Use of Computational Simulation to Evaluate the Safety of a Nuclear Power Plant to the Detonation of Explosives Nearby

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ESSS – Engineering Simulation and Scientific Software

INTRODUCTION AND OBJECTIVES

Despite the stagnation in the amount of operational nuclear power plants in the last decades [1], nuclear power remains as one of the main sources of energy worldwide, with about 10% of the electricity generated in the world being due to this type of technology [2]. Among its main advantages, nuclear fuel is a clean resource, which, unlike fossil fuels, does not contribute to emission of deleterious gases to the atmosphere; also, its efficiency is higher, allowing production of more energy with a same mass of fuel. Moreover, unlike eolic or solar power, it is not prone to reduction in productivity due to nature-related features like regimes of wind or number of hours of sun in a given day. Thus, it is clear that nuclear power plays an important role in the world energy generation context.

During the design of a nuclear plant, one of the main concerns is its safety, as any incident can lead to serious consequences, from leakage of radiation to nuclear explosions, threatening thousands of lives and potentially damaging local economy. Apart from internal safety issues, it is mandatory to ensure that the facilities are safe with regard to external agents. Such concern is amplified by the rising number of terrorist acts in the last decades, from which no country seems to be safe.

Among other weapons and strategies, several acts of terrorism involved the use of explosive artifacts. To take this type of menace into account when designing a nuclear plant, engineers can currently rely on regulations from the US nuclear commission [3,4], which provides means for evaluating the hazard of an explosion occurring under certain conditions around a plant. More specifically, the regulations provide an equation, Eq. 1, that relates the amount of TNT and the distance below which the explosion will be potentially harmful, based on [5]:

$$Z = \frac{R}{W^{1/3}} \tag{1}$$

where Z is a factor that equals 18 for the distance R in meters and the mass of TNT W in kilograms. The recommended mass to be used in the calculations is 23 tons [3,4]. Using this equation, a secure radius of 512 meters can be assumed, inside which only the plant staff or security-cleared guests are allowed. Any explosion occurring outside of this zone will theoretically cause no harm to the facilities.

Although clearly useful, such procedure shows an important drawback: it considers that the distance calculated refers to a straight line between the explosion and the plant. Moreover, no influence of local topography is taken into account - that is, no mountains, valleys, towers, trees or any other structure in the way of the pressure wave caused by the detonation are thought to interfere in its propagation. Thus, when applying the standard, the outcome may be (i) an overestimation of the pressures reaching the plant, due to constructive interaction of waves after reflection throughout their paths, (ii) underestimation of the same pressures, by destructive interaction, or (iii) both scenarios, in different regions of the model. This uncertainty is highly undesirable, making mandatory a search for alternative, more precise means of calculating overpressures.

In this sense, a promising candidate is the use of numerical simulation, which can combine the features of free-field wave propagation with the consideration of any obstructions that may be on the path. Within the large number of engineering softwares available, those classified as "hydrocodes" are the ones which can be more helpful in this context. A hydrocode can be defined as a code for solving large deformation, finite strain transient problems that occur on a short time scale [6]. Although there is much similarity between hydrocodes and ordinary finite-element codes, the numerical solution of the former is done using explicit time integration of mass, momentum and energy equations, accounting for very sharp gradients in time. Also, these codes include means of dealing with shocks, as those resulting from explosions.

Thus, in this work, a scenario of an explosion near an actual nuclear plant was numerically simulated, taking into account the real topography of the terrain and the buildings around the detonation spot. The hydrocode embodied into ANSYS Inc. Explicit Dynamics module was used, as it combines the robustness of its solver (Autodyn, developed and improved for about 30 years now) with ease-of-use from ANSYS Workbench platform, which allowed simple geometry import and meshing operations. As a result, values of overpressures in different regions of the domain were investigated and compared with analytical calculations.

DESCRIPTION OF THE MODELLING

The plant being investigated is ANGRA 3, currently under construction in Brazilian state of Rio de Janeiro, as shown in Figure 1. Figure 2 shows the numerical model developed for this case. The red dot near the top of the mountain indicates a spot where the detonation could occur, as there is a public road that runs near the summit. The plant buildings are shown in gray, some hundreds of meters apart from the road. In Figure 3, several spots (gauges) are marked with numbers. These are the locations in which overpressures were evaluated. Table 1 shows the linear distance between each point and the detonation spot.

