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THE MECHANICAL WAVES EFFECTS INDUCED BY THE UNDERGROUND ROCK BLASTING TECHNOLOGY ON ADJACENT CONSTRUCTIONS

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Abstract: This article presents the effect of mechanical waves on an adjacent building due to the rock blasting process during the construction of a tunnel. The rock blasting process is simulated using a 3D finite element model. To reduce the dynamic effect transmitted by the underground work, different types of trenches are analysed.

Keywords: excavations in rocks, shockwave, vibration, 3D finite element model

1. Introduction

The use of explosives for excavations in rock formations is inevitable. The technology of underground excavation using explosives remains the most widespread technology in the world for tunnelling in hard rocks. This involves dislocating the mass with explosives placed in drill holes, loading the displaced rock mass with large-capacity excavators, and transporting the excavated rocks by truck.

The secondary effects produced by rock blasting have different magnitudes depending on a wide variety of factors, the most important of which are:

- the quantity and type of explosive
- the technology
- the distance from the explosion source to the analysed target
- the geological structure
- the adoption of limit values for the oscillation speed of the material particle measured in the vicinity of the protected target.

The permissible values of oscillation velocity differ depending on several factors, the most important being the type and technical condition of the construction, its social use destination, and are usually established by specialized technical standards [1]

Since there is no such norm in Romania to regulate the protection of constructions against the seismic effect generated using explosives for engineering works, the present study used the limit values recommended by the specialized standard in Germany (DIN 4150/83), which is currently the most demanding norm in Europe.

2. Rock blasting technology

The mechanism of underground excavation using explosives can be explained as follows [2]:

- the explosive generates a detonation pressure on the rock through direct contact.
- the entire phenomenon lasts for a few microseconds, after which the rock is subjected to the action of expanding gases. Depending on the charge, this pressure can last from tens to hundreds of milliseconds.

- the propagation velocity of these waves depends on the modulus of elasticity and the damping ratio of the surrounding medium, being constant within the elastic domain. Pressure waves propagate into the rock mass from the explosion site until they reach a free surface, where they are reflected as stress waves. Stress waves carry the part of the energy that became free due to the explosion, as the difference between the acoustic impedance of the rock and the air is quite significant, and therefore some of the energy returns as reflected waves.
- the rock, being subjected to very high pressures, breaks in the vicinity of the explosion due to exposure to tangential efforts in the form of an outgoing shock wave. These waves travel through the rock at a speed of up to 5000 m/s. The thickness of the fractured rock around a drill hole with a diameter, for example, of 40 mm, is also 40 mm or even less. However, a system of cracks starting partially from the centre of the hole can affect the rock to a depth of 1 m. The lower resistance of the rock to stretching compared to compression explains the development of radial cracks.
- the formation of cracks upon shooting depends on the volume of rock affected by each borehole, the distance between the boreholes and also whether the ignition of the explosive material is simultaneous or staggered.

3. Geometric parameters of surface rock excavation

In carrying out a project that involves the use of explosives, the first thing to consider is the diameter of the borehole into which the explosive material will be inserted. This was chosen by the designer based on the limitations imposed by the drilling equipment. The diameter of the borehole, together with the type of explosive used and the type of rock at the site, determines the amount of charge used, which in turn determines the distance between the center of gravity of the borehole into which the explosive material will be inserted and the nearest free face of the engineering work for which the excavation is being carried out, denoted B [3]. All other coefficients that need to be calculated consider this distance.

Usually, the diameter of the borehole ranges from 75 mm to 38 cm. The larger the chosen diameter, the fewer boreholes are needed, and therefore the costs required to carry out the project are lower. In addition, larger diameters lead to a greater distance and coarser fragmentation of the rock [3].

In general, the smaller the diameter of the borehole, the faster the execution speed. A shorter distance between boreholes leads to a better distribution of tangential forces induced by the explosion in the mass and, therefore, better fragmentation. Also, the advantage of smaller diameter boreholes is that the explosion produced inside them will generate smaller vibrations. Boreholes with a large diameter can be used for shallow depths due to limitations imposed by drilling equipment. However, the factor that ultimately dictates the choice of diameter is, obviously, the location and geotechnical properties or the rock.

Following studies conducted over the years [2], [3], it has been observed that the explosive material used in the case of rock removal technology using larger diameter boreholes is less sensitive, resulting in a lower cost compared to rock removal technology using smaller diameter boreholes.

The diameter of the borehole directly influences the distance between the axes of two adjacent boreholes. If this distance is not calibrated correctly, there is a risk of a violent and uncontrolled explosion.

According to the specialized norms, the most used drilling patterns are those with boreholes arranged in a square, rectangular, or triangular network [3].

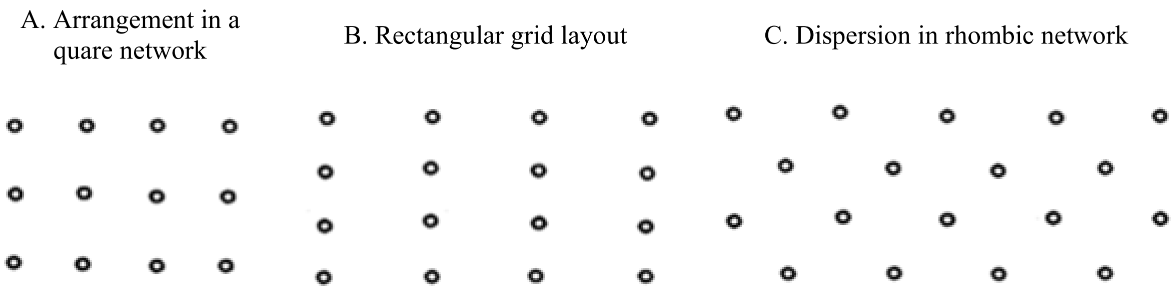

Fig. 1 - Drilling holes arrangement

In the case of using a square or rectangular grid, the distance value, B, is equal to the distance between two adjacent boreholes, S, but in the case of rhomboidal arrangement, it is recommended that the distance between two adjacent holes be greater than the distance from the centre of a marginal borehole to the nearest free face of the engineering work for which the blasting is carried out [3].

Of course, the method of arranging the boreholes is chosen by the designer, taking into account the specific features of each work.

As mentioned earlier, the diameter of the borehole practically dictates the rest of the dimensions to be considered when carrying out a project necessary for blasting works with explosives [4].

