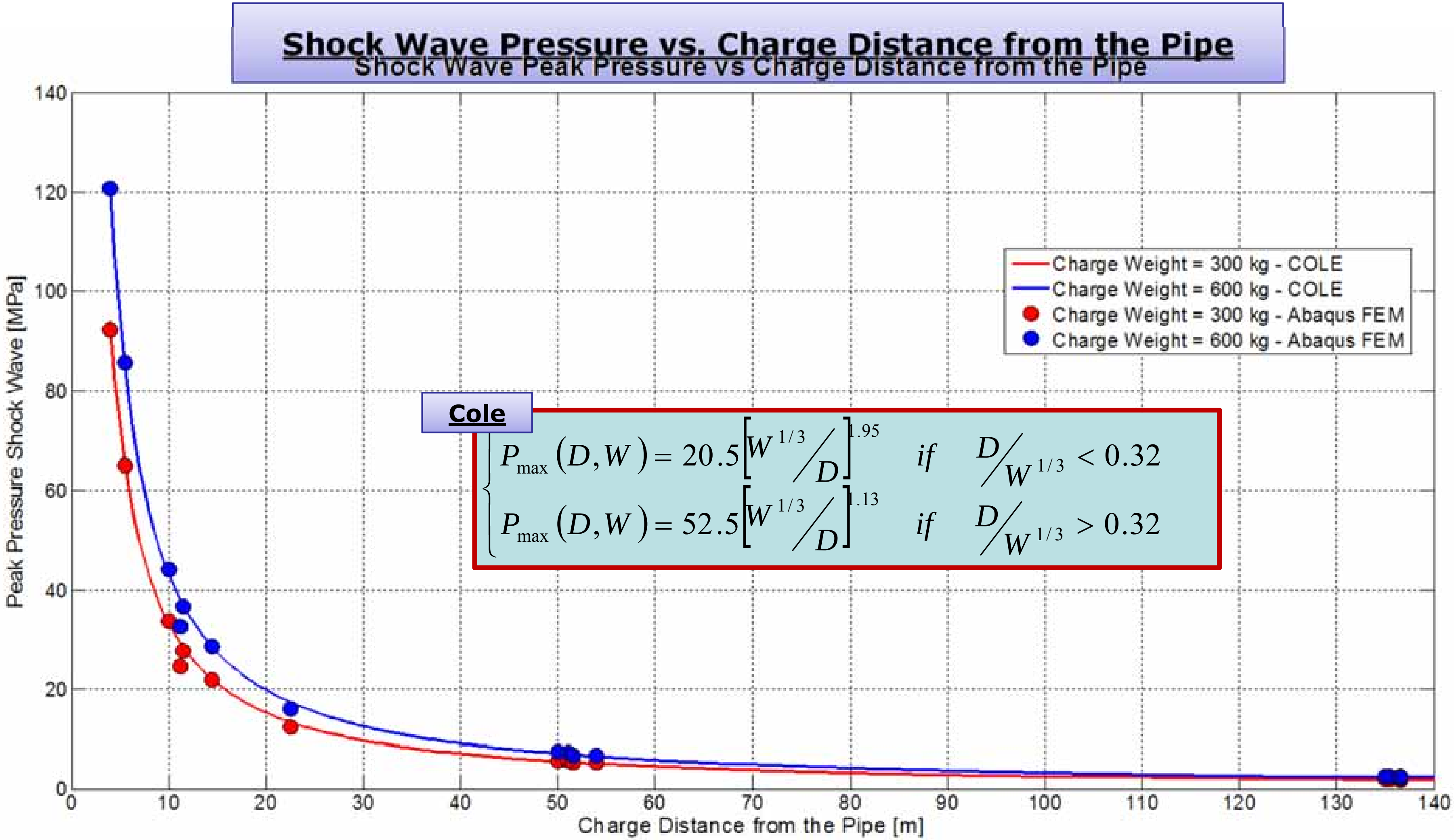
UNDEX CHARACTERIZATION AND FE MODEL VALIDATION

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



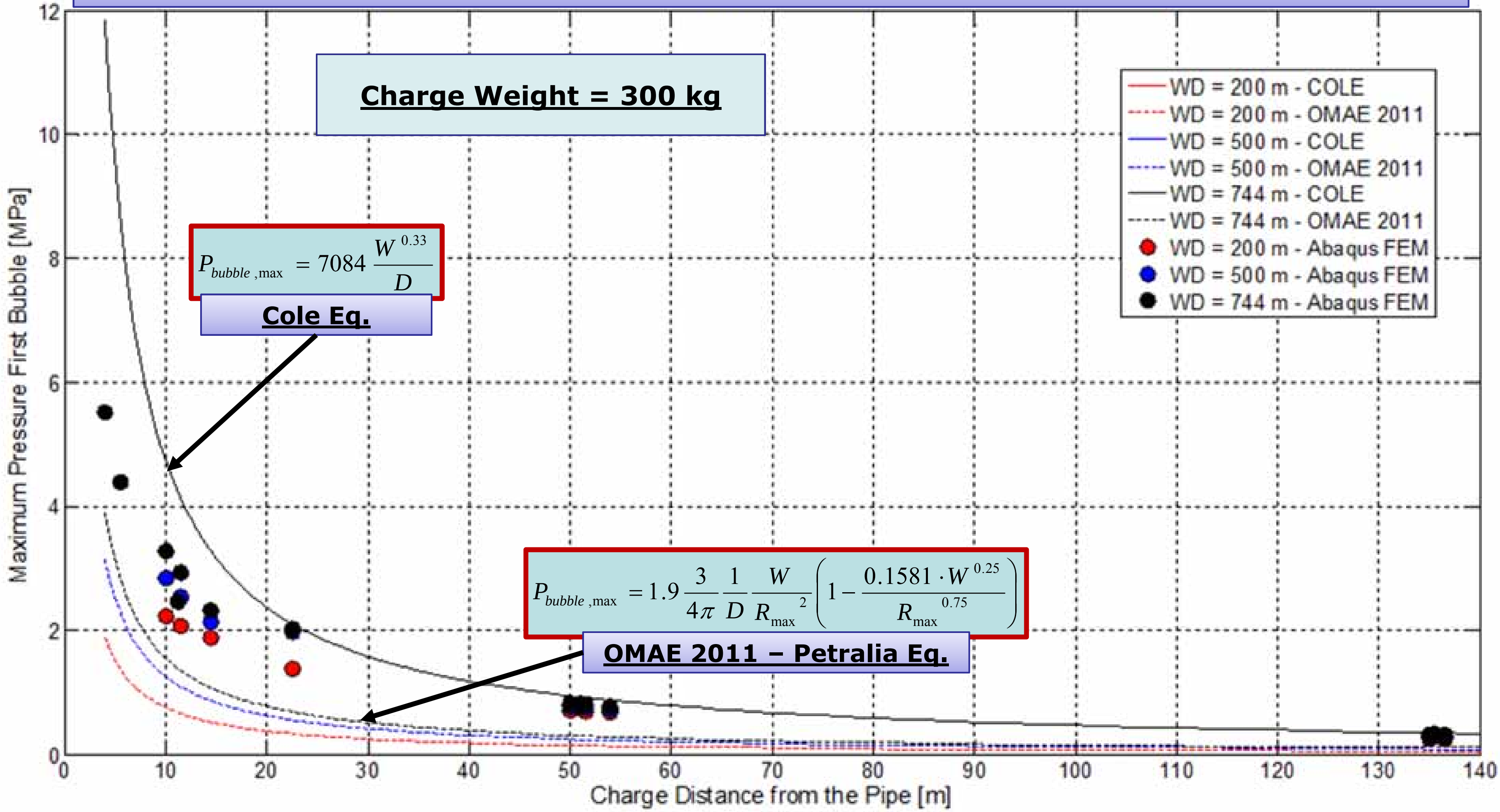
Cole

$$
\begin{cases}
P_{\max}(D,W) = 20.5\left[\frac{W^{1/3}}{D}\right]^{1.95} & \text{if } \frac{D}{W^{1/3}} < 0.32 \\
P_{\max}(D,W) = 52.5\left[\frac{W^{1/3}}{D}\right]^{1.13} & \text{if } \frac{D}{W^{1/3}} > 0.32
\end{cases}
$$

saipem

UNDEX CHARACTERIZATION AND FE MODEL VALIDATION

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



Cole Eq.:

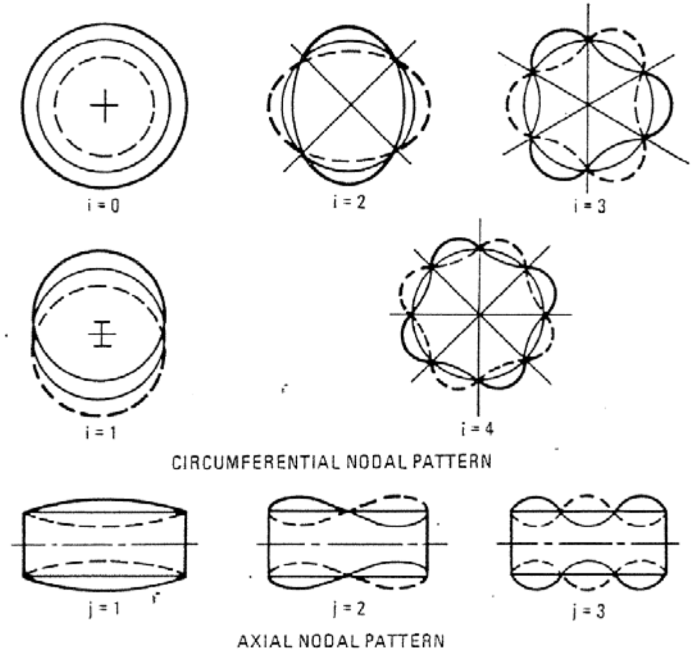
$$P_{bubble,\max} = 7084 \frac{W^{0.33}}{D}$$

OMAE 2011 – Petralia Eq.:

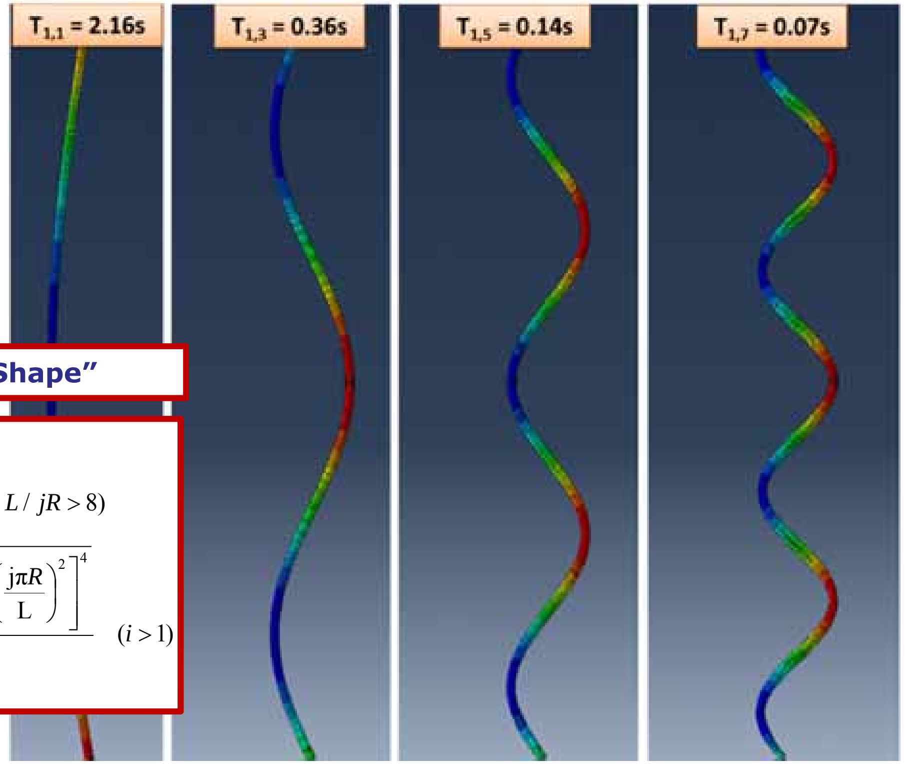
$$P_{bubble,\max} = 1.9 \frac{3}{4\pi} \frac{1}{D} \frac{W}{R_{\max}^{2}} \left(1 - \frac{0.1581 \cdot W^{0.25}}{R_{\max}^{0.75}} \right)$$

saipem

PIPELINE DYNAMIC RESPONSE – FEM VS. ANALYTICAL RESULTS



T_{ij} [s]	1,1	1,3	1,5	1,7
FEM	2.16	0.36	0.14	0.07
Analytic	2.39	0.26	0.10	0.05



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

$$\begin{cases} u_{i,j}(x,\theta) = A\cdot\cos(i\cdot\vartheta)\cdot\cos\left(\frac{j\pi R}{L}\right) \\ v_{i,j}(x,\theta) = B\cdot\sin(i\cdot\vartheta)\cdot\sin\left(\frac{j\pi R}{L}\right) \quad ,(i\geq 1) \\ w_{i,j}(x,\theta) = C\cdot\cos(i\cdot\vartheta)\cdot\sin\left(\frac{j\pi R}{L}\right) \end{cases}$$

