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Exploitation of Meta-material Concepts for the Resilience of Infrastructures and Systems towards Multiple Hazardous Events

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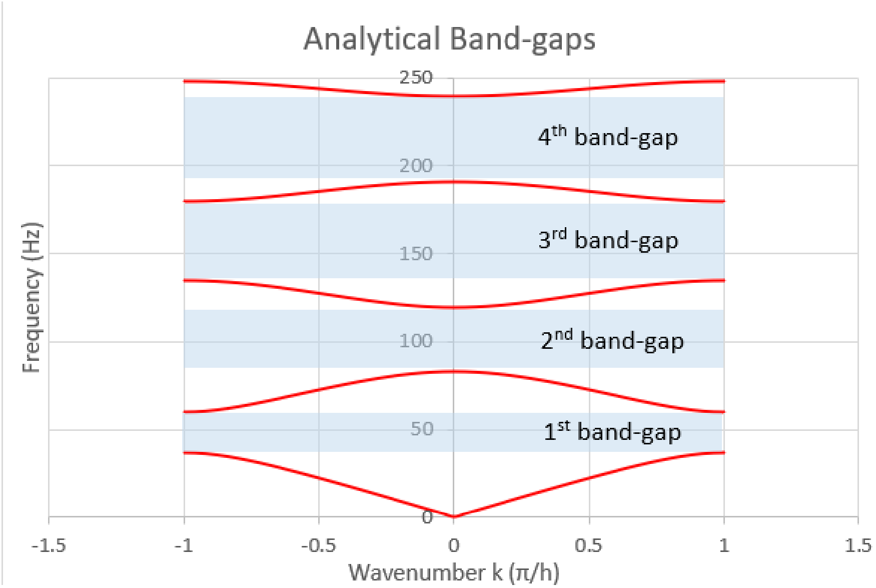
Meta-materials: a definition

A **metamaterial** is any material engineered to have a property that is not found in naturally occurring materials. They are made from assemblies of multiple elements fashioned from composite materials such as metals and plastics, usually arranged in repeating patterns. A key design characteristic is the **periodicity of their structure**.

Their main characteristic is the ability to manipulate waves (via the creation of the **band-gaps**), and this is their novelty, as they can practically **isolate** the structures from **dynamic-nature hazards**. The band-gaps are considered as attenuation or mitigation zones for specific frequency ranges of the transmitted waves.

It can be potentially implemented as design methodology to various problems, from low-vibration effects and shocks to earthquakes and road/railway sustainable design.

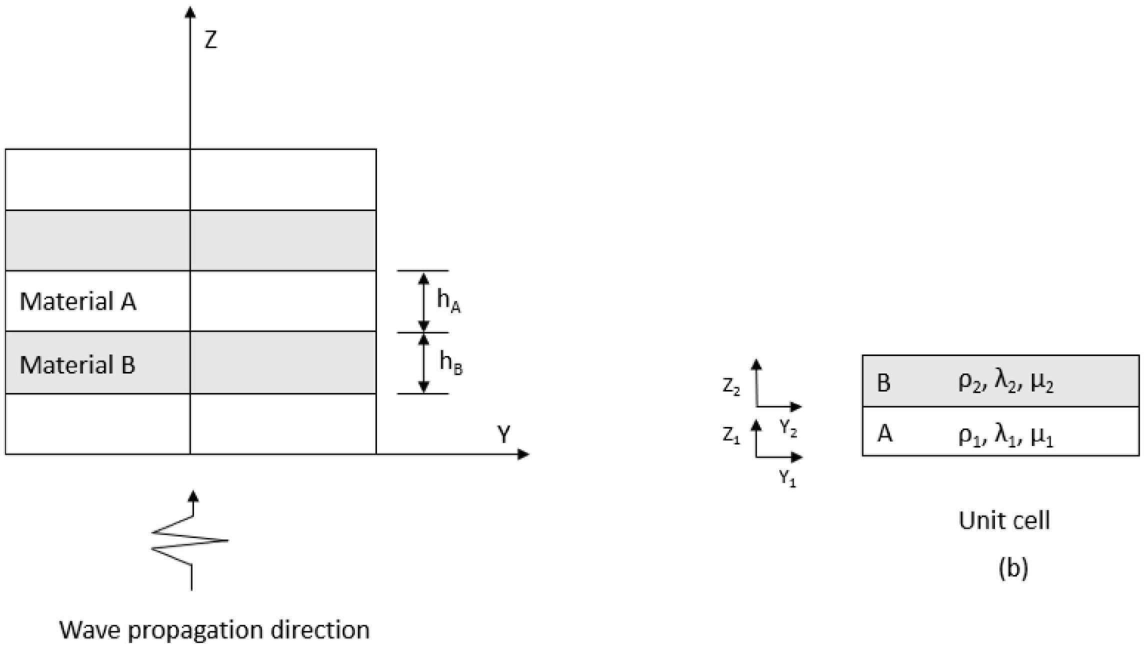
Meta-materials: band-gaps



The band-gaps are expressed in **frequency terms** and via the **dispersion relationship**.