The calculation formulas presented below, used in this work, are based on research conducted by the "Australian Drilling Industry Training Committee" and published in the book "Calculation & Terms used in Drill & Blast Operations".

$$B=(20\div35)\times d \ \ (m) \tag{1}$$

$$S = (1 \div 1.8) \times B \ \ (m) \tag{2}$$

$$ST = (0.7 \div 1.0) \times B \ \ (m) \tag{3}$$

$$PWT = \frac{L \times (0.304 \times \rho) \times D^2}{27 \times B \times S \times H} \tag{4}$$

Where:

d represents the diameter, in mm, of the borehole in which the explosive will be inserted

B represents the distance from the centre of a marginal borehole to the nearest free face of the engineering work for which the blasting is being carried out, in m. The variable coefficient depends on the hardness of the soil (20 for rock that does not show significant fissures, 35 for rock with visible fissures with the naked eye)

S represents the distance between the centres of gravity of two adjacent boreholes, in m. The coefficient varies from 1, for rock that does not show significant fissures, to 1.8, for rock with visible fissures with the naked eye

ST represents the depth measured from the face of the borehole, in m, which will be filled with an inert material. It serves to ensure a tight closure of the explosive inside the borehole. For rock without visible fissures, it is equal to 0.7 x B, and for altered rock, it is 1 x B

PWT, known as powder factor, represents the amount of explosive, in kg per cubic meter of rock transformed into powder

L represents the height, in m, of a single column of explosive

ρ represents the density of the explosive and is expressed in g/cm^3

D represents the diameter, in mm, of the explosive capsule

H represents the depth of the borehole in which the explosive material will be inserted, in m.

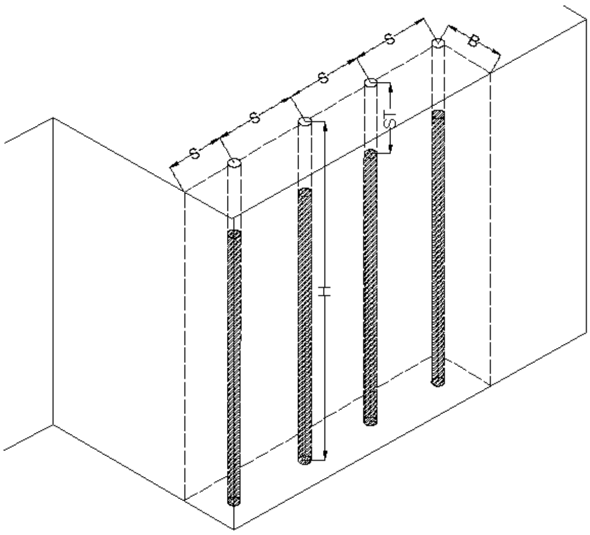

Fig. 2 - isometric view of a rock excavation. Where: S - distance between two adjacent drill holes, B - distance between a marginal drill hole and the nearest excavation side, ST - depth measured from the face of the drill hole. [3]

4. The effect of short-term vibrations on buildings

Due to numerous studies carried out to determine an acceptable limit value for the particle velocity caused by an underground explosion, so that adjacent structures are not damaged [5], an empirical value has been reached. This is generally denoted as v_i, where i represents the direction considered (x, y, or z) and is measured at the foundation level. This value in turn determines the maximum allowable value of structural vibration, $|v|_{i,max}$.

The DIN 4150-3 standard presents some general values that must be respected to avoid damage that can lead to loss of stability or functionality of the structure. However, if these values are exceeded, it does not necessarily mean that the building will collapse. At the same time, there are cases where even if these values are respected, the structure is damaged, not meeting the limit states provided in specialized standards [6]. In this latter case, however, it is considered that the damage has occurred due to other causes, and not due to vibrations induced by explosions.

Tab. 1

Reference limit values for the particle velocity of the ground v_i, in mm/sec [6]

No.	Type of structure	Velocity of the ground particles at the base foundation of the structure		
		1 Hz – 10 Hz	10 Hz – 50 Hz	50 Hz – 100 Hz*
1	Shopping centres, industrial buildings, and other similar buildings.	20	20 – 40	40 – 50
2	Residential buildings or other similar buildings	5	5 – 15	15 – 20
3	Buildings with load-bearing structures that, due to their sensitivity to vibrations, cannot be classified in categories 1 or 2.	3	3 - 8	8 - 10
* For values greater than 100 Hz, the values provided in this table should be considered as minimum.				

5. Modelling of the rock, boreholes, and adjacent structure

In order to analyse the effect of explosion shockwaves on adjacent structures, a three-dimensional model was created and analysed using the finite element method in the MIDAS GTS software. A rock mass with dimensions of 650x300x155 was modelled, with an irregular ground surface.

A single concrete building was considered on this site, represented as a solid. To study the influence of explosion detonation in an underground environment, the possibility of constructing a tunnel at a depth of 30 m and 20 m away from the structure of interest was considered. The dynamic loading to be applied in the tunnel, necessary for the progress of underground works, will be applied on the free face of the tunnel in the Y+ direction. It is assumed that the boreholes required for introducing the explosive have a diameter of 76 mm.

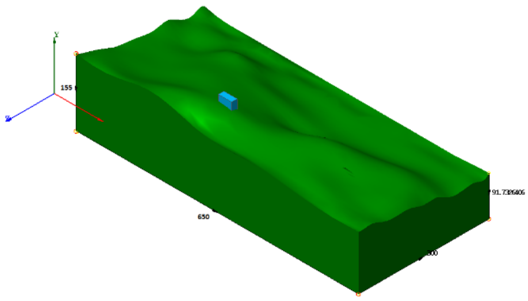

Fig. 3 – Dimensions of the 3D model

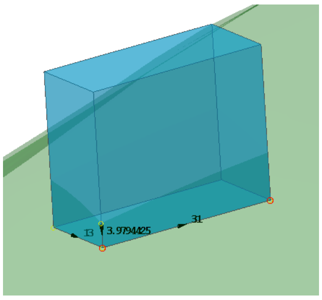

Fig. 4 – Foundation depth of the concrete structure

Table 1

Materials properties used [7]

No.	Material	Constitutive model	E [kN/m^2]	γ [kN/m^3]	μ [-]	c [kN/m^2]	Φ [°]	ξ
1	rock	Mohr-Coulomb	6.5 e6	25	0.24	295	35	0.05
2	concrete	Linear elastic	2.86 e7	25	0.25	-	-	0.05

The finite element dimensions resulting from the discretization have different sizes depending on their distance from the area of interest, i.e., the location where the dynamic load of explosion type will be applied, and the position of the modelled concrete structure. Thus, a distance between discretization nodes ranging from 40m for the earth mass to 4m for the excavation and existing concrete structure was assigned, resulting in the following discretization of the model. Additionally, to accurately consider only the area of interest, and not the entire earth surface, contour elements of the "quiet boundary" type (semi-infinite elements) were added to the model. This was done to avoid reverberations.