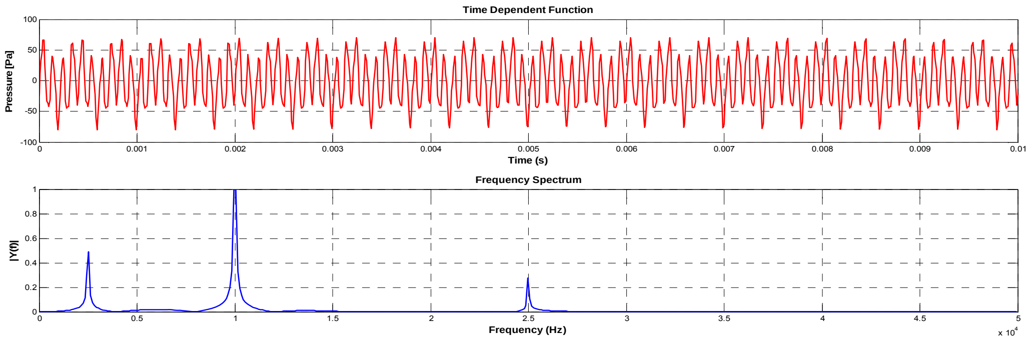
$$\lambda_{0,j} = 1 \quad (i=0 \quad and \quad L/jR > 8)$$

$$\lambda_{1,j} = \frac{j^2\pi^2(1-\upsilon^2)^{1/2}}{\sqrt{2}}\frac{R^2}{L^2} \quad (i=1 \quad and \quad L/jR > 8)$$

$$\lambda_{1,j} = \frac{\sqrt{(1-\upsilon^2)\cdot\left(\frac{j\pi R}{L}\right)^4 + \left(\frac{thk^2}{12R^2}\right)\left[i^2+\left(\frac{j\pi R}{L}\right)^2\right]^4}}{i^2+\left(\frac{j\pi R}{L}\right)^2} \quad (i>1)$$

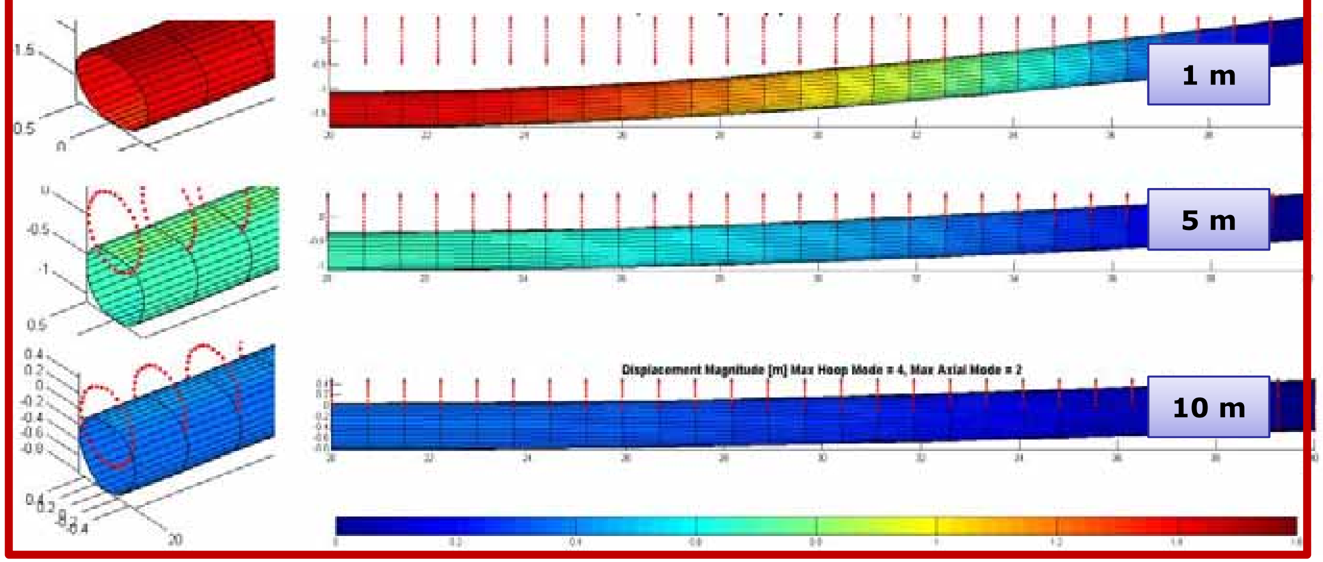
saipem

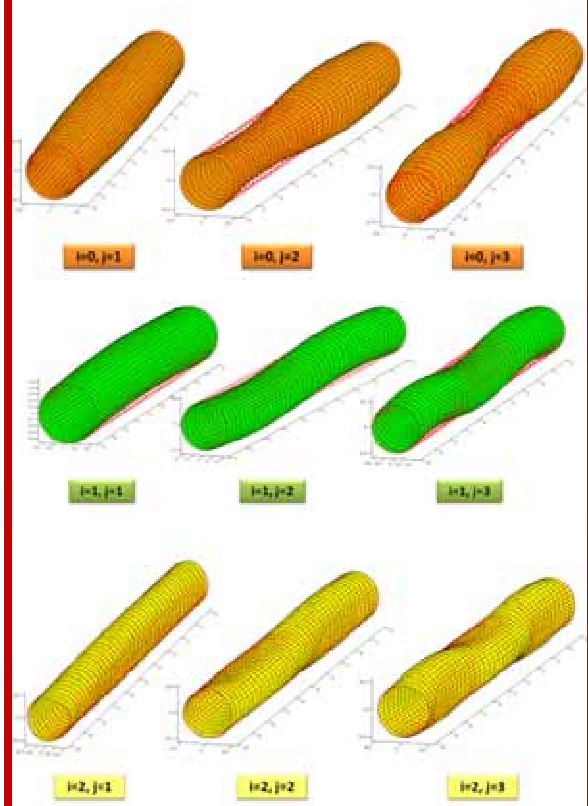
PIPELINE DYNAMIC RESPONSE – EXCITED NATURAL MODES



FREQUENCY SPECTRUM OF SHOCK WAVE (FFT)

PIPELINE RESPONSE





EXCITED PIPELINE NATURAL MODES

APPLICATION – PIPELINE BASIC DATA

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

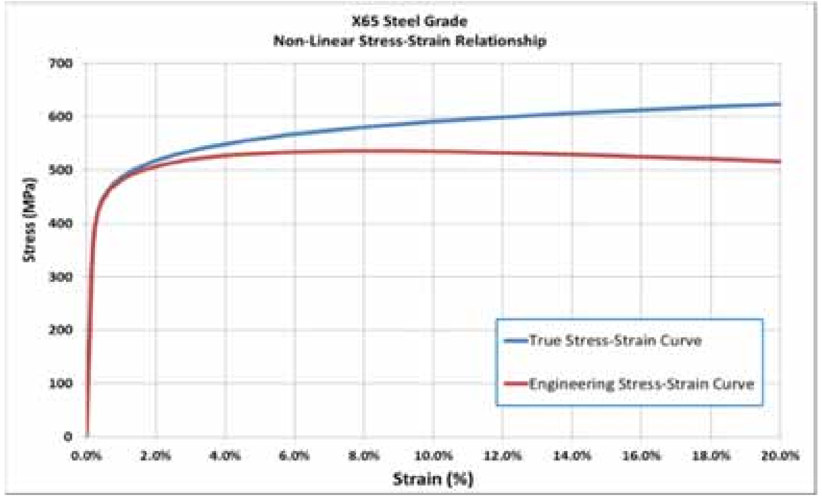
Pipeline Water Depth

- **WD = 744 m**

Two scenarios have been analysed:

- **Pint = 0**
- **Pint = Pdes = 145 barg**

Property	Units	Offshore 36" Pipe
Material Grade	-	L450
Specified Minimum Yield Stress at 20°C	MPa	450
Specified Minimum Tensile Stress at 20°C	MPa	535
Density	kg/m^3	7850
Coefficient of linear thermal expansion	$°C^{-1}$	1.16×10^{-5}
Young's Modulus	MPa	207×10^3
Poisson's Ratio	-	0.3