The adopted methodology for their calculation is the **Periodic materials' theory**

Periodic materials' theory (for 1D)



- based on the resolution of **equation of motion for each layer**:

$$\frac{\partial^2 u_i}{\partial t^2} = C_i^2 \frac{\partial^2 u_i}{\partial {z_i}^2}$$

- **wave equations:**

$$u_i(z_i) = A_i \sin(\omega z_i / C_i) + B_i \cos(\omega z_i / C_i)$$

$$\tau_i(z_i) = \mu_i \partial u_i / \partial z_i = \mu_i \omega \left[A_i \cos(\omega z_i / C_{ti}) - B_i \sin(\omega z_i / C_{ti}) \right] / C_{ti}$$

- **Boundary Conditions (Bloch-Floquet):**

$$u_1(h_1) = u_2(0),\ \tau_1(h_1) = \tau_2(0)$$

$$u_1(0) e^{jk \cdot h} = u_2(h_2),\ \tau_1(0) e^{jk \cdot h} = \tau_2(h_2)$$

Periodic materials' theory (for 1D)

- **System solution:**

$$\begin{bmatrix} \sin(\omega h_1/C_{t1}) & \cos(\omega h_1/C_{t1}) & 0 & -1 \\ \mu_1 C_{t2}\cos(\omega h_1/C_{t1}) & -\mu_1 C_{t2}\sin(\omega h_1/C_{t1}) & -\mu_2 C_{t1} & 0 \\ 0 & e^{jk\cdot h} & -\sin(\omega h_2/C_{t2}) & -\cos(\omega h_2/C_{t2}) \\ \mu_1 C_{t2}\cdot e^{jk\cdot h} & 0 & -\mu_2 C_{t1}\cos(\omega h_2/C_{t2}) & \mu_2 C_{t1}\sin(\omega h_2/C_{t2}) \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \\ A_2 \\ B_2 \end{bmatrix} = 0$$

- **dispersion relationship:**

$$\cos(k\times h) = \cos\left(\frac{\omega h_1}{C_{t1}}\right)\cos\left(\frac{\omega h_2}{C_{t2}}\right) - \frac{1}{2}\left(\frac{\rho_1 C_{t1}}{\rho_2 C_{t2}} + \frac{\rho_2 C_{t2}}{\rho_1 C_{t1}}\right)\sin\left(\frac{\omega h_1}{C_{t1}}\right)\sin\left(\frac{\omega h_2}{C_{t2}}\right)$$

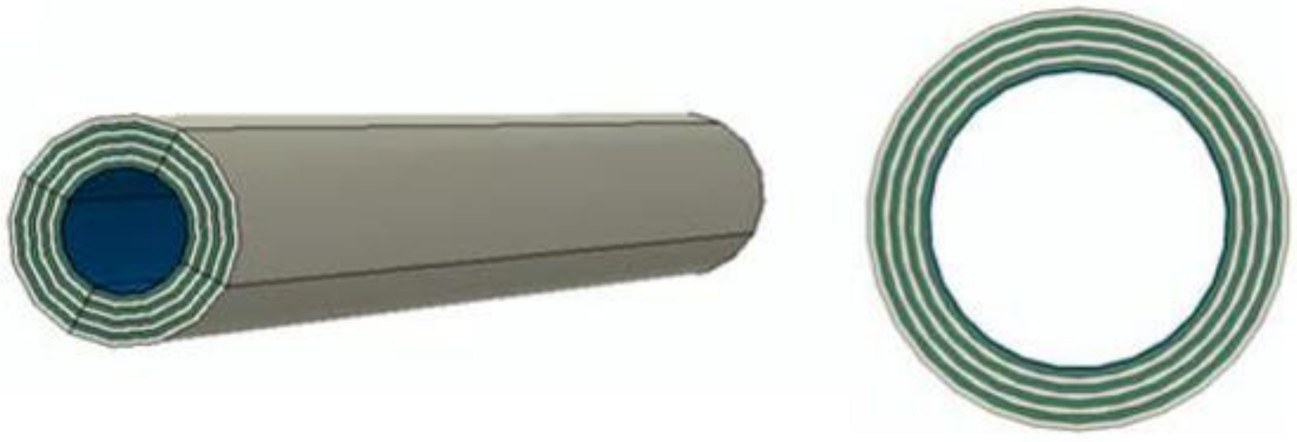
Meta-material Layout for the Blast Protection of Pipes towards explosions

Materials Used as Periodic Layers:

Polyurethane foam: 5cm

Rubber: 5cm

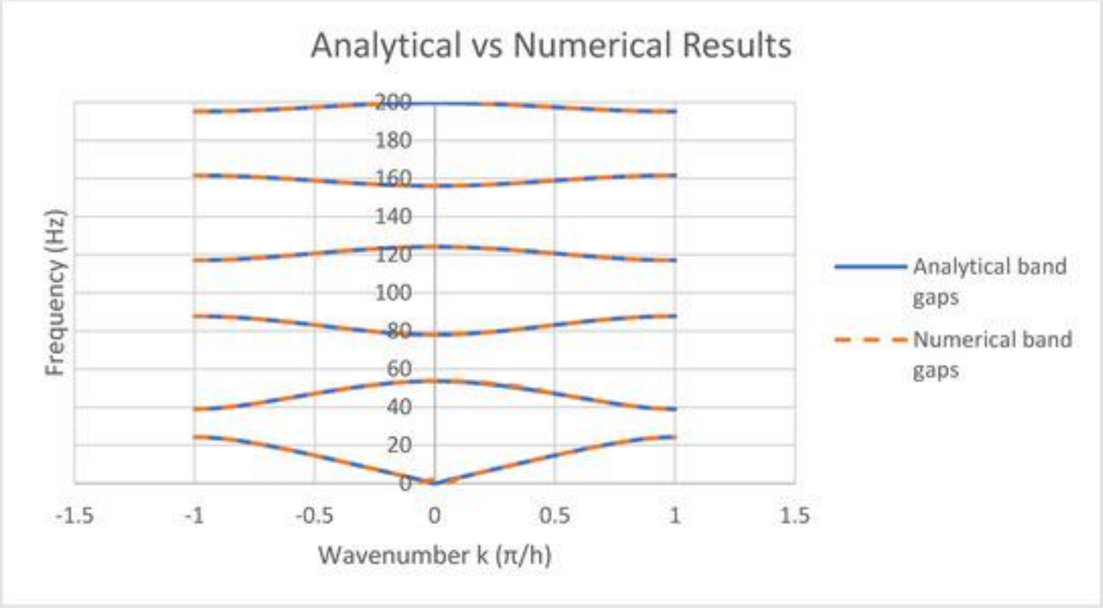
Total thickness: 40cm

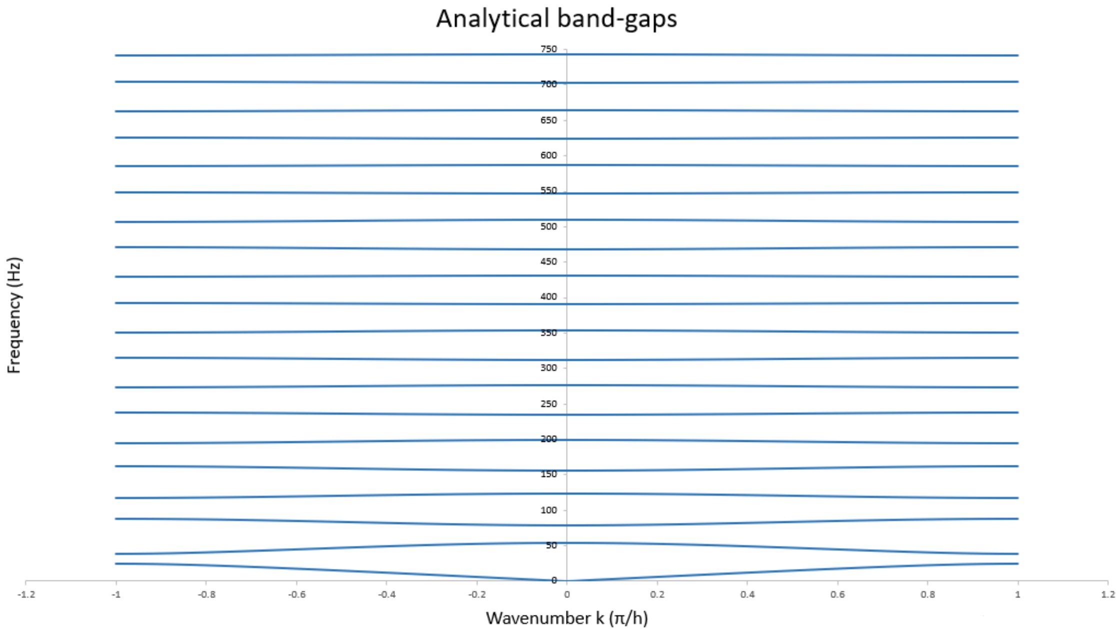


(a) (b)

Properties	Material 1 Polyurethane Foam	Material 2 Rubber
Density ρ (kg/m^3)	900	1300
Young's Modulus E (Pa)	1.47×10^8	58000
Poisson's ration ν	0.42	0.463

Meta-material Layout for the Blast Protection of Pipes towards explosions





- **Band-gaps for the buried pipes towards surface explosion**

(The interested frequency range for explosions: 0-200 Hz)

- **Band-gaps for the above-ground pipes towards explosion until 750 Hz**

(The interested frequency range for explosions: 0-50 kHz)

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Explosion case scenarios

The explosion case scenarios considered, with and without the meta-material layout