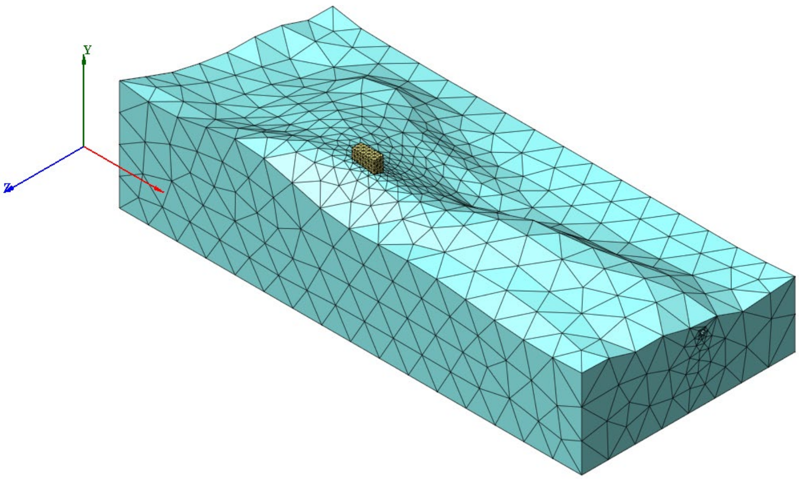

Fig. 5 – Meshing the computation model.

6. Computing the dynamic load

To consider the pressure generated during the explosion, equations suggested by the "US National Highway Institute" [8] were used, and the relationships used were determined empirically. The time-varying pressure required for the "Time History" type of study will be automatically calculated using the calculation program used. The calculation formula is based on "Window" functions, and the relationships are suggested by Starfield et al [8].

$$P_{det} = \frac{4.18 \times 10^{-7} \times S_{ge} \times {V_e}^2}{1 + 0.8S_{ge}} \tag{5}$$

$$P_B = P_{det} \times \left(\frac{d_c}{d_h}\right)^3 \tag{6}$$

$$P_{det}(t) = 4 \times P_B \left[exp\left(\frac{-Bt}{\sqrt{2}}\right) - \exp\left(-\sqrt{2}Bt\right)\right] \tag{7}$$

Where:

P_{det} represents the explosion pressure (kN/m^2)

S_{ge} represents the explosive density (g/cm^3)

V_e represents the detonation velocity (m/sec)

P_B represents the uniformly distributed surface load (kN/m^2)

d_c represents the diameter of the container in which the explosive is introduced (mm)

dh represents the diameter of the borehole in which the explosive container is introduced (mm)

B represents an empirically determined coefficient, equal to cu 16.338

t represents the time over which the analysis is performed.

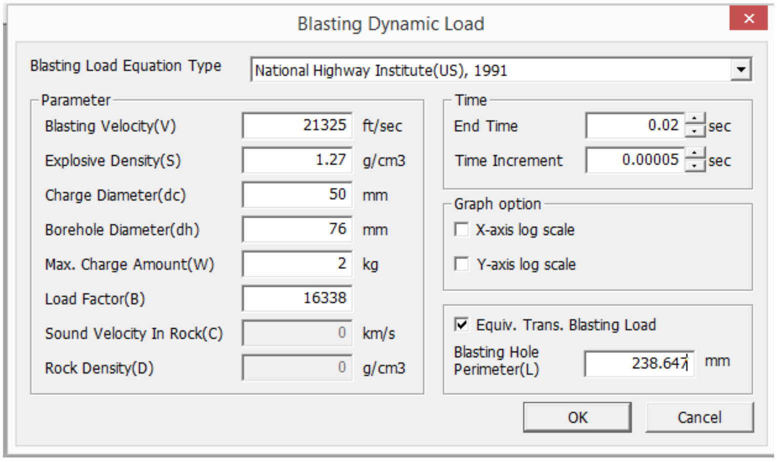

Fig. 6 – Date of the dynamic loading

The explosive used falls into the category of high-power explosives, hexogen (also known as RDX; it is made from a mixture of nitric acid, hexamethylene-triamine, and ammonium nitrate), with an explosion velocity of 6500 m/s, equivalent to 21325 ft/s.

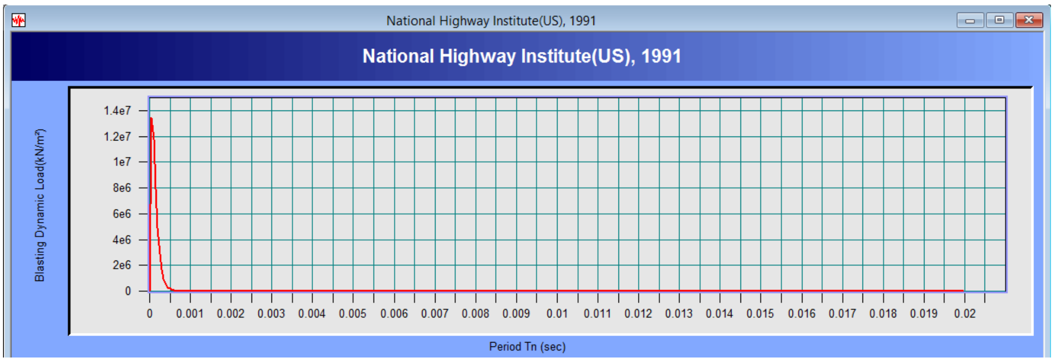

Fig. 7 – Dynamic loading spectrum

7. Analysis of the seismic effect of the blasting on the adjacent concrete structure

7.1. Model 1

The first model consisted of determining the maximum velocity at ground level under the foundation of the adjacent building to the rock basting. The lower ends of the excavation corresponding to the structure were labeled with letters from A to D, see Fig. 8.