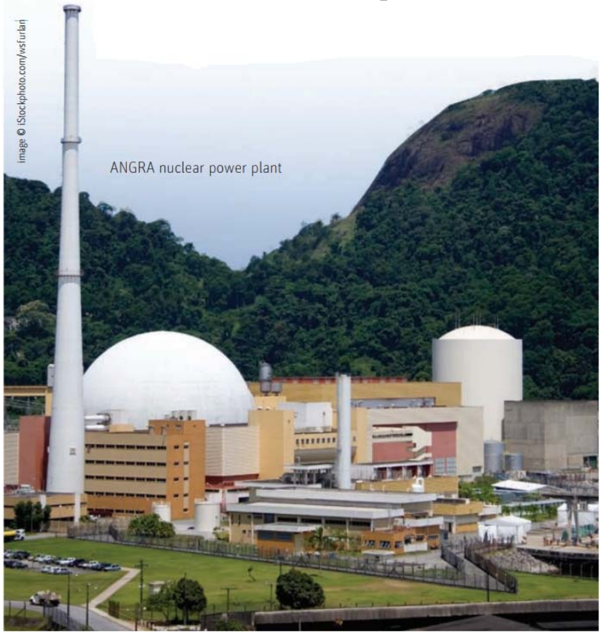

Figure 1 – Photo of the Angra 3 nuclear power plant

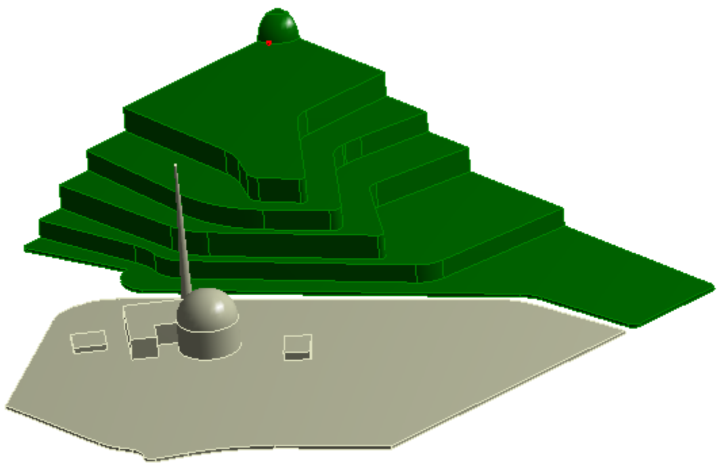

Figure 2 – Geometry for the numerical model of the plant

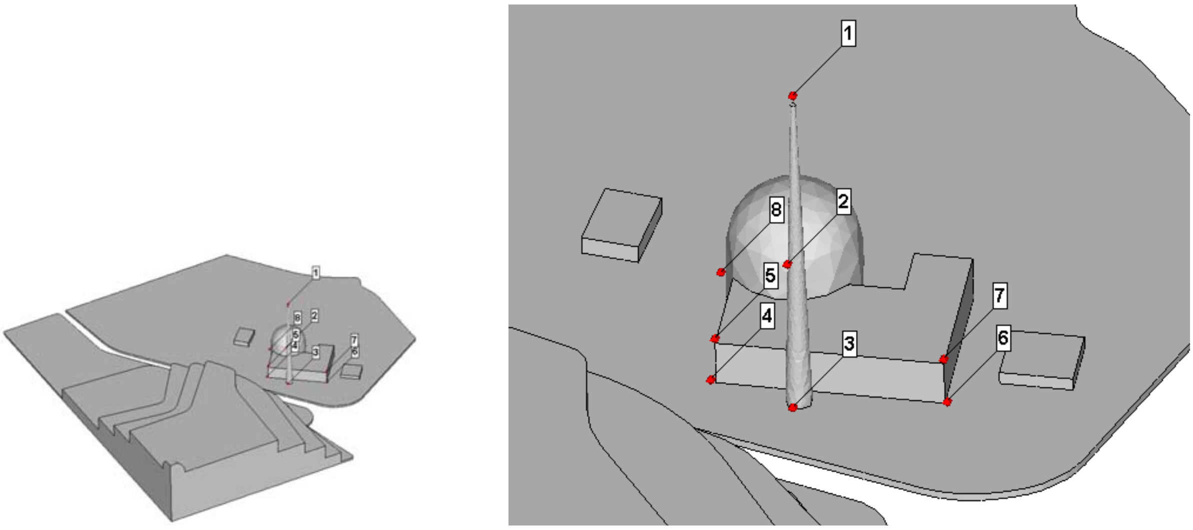

Figure 3 – Location of the inspection points (gauges)

Table 1 – Distance of each gauge to the detonation point

Gauge	Distance to detonation (m)
1	330.98
2	320.62
3	328.79
4	331.65
5	329.34
6	359.39
7	356.72
8	368.71

As the focus is to quantify the overpressures and compare its values to analytical, free-field values at the same distances, deformation of topography and buildings is not of main interest. These bodies were then considered as rigid, acting only as barriers for the propagation of the waves. As for the TNT and atmospheric air, Table 2 shows their reference densities and equations of state. For the air, an ideal gas simplification was assumed, while for the TNT, the JWL equation of state was used to describe the expansion of the detonation products. JWL stands for Jones, Wilkins and Lee, which proposed the following equation, Eq. 2, relating pressure and expansion [7,8,9]:

$$p = A\left(1-\frac{w\eta}{R_1}\right)e^{-\frac{R_1}{\eta}} + B\left(1-\frac{w\eta}{R_2}\right)e^{-\frac{R_2}{\eta}} + w\rho e \qquad (2)$$

Where p is the pressure, ρ0 is the reference density, ρ the density and η = ρ/ρ0. The remaining parameters are constants, listed in Table 3.