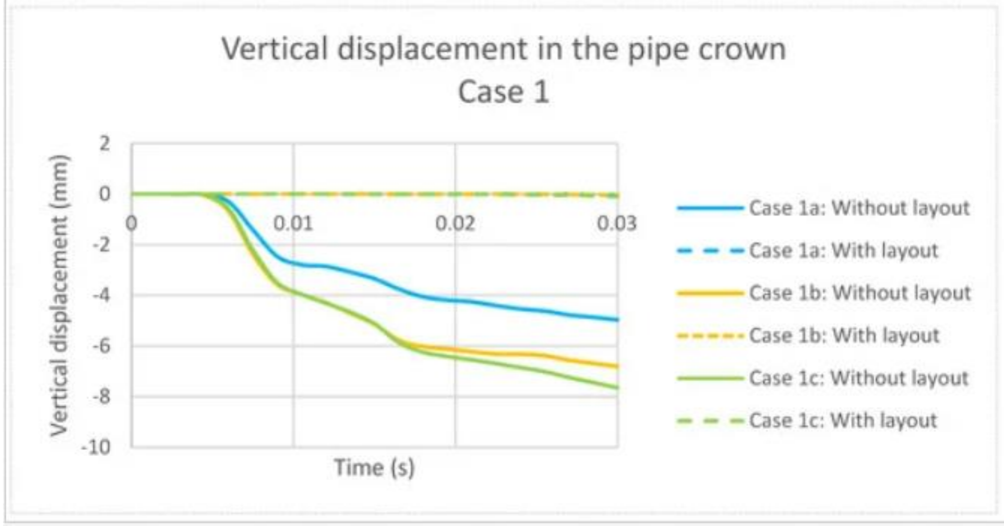
Case No.	Subcase	TNT Charge (kg)	Distance from Pipe (m)	Height above Ground Surface (m)
1	a	100	5.00	0.50
	b	200	5.00	0.50
	c	400	5.00	0.50
2	a	100	2.50	0.50
	b	200	2.50	0.50
	c	400	2.50	0.50
3	a	100	5.00	0.60
	b	200	5.00	0.60
	c	400	5.00	0.60

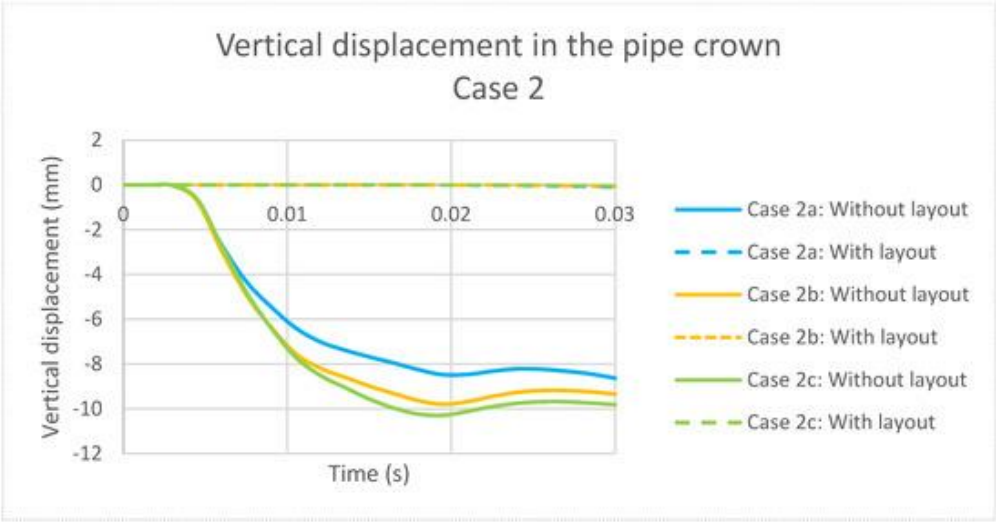
(Explosion case scenarios for the buried pipes)

