Assessment Study on the Seismic Effect of Blasting Explosions on the Protected Sites and Methods used to mitigate this effect of explosions – control and monitoring procedures – Rosia Montana

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ANNEXES – Technical Sheets of several Seismometers

Assessment Study on the Seismic Effect of Blasting Explosions on the Protected Sites and Methods used to mitigate this effect of explosions – control and monitoring procedures

1. Generation of seismic waves due to explosions in rocks

The blasting explosions performed within the mining industry are the main sources of seismic waves. Depending on the physics-technical conditions where these explosions are conducted, they may generate different types of seismic waves.

Several physics-mathematical models have been founded for the explosions in rocks by starting with the idea of a point concentrated sources and ending in the assumption of a sources placed in spherical, cylindrical or rectangular cavities of insignificant dimensions.

The physics-mathematical model is a major instrument of analyzing the generation of seismic waves due to explosions.

From the many models existing in specific literature, three are to be detailed:

- Spherical seismic source, equivalent to the explosion that generates longitudinal and transversal waves;
- The seismic source equivalent to the explosion produced within the cylindrical cavity;
- The seismic source equivalent to the explosion produced within the rectangular cavity.

In the case of the Rosia Montana site, the blasting is conducted with explosives placed in boreholes and that is equivalent to the physics-mathematical model entitled “seismic sources in cylindrical cavity”.

1.1. Spherical seismic source, equivalent to the explosion that generates longitudinal and transversal waves

The experiments showed that the underground blasts of spherical loads generate both P longitudinal waves as well as S transversal waves.

The detonation of an explosive load placed within a spherical cavity of R_0 radius shall produce on the walls of this cavity a pressure p. If the environment around the cavity is perfectly elastic, homogenous and isotropic, the application of a regular pressure $p(t)$ on the inner surface of the cavity shall generate only longitudinal waves.

In fact, the rocks bulk where the explosion shall be performed is imperfect elastic, so as the very high pressures acting in the front of the shock wave are producing in the vicinity of the cavity with R_0 radius an area of breakages, fissurations and shearings that are capable to generate both types of waves (longitudinal and transversal). Another cause favoring the occurrence of the two types of waves is the pretension of the mountain due to several tectonic forces or due to previous explosions.

During the explosion, a detonation wave is propagated through the load at a velocity that depends on the composition of the explosive substance, its compaction, and the pressures of the surrounding environment. The expansion of the gas products resulting after an explosion results in large movements of the environment particles. The velocity of the shock wave depends on the properties of the environment through which it travels and the size of the produced deformations. When the pressure of the shock wave is very high, the large deformations are travelling faster than small ones and the shock wave shall present a front on which the pressure is varying suddenly. When the pressure becomes lower than the critical one, the deformations are smaller and the shock wave becomes an elastic wave whose velocity does not depend on the size of the deformations.

The actual environment through which it travels is behaving as an elastic environment provided that the tensions and deformations are low. Due to the fact that the pressures are very high around the explosion, they exceed by far the breaking resistance of rocks and thus, after the explosion a breaking area of R_1 radius (see figure no. 1) occurs around the source and within this area the rocks are broken.

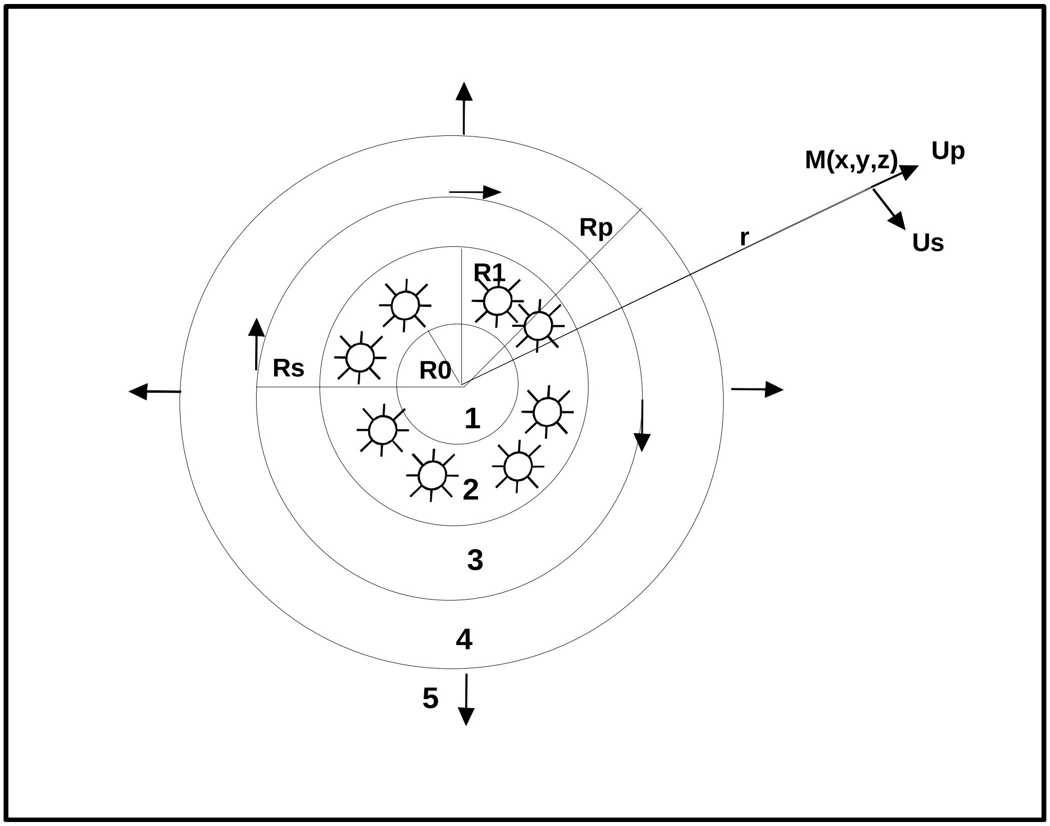

Figure no. 1. Spherical seismic source generating longitudinal and transversal waves
1 - explosion cavity; 2 - area of breakages, fissurations and shearings;
3 – area of non-elastic deformations for S waves;
3 and 4 - area of non-elastic deformations for P waves; 5 – elastic area.

A large portion of the explosion generated energy is consumed with crushing and heating rocks. Due to these losses, the density of the wave front is rapidly decreasing so as at the distance R_1 the pressure on the wave front becomes lower than the rocks breaking resistance, remaining higher then their elasticity limit. That is why, around the breaking area another area occurs where rocks are undergoing non elastic deformations represented by dilations, compressions or shearing that are irreversible to the environment, and these lead to formation of fissures up to distance $\boldsymbol{r = R_p;R_s}$.
For $\boldsymbol{r > R_p}$, the pressure on the wave front drops, and the deformations become sufficiently low so as to be considered elastic.
The way in which P and S waves are generated in case of a spherical source is presented in figure no. 1.
Zone 2 is responsible with the production of the two types of waves.
For $\boldsymbol{r > R_s}$, the pressure on the wave front becomes lower than the breaking resistance of rocks, but it remains until $\boldsymbol{r = R_p}$ distance higher than the elasticity limit. Due to the fact that the element composing the forces generating longitudinal waves are different in intensity than the ones responsible with the generation of transversal waves, one can accept the fact that the P waves become elastic at distance R_p, and S waves at distance R_s. it results the fact that things are happening like it is about two spherical sources of elastic waves: source of R_p radius that generates longitudinal waves and a source of R_s radius that generates transversal waves.
Starting with the fundamental equation of seismic waves:

$$[\lambda + \mu]grag.div.U + \mu\Delta U + \rho F = \frac{\rho\partial^2 U}{\partial t_2} \quad \textbf{(1)},$$

where:

$\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$ **-** Lame coefficients;

$\boldsymbol{\rho}$ – environment density;

t – time;

U – travelling vector;

F – force related to the mass unit; it results the movement $\boldsymbol{U_p}$ and $\boldsymbol{U_s}$ for longitudinal and transversal waves, generated by a spherical source.