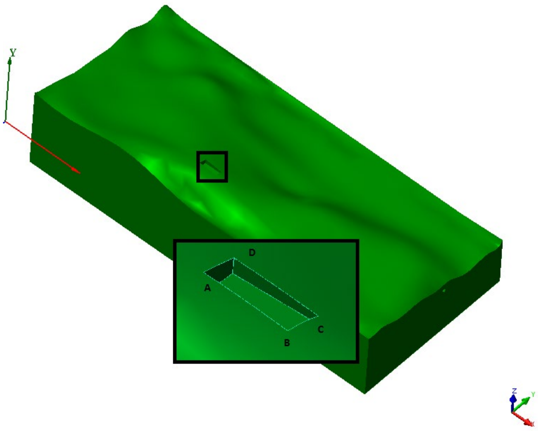

Fig. 8: Numbering of the interested nodes for the current model

The induced deformations in the rock mass at the excavation front, see Fig. 9, at the time of the explosion detonation are equal to 2.27 mm in the central area, reaching up to 0.4 mm in the contour zone. In other words, the deformations that lead to rock fracturing are only felt in the vicinity of the explosion zone, as the deep excavation technology is designed.

The expansion of the stresses generated by the explosion in the earth mass can be observed over time in the accompanying figures. These are essentially due to changes in the stress state in the rock mass. Although the values recorded by the MIDAS GTS calculation program are quite small, they can generate particle speeds large enough to affect adjacent engineering structures.

The velocity felt at the level of the drill holes are high, with values ranging from 9.066 m/sec to 2.266 m/sec, equivalent to 9066 mm/sec and 2266 mm/sec, respectively. If these velocities were to intercept the foundation of an adjacent structure, regardless of how it was designed and executed, it would result in a general collapse of the building. Fortunately, the damping capacity of the rock, ξ, is equal to 0.05, a value sufficient to reduce the speed of the solid particles intercepting the structure to 4.7 mm/sec.

Because of the high velocity intercepted in soil below the foundation of the structure, the next models will be by adding tranches with different length and deeps.

The induced velocities in the rock mass upon detonation of the explosive are illustrated in the fallowing figures because of the finite element 3D model simulation at different times.

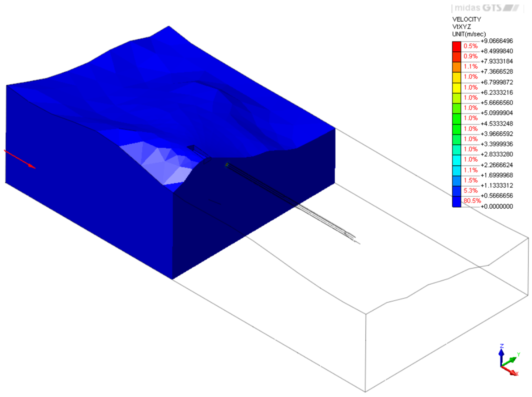

Fig. 9 – The velocities at time T = 0.0005 sec

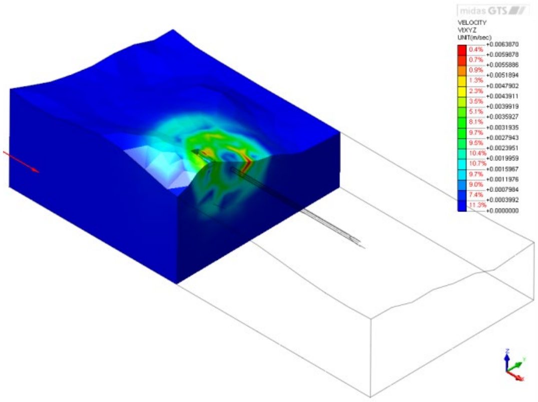

Fig. 10 - The velocities at time T = 0.05 sec

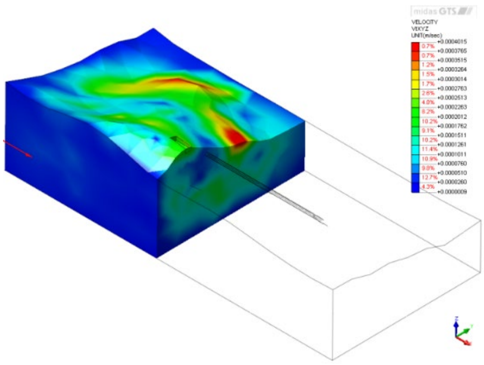

Fig. 11 - The velocities at time T = 0.25 sec

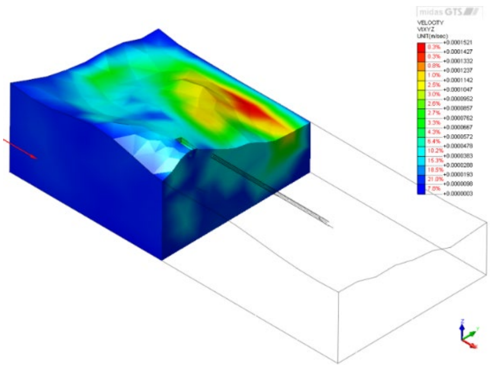

Fig. 12 - The velocities at time T = 0.50 sec

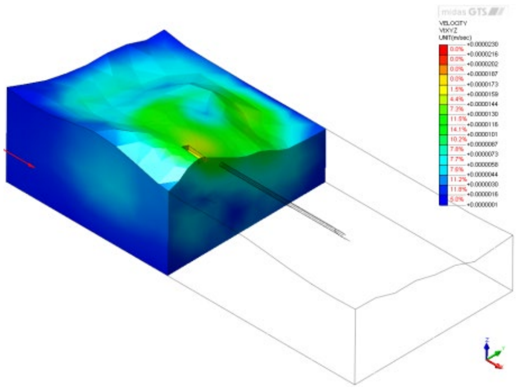

Fig. 13 - The velocities at time T = 1.00 sec

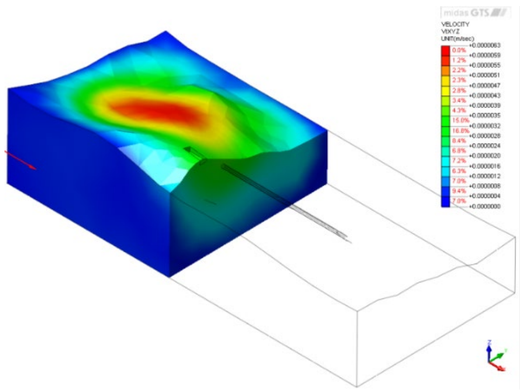

Fig. 14 - The velocities at time T = 1.50 sec

7.2. Model 2

Model 2 consisted of in adding from initial Model 1 of 1 trench with a length of 31m, a depth 5 m, and a thickness of 1m to prevent the propagation of waves generated from blasting. The trench is positioned at 10 meters distance from the building.