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

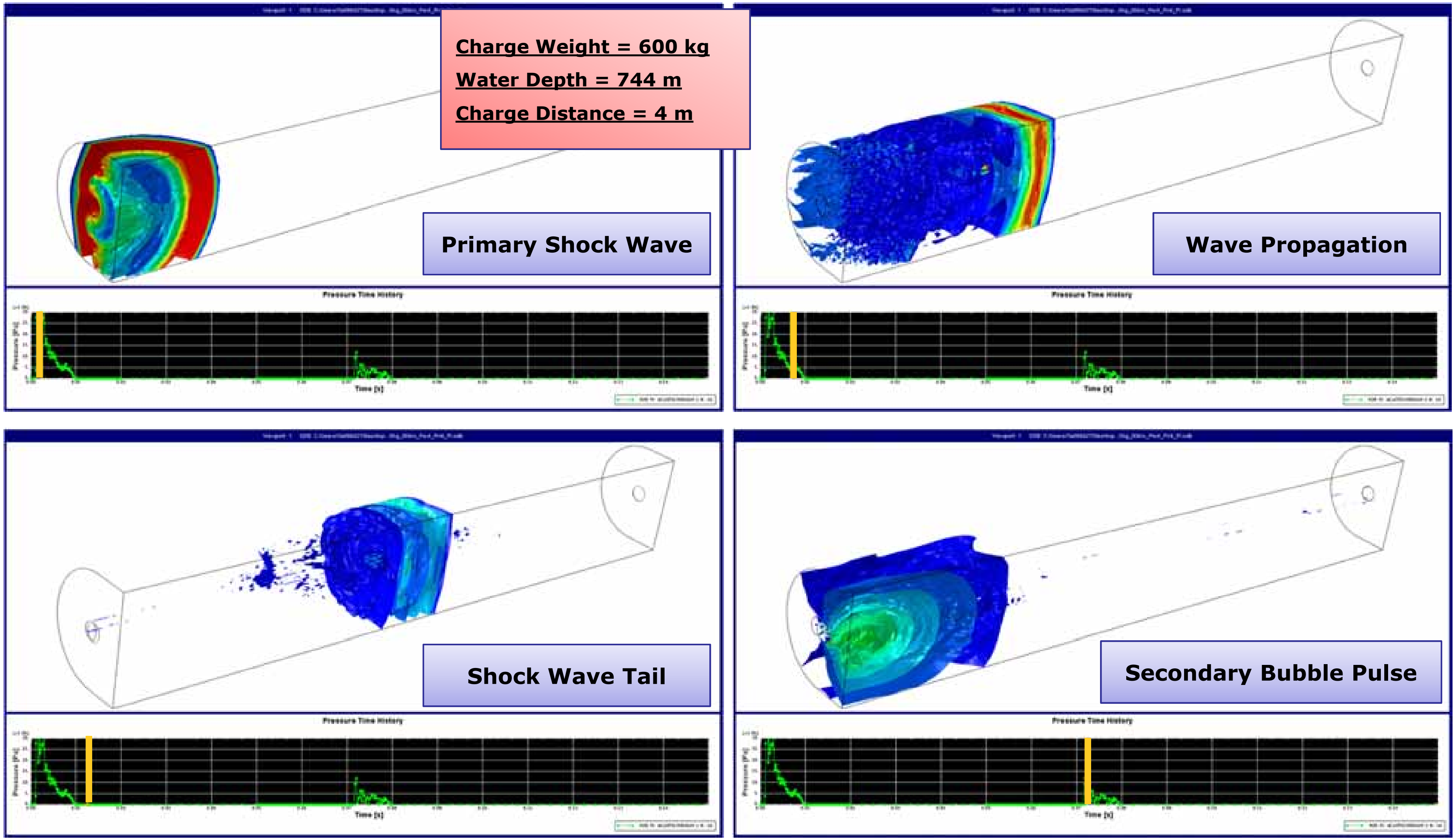
Assumed as Point Source in FE Model

Typical Torpedo used during the WW2

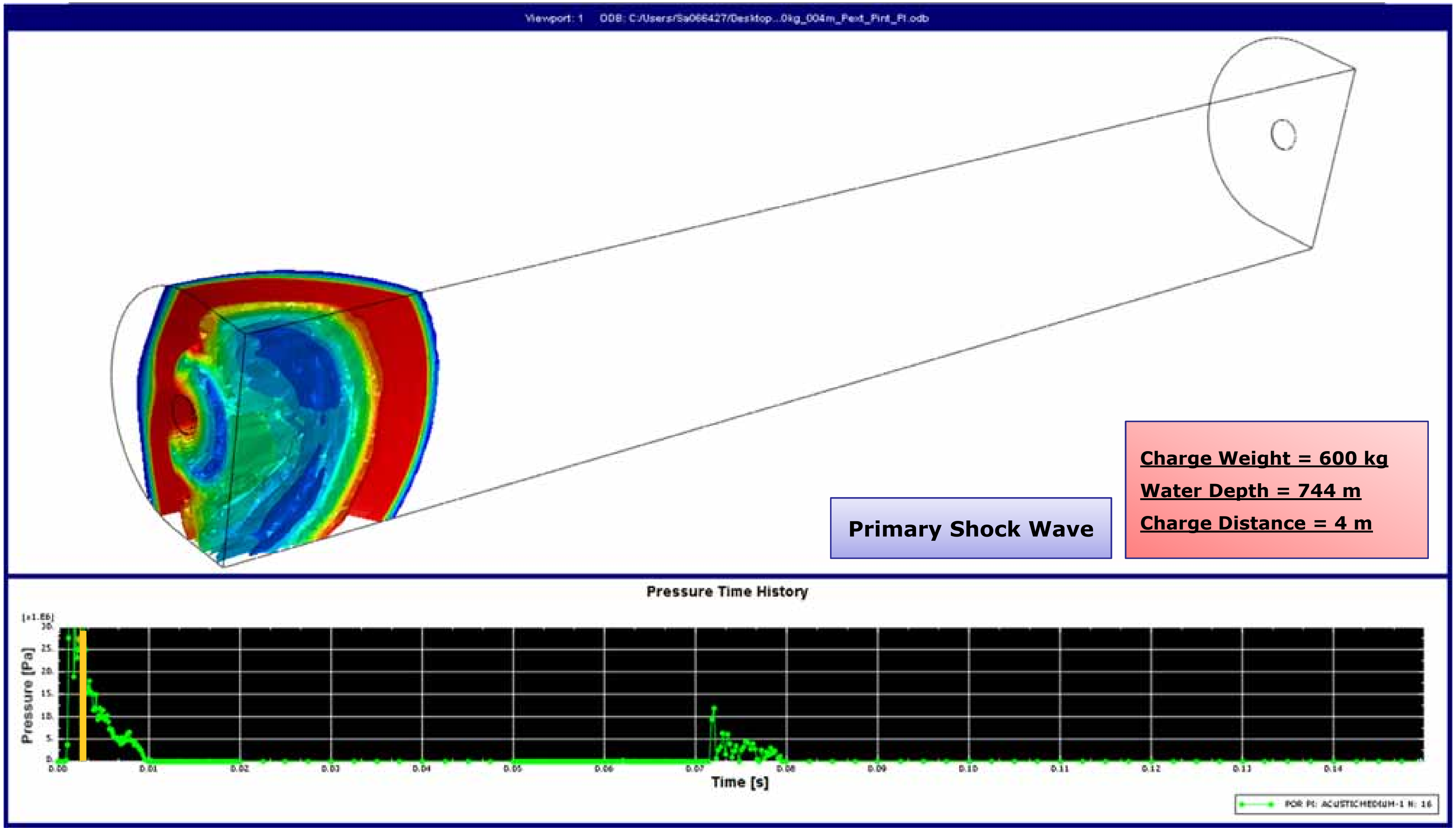
Geers-Hunter model	
Charge constant K	5.97e+07
Charge constant k	8.83e-05
Similitude spatial exponent A	0.13
Similitude temporal exponent B	0.18
Charge constant K_c	1.05e+09
Ratio of specific heats for explosion gas	1.27
Charge material density	1654

saipem

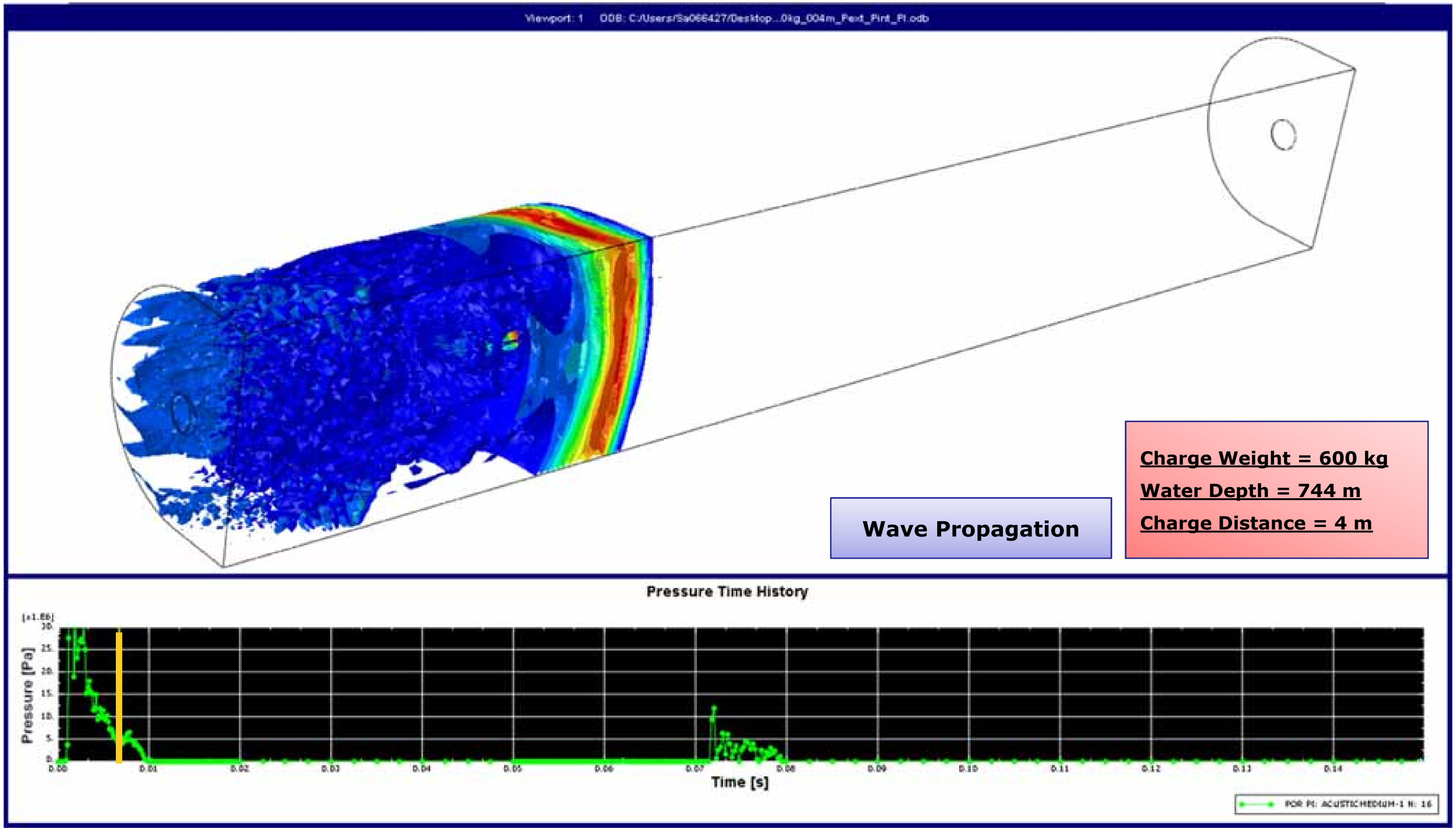
FEM STUDY RESULTS – UNDERWATER EXPLOSION



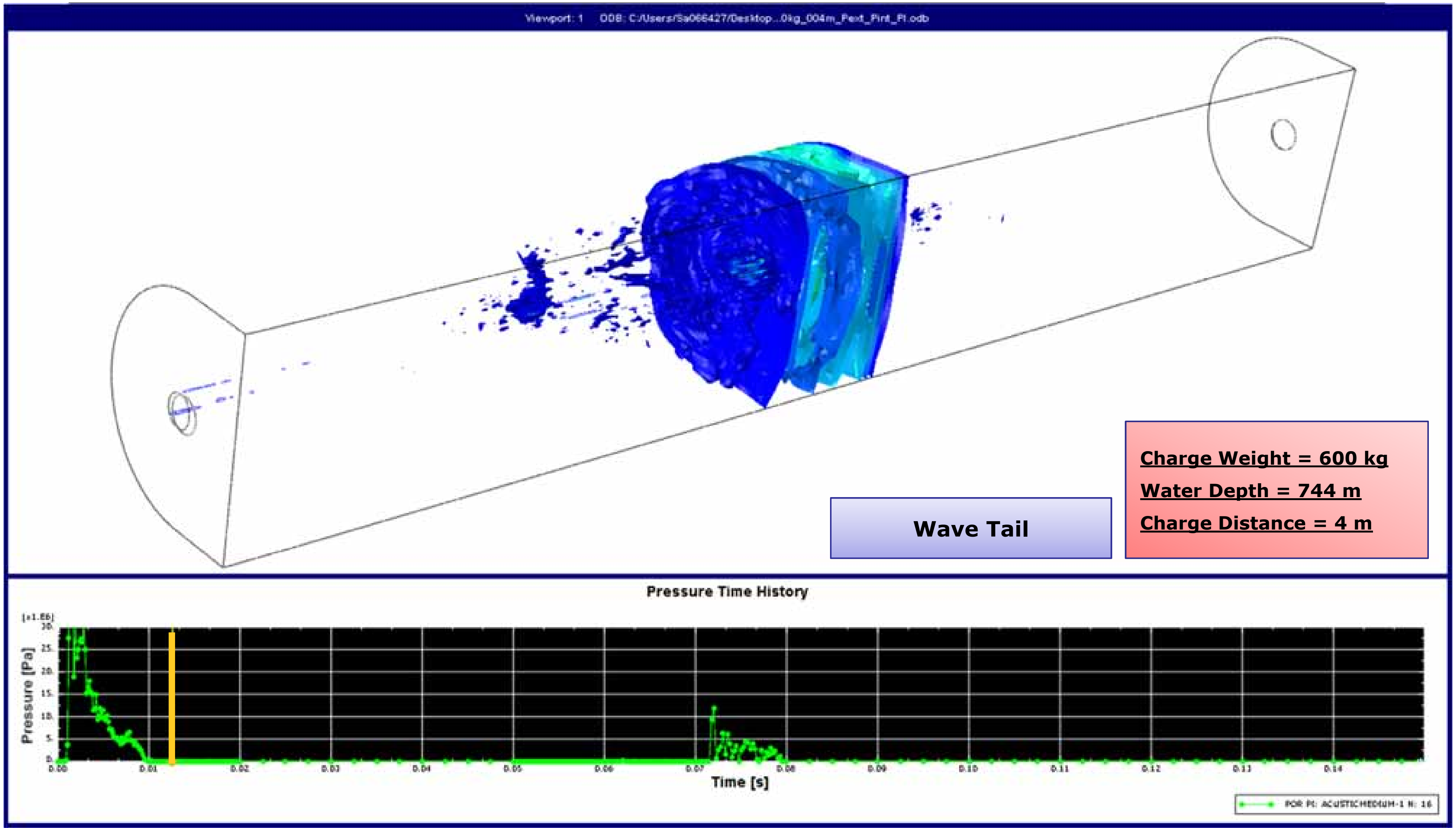
FEM STUDY RESULTS – UNDERWATER EXPLOSION