1.2. The seismic source equivalent to the explosion produced within the cylindrical cavity

During mining operations, most explosions are produced within cylindrical cavities, in vertical, horizontal or inclined boreholes. In this case, some of the hole is filled with packing material that is aimed at directing the energy of explosion towards the hole bottom and at mitigating and removing the aerial shock and the sound waves.

In the case of these explosions, a pressure *p* is produced on the side walls of the cavity, which generates both types of waves: longitudinal and transversal.

Starting with the general equation of seismic waves, it results the equation of movement for longitudinal waves $\boldsymbol{U_p}$ and and for the transversal waves $\boldsymbol{U_s}$ as follows:

$$U_p = \frac{\Omega}{4\pi\mu V_p r}[1 - 2V_S^2 \cos^2 \alpha]\frac{d}{d_t}[p(t - \frac{r}{V_p})] \quad \textbf{(2)}$$

$$U_s = \frac{\Omega}{4\pi\mu V_s r}[1 - 2V_s^2 \sin 2\alpha]\frac{d}{d_t}[p(t - \frac{r}{V_s})] \quad \textbf{(3)},$$

Where, $\boldsymbol{\Omega}$ is the volume of the cylindrical source, ***r* and** represent the polar coordinates of the point in which the $\boldsymbol{U_P}$ and $\boldsymbol{U_S}$ movements are considered.

The angle is determined by the axis of the cylindrical cavity with the direction from receptor towards source center.

In the case of explosions within cylindrical cavities, P and S waves have directional properties. Thus, the amplitude of wave P is maximum in the direction where it forms a 90° angle with the axis of the cylindrical cavity, and wave SV has maximum amplitude in the direction where it forms a 45° angle with this axis.

From the equations (2) and (3) it results that the ratio between the maximum amplitudes of the two waves is equal to V_P/V_S.

The occurrence of a delayed transversal wave is typical to the explosions within cylindrical cavities due to the reflection of the shock wave on the cavity bottom.

The experiments showed that for lower α angles, the ratio of the S/P amplitudes decreases as the load increases, and for = 90° the ratio remains practically constant with the load increase.

As previously mentioned, the borehole blasting used at Rosia Montana is equivalent with the explosions produced within cylindrical cavities.

In the case of Rosia Montana, the angle is formed by the axis of the borehole and the direction of the site that needs protection and its value does not exceed 90°.

Thus, for the eight sites that need protection at Rosia Montana, S/P ration shall not increase with the increase of the load, and the amplitude of the transversal wave shall decrease as the amplitude of the longitudinal wave increases.

1.3. The seismic source equivalent to the explosion produced within the rectangular cavity

The detonation of a load within a rectangular cavity is equivalent with a bilateral break, which resembles a fault with normal movements at the surface of the fault.

The travelling vectors for P and S waves have the following equations:

$$U_p = \frac{r_0}{4\pi V_r^2 r}[V_p - 2V_s^2 + \left(\frac{V_p^2}{v} - 2\frac{V_s^2}{v}\right)\cos\alpha + 2V_s^2 \sin^2\alpha]\delta(t - \frac{r}{V_p} - \frac{x}{v}) \quad \textbf{(4)}$$

$$U_S = \frac{\alpha_0}{4\pi V_S^2 r}[(2V_S^2 - V_p^2)\frac{\sin\alpha}{v} + 2V_S \sin\alpha\cos\alpha]\delta(t - \frac{v}{V_S} - \frac{x}{v}) \quad \textbf{(5)}$$

From these equations it results the fact that the movements caused by explosions within rectangular cavities are similar with the model of explosion developed within a cylindrical cavity.

1.4. Energy of the explosion

During the excavation operations, explosive is used to blast a predefine rock quantity.
"*To detonate*" means to fracture *in situ*, to break and to move the rock from its natural state so as to be easily removed.
"*Predefined"* refers to the fact that the explosion needs to be produced within a well defined transversal section and the soil surrounding the excavation must not be impacted or disturbed (or in case these are acceptable, they need to observe the previously established limits, which are based on a conservative assessment).
When planning an excavation, two distinct issues need to be approached:

1) The establishment of the energy necessary to detach, break and project the blasted rock;
2) The definition of explosive distribution within the rock for a better exploitation of the available energy as per the excavation and environmental protection standards.

In other words, the issue is to define how much explosive with known features is required to detonate a certain quantity of rocks and to establish how much of the explosive must be placed.
The essential feature of any blast is that is developing for a very short period of time a large quantity of energy as shock waves and high pressure gasses.
The detonation front in the blasting hole is passing through the explosive load at several thousand meters per second (detonation velocity).
The detonation front is characterized by a very high peak of dynamic pressure of over 10^4 MPa. On the other hand, the level of the pressure within the wave section that is immediately following the shock wave is "almost static" at approx. 10^3 MPa. As the detonation front progresses, a shock wave is sent into the rock, which initially has a pressure peak that is able to blast and plasticize the rock around the blast hole within a R distance, which usually is not higher than the diameter of the load Φ_c. this occurs when the diameter of the load $_c$ is almost equal to the diameter of the blast hole $_f$.
Away from this area, the pressure peak decreases greatly, but, however, the perpendicular elastic tension on the direction of the shock wave is sufficient to produce radial factures at the rock micro-defects. Such fissures may extend outside the blasting hole on distances 4 to 6 times longer than the load radius (R = 4-6 $ø_c$, as pictured in figure no. 2).

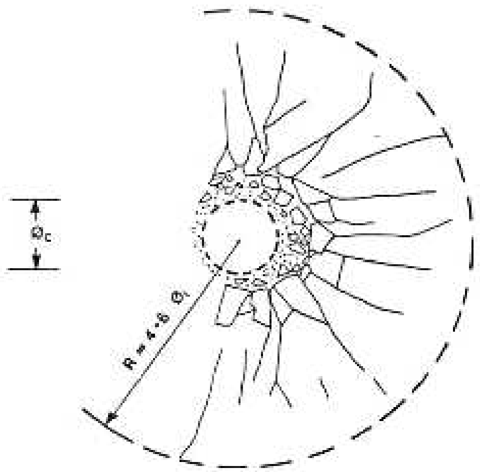

Figure no. 2. Crushed and fractured areas from the immediate vicinity of the load

At higher distances than that, the intensity of the shock wave decreases down to a point where is travelling the rocks without causing more fractures.

The rock behavior is like an elastic field, and the effects are low level vibrations. But, when the shock wave is reaching a free surface it is reflected back into the rock as an elastic wave whose intensity if exceeds the rock elastic strength may induce fractures within a parallel direction with the one of the free surface (see figure no. 3 a).