Due to the damping system that the rock structure possesses, the displacement values and implicitly, the velocities and accelerations of solid particles decrease as they approach the building area of interest. It can be observed that the velocity of solid particles is influenced by the presence of the damping trench, but not sufficiently. The wave of the solid particles “by pass” the trench and reach values approximately equal to 4.4 mm/sec at the extremity of the excavation area of interest at the moment of maximum intensity T=0.32 sec.

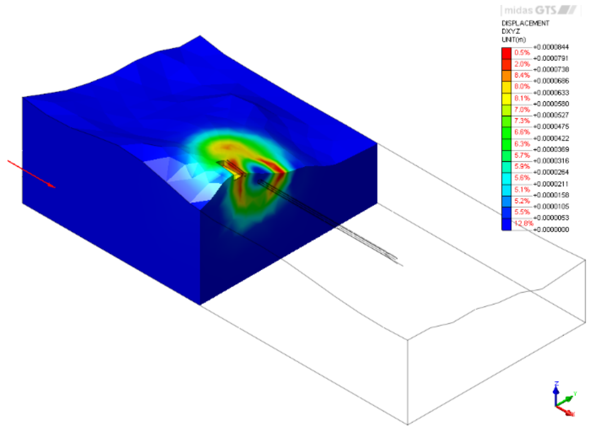

Fig. 15: The velocities at time T = 32 sec

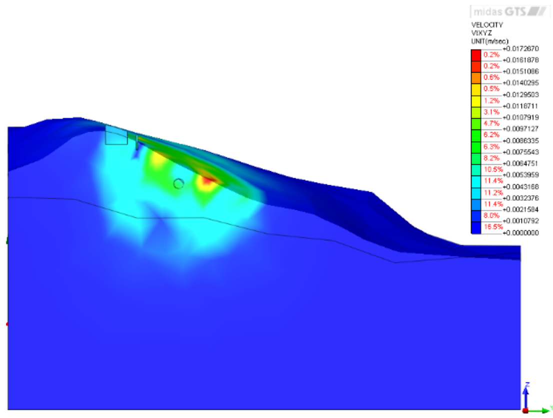

Fig. 16: The effect of the presence of on trench at 5m depth in the path of the explosion blast

The induced velocities in the rock mass upon detonation of the explosive are illustrated in the fallowing figures because of the finite element 3D model simulation at different times.