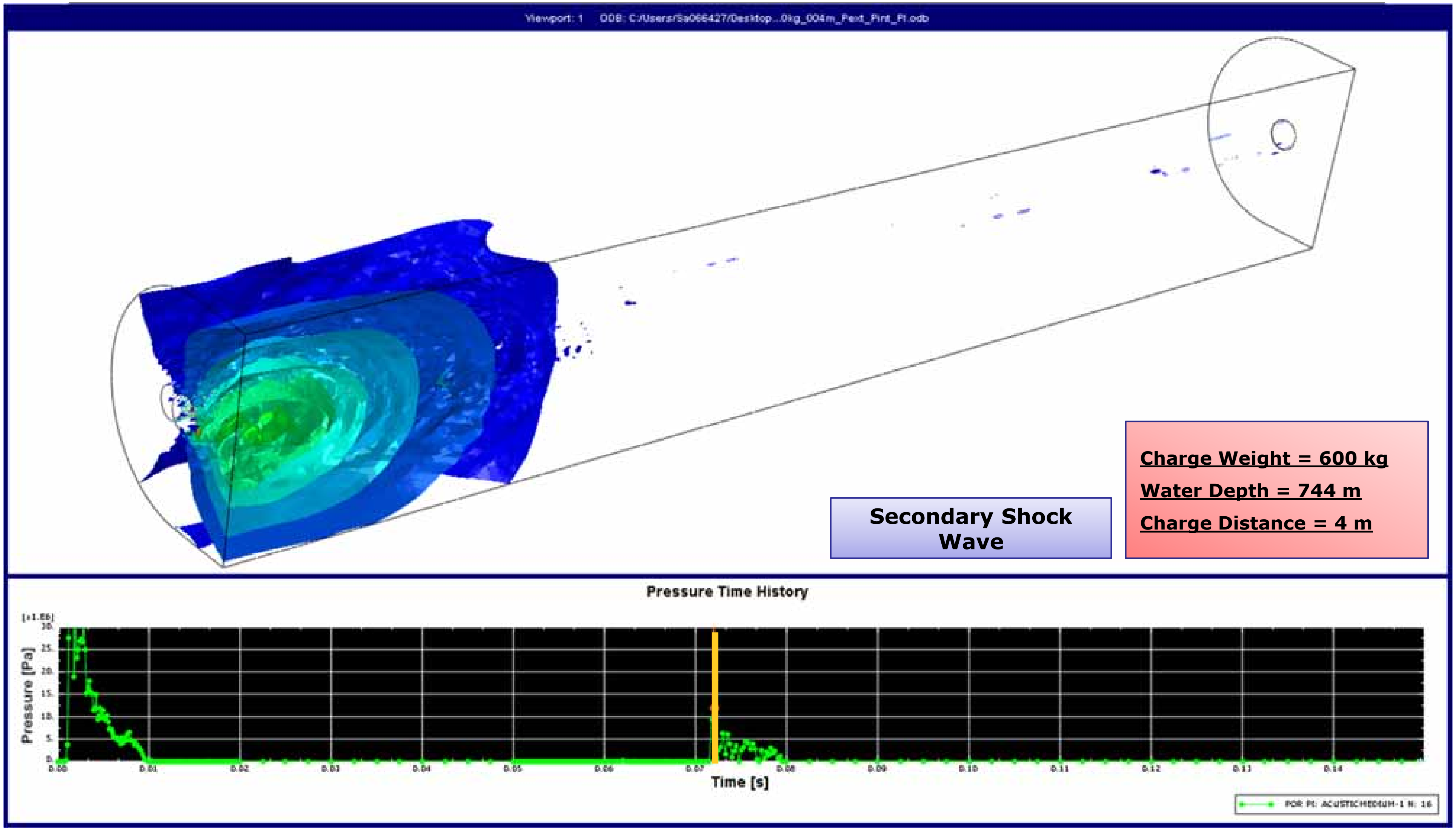
FEM STUDY RESULTS – UNDERWATER EXPLOSION



FEM STUDY RESULTS – UNDERWATER EXPLOSION



FEM STUDY RESULTS – UNDERWATER EXPLOSION

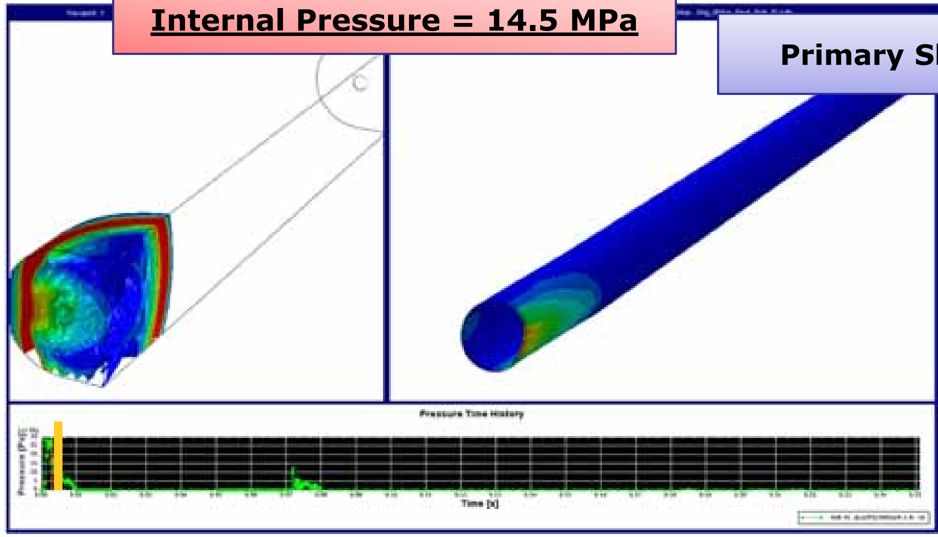


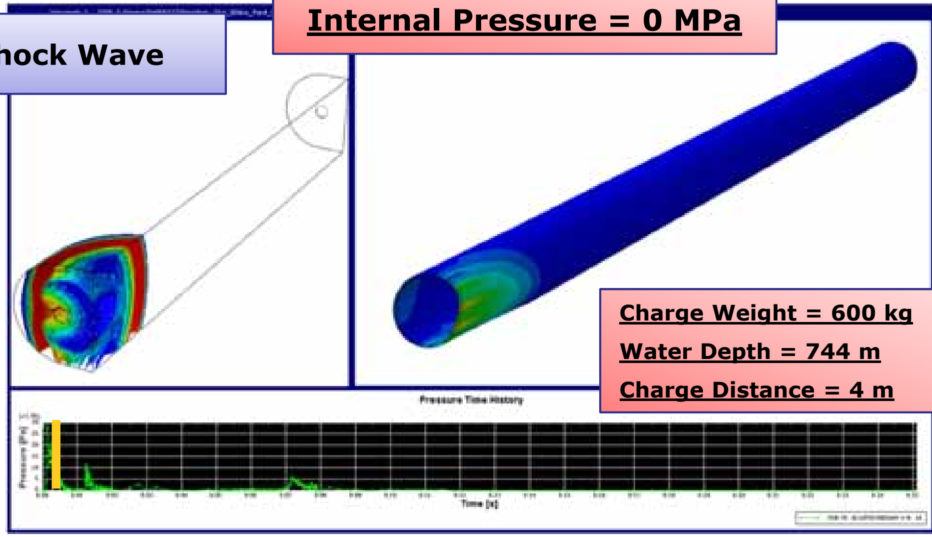
FEM STUDY RESULTS – PIPELINE DEFORMATION