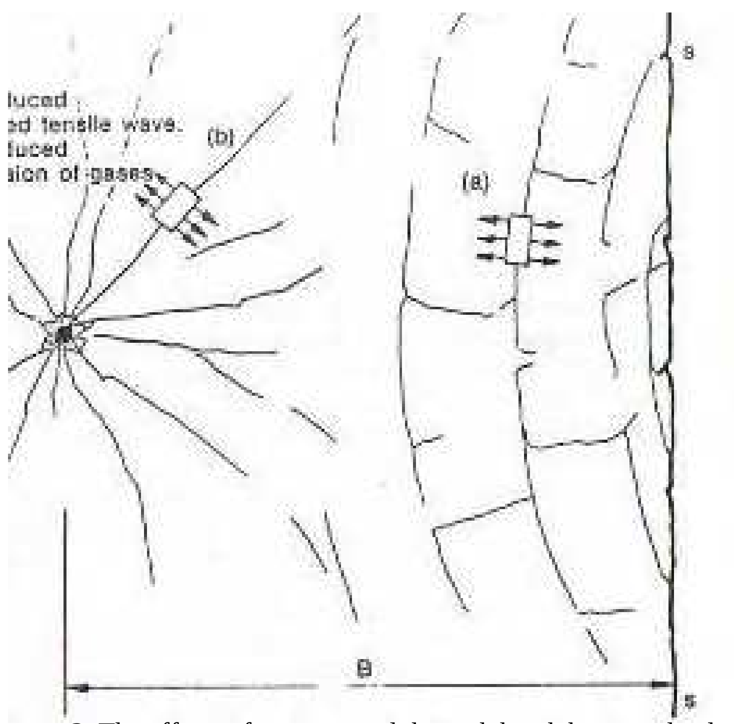

Figure no. 3. The effects of pressure and the rock break between load and free front

In order for the rock to break due to the reflection of the shock wave, the free surface s - s must be at distance B from the load, and that distance depends on the type of explosive and rock. This distance B is also related to the load diameter, and the relation may be written as: $B \leq 50 \ {}_{c}$

This ratio is valid only when the blast hole is ideally loaded, when the load diameter and hole diameter $_f$ and $_c$ are the same.
The fissures around the hole are weakening the rock, reducing its strength in this manner and the rock breaking process is assisted by allowing gasses to infiltrate in cracks (see figure no. 3b).
Depending on distance B (the distance to the free surface), the detonation of the load into the borehole shall produce different quantitative effects, as follows:

a) If the blast hole is far from the free space (for instance B > 60 $_c$), the results of the rock explosion are breaking and blasting in the immediate vicinity of the hole with several radial cracks induced into the rock body (see figure no. 4.a);
b) If the blast hole is close to the free space, let’s say at approx. 60 $_c$, it is possible that additionally to the effect described above to see several cracks between the blast hole and the free space. The rock section impacted by this fracturing may not be however easily separated by the mountain and tends to “sit” on the frontal wall and is difficult to move it (see figure no. 4.b);
c) If the blast hole is much closer to the free space B = 40 $_c$, the explosion shall result in an extensive fracturing of the rock of the section covering the hole and the free space. Now, the material is not “hanged” on the wall, but it falls in a bulk that may be easily removed (figure no. 4.c);
d) If the blast hole is very close to the free space, let’s say B = 20 $_c$, the removed rock that is smaller than the rock from the previous case is violently projected and may be spread on a very extensive area (figure no. 4.d).

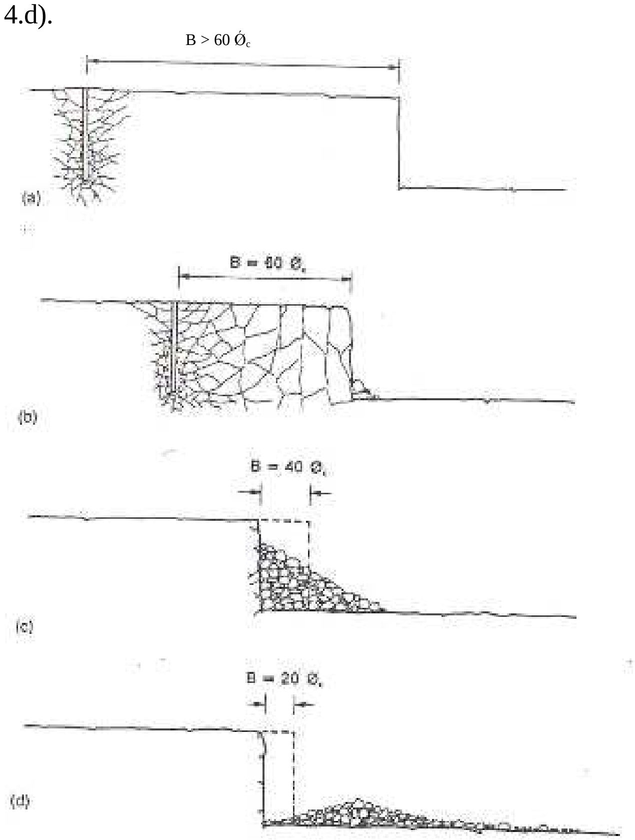

Figure no. 4

If an optimum distance is defined for the best performance B_{opt}, then:
For **B > B$_{opt}$**, the rock break is limited in the immediate vicinity of the hole, and the rock continues t”to hang” and is difficult to remove it.
For **B < B$_{opt}$**, a low quantity of rocks is broken and the rock pieces are projected on a distance that increases when B decreases.
When **B = B$_{opt}$**, it is possible to obtain a maximum quantity of broken rock, thoroughly fragmented, a correct movement and a proper outline of the bulk.

B_{opt} is direct proportional with the load diameter. Thus, the distance may be altered, but may remain optimum provided that the load diameter (and consequently the borehole diameter) is altered so as to be compatible with the distance.
In the case of Rosia Montana site, it results that $\mathbf{B_{opt} = 5\text{-}8\ m}$ within the area where special blasting technology is to be applied.

1.4.1. Energy transfer onto the rock

The dynamic of the explosion shows that the energy developed by a blast is producing different effects, among which some represent the useful work, and other are non-productive and unwanted consequences and others are unavoidable.
Usually, the productive effects are:

a) The movement of a pre-established rock volume;
b) The rock fragmentation into well defined elements and of regulated dimensions;
c) The projection and resettlement of rocks on and at a certain distance against their initial position.

Unwanted consequences are:

a) Excessive breaking of some of the rock;
b) Projection (throw) in an excessive manner (“flying rocks”);
c) Fractures and deformations of rock that are permanent, after explosion;
d) Soil vibrations;
e) Air vibrations.

That is why, it is necessary to estimate the factors on which the energy transferred to rocks depend upon.
The energy developed by the explosive reactions is an intrinsic thermal-dynamic feature of the explosive due to the fact that depends on its composition, by the reaction products and by the heat that is produced by the involved substances. Its value may be calculated and is expressed in thermal and mechanical units. Usually, the energy of explosives is defined by mechanical units per mass unit (MJ/kg).
The energy transfer is impacted both by the explosive characteristics and the rock that receives the energy and depends on the acoustic impedance of the two.
The explosion impedance I_e is defined as the product of explosive density (ρ_e) and detonation velocity (*VOD*).
The rock impedance (I_r) is defined as the product between its density (ρ_r) and the propagation velocity of the elastic waves (*C*).
The energy that is to be transferred is impacted by a factor η_1 (impedance factor), represented by the following equation:

$$\eta_1 = 1 - \frac{(I_e - I_r)^2}{(I_e + I_r)^2} \quad \textbf{(6)}$$

This equation shows that as I_e and I_r are close in value, the impedance factor increases ($\eta_1 \rightarrow 1$), while if they are different the factor is lower.
To conclude, the capacity to send and receive energy depends on the combined characteristics of the explosive and of the rock.
The following parameters exist in the case of Rosia Montana:

– Explosive type: ANFO:
  - Explosive density: $\rho_e = 800$ kg/m^3,
  - Detonation velocity: VOD = 2,300 m/s;
– rock: weathered dacite
  - rock density: $\rho_r = 2{,}300$ kg/m^3,
  - the propagation velocity of the elastic waves: C = 2,300 m/s.

it results:

$$\eta_1 = 1 - \frac{(800 * 2300 - 2300 * 2300)^2}{(800 * 2300 + 2300 * 2300)^2} = 0{,}23$$

$$\boldsymbol{\eta_1 = 0{,}23}$$

Another factor impacting the energy transfer onto the rock is the coupling ratio, expressed through the ratio between the blast hole diameter and load diameter: ($_f$/ $_c$).
When the blast hole is ideally load, i.e. load diameter equals the blast hole diameter (a coupling ratio very close to 1), the shock pressure on the hole sides is maximum.