For simulation, the domain in which pressure waves can propagate is shown in Figure 4. It is an Eulerian domain, meaning that he mesh is fixed in space, with material flowing inside the cells. For every face except the bottom of the domain, material is allowed to escape through the boundaries. However, as such escape must be limited to keep the accuracy of the calculation, the dimensions of the domain are much larger than the distances between gauges and the detonation point (800 meters x 800 meters x 336 meters), allowing for the explosion to reach the plant before a significant amount of gases leave the domain.

Table 2 – General information for the materials involved in the calculations

	Air	TNT
Reference density at 15°C (kg/m³)	1.225	1630
Equation of state	Ideal Gas	JWL

Table 3 – Parameters for the JWL equation of state applied to the TNT

A (kPa)	3.7377×10^8
B (kPa)	3.7471×10^6
R1	4.15
R2	0.9
W	0.35
C-J Detonation velocity (m/s)	6.93×10^3
C-J Energy / volume (kJ/m3)	6×10^6
C-J Pressure (kPa)	2.1×10^7

The domain is divided into 15.36 million cells, being 150 in the vertical and 320 in each horizontal direction. This results in each cell having a dimension of 2.5 meters x 2.5 meters x 2.24 meters, and thus some 14 m³ of volume, so that a single cell is filled with 23 tons of TNT, as stated by the US regulations referenced. An analysis of mesh convergence was done, comparing analytical and numerical results for free-field detonation, as shown in Figure 5. This analysis confirms that cell sizes below about 4 meters each side are accurate enough to be used in this calculation.