Internal Pressure = 14.5 MPa

Primary Shock Wave

Internal Pressure = 0 MPa



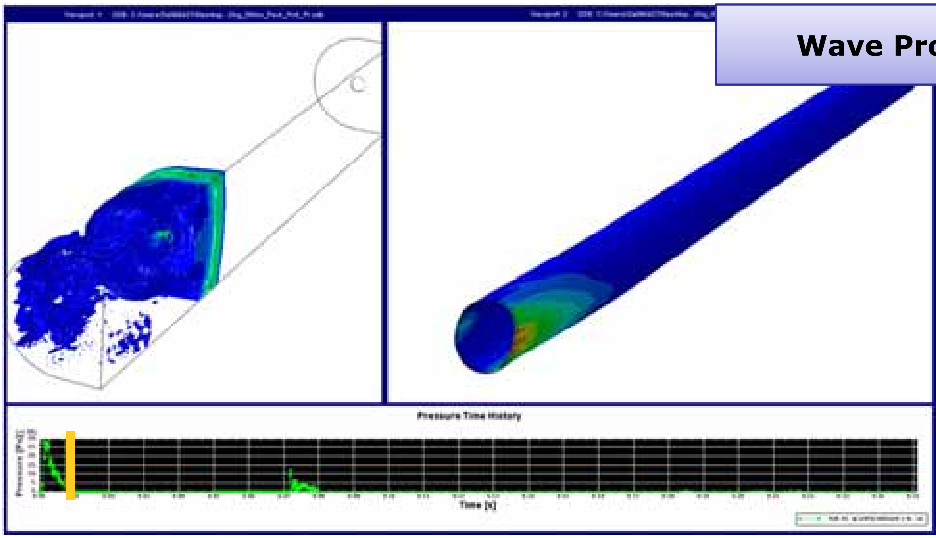


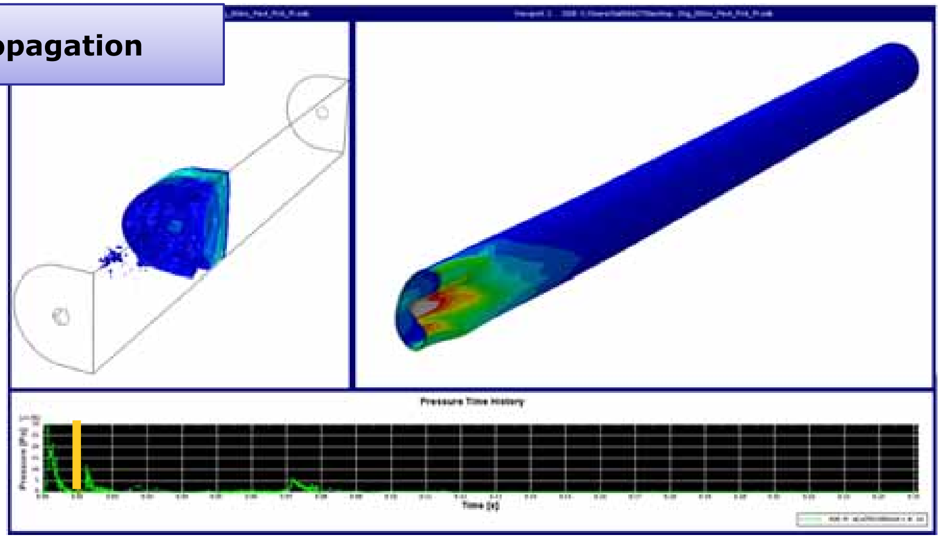
Charge Weight = 600 kg

Water Depth = 744 m

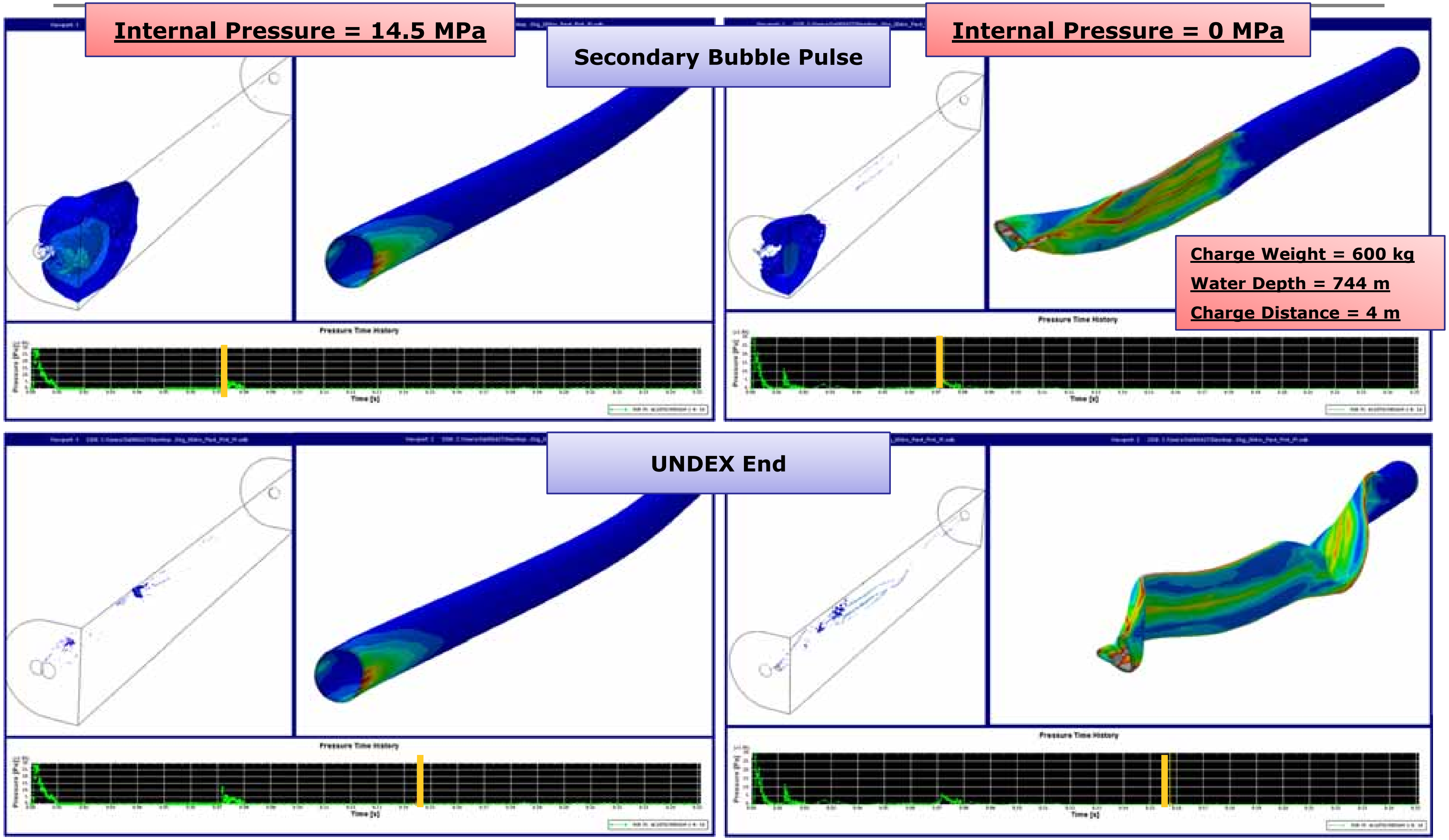
Charge Distance = 4 m

Wave Propagation