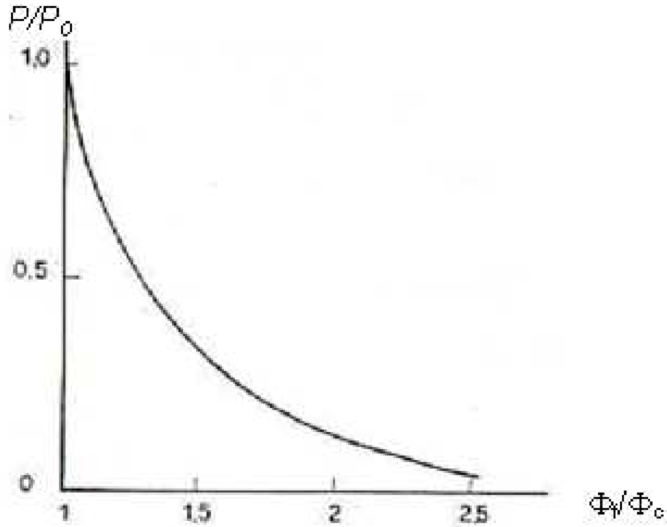

Figure no. 5.

Considering the fact that the value of the dynamic pressure on the hole sides varies as a function of the relation between the hole diameter and load diameter (f/ c - see figure no. 5) and taking into account the fact that a reduction of the pressure in the hole wall corresponds in practice to a reduction of the energy, one can deduce that the energy transfer onto the rock during a situation that is not ideal is developed at a coupling factor of η2, which is a function of (f/ c) expressed by the following relation:

$$\eta_2 = \frac{1}{[e^{\frac{\Phi_f}{\Phi_c}} - (e-1)]} \quad \textbf{(7)}$$

The relation is the mathematical expression of the curve presented under figure no. 5 and it shows the way in which the factor tends to its maximum (η2 → 1) when f → c and it is rapidly decreasing as the coupling ration f/ c increases.
The practical observations show that the best blasting result is obtained when the explosive is compacted with a pole, so as to ensure that the load is fully covering the blasting hole, i.e. it is equal to the hole diameter and the coupling is more than ideal.
On the other hand, if excessive force is to be avoided on the respective rock, the energy may be reduced through decoupling, and the coupling ratio (f/ c) must increase. To this aim, cartridges of a lower diameter than the borehole may be used.
In the case of Rosia Montana, where f ≈ c, it results:

$$\eta_2 = \frac{1}{[e^1 - (e-1)]} = 1 \quad \textbf{(7')}$$

As shown by η1 and η2, only some of the explosion energy is transferred onto rocks. The energy percentage may increase by changing the impedance parameters and the coupling factors η1 and η2.
In particular, for η1 it is necessary to use an explosive whose impedance characteristics would correspond better with the rock characteristics and ideally to be equal.
For η2, it is critical to have a full blast hole in order for the diameters to be as much as possible equal. In other words, the explosion may transfer some of the energy into the rock, as expressed by the following relation:

$$\varepsilon^* = \eta_1 \times \eta_2 \times \varepsilon \quad \textbf{(8)}$$

Much of the energy produced by explosion is consumed by inducing vibrations (the seismic effect) into the mined mountain.
The seismic effect or the soil vibration last longer than the movement, breaking and projection and impact a larger volume than the actual blasted material.
In the case of Rosia Montana, it results that the energy transferred onto the rock is:

$$\varepsilon^{*} = 0{,}23 \times 1 \times \varepsilon = 0{,}23 \cdot \varepsilon \quad \textbf{(8')}$$

There is something important to consider on this, the period of time after which the vibrations are sustained at a certain distance of the load. When distance increases and duration also increases and the intensity decreases.
The drawings recording the vibrations show that the vibrations amplitude is low as the recording point is farer than the sanding point but their duration is longer. Thus, while soil vibrations last for several tens of milliseconds at the 10 – 20 m away from the blast, they may last very well for over a second when measured at several hundred meters.
The energy produced by blasting, dissipated into the soil vibrations represents a large portion of the total energy. It is, however, difficult to estimate this due to the fact that the evolution of the seismic energy is not the same in every direction. Soil vibrations occur in a complex manner, with longitudinal and transversal oscillations, high variations in frequency and with different characteristics in different directions.
The energy absorbed by the seismic effect of the explosion may be calculated by using the following relation:

$$\varepsilon_g = 4\pi^3 R^2 \times \rho_r \times C \times a^2 \times f^2 \times t_v \times 10^{-6} \text{ [MJ]} \quad \textbf{(9)}$$

where:

ε_g = energy dissipated into the seismic effect [MJ],
R = distance between the explosion point and recording point [m],
ρ_r = rock density [kg/m^3],
C = wave velocity into the rock [m/s],
a = vibration amplitude [m],
f = vibration frequency [s^{-1}],
t_v = vibration time [s].

Another assessment method is the one based on the calculation of the seism magnitude.
Any explosion is accompanied by an air blow (aerial wave). The blow is in fact the analogous effect of the seismic effect into the air, but is difficult to assess it (even for approximate values). Typically, the measurements reflect the sound effect of this phenomenon, due to the fact that it is reasonable to assume that a great portion of the energy is dissipated as non-sounding vibrations, where frequency is either too low (infrasonic) or very high(ultrasonic).
The effects of the air blow correspond to the activity of gases expansion that is not involved in breaking or moving the rock. One of these effects is that some of the energy released by the rock as heat is released into the air as a consequence of its cooling. The energy lost into the air is usually estimated as a difference and represents a substantial portion of the total, around 38–39 % of the total energy transferred into the rock.
From researches conducted within the field of explosive use in blasting operations, it results the fact that the energy sent into the rock is distributed approximately like this:

a) fracture in situ: < 1 %,
b) breaking: 15 %,
c) movement: 4 %,
d) cracks near the blast hole: 1.5-2 %,
e) “rocks projection”: < 1 %,
f) Deformations of the solid rock behind the blast: < 1 %,
g) Soil vibrations; 40 %,
h) Air blow: 38-39 %.

2. Propagation of the seismic waves that are generated by explosions

The blasting operations generate seismic waves. It is possible to have two types of seismic waves within the isotropic and homogenous elastic environment:

- Longitudinal waves,
- Transversal waves,

which, due to their propagation inside the Earth are called interior or volume waves. These waves reflect, refract or diffract onto the separation limits present in the propagation environment without changing their volume character.

Another category of seismic waves propagating only near a separation surface is the surface waves.

2.1. Volume waves

The characteristic of the longitudinal waves is that they propagate through successive compressions and decompressions (see figure no. 6) along the propagation direction.

In the case of the transversal seismic waves (see figure no. 7), the material particle is travelling within a plane that is tangent to the wave front. The travelling vector U_S may change its direction within this plane. This makes the trajectory of the particle within the tangent plane to be a curve line, like an ellipse, circle etc.