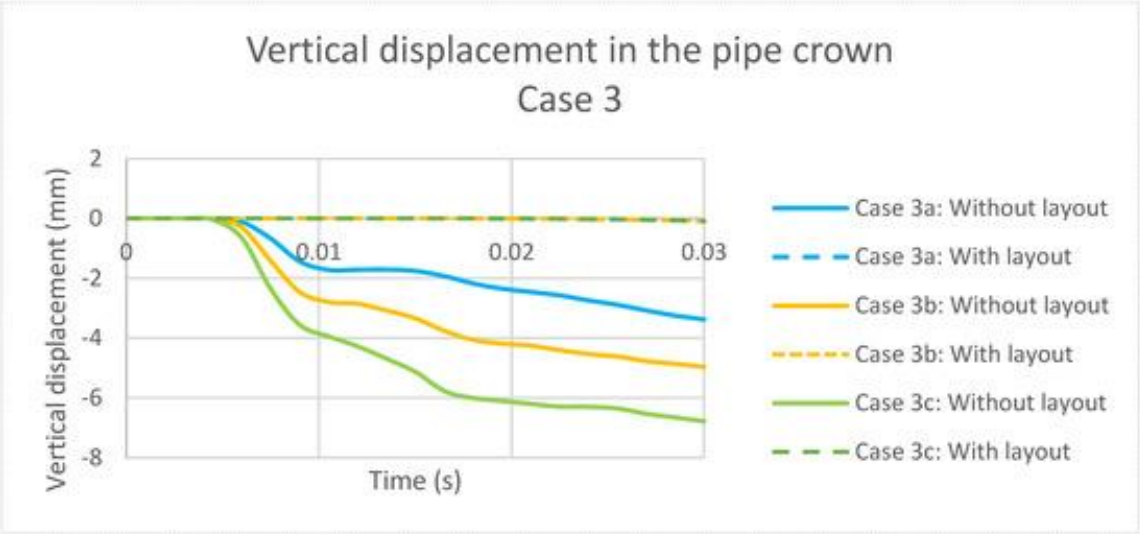
Case No.	Subcase	TNT charge (kg)	Distance from pipe (m)	Z ($m/kg^{0.333}$)	$t_{tot}= t_A+t_o$ (ms)
1	a	50	2.50	0.68	4.79
	b	100	2.50	0.54	2.18
	c	150	2.50	0.47	2.23
2	a	50	3.50	0.95	8.44
	b	100	3.50	0.75	7.57
	c	200	3.50	0.60	4.09
3	a	150	5.00	0.94	10.33
	b	250	5.00	0.79	9.76
	c	400	5.00	0.68	8.84

(Explosion case scenarios for the above-ground pipes)

Meta-material Layout for the Blast Protection of Pipes towards explosions (case of buried pipes)







The presence of the layout practically eliminates the displacements!!

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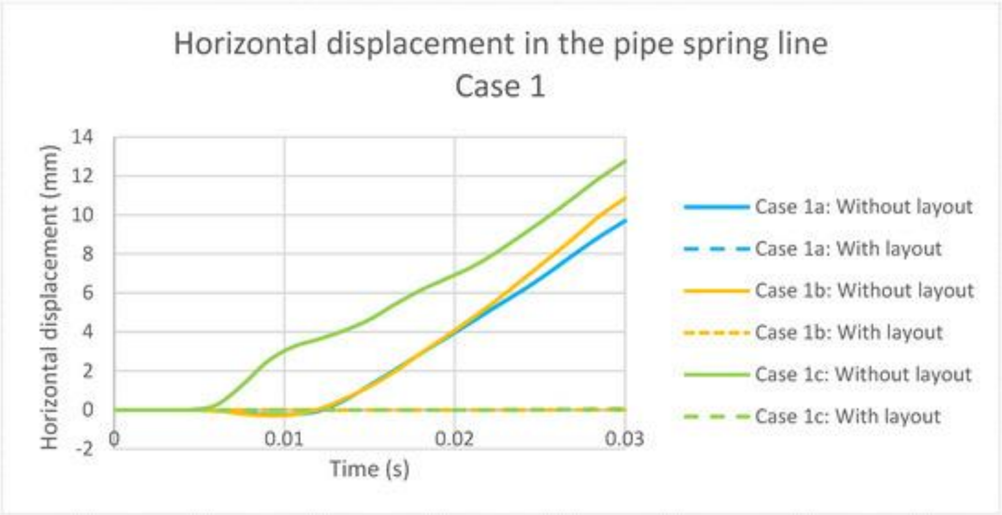
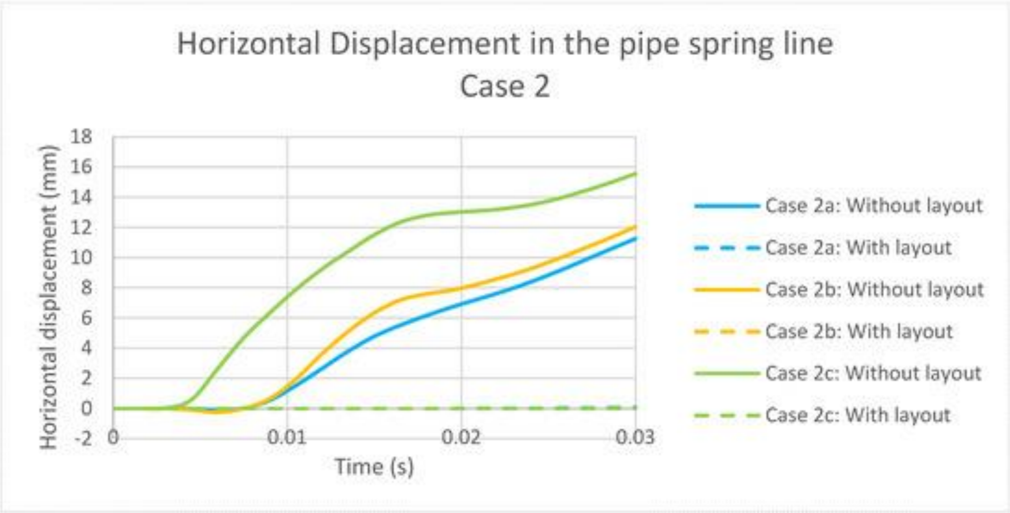
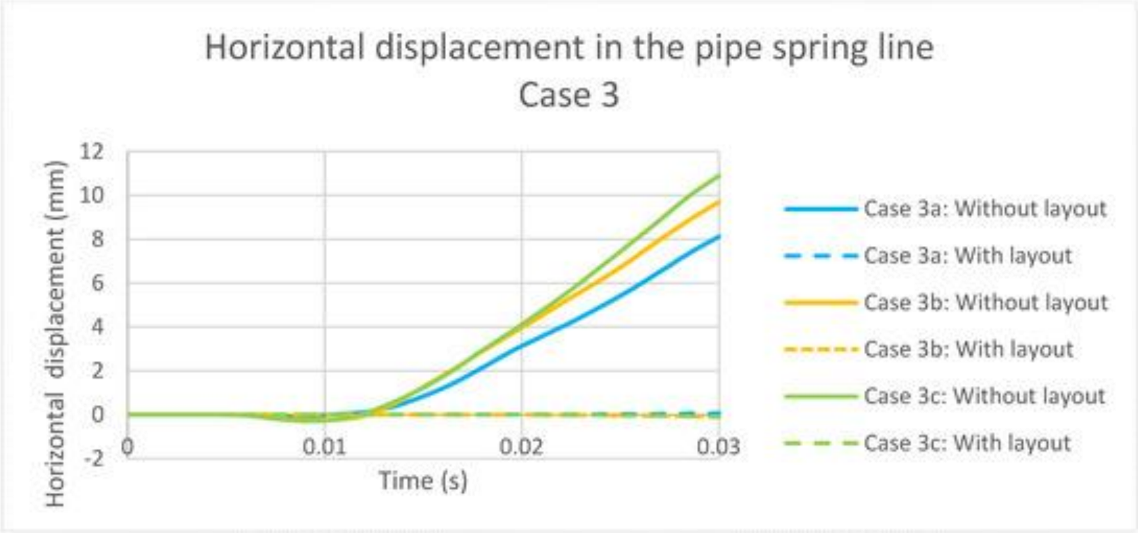
Meta-material Layout for the Blast Protection of Pipes towards explosions (case of buried pipes)