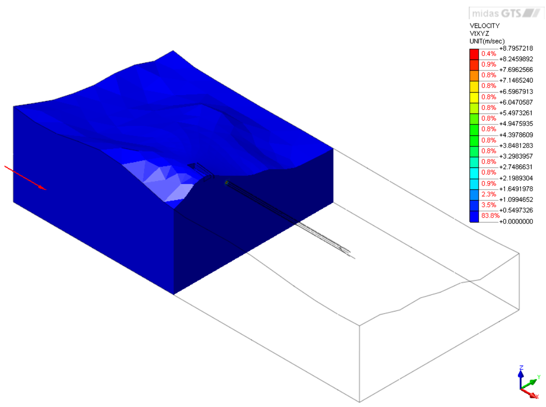

Fig. 17 – The velocities at time T = 0.0005 sec

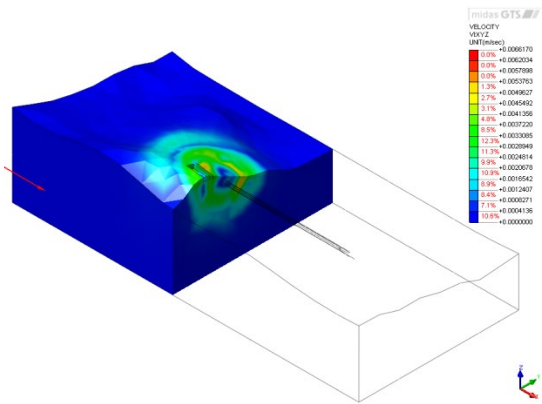

Fig. 18 - The velocities at time T = 0.05 sec

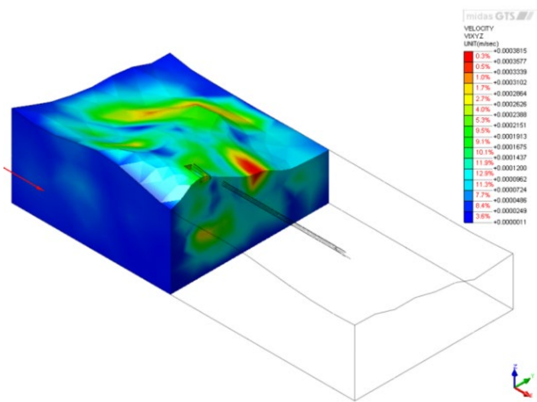

Fig. 19 - The velocities at time T = 0.25 sec

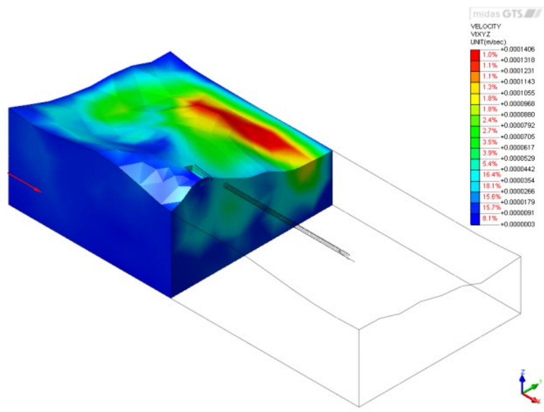

Fig. 20 - The velocities at time T = 0.50 sec

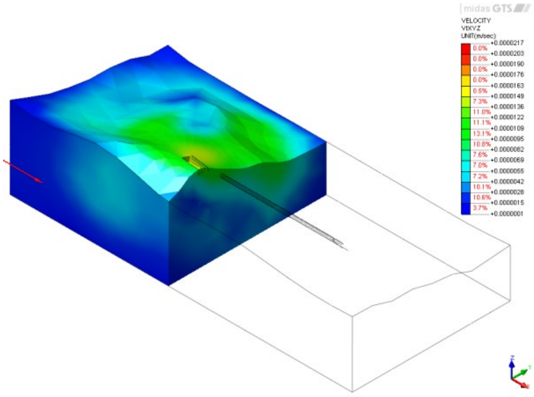

Fig. 21 - The velocities at time T = 1.00 sec

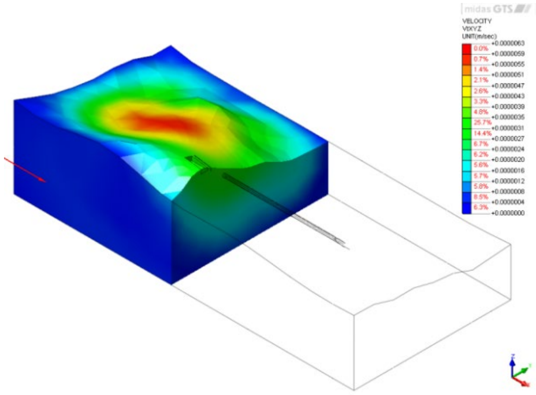

Fig. 22 - The velocities at time T = 1.50 sec

7.3. Model 3

Model 3 consisted of in adding from initial Model 1 of 2 trenches with a length of 31m, a depth of 2m and 5 m, and a thickness of 1m to prevent the propagation of waves generated from blasting. The external trench is positioned at 10 meters distance from the building, having the following dimensions: a depth of 5 meters, a length of 31 meters and a width of 1 meter. The inner trench is positioned at approximately 2 meters away from the building of interest and has the following dimensions: a depth ranging from 2.22 to 5.88 meters, a length of 31 meters and a width equal to 1 meter.

The velocities become zero in the immediate vicinity of the first trench, amplifying as they approach the building, reaching values equal to 4.6 mm/sec, values that are not accepted by the reference standard DIN 4150-3. This phenomenon is due to the arch effect, or the morphological variation which is delimited by the presence of the two trenches.

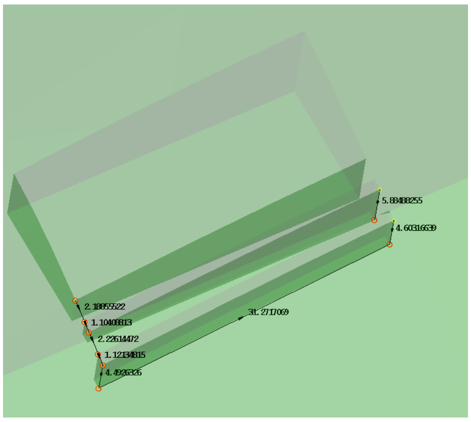

Fig. 23: Displacement of the tranches

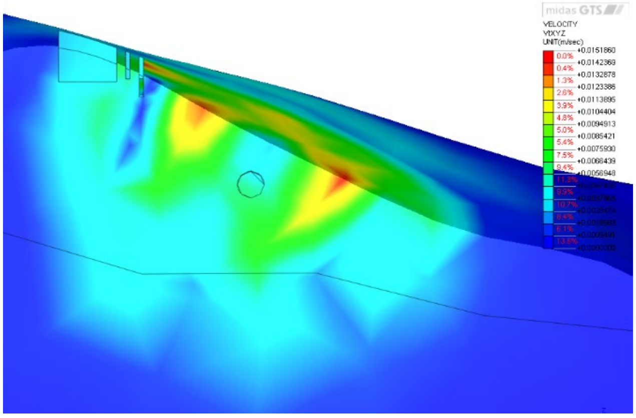

Fig. 24: The effect of the presence of two trenches at 2 and 5m-depth trenches in the path of the explosion blast

The induced velocities in the rock mass upon detonation of the explosive are illustrated in the fallowing figures because of the finite element 3D model simulation at different times.