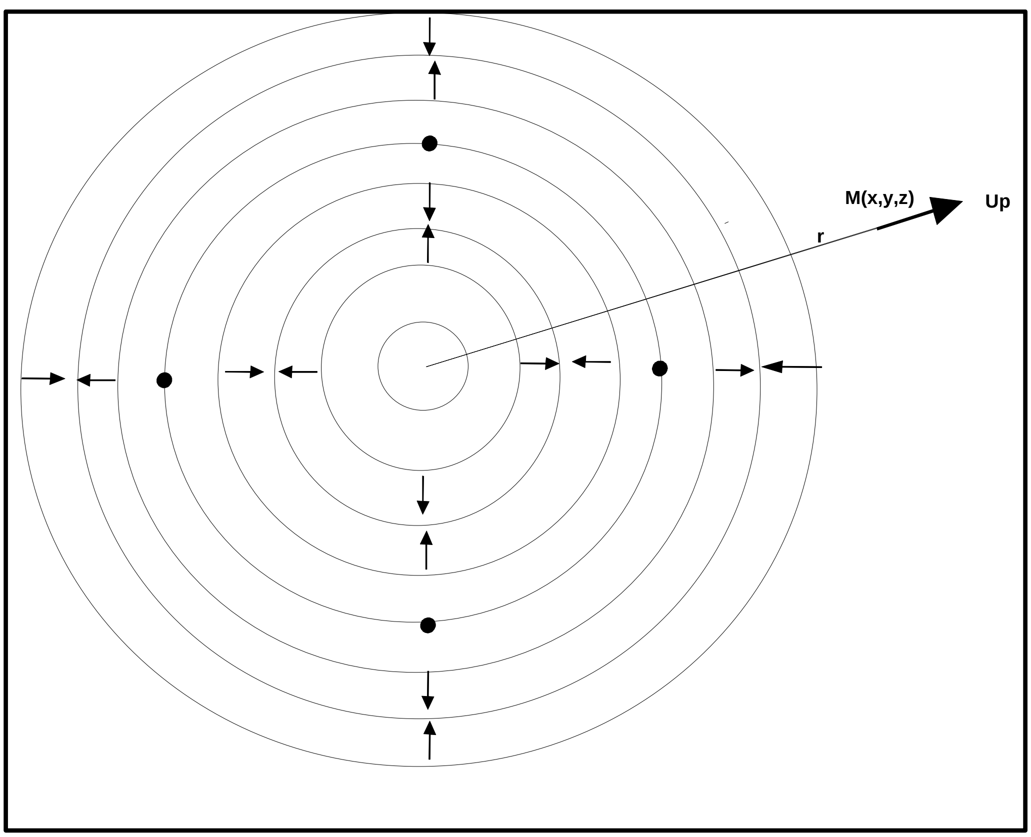

Figure no. 6. Drawing presenting the propagation of the longitudinal waves

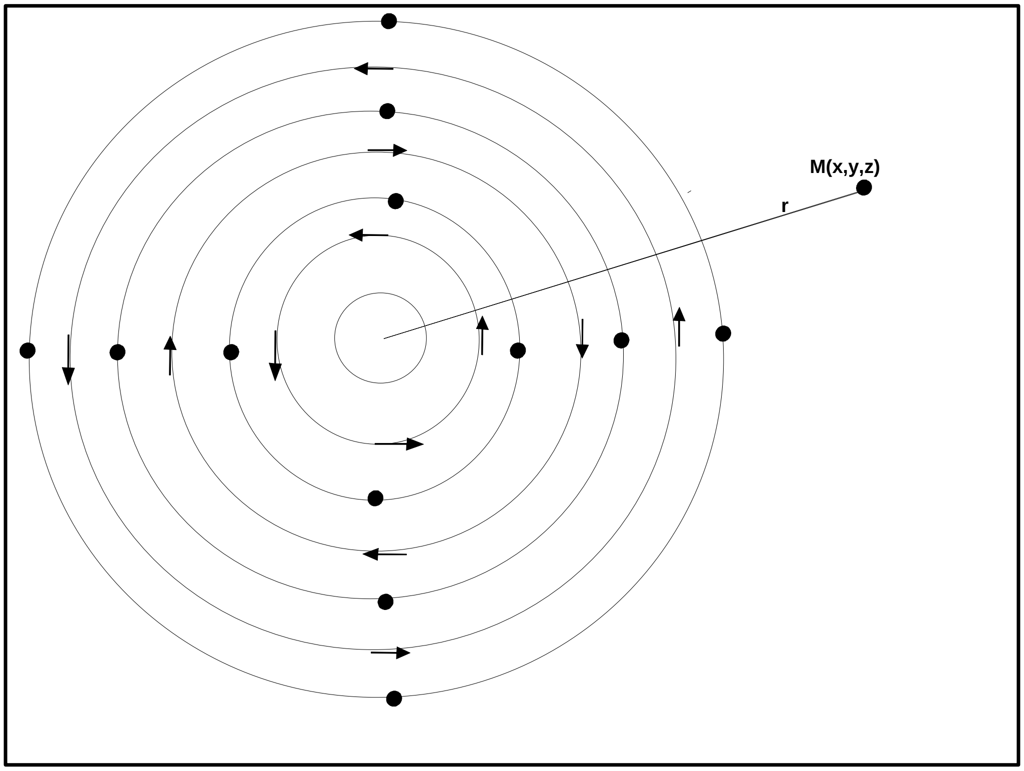

Figure no. 7. Drawing presenting the propagation of the transversal waves

2.2. Surface waves

The main surface waves are represented by Rayleigh and Love waves.

2.2.1. Rayleigh Waves

The Rayleigh waves occur at Earth surface being produced by an elastic force and they present both longitudinal and transversal elements, and their travelling vector rapidly decreases with depth.

The formation of the Rayleigh waves is the result of the non-plane character of the volume wave's front that is impacting on the land free surface. That is why, the Rayleigh waves are more intense as the curving radius of the volume wave's front is lower.

The Rayleigh wave is a sum of harmonic oscillations of frequencies, amplitudes and initial phases, and also in the case of heterogeneous semi-space with a particular velocity, called phase velocity. The impulse wave is the result of overlapping several harmonic frequencies travelling with their own velocity V_F.

The velocity of the impulse wave is the travelling velocity of the maximum coat of the impulse oscillation, entitled group velocity V_G.

The front of Rayleigh wave has a cylindrical shape in the case of homogenous environment and a quasi-sonic shape in the case of homogenous environment. If *h* is the generator of the wave front and *r* the distance from the source, it results the fact that the area of the wave front is proportional with the multiplication *rh*. Thus, the density of energy from Rayleigh waves decreases with *r*, and the amplitude of travelling with $r^{1/2}$.

That is why the amortization of Rayleigh waves is lower than the amortization of the volume waves that are produced by the same cause. That results in the fact that for long distances away from the source, the superficial Rayleigh waves(R) may have larger amplitudes than the volume waves.

2.2.2. Love waves

Another type of superficial waves is the Love wave or transversal superficial wave. The Love wave results after the SH waves are reflected on the free surface of Earth. The particles are travelling in the case of this wave at horizontal, being transversally directed on the propagation direction of the wave front. The propagation velocity of the Love waves is determined by the velocities recorded by the transversal waves from strata and depends on the relation between the length of the wave and the thickness of stratum. The formation of the Love waves in the case of explosions is possible only when the explosion also produces SH waves.