The presence of the layout practically eliminates the displacements!!

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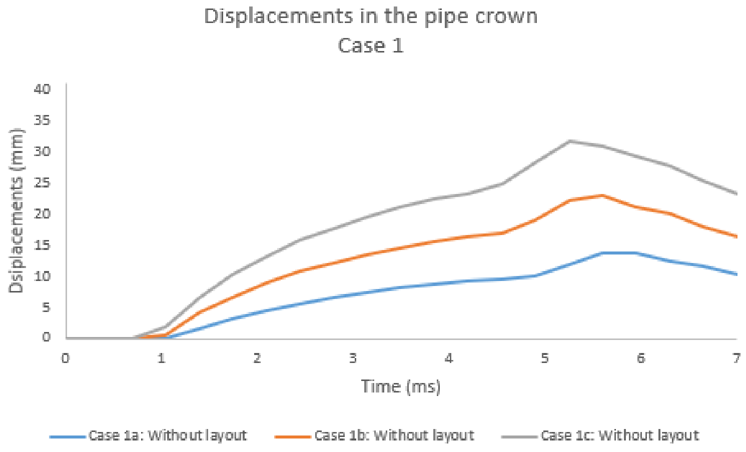
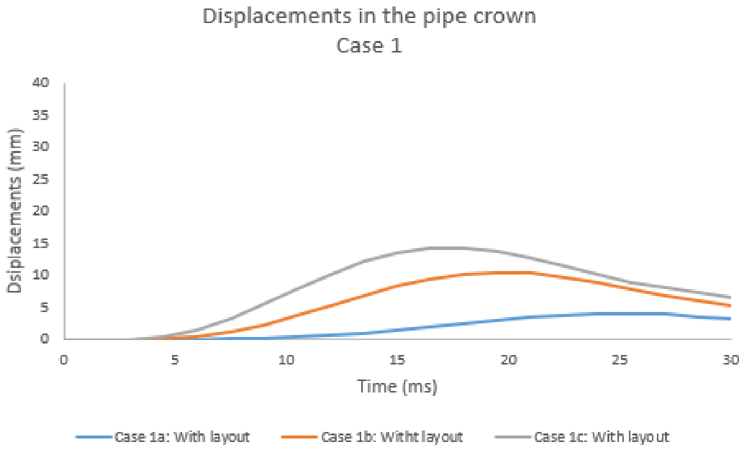
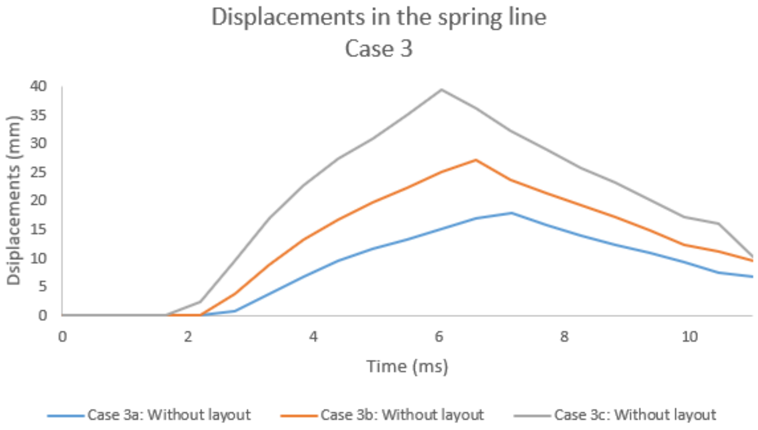
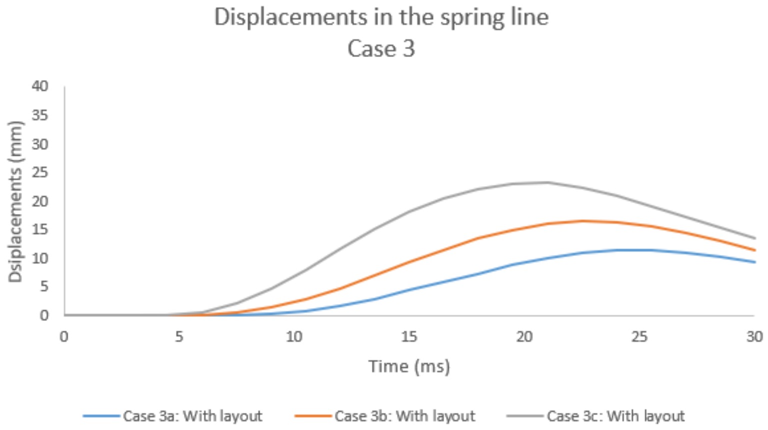
Meta-material Layout for the Blast Protection of Pipes towards explosions (case of above-ground pipes)