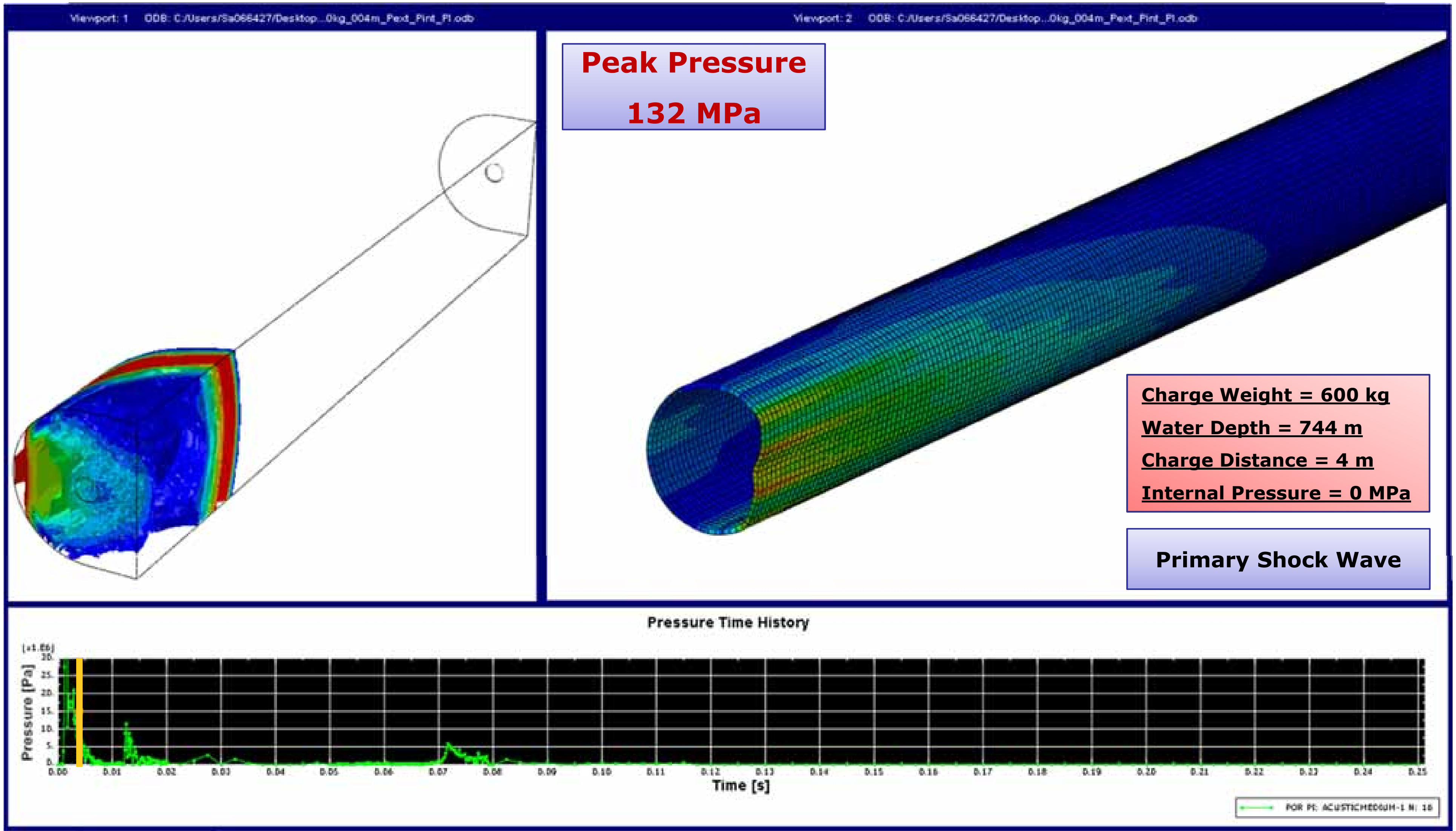


FEM STUDY RESULTS – PIPELINE DEFORMATION



FEM STUDY RESULTS – PIPELINE DEFORMATION

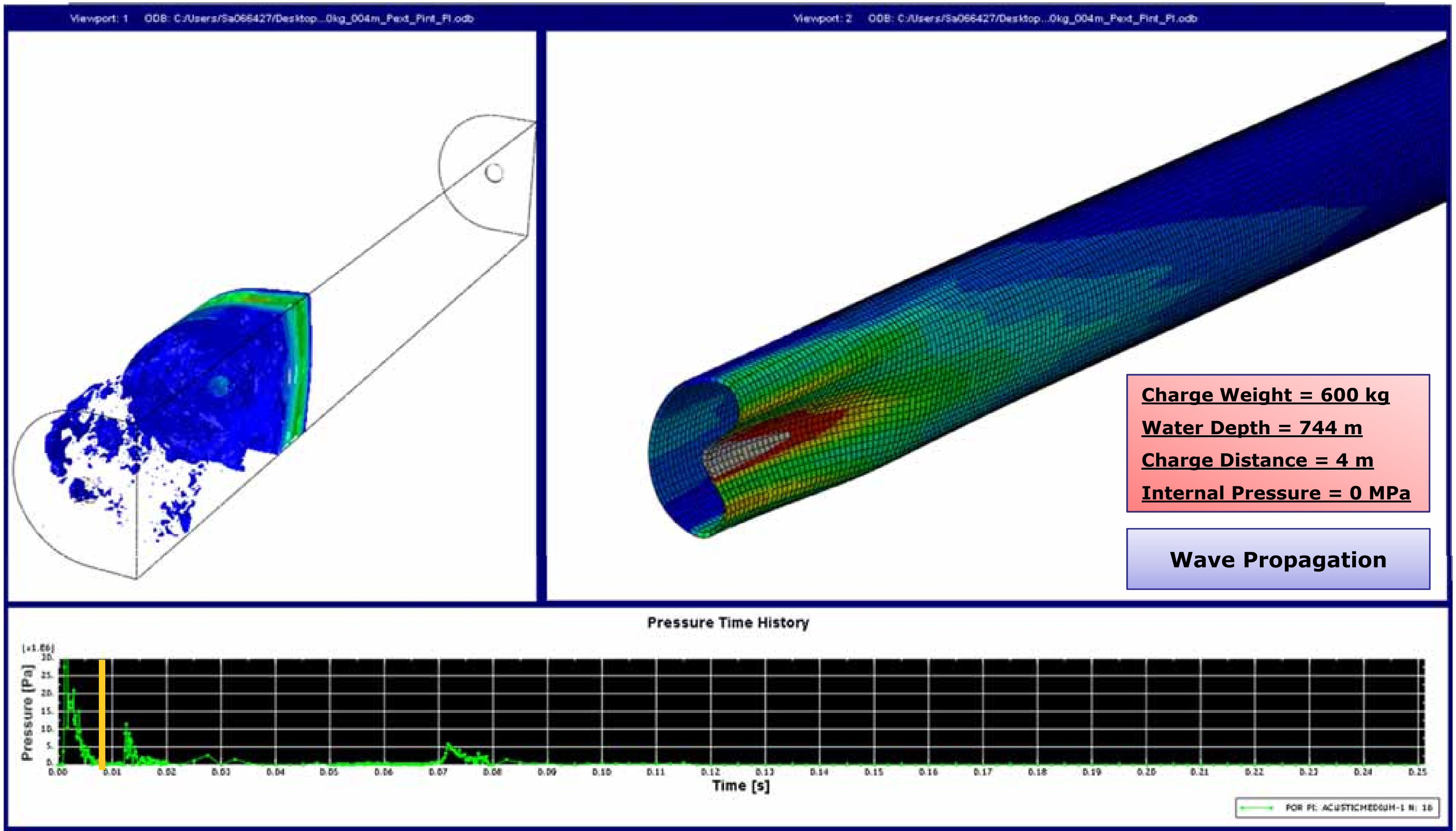
No Internal Pressure



saipem

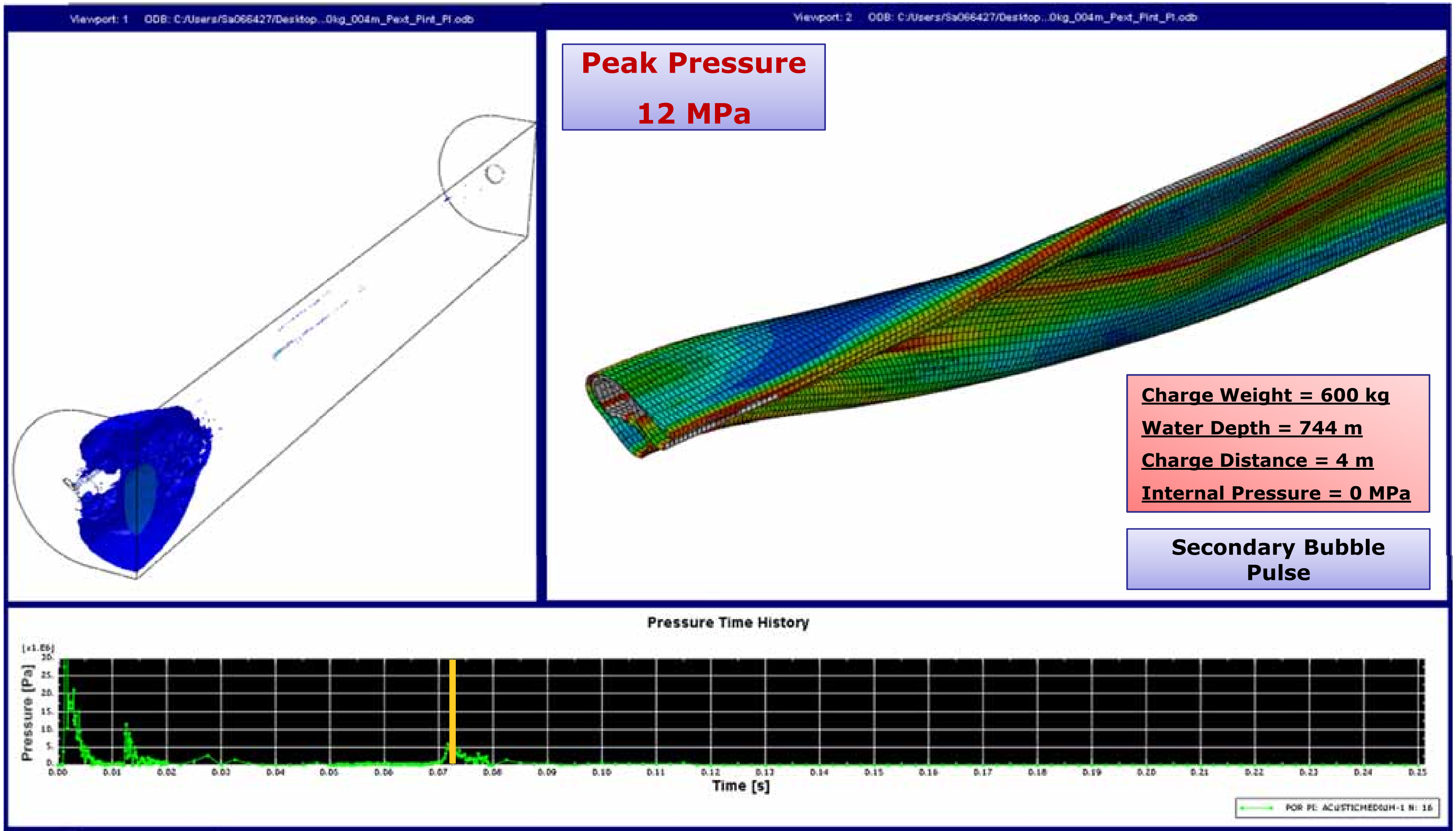
FEM STUDY RESULTS – PIPELINE DEFORMATION