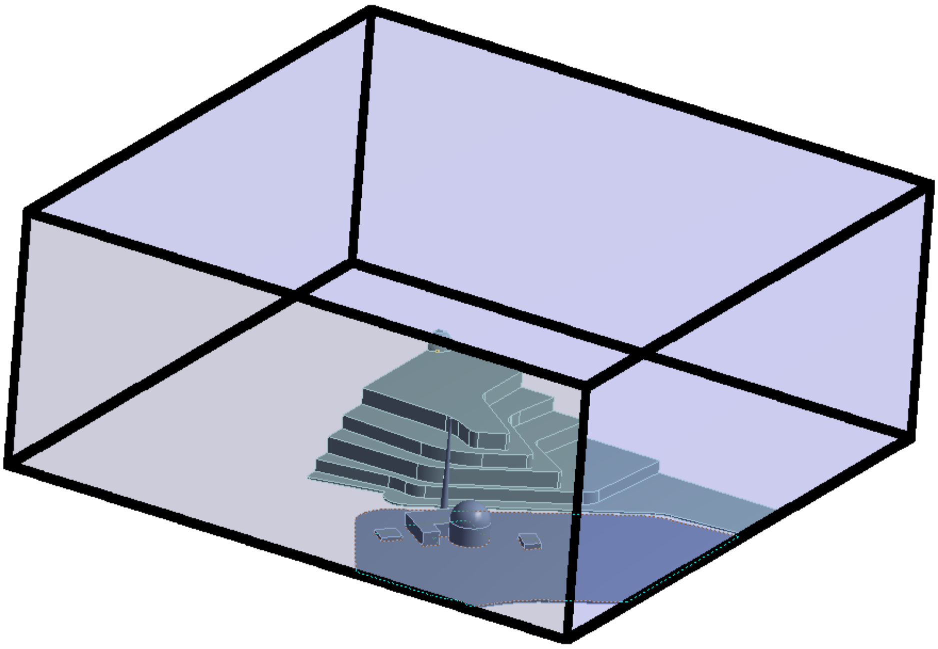

Figure 4 – Eulerian domain used in the simulation.

To compare with the numerical results, the analytical formulation presented on [10] will be used. Recalling Equation 1, it is possible to obtain a value for the coefficient Z, based on the amount of TNT being detonated and on the distance in which the overpressure is to be evaluated. This coefficient can then be used in the following empirical equation, Eq. 3, to obtain the values of overpressure:

$$\frac{p_0}{p_a} = \frac{808\left[1+\left(\frac{Z}{4,5}\right)^2\right]}{\sqrt{1+\left(\frac{Z}{0,048}\right)^2}\sqrt{1+\left(\frac{Z}{0,32}\right)^2}\sqrt{1+\left(\frac{Z}{1,35}\right)^2}} \quad (3)$$

where p_0 is the overpressure and p_a is the atmospheric pressure.

Based on the boundary conditions and loadings detailed above, the simulation was set with one second duration, enough to allow the waves to reach the plant, considering the detonation occurring right at the beginning of the analysis. The results of this simulation will be detailed next.

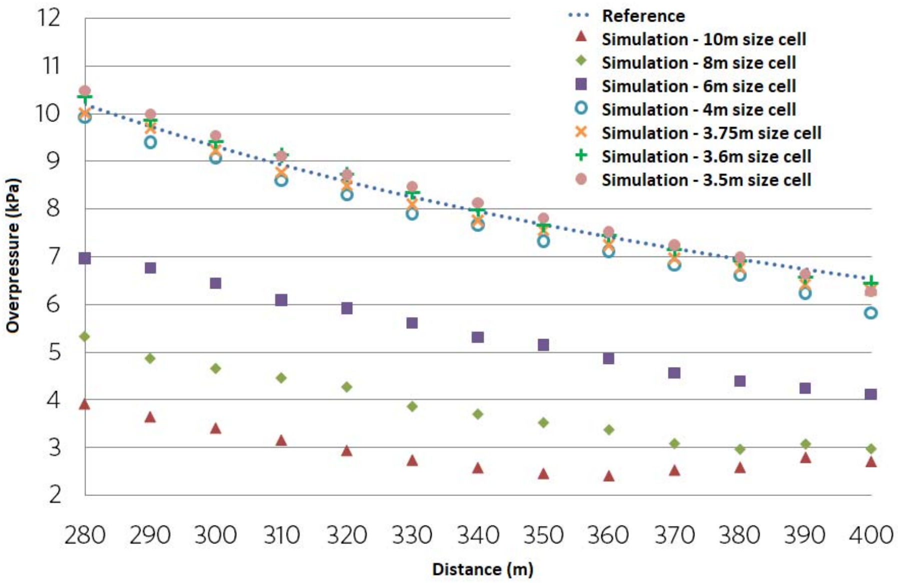

Figure 5 – Mesh convergence study done for the Eulerian domain

RESULTS

The comparison between the overpressure for each of the gauges on the model is shown on Table 4. It is clear that the numerical simulation predicts a much lower overpressure than calculated using Eq. 3. Some explanation is provided by Figure 6, which shows a cross-section of the domain that includes the detonation zone and some structures around the plant. The image shows a contour of pressures in the cross-section, with values in red referring to higher pressures. Results indicate that the higher pressures occur at higher altitudes, what is supposed to be due to the reflection of the pressure wave with the terrain, and consequent interference between incident and reflected wave.