Indicative displacements in the Pipe crown





Indicative Displacements in the Pipe Spring Line

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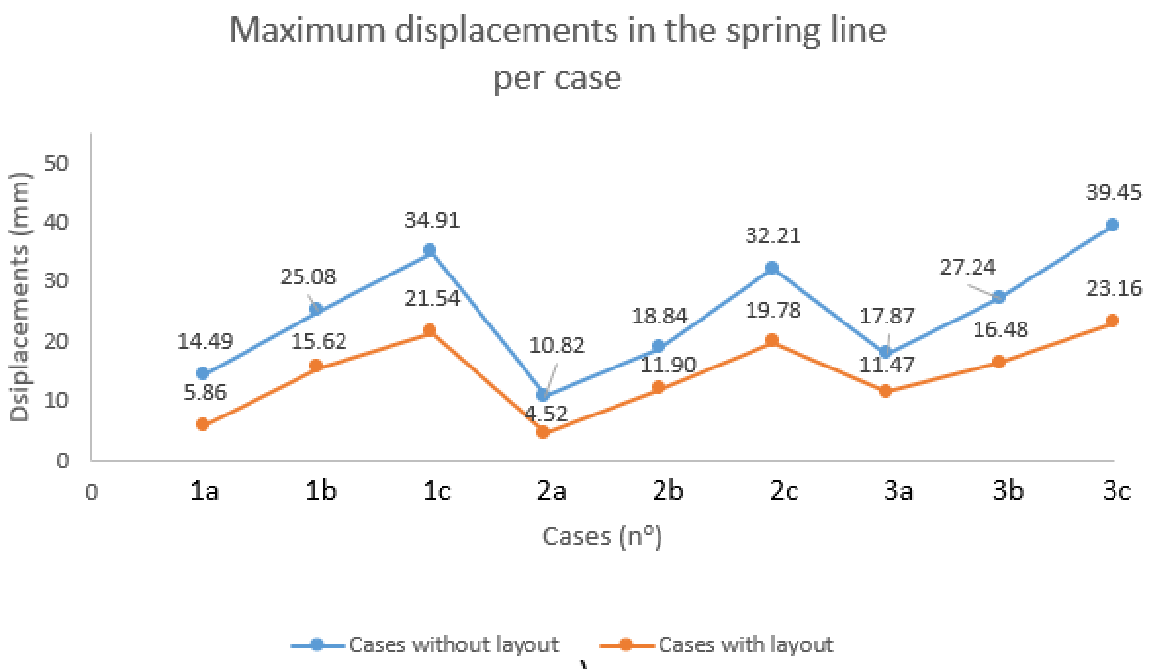
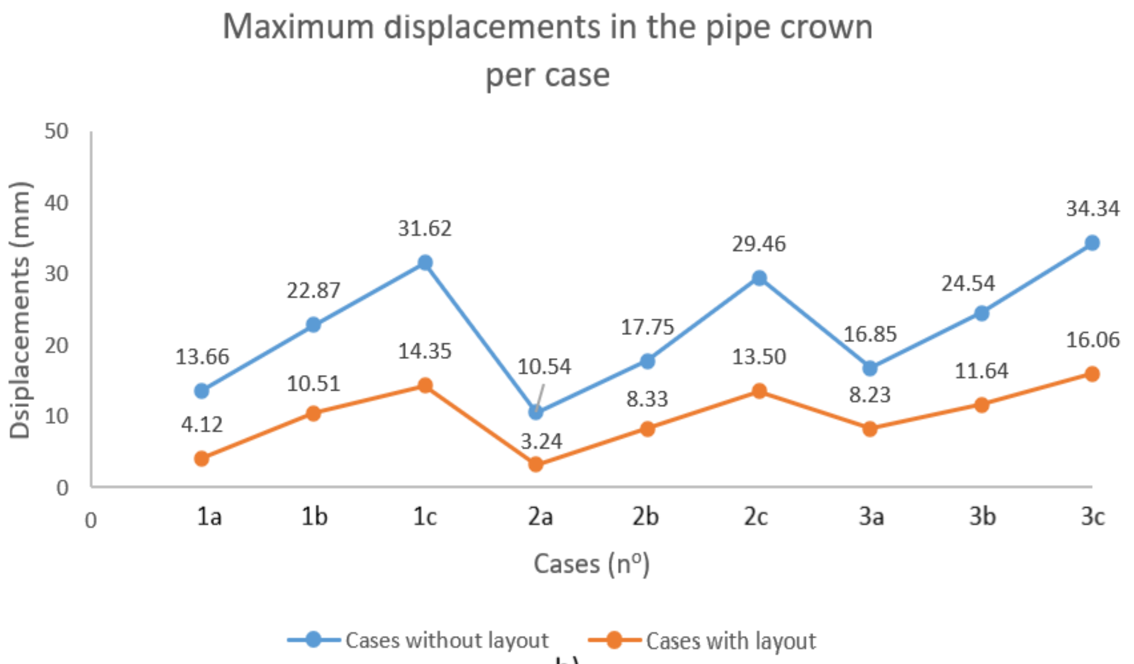
Meta-material Layout for the Blast Protection of Pipes towards explosions (case of above-ground pipes)