No Internal Pressure



FEM STUDY RESULTS – PIPELINE DEFORMATION

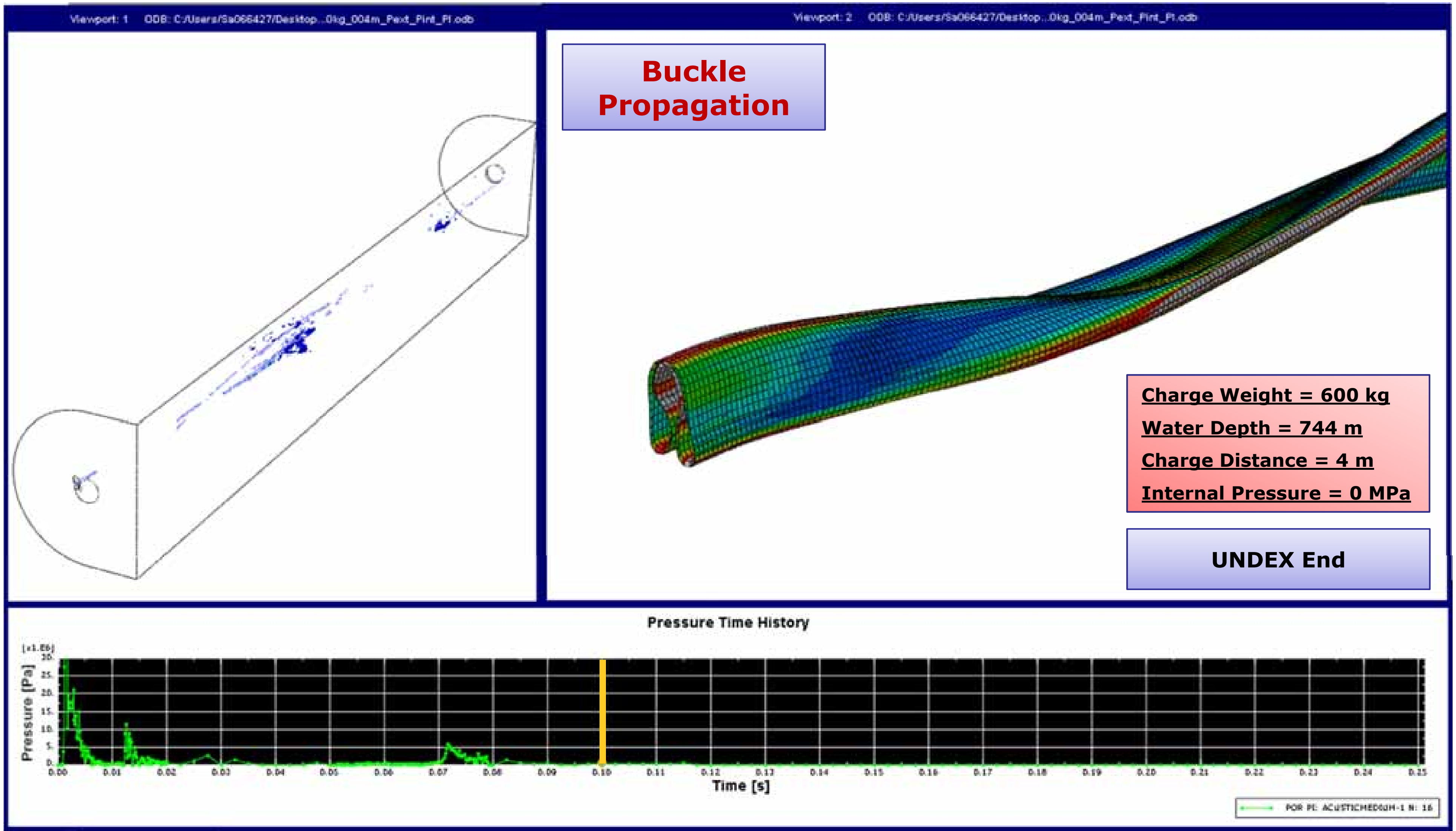
No Internal Pressure



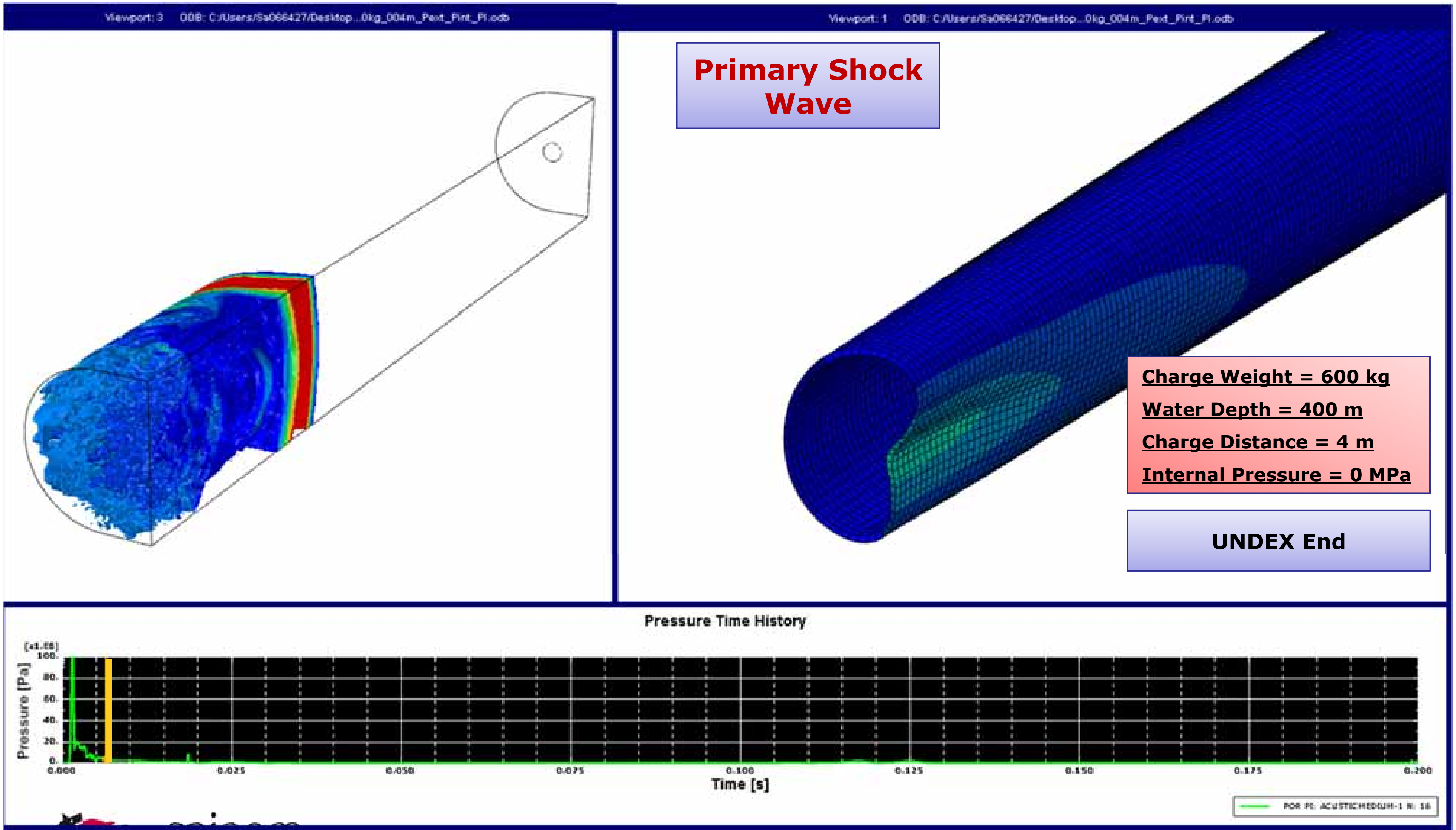
saipem

FEM STUDY RESULTS – PIPELINE DEFORMATION

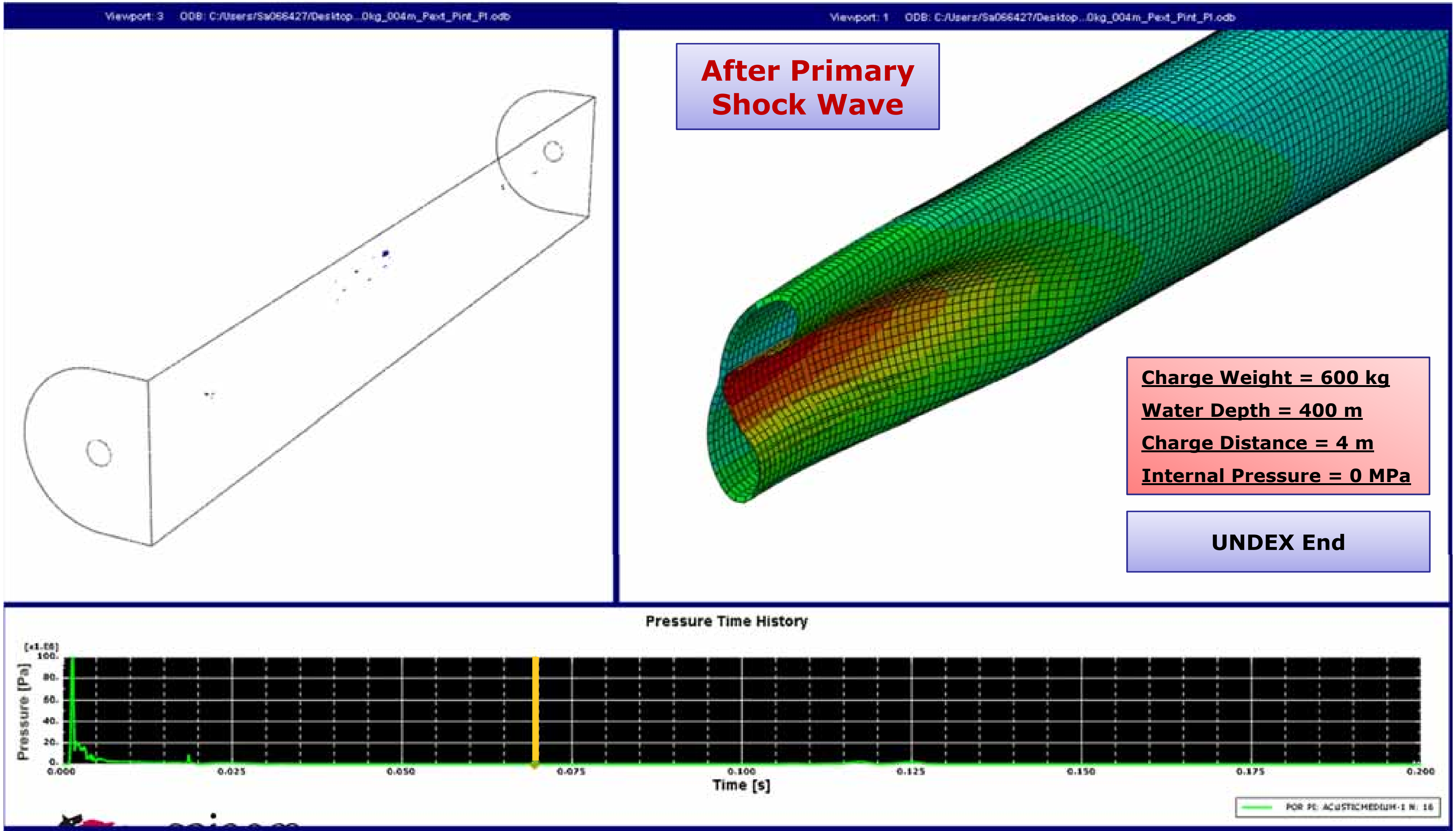
No Internal Pressure



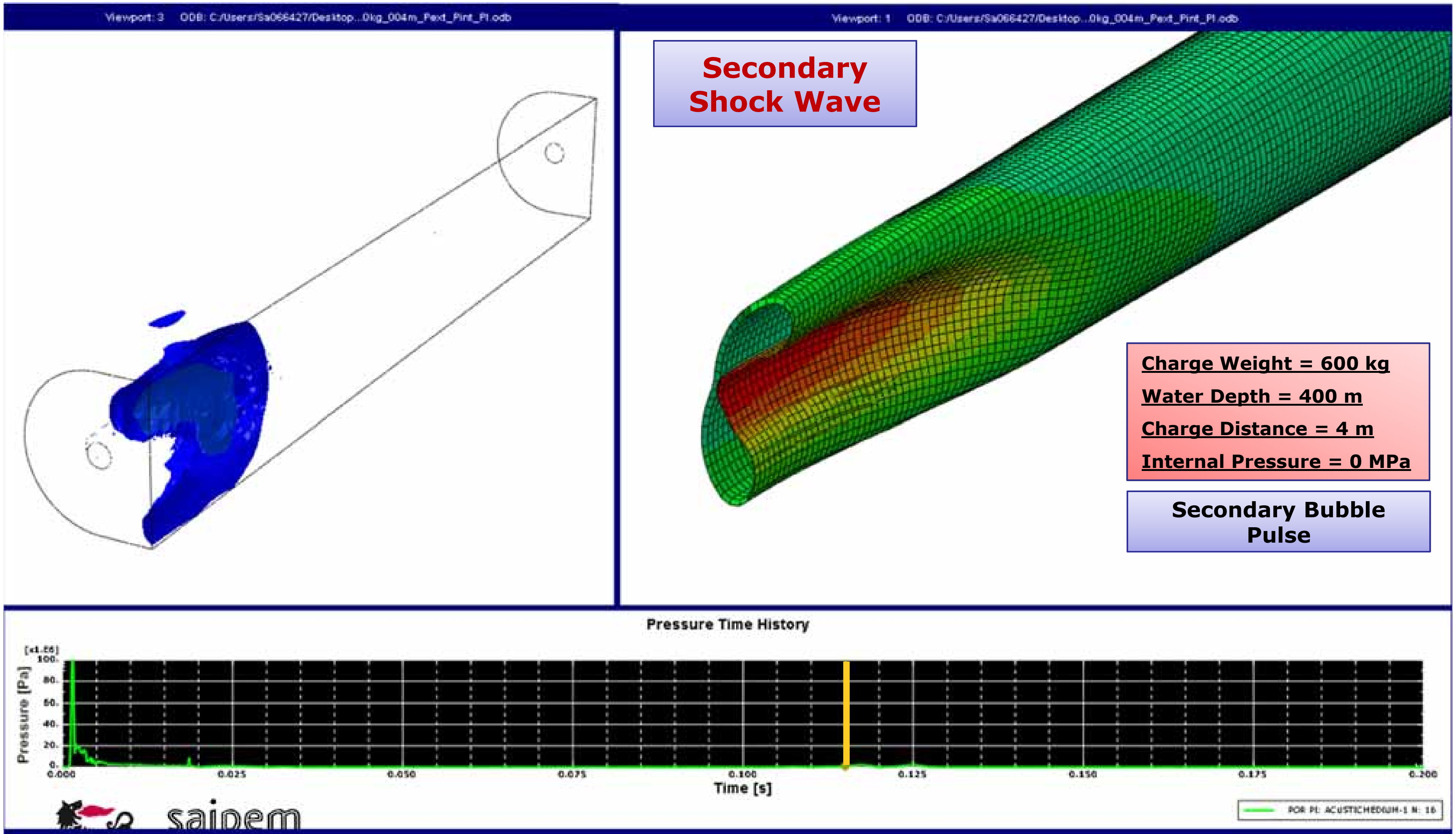
FEM STUDY RESULTS – PIPELINE DEFORMATION
No Internal Pressure