Figure 7 adds more depth to this hypothesis. It shows a cross-section parallel to the ground level, in different scenarios. Images on the left and center show the same vertical position, that is, around 78 meters from ground level. The difference between them is that the picture to the left shows the contour of pressures right after the detonation, while in time elapsed from the explosion is about 400 milliseconds in the center picture. The color code showing a deep red zone in the picture right after the explosion means that pressures in this vertical position are at their maximum for this time instant. Nonetheless, after 400 ms, the pressure wavefront is shown in orange, meaning that maximum pressures are elsewhere – in this case, at a vertical position of about 122 meters, whose contour is shown in the picture to the right. Thus, the model is taking into account the interaction between incident and reflected wave, what is not considered by the analytical equation, Eq. 3.

Table 4 – Comparison between analytical and numerical predictions of overpressure.

	Gauge #1	#2	#3	#4	#5	#6	#7	#8
Analytical	7.78	8.10	7.85	7.77	7.83	7.04	7.11	6.83
Numerical	4.57	3.52	4.69	4.63	3.19	4.48	3.22	3.61
Distance to detonation (m)	330.98	320.62	328.79	331.65	329.34	359.39	356.72	368.71
Difference (%)	41.3	56.5	40.2	40.4	59.3	36.4	54.7	47.1

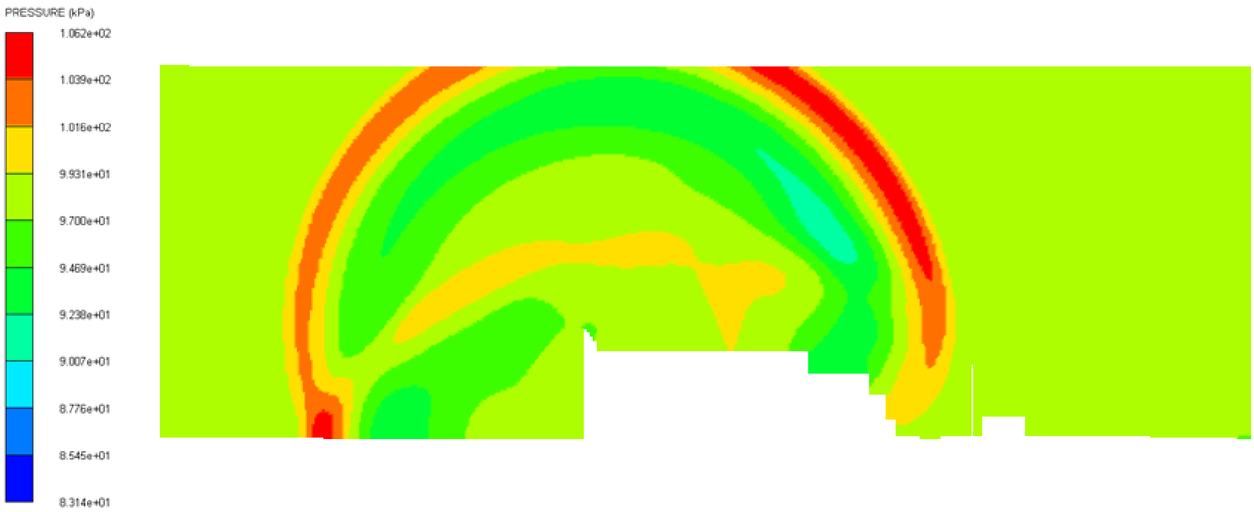

Figure 6 – Cross-section perpendicular to the ground, showing that pressure magnitudes vary with the height.