a)



b)

reduction ratio varies from 36% to 70% for all the cases, with a median value ranging around 53%.

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Resilience Assessment Method

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Resilience Assessment Method

System Characterization

Description of the entire system and relevant assets to be analyzed:

- location of the system in the external context
- identification of the system's elements/assets;
- Identification of relationships between the system's elements/assets.

Asset Characterization

Description of the individual asset and its qualifying characteristics necessary for the analysis:

- geometrical characterization
- mechanical characterization
- organizational characterization
- economic characterization
- environmental characterization

Event Characterization

Evaluation of possible disruptive events:

- Natural hazard (earthquake, wind, flood, etc.)
- Manmade hazard (human error, terrorist attack, cyber attack)

Definition of relevant hazard scenarios, and relevant hazard modeling in the area considered (based on basis of Literature Database, National Codes, Websites Databases)

Resilience Assessment Method

Risk, Vulnerability, Consequences & Impact Analysis

Starting from the defined systems and assets and according to the considered hazards: analysis of the assets risks, vulnerability, consequences and the quantification of the impacts.

Assets where hazards lead to low probability - low severity scenarios only can be neglected from the analysis.

Resilience Assessment

Resilience Analysis carried out on the asset/s considered and/ or on the entire system considering the cascade effects. The determination of the level of Resilience (AS IS) is carried out.

The Analysis considers:

- Robustness
- Rapidity
- Resourcefulness
- Redundancy

and assets weights on the overall system.

The final assessment is expressed via a resilience matrix based on specific indicators and the final result in term of Avoided Losses

Meta-materials integrated in the Resilience Assessment Method

Risk, Vulnerability, Consequences & Impact Analysis

- Innovative meta-material concepts developed towards the respective hazards and the hazard scenarios. (e.g., blast protection of the pipes in a gas transmission system)
- Comparative studies with and without the presence of the meta-materials concepts, showing the reduction of the risk and the mitigation of the consequences and the impact.

Resilience Assessment

Comparative studies on the resilience capacity of the Infrastructures and System, before and after the implementation of advanced solutions based on the meta-materials.

Potential meta-concepts of today and the future

Type of Infrastructure	Hazard	Potential Meta-material Concept
Gas Transmission Pipelines	Surface & Underground Explosion	Layered periodic material, bonded around the pipe
Underwater Transmission Pipelines	Underwater Explosion	Layered periodic material, bonded around the pipe
Offshore Wind Turbine	Underwater Explosion	Layered periodic material, bonded around the foundation and the underwater part of turbine
Electricity and Nuclear Plants	Seismic Protection	Meta-foundations, or seismic meta-barriers around the plant
City Buildings	Seismic Protection	Meta-barriers covering the perimeter of a built area and environment
Road & Railway Network	Blast protection	Meta-asphalt and blast protection of the critical transportation network towards warfare-nature events

And the further development of meta-concepts continues..

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Thank you for your attention!

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