FEM STUDY RESULTS – PIPELINE DEFORMATION
No Internal Pressure

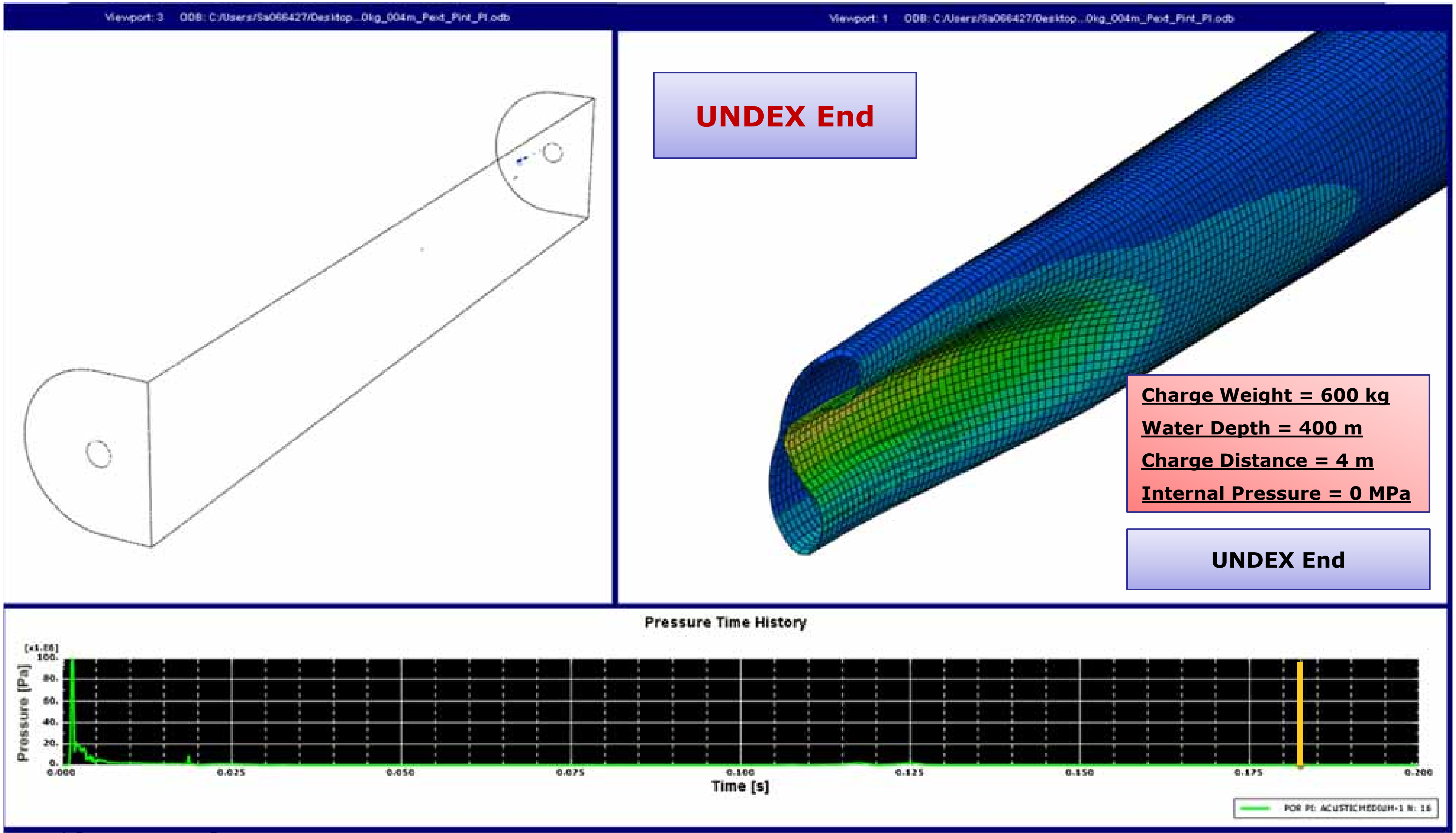


FEM STUDY RESULTS – PIPELINE DEFORMATION
No Internal Pressure

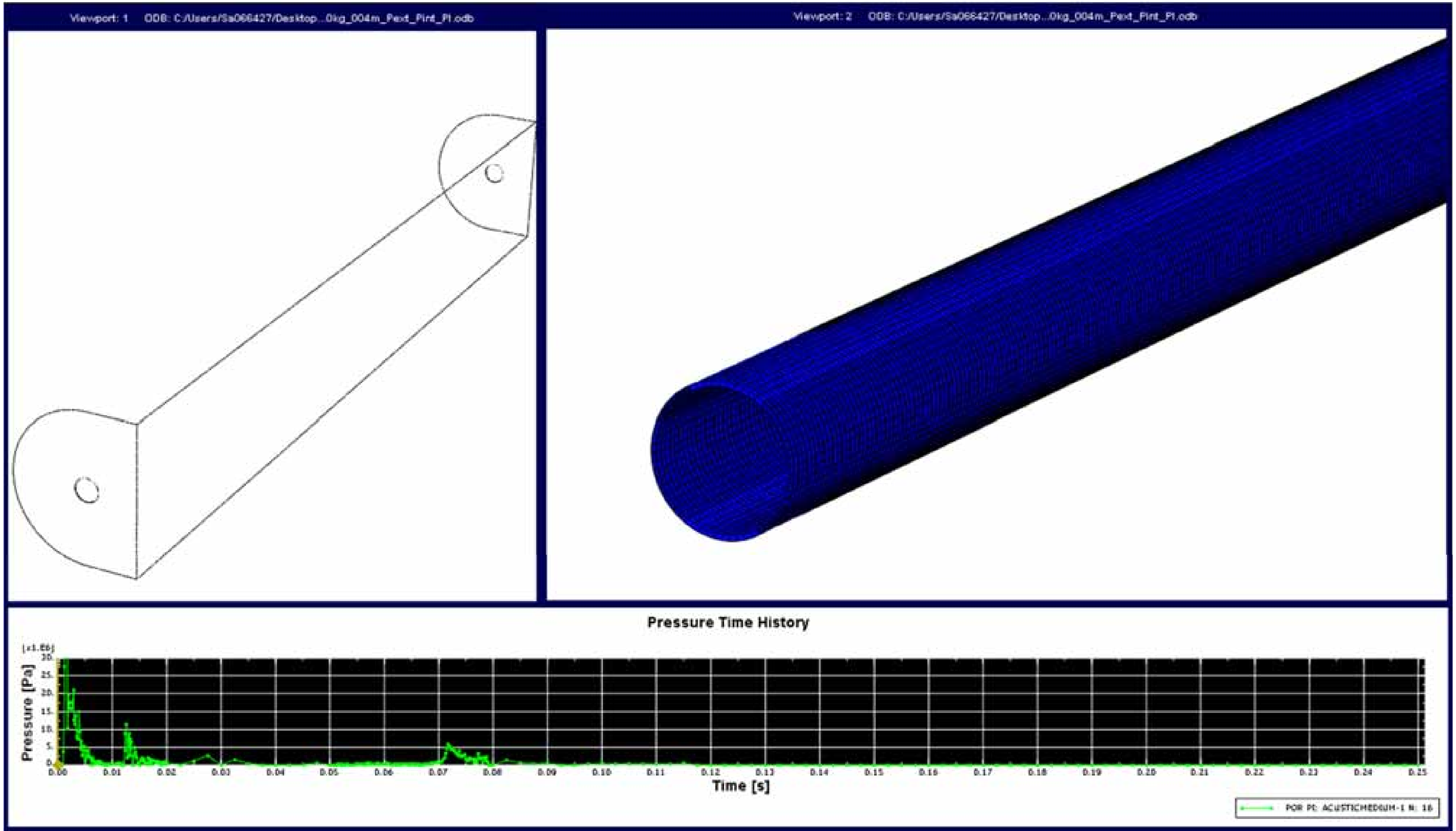


FEM STUDY RESULTS – PIPELINE DEFORMATION

No Internal Pressure



FEM STUDY RESULTS – PIPELINE DEFORMATION



UNDEX – FEM STUDY RESULTS – SUMMARY

Charge Weight = 300 kg — Internal Pressure = 0 barg

Charge Distance (m)	Ovalisat. (%)		Dent (mm)		Dent / Diameter (%)		Longit. Strain (%)		Hoop Strain (%)		Eq. Plastic Strain (%)	Von Mises Stress (MPa)		Max Displ. (m)
	Max	Res	Max	Res	Max	Res	Max	Res	Max	Res	Max	Max	Res	Max
4	11.2	7.7	73	56	8.0	6.2	0.8	0.4	6.3	6.1	7.2	575	411	0.25
5	7.2	4.4	42	29	4.6	3.2	0.6	0.3	3.3	3.1	3.5	544	266	0.18
7.5	4.9	3.2	21	13	2.3	1.4	0.3	0.1	0.9	0.8	0.8	481	178	0.06
10	3.2	2.3	11	6	1.2	0.7	0.1	0.0	0.4	0.3	0.2	441	148	0.04
20	1.5	1.2	2	1	0.3	0.1	0.1	0.0	0.2	0.1	0.0	330	121	0.01
40	1.2	1.0	1	0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	208	114	0.00
130	1.1	1.0	0	0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	126	104	0.00

Charge Weight = 300 kg — Internal Pressure = 145 barg

Charge Distance (m)	Ovalisat. (%)		Dent (mm)		Dent / Diameter (%)		Longit. Strain (%)		Hoop Strain (%)		Eq. Plastic Strain (%)	Von Mises Stress (MPa)		Max Displ. (m)
	Max	Res	Max	Res	Max	Res	Max	Res	Max	Res	Max	Max	Res	Max
4	6.4	3.4	37	23	4.1	2.5	0.6	0.2	3.6	3.3	4.1	550	302	0.28
5	4.5	2.7	21	12	2.3	1.3	0.3	0.2	1.7	1.4	1.7	514	239	0.16
7.5	2.5	1.7	8	3	0.9	0.4	0.2	0.0	0.4	0.1	0.2	439	144	0.07
10	2.0	1.1	5	1	0.6	0.1	0.2	0.0	0.2	0.0	0.1	385	164	0.05
20	1.5	1.1	2	0	0.3	0.0	0.1	0.0	0.1	0.0	0.0	206	94	0.01
40	1.2	1.0	1	0	0.1	0.0	0.1	0.0	0.1	0.1	0.0	144	100	0.00
130	1.1	1.0	0	0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	108	93	0.00

SLS Oval.   SLS Dent   ULS   96% SMYS

UNDEX – FEM STUDY RESULTS – SUMMARY

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

Charge Distance (m)	Ovalisat. (%)		Dent (mm)		Dent / Diameter (%)		Longit. Strain (%)		Hoop Strain (%)		Eq. Plastic Strain (%)	Von Mises Stress (MPa)		Max Displ. (m)
	Max	Res	Max	Res	Max	Res	Max	Res	Max	Res	Max	Max	Res	Max
4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
5	22.0	**20.6**	137	130	15.1	**14.4**	0.8	0.5	10.1	10.0	**11.7**	**597**	323	0.54
7.5	6.9	**4.2**	37	25	4.1	**2.7**	0.5	0.2	2.4	2.2	**2.5**	**530**	199	0.22
10	5.2	**3.6**	23	15	2.5	**1.7**	0.4	0.2	1.0	0.8	**0.8**	**485**	125	0.08
20	1.7	**1.1**	4	1	0.4	**0.1**	0.2	0.0	0.2	0.1	**0.3**	**374**	84	0.02
40	1.3	**1.1**	2	0	0.2	**0.0**	0.1	0.0	0.1	0.1	**0.0**	**250**	116	0.01
130	1.1	**1.0**	0	0	0.1	**0.0**	0.0	0.0	0.1	0.0	**0.0**	**137**	102	0.00

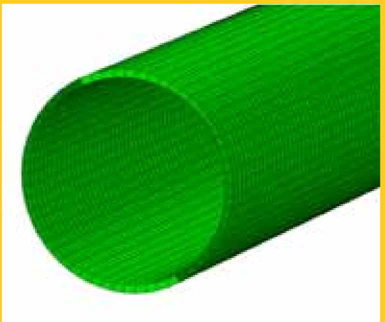
Charge Weight = 600 kg **Internal Pressure = 145 barg**

Charge Distance (m)	Ovalisat. (%)		Dent (mm)		Dent / Diameter (%)		Longit. Strain (%)		Hoop Strain (%)		Eq. Plastic Strain (%)	Von Mises Stress (MPa)		Max Displ. (m)
	Max	Res	Max	Res	Max	Res	Max	Res	Max	Res	Max	Max	Res	Max
4	14.4	**5.4**	100	56	11.1	**6.2**	1.1	0.7	10.7	9.8	**13.2**	**600**	377	0.77
5	7.4	**3.3**	46	26	5.1	**2.9**	0.7	0.3	4.5	4.1	**5.2**	**561**	193	0.45
7.5	3.8	**2.6**	16	9	1.7	**1.0**	0.3	0.1	1.0	0.7	**1.0**	**489**	158	0.18
10	2.5	**1.6**	8	3	0.9	**0.3**	0.2	0.1	0.4	0.1	**0.2**	**431**	133	0.09
20	1.6	**1.1**	3	0	0.4	**0.0**	0.1	0.0	0.1	0.1	**0.0**	**244**	100	0.02
40	1.3	**1.0**	2	0	0.2	**0.0**	0.1	0.0	0.1	0.0	**0.0**	**163**	107	0.01
130	1.1	**1.0**	1	0	0.1	**0.0**	0.0	0.0	0.1	0.0	**0.0**	**111**	93	0.00

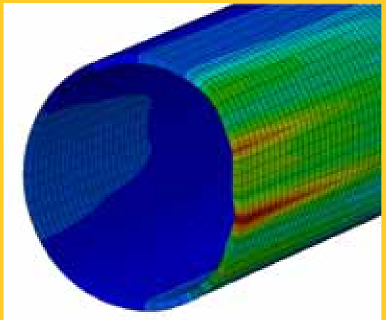
SLS Oval. SLS Dent ULS 96% SMYS

UNDEX – FEM STUDY – CONCLUSIONS

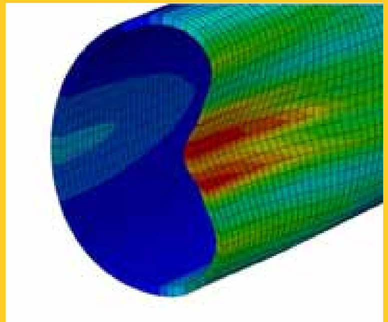
CHARGE FAR FROM THE STRUCTURE	CHARGE CLOSE TO THE STRUCTURE	CHARGE VERY CLOSE TO THE STRUCTURE
Distance >> 20 m	20 m > Distance > R_{bubble}	Distance < R_{bubble}
PRIMARY SHOCK WAVE	PRIMARY SHOCK WAVE + SECONDARY SHOCK WAVES (No Interaction with Gas Bubble)	PRIMARY SHOCK WAVE + SECONDARY SHOCK WAVES + WATER JETTING (Interaction with Gas Bubble)
LOW or UNEXISTENT RISK	NEED OF INTEGRITY ASSESSMENT	HIGH RISK



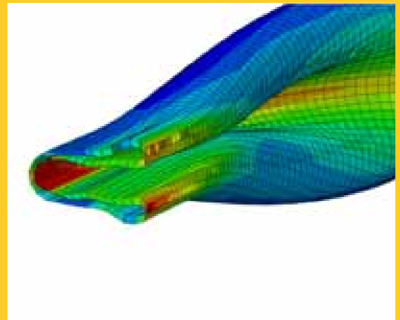
UNDAMAGED PIPE



DENTED PIPE (SERVICEABILITY OK)



DENTED PIPE (SERVICEABILITY TO BE ASSESSED)



BROKEN/HEAVY DAMAGED/FLATTENED

ANALYTIC

DETAIL FEM ANALYSIS

- UXO Removal
- UXO Neutralization
- Pipeline Route Modification

saipem

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