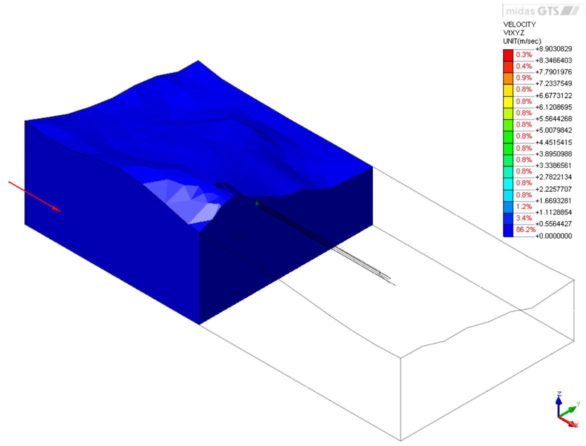

Fig. 25 – The velocities at time T = 0.0005 sec

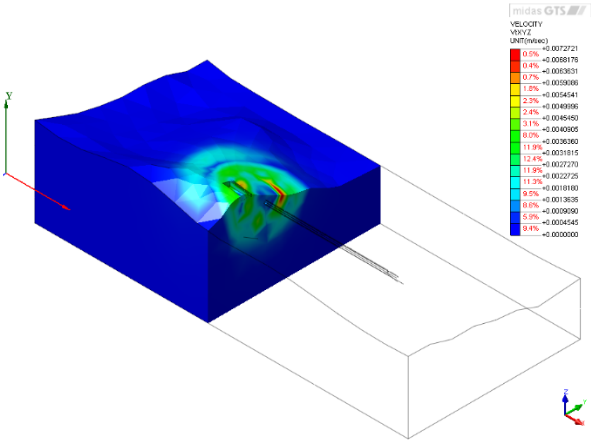

Fig. 26 - The velocities at time T = 0.05 sec

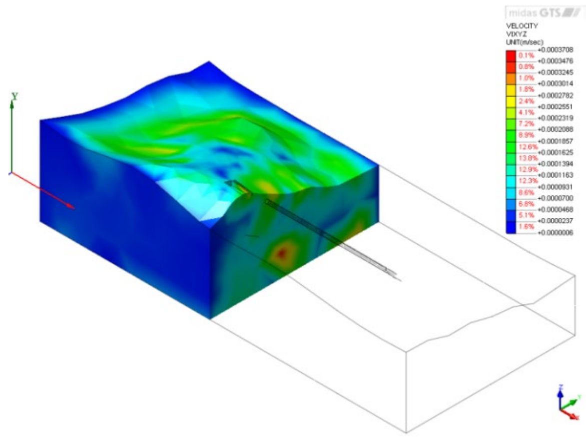

Fig. 27 - The velocities at time T = 0.25 sec

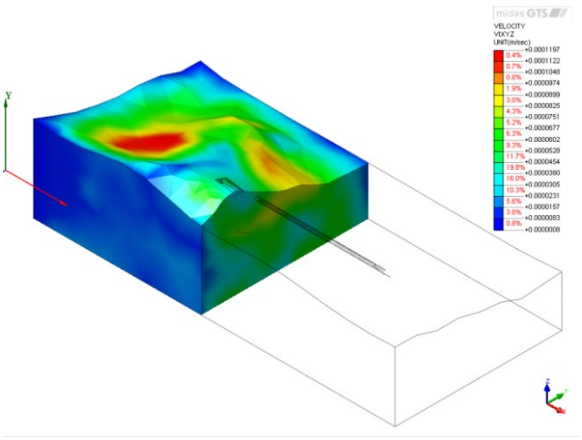

Fig. 28 - The velocities at time T = 0.50 sec

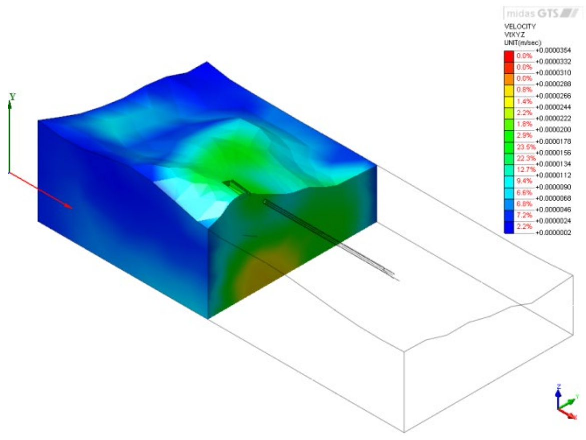

Fig. 29 - The velocities at time T = 1.00 sec

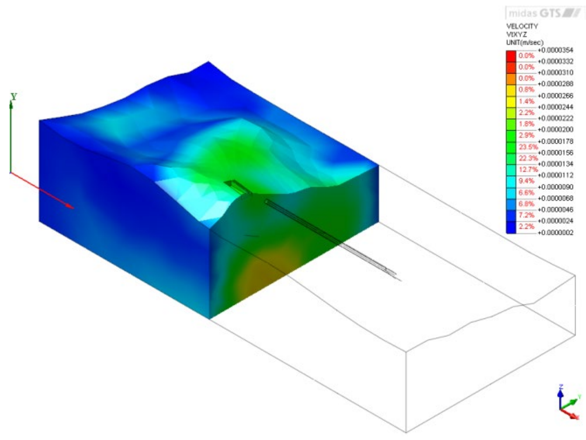

Fig. 30 - The velocities at time T = 1.50 sec

7.4. Model 4

Model 4 consisted of in adding from initial Model 1 of 2 trenches with a length of 36m, a depth of 10m, and a thickness of 1m to prevent the propagation of waves generated from blasting.

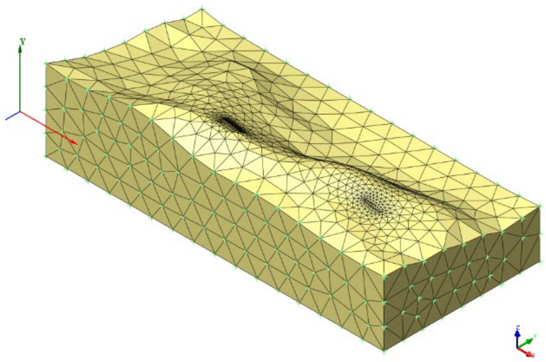

Fig. 31: Meshing of the numeric model

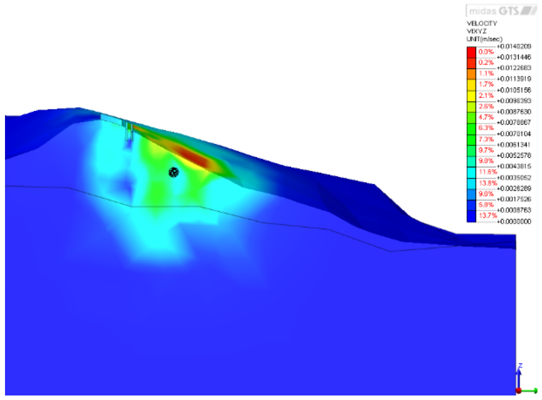

Fig. 32: The effect of the presence of two 10m-depth trenches in the path of the explosion blast

The induced velocities in the rock mass upon detonation of the explosive are illustrated in the fallowing figures because of the finite element 3D model simulation at different times.