2.3. Principles based on which the seismic waves are propagated

The process of propagating the seismic waves is governed by a series of fundamental principles of physics, as follows:

a) The principle of superposition: if deformations resulted from different sources occur in the elastic environment, then each of them are propagating and exist independently of the others, and the total deformation is the algebraic sum of the individual deformations;
b) The principle of reciprocity: the seismic waves generated within a point O_1 and received at another point O_2 of the environment must be recorded with their travelling time, form and intensity identical with the waves generated in O_2 and received at O_1, if in O_1 and O_2 the generation and reception conditions are identical;
c) The Huygens principle: each point of an advancing wave front is behaving as a point source of oscillations;
d) The Fermat principle or the principle of least time: the seismic wave is traveling the path between two points in the least time.

2.4. The significant dynamic and cinematic characteristics of the seismic waves

Any seismic wave is characterized by the following dynamic and cinematic parameters:

- Travelling velocity: ***V* [m/s]**
- Oscillation velocity: ***v* [cm/s]**
- frequency: ***f* [Hz]**
- travelling: ***d* [mm]**
- acceleration***:*** ***a* [cm/s^2]**
- wave length: **λ [cm]**

Seismic records have been performed at Rosia Montana during four experimental blasts and the following parameters have resulted:

- oscillation velocity: ***v* = 0,32 ÷ 0,78 cm/s**;
- frequency: ***f* = 3,0 ÷ 5,0 Hz**;
- travelling: ***d* = 0,010 ÷ 0,028 mm**;
- acceleration***:*** ***a* = 0,17 ÷ 0,48 cm/s^2**.

3. Mitigation of the seismic wave – absorption and diffraction

3.1. Absorption of seismic waves

The experimental data showed that the intensity of the seismic waves decrease as their propagation distance increases. This is due to the absorption of the energy into environments that are elastically imperfect.
Due to absorption, the amplitude of the harmonic seismic wave decreases in accordance with a law as follows:

$$A_r = A_0 e^{\alpha r} \quad \textbf{(10)},$$

where A_0 is the initial amplitude of the wave in point O, and A_r represents the amplitude of the wave at distance r from point O.

$\boldsymbol{\alpha}$ = absorption coefficient that may be expressed as follows:

$$\alpha = \frac{1}{r} \ln \frac{A_0}{A_r} \quad \textbf{(11)}$$

Another parameter expressing absorption is the absorption decrement δ = αλ, which is characterizing the decrease of the amplitude on a distance equal with the λ wave length.
In order to explain the absorption, several theories have been proposed, among which we would like to state only two: *Theory of Elastic After-Strain and Theory of Internal Friction*.
In accordance with the Theory of Elastic After-Strain, the absorption coefficient and decrement for P waves have the following expressions:

$$\alpha_r = \frac{\pi c V_s^2 \omega}{3V_p^3}; \delta = \frac{2\pi c V_s^2}{3V_p^2} \quad \textbf{(12)},$$

where:

c – constant typical for the relative size of the seismic post-effect,
V_P – traveling velocity of longitudinal waves,
V_s – traveling velocity of transversal waves,
ω – oscillation frequency.

One can see that the absorption decrement does not depend on the frequency and the absorption coefficient is proportional with frequency ω.

In accordance with the abovementioned theories it results:

$$\frac{\alpha_p}{\alpha_s} = 4V_s^3 \times 3V_p^2 \quad \textbf{(13)},$$

from which results a more powerful absorption of the transversal waves against the longitudinal ones.

3.2. Diffraction of the seismic waves

The diffraction is a phenomenon that occurs when in the path of the wave discontinuities occur that are comparable in size with the wave length or lower.
The geological environment through its heterogeneous structure provides the possibility of diffracted waves to occur in close relation with the presence of faults, vertical separation limits, small irregularities of the separation limits, non-homogeneities comparable with the wave length etc.
In accordance with the type of the incidental wave that is suffering the diffraction phenomenon under the above-presented conditions, one can find the following types of diffracted waves: direct-diffracted waves, reflected-diffracted waves, refracted-diffracted waves etc.
The intensity of any type of diffracted wave is lower than the intensity of the wave that has produced it because the formation of the diffracted wave is performed with an energy consumption that is transferred by the incidental wave to the geological element causing the diffraction.
The amplitude of the diffracted waves is proportional with the absorption decrement in accordance with the following:

$$\frac{\delta^3}{\lambda^2} = \frac{\delta^3}{\frac{\omega^2}{V^2}} \quad \textbf{(14)}$$

Relation (14) show that the wave spectrum encountering on its path non-homogeneities comparable with the wave length shall be depleted by elements of high frequency, the environment behaving as up-cutting filter.
This effect of environment non-homogeneities on the spectrum of seismic waves is similar with the effect og absorption.
In the case of Rosia Montana, for distances longer than 300 m from blasting center and site, due to the diffraction and absorption, it is estimated that the seismic effects are reduced and no special technology is required to blast the rocks.

4. The seismic effect of the explosions on the constructions on mining constructions and works

4.1. Types of deteriorations produced by the seismic effect of explosions

The deteriorations of the constructions produced by the seismic effect of explosions may be of two types: architectural or structural. The structural deteriorations are exhibited in the main elements of a construction, on which the stability and the safety of the dwellers depends upon, and the architectural ones are superficial and do not impact the resistance structure.

The level of the structural deteriorations is closely connected with the "seismic" coupling structure-land.

Thus, the resonance effect when the own frequency f_0 of the building is very close to the frequency of the seismic vibrations f, may result in serious deteriorations even at low amplitudes of the vibration.

The deterioration criteria may be expressed in general as follows:

$$D(\alpha,\beta,\gamma) = K_D \cdot A \cdot f^{\alpha} \cdot c^{-\beta} \cdot f_0^{-\gamma} \quad \textbf{(15)},$$

where:

K_D – constant;

A – amplitude of soil travelling;

f – oscillation frequency;

c – oscillation travelling velocity.

The issue at hand is to determine the values of the coefficients , , that are applying under certain circumstances.

In the case of a wall hit by a vibration for which $f/f_0 < 1$:

$$D = \varepsilon = \frac{2\pi f^2 A}{f_0 c} \quad \textbf{(16)}$$

In this case, the deterioration criterion is D (2,1,1) i.e. = 2; = 1; = 1.

When the frequency of vibrations is much higher than the wall frequency $f/f_0>1$, then:

$$D = \varepsilon = \frac{2\pi f A}{c} \quad \textbf{(17)},$$

where *2 fA* = v is the travelling velocity of the particle.

In this case, the deterioration criterion is D (1,1,0).

In the case of transversal waves, shearing stresses are produced and the deterioration criterion is:

$$D = \frac{v}{c} = \frac{2\pi f A}{c} \quad \textbf{(18)},$$

i.e., D(1,1,0).

The vertical vibrations may produce also bending efforts in the upper side of the wall. In this case, the deterioration criterion shall be:

$$D = \frac{2\pi f^2 H A}{c^2} \quad \textbf{(19)},$$

(H – wall height), and it is D (2,2,0).

From the theoretical cases analyzed within this subchapter it results that in most cases the deterioration criterion is considering the *2 fA* term, which is the expression of the oscillation travelling velocity.

This shows that the oscillation velocity of the particle may be a good assessment criterion of the destructive effect of vibrations.

4.2. Assessment criteria of the seismic effect of explosions

The assessment criteria of the seismic effect of explosions are based on the main dynamic parameters of the seismic vibrations, represented by:

- particle travelling;
- particle velocity and acceleration;
- oscillation frequency.