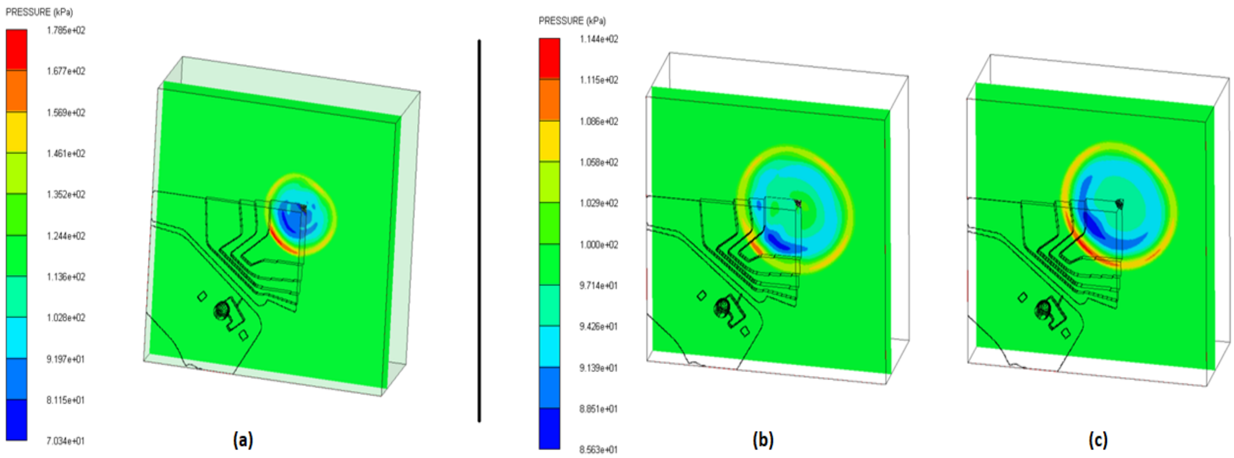

Figure 7 – Cross-section parallel to the ground, providing more information about wave-ground interaction effects: (a) 78 m from ground, right after detonation; (b) 78 m from ground, after 400 ms; (c) 122 m from ground, after 400 ms.

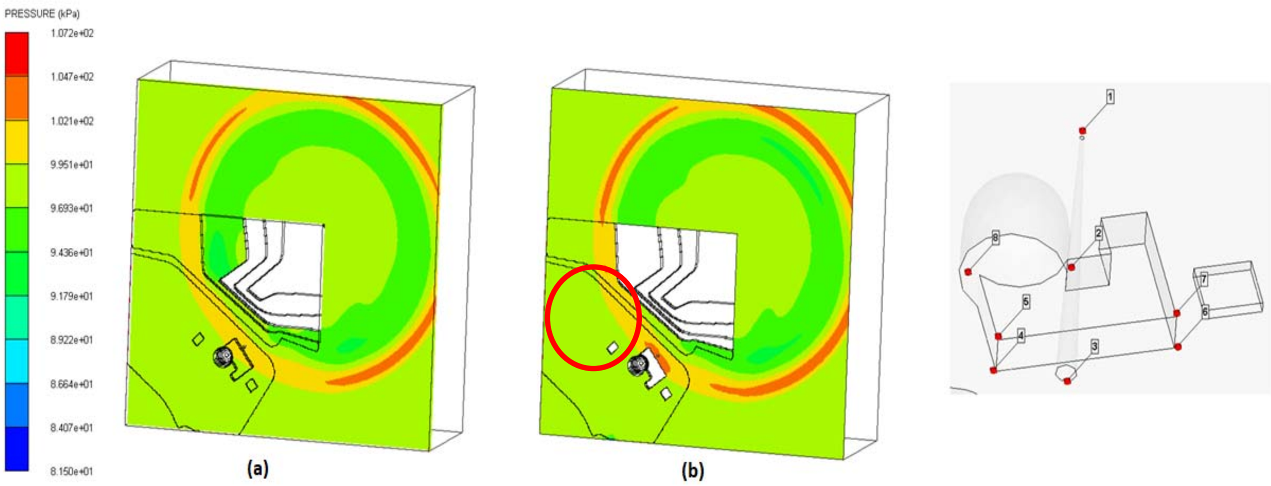

Figure 8 – Cross-section, parallel to the ground, showing the local effects of the buildings in pressure calculated in the gauges: (a) 30 m from the ground and (b) at ground level, both 900 ms after detonation.