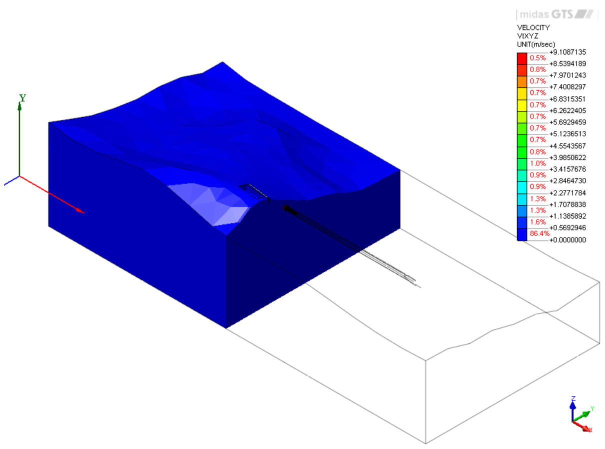

Fig. 33 – The velocities at time T = 0.0005 sec

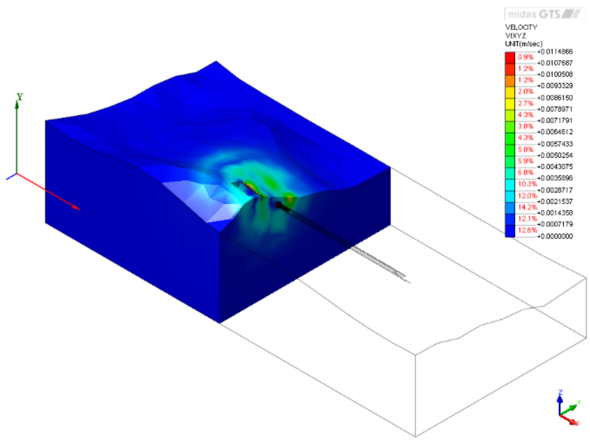

Fig. 34 - The velocities at time T = 0.05 sec

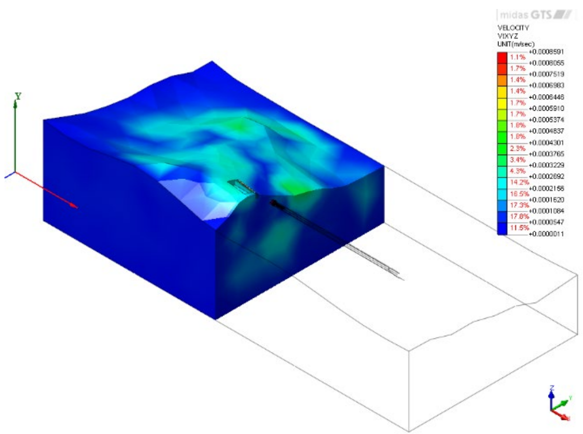

Fig. 35 - The velocities at time T = 0.25 sec

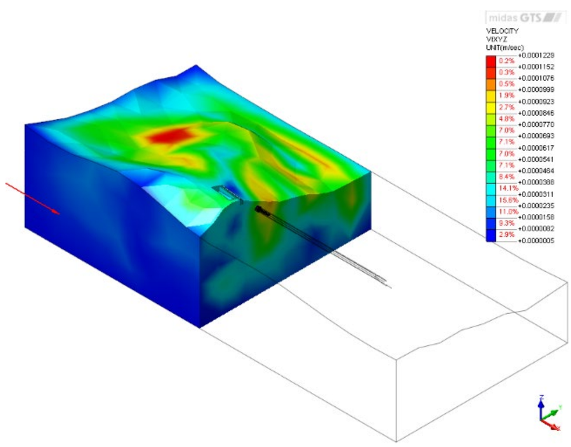

Fig. 36 - The velocities at time T = 0.50 sec

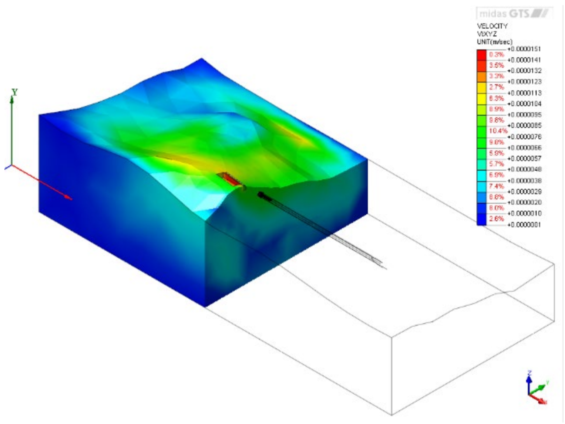

Fig. 37 - The velocities at time T = 1.00 sec

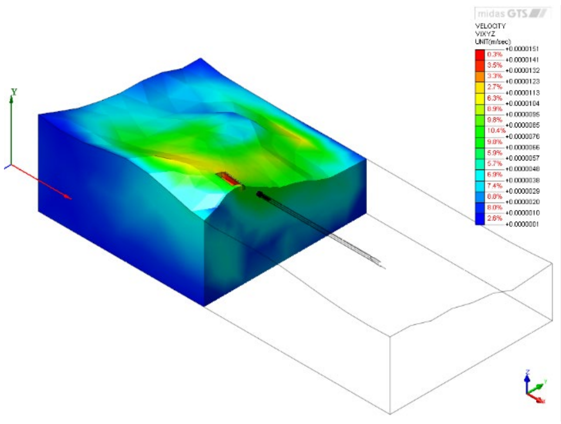

Fig. 38 - The velocities at time T = 1.50 sec

8. Conclusions

By carrying out the calculation models, the seismic effects on neighbouring buildings caused by the detonation of an explosion underground environment made of rock mass were observed and highlighted.

The results obtained from the analysis of the four calculation models are centralized in the following table and are also represented graphically in Fig. 39.

Table 2

Summary of computation models

No.	Computation model	The maximum displacement of solid soil particles [mm]	The maximum velocity of solid soil particles [mm/s]	The maximum acceleration of solid soil particles [mm/s^2]
1.	Model 1 – homogeneous rock mass	0.073	4.72	5.9
2.	Model 2 –5m deep trench	0.067	4.45	5.3
3.	Model 3 – 2 and 5m deep trenches	0.074	4.54	5.6
4.	Model 4 – 10m deep of 2 trenches	0.069	3.34	3.74

As it can be observed, even if tranches are made to intercept the propagation direction of seismic waves generated by the explosion, it does not necessarily mean that there will be a reduction in the displacements, velocities, or accelerations of solid particles (see the results obtained from calculation models 2 and 3).

The continuity of the underground rock excavation process must also be taken into account. In cases where the underground gallery is located in the area of interest, the seismic effects generated by the explosion will be cushioned due to the convex mirror effect, a phenomenon achievable thanks to the presence of cushioning trenches with a depth of 10 m (calculation model No. 4).

To increase the convex mirror effect and achieve a reduction of less than 3 mm/s, the length of the 10 m deep trench should be increased on the other existing sides of the building.

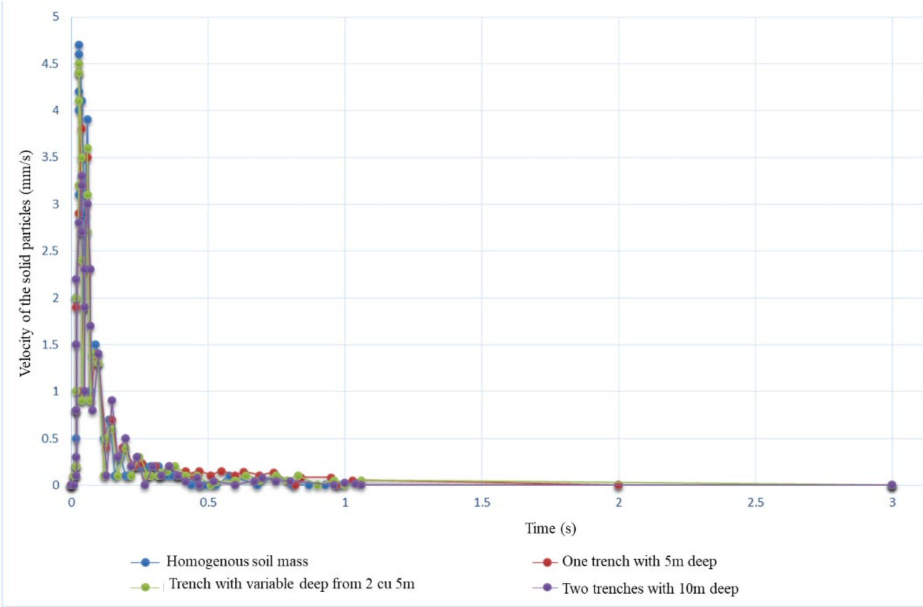

Fig. 39 - The variation of solid particle velocity in the rock mass, at the foundation level, over time

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