The study of the size of these parameters, correlated with the deterioration degree of constructions lead to the establishment of several assessment criteria of the seismic effect of explosions on constructions.
Based on these criteria, standards have been prepared on the accepted levels for the vibration wave, which will ensure the integrity of constructions.

4.2.1. Assessment of the seismic effect in accordance with the travel distance

The experiments conducted on the travel size have lead to a correlation between the deterioration of constructions and the particle travelling amplitude.
The results of these researches are presented in tables 1 and 2.

Table no. 1

Accepted levels for particle travelling depending on the type of building
(I.C.I. 1972)

Building Type	Accepted travelling amplitude [mm]
Ancient constructions, great value and fragility	0.10
Houses under poor status	
Art monuments	
Houses within assemblies	0.20
Secluded houses	0.40
Civil and industrial buildings designed in accordance with relevant regulations	0.76

Table no. 2

Accepted levels for particle travelling depending on the frequency
(Buzdugan et al, 1976)

Vibration Frequency	Accepted level of travelling so as to avoid formation of cracks [mm]
5	2.67
10	1.35
20	0.66
30	0.46
40	0.33
50	0.26

4.2.2. Assessment of the seismic effect in accordance with the size of particle velocity

It is unanimous within specific literature that a criterion on the assessment of the seismic effect produced by explosions is the **oscillation velocity**.
On this, there are several ways to assess the seismic effect of explosions and they are set forth in tables 3 to 5.

Table no. 3

Correlation between the deterioration of a construction and the size of the oscillation velocity
(Greenland and Knowles,1970)

Maximum velocity of the particle [mm/s]	Probable deterioration degree
> 190	Major – structural deteriorations due to fissuration, deformation or dislocation
> 140	Minor – no apparent weaken of the resistance structure; plastering works deteriorated; deteriorations of windows and masonry
> 100	Threshold – minor deteriorations, cracks in the plastering work, dislocation of the poorly fixed items
< 50	Recommended safety level

Table no. 4

Correlation between the deterioration of a construction and the size of the oscillation velocity
(Rowe,1973)

Maximum velocity of the particle [mm/s]	Deteriorations of constructions
0.2	None
2.0	Upper limit for historic monuments, very fragile structures
5.0	Lower limit for architectural deteriorations for regular buildings
15.0	Architectural deteriorations, potential structural deteriorations
50.0	Structural deteriorations at buildings that enter into resonance

Table no. 5

Scale of seismic intensities
(Medvedev,1968)

I [MSK degrees]	Description	Particle Velocity [mm/s]
I	Vibrations below human perception and registered only by instruments	≤ 2
II	Vibrations felt by humans under favorable conditions	2-4
III	Vibrations felt by few people who are aware.	4-8
IV	Vibrations are felt by many, noise is produced at the windows glass	8-15
V	Deteriorations of the shaky constructions	15-30
VI	Deteriorations of the poorly built constructions	30-60
VII	Deteriorations of the fairly built constructions	60-120
VIII	Considerable deteriorations of constructions	120-240
IX	Large cracks in walls, wall portions fell	240-480
X - XI	Massive destructions and constructions collapse	over 480

4.2.3. Assessment of the seismic effect according to the oscillation acceleration

According to the size of the **acceleration** there is a classification of the effects of vibrations on buildings (Buzdugan et al. 1976), which has four levels as provided under table no. 6.

Table no. 6

Acceleration [cm/s^2]	Effects on buildings
2	Sensitivity threshold of the construction, there is no hazard to the building below this threshold
10	Rigidity threshold of the construction, below this there aren't any major deteriorations of the construction
50	Breaking threshold for some elements in the construction, and over this threshold there is a hazard to have serious deteriorations
230	Sensitivity threshold of construction, over this threshold the buildings are destroyed

The values presented under table 6 are valid only for vibration frequencies lower than 20 Hz and for small buildings.

4.2.4. Assessment of the seismic effect in accordance with Relative Energy ER

The Relative Energy of the seismic oscillation has been defined through the following equation:

$$ER = \frac{a^2}{f^2} = 4\pi^2 v^2 \quad \textbf{(20)},$$

where:

a – maximum acceleration;
v – maximum velocity;
f – frequency associated with the maximum amplitude.

On this criterion, Crandell (1949) has established a correlation between ER and the safety of constructions.

Table no. 7

Correlation between ER and Buildings Safety

Relative Energy – ER [m^2/s^2]	Safety
< 0.27	Total safety
0.27-0.54	Caution for poorly built buildings
> 0.54	Hazard for all buildings

4.2.5. Assessment of the seismic effect in accordance with Zeller – vibrar factor

The Zeller factor is defined by the following equation:

$$Z = \frac{a^2}{f} \quad \textbf{(21)},$$

where:

a – maximum acceleration;
f – frequency of vibrations associated with the maximum acceleration.

Table no. 8

Scara ZELLER

Magnitude Factor Z [cm^2/s^2]	Seism Effect
1	Unperceivable
2	Very low
10	Low

50	Measurable
250	Rather strong
1,000	Strong – below hazard threshold
5,000	Very strong – large fractures
20,000	Destructive
100,000	Devastating
500,000	Blighter
2,500,000	Catastrophic
10,000,000	Very catastrophic catrastofal

The intensity of vibrations is expressed in “vibrar” and defined by the following equation:

$$S = 10\log\frac{Z}{Z_s} \quad \textbf{(22)}$$

If ZS = 0.1 cm^2/s^2 is a reference value, the S equation becomes:

$$S = 10\log(10Z) \quad \textbf{(23)}$$

Based on this relation, a scale of hazards has been prepared depending on the value of the “vibrar”.

Table no. 9

Hazards Scale (vibrar)

Vibrations Intensity S [vibrar]	Vibrations Classification	Effects on Buildings
10-20	Light	No hazard
20-30	Medium	No hazard
30-40	Strong	Light deteriorations
40-50	Severe	Cracks in walls
50-60	Very severe	Destruction of buildings

4.3. Assessment of the seismic effect of explosions on mining works

4.3.1. Seismic effect of underground explosions on underground mining works

The partile oscillation velocity may be estimated through the following equation:

$$v = \frac{kQ^a}{r^b} \quad \textbf{(24)},$$

where:

v – is the maximum velocity of the particle [mm/s];

Q – load weight [kg];

R – distance to explosion [m];

k, a, b – coefficients depending on the type of explosion and rock and that are experimentally established for each site.

For guiding estimates, the values presented in table 10 for k, a and b coefficients may be used.

Table no. 10

Values of k, a and b coefficients presented in equation (47) as recommended by different authors

k	a	b	Conditions	Authors
730	0.66	1.54		Lundborg et al.(1978)
2,083	0.53	1.60	$\frac{r}{\sqrt[3]{Q}} > 3.97$	Ambraseys and Henderson(1968)
11,455	0.93	2.80	$\frac{r}{\sqrt[3]{Q}} < 3.97$	Ambraseys and Henderson(1968
1,686	0.71	1.78		Holmberg (1979)
707	0.68	1.56		Vorobiev et al. (1972)
700	0.70	1.50	Average exposed rock	Holmberg and Persson (1980)
193-1,930	0.80	1.60	Blasting on stages	Oriard (1972)
37-148	0.55	1.10	Massive explosions	Oriard (1972)
5,985	0.80	1.60	Pre-splitting explosions	Oriard (1972)

4.3.2. Seismic effect of explosions conducted in the pits on underground mining works

In this case the oscillation velocity may be calculated through the following equation (Mironov, 1973; Mosinet, 1976):

$$v = \frac{70\sqrt[3]{Q}}{p(R_0 + H^{\frac{3}{2}})} \quad \textbf{(25)},$$

where:

v – maximum velocity of the particle;

Q – explosive quantity;

H – level difference between the explosion location and the underground mining work;

R_0 – the horizontal distance between the explosion location and the underground mining work;

p – a coefficient depending on the number of blasting stages and it is calculated as follows:

$$p = \frac{n}{(0.445n + 0.45)} \quad \textbf{(26)}$$

For instant blasting: n = 1.