Another remarkable result is shown in Figure 8: pictures to the left and at the center refer to the same time instant (around 900 milliseconds), but the cross-sections are taken from slightly different heights: the left picture is some 30 meters above ground, while the center one is taken at the ground. The zone in orange right in front of the plant makes clear that the pressure wave is reflecting in the walls of the plant, thus locally raising the pressure while retaining the propagation of the wave. Indeed, a comparison between the picture to the right, showing in more detail the position of the gauges, and Table 4 or Figure 9, which plots the curve of pressure as a function of time for each of the gauges, allows one to conclude that the pressure waves are higher at points 3, 4 and 6, which are trapped between walls and ground, and lower at points 2, 5, 7 and 8, in which the products of the explosion have field to move and avoid pressure concentrations. Again, this is an effect that can be only considered when performing the analysis using numerical means. Of course, for the gauge 1, the pressures are higher due to its height, as already discussed.

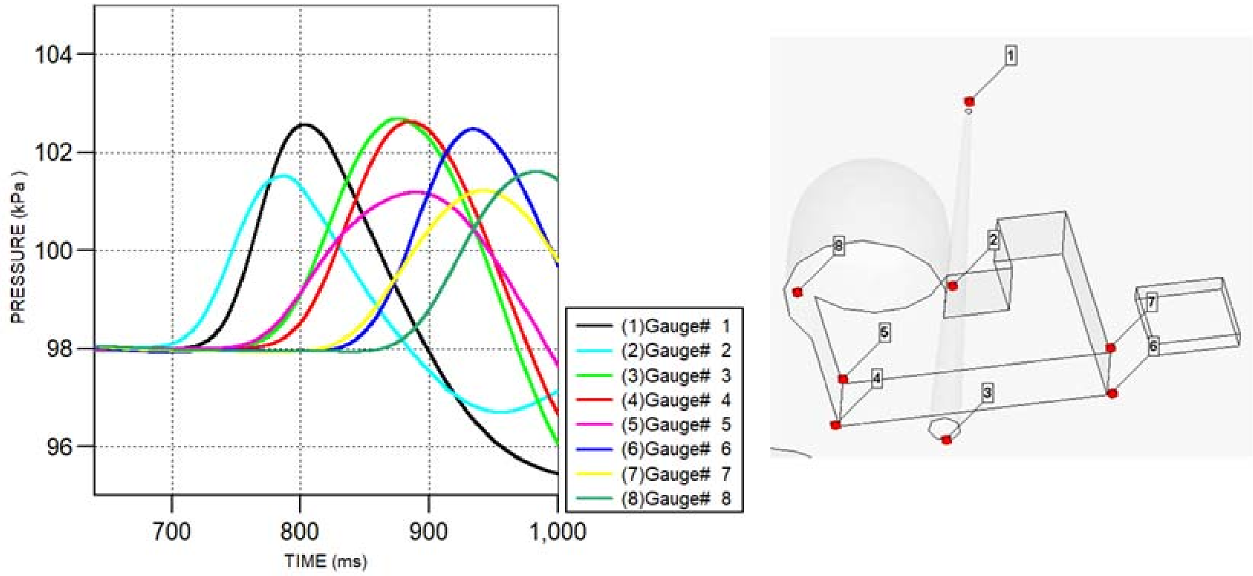

Figure 9 – Evolution of pressures at the gauges.

CONCLUSIONS

In this work, numerical simulation was applied to evaluate the pressures at points around a nuclear power plant, resulting from the detonation of an explosive at a road nearby. Results show that analytical calculation, which does not take into account the interaction of pressure waves with the terrain and, afterwards, within themselves, may result in over-conservative predictions, as it assumes an hypothesis of free field propagation that does not sustain in reality.

Numerical simulation, on the other hand, showed potential to reproduce some mechanisms of pressure reduction and intensification depending on topography conditions. Further work might be able to verify confirm this potential, which could then be extended to allow engineers to propose the addition of anti-pressure barriers in the domain, thus reducing largely the secure area needed around nuclear plant buildings.

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