The maximum accepted levels for rock deformation and the accepted levels for vibrations are presented un tables 11 and 12, expressed through the particle velocity for different mining constructions.

Table no. 11

Maximum accepted levels of rock deformations for mining facilities

Rank	Characterization of facilities	Maximum accepted deformation
I	Mining facilities that are very important, with an extended usage (over 10-15 years): hydro-technical tunnels, adits, main galleries, underground chambers	0.0001
II	Mining facilities of great importance, which are to be used between 5 and 10 years: hauling channels and tunnels, hydro-technical constructions, safety pillars, transversal galleries, side slopes of the pits	0.0002
III	Mining facilities that are to be used for a short period of time (1-5 years): chambers, galleries, benches	0.0003
IV	Mining facilities with no relevance, which are to be used below 1 year: workfaces panels, pits benches	0.0005

Table no. 12

Maximum accepted levels of vibration, expressed through the particle velocity for the mining facilities

Rock Type	Hardness coefficient, f	V_P [km/s]	Maximum accepted Velocity for the ranking of mining facilities [cm/s]			
			I	II	III	IV
Sediments, detritus, loosen and alluviums	0.5-1	1-2	4.1	8.2	12.2	20.4
Fissured sediments, with clay and high porosity	1-3	2-3	6.8	13.6	20.3	34.0
Rocky areas with an extensive natural fissuration	3-5	3-4	9.5	19.0	28.4	47.5
Relatively monolithic, with isolated fissures	5-9	4-5	12.2	24.4	36.7	60.0
Monolithical, poorly fissured	9-14	5-6	14.9	29.8	44.6	74.5
Very hard and monolithic with no fissures	14-20	6-7	17.8	35.6	53.3	89.0

The historic galleries from Rosia Montana are classified as having rank I – special mining facilities – and for their protection the maximum amplitude of the oscillation must not exceed 0.0001 mm, and the velocity must be below 6.8 cm/s (rocks with V_P = 2 - 3 km/s).

The explosive quantity is presented in the table no. 13, which has been calculated by applying the equation (25) and which may be detonated at different distances from the mining facility that needs protection (v = 6.8 cm/s) in the case of a blast with 10 delay stages at a level difference of H = 10 m.

Table no. 13

V = 6.8 cm/s				
R_0 [m]	25	50	75	100
Q [kg TNT]	1,331	3,988	8,889	16,723

From the previous table (13), it results that from seismic point of view, the galleries from Rosia Montana are not in danger, due to the fact that the proposed blasting technology is using explosives in quantities lower than the quantities calculated with the equation (25).

4.3.3. Seismic effect of explosions on pit slopes

The following equation may be used in order to assess the seismic effect of explosions on pit slopes:

$$v = \frac{k_t}{\sqrt[3]{n}} \cdot \sqrt{\frac{Q}{L}} \cdot \frac{e^{-0,03r}}{r} \quad \textbf{(27)},$$

where:

- v – maximum oscillation velocity [cm/s];
- Q – total quantity of explosive [kg];
- L – length of the blasting block [m];
- r – distance from blasting block to the slope that needs protection [m];
- n – number of delay stages.

The equation is valid for $r \leq 70$ m.

The maximum accepted levels of the oscillation velocity are presented in table 14, necessary for the seismic protection of pit slopes.

Table no. 14

Maximum accepted levels of the oscillation velocity for the protection of pit slopes

Slope life	Velocity for the following values of the hardness coefficient associated with the blasted rock f [cm/s]					
	1	**1-3**	**3-5**	**3-9**	**9-14**	**14-20**
> 5 years	8.2	13.6	19.0	24.4	29.8	35.6
< 5 years	12.2	20.3	28.4	36.7	44.6	53.3

The k_t coefficient depends on the rock types present within the composition of the slope and on the hardness of the rock that is to be blasted, as presented under table 15.

Table no. 15

Values of k_t coefficient

Rock types present in the composition of the slope	k_t coefficient for the following f hardness coefficient values of the blasted rock		
	$f \geq 14$	**$6 \leq f < 14$**	**$f < 6$**
$f \geq 6$	300-310	390-415	560-585
$f < 6$	310-315	415-425	585-620

For the protection of the final slopes of the pits in Rosia Montana, the seismic effect of explosions expressed through velocity must not exceed 8.2 cm/s (life of slopes higher than 5 years and hardness coefficient of the excavated rock f = 1).

The explosive quantity calculated by using equation (27) is presented din table 16, a quantity that may be detonated at the future pits at different distances from the slopes provided that blasting with 10 delay stages is applied.

Table no. 16

V = 8.2 cm/s					
r [m]	10	20	40	60	70
Q [kg TNT]	8	58	772	5,800	26,347

4.4. Estimation equations of the parameters associated with the explosion vibrations

Upon designing an explosion, it is critical to consider the hazard level (although it is an approximate value) associated with the explosion vibration.

This is also required when explosives are to be used near fragile structures.

Under these circumstances, it is critical to define the load limit value, which is the maximum quantity of explosive that may be used without exerting pressures on the structure above safety levels.

For this, it is critical to establish believable correlations between the significant dynamic parameters of vibrations (especially the oscillation velocity) and the detonated explosive quantity.

Based in the conducted experiments, several formulas have been established for the calculation of velocity - (*v*), travelling - (*u*) or acceleration - (*a*) of the particle depending on the explosive quantity (*Q*) *and* the distance between the blast center and the site that needs protection (*r*).

4.4.1. Calculation formulas for Velocity

The experimental researches showed that the relation between the oscillation velocity and the explosive quantity is as follows:

$$v = f(K_1, ...K_{n)})\frac{Q^\alpha}{R^\beta} \quad \textbf{(28)},$$

where $K_{1......}K_n$ and α, β are coefficients depending on the properties of explosives, the geological environment and the blasting technology.

Due to the fact that the oscillation velocity represents the dynamic parameter that is the most critical in studying the seismic effect of explosions on buildings, several calculation formulas have been established.

Thus,

- **Medvedev et al. - 1962** proposed for the calculation of the radial element of velocity, the following formula:

$$v = 268(\frac{\sqrt[3]{Q}}{r})^{\frac{3}{2}} \quad \textbf{[cm/s] (29)},$$

where:

Q – explosive quantity **[kg]**
r – distance from blast center and the site that needs protection.

- **Kuznetov - 1971** proposes the following formula:

$$v = k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 \cdot k_6 (\frac{\sqrt[3]{Q}}{r})^{\frac{3}{2}} \quad \textbf{(30)},$$

where:

k_1 – coefficient that considers the rock types where the blast is performed, the base rock and the season (table 10);
k_2 – coefficient that depends on the location of the explosion relative to the site that needs protection (table 11);
k_3 – coefficient that considers the blasting technology (table 12);
k_4 – coefficient that considers the blasting type: instant, $k_4 = 1$;
k_5 – coefficient that considers the ratio between explosion point – site to be protected and the length of the blasting block (table 13);
k_6 – coefficient that considers the placement of the load (table 14).

Table no. 17

Values of k_1

Rock Types where the explosion is performed	Base rock	k_1		
		Summer	**Autumn and spring**	**Winter**
Rocky formations harder than average	Semi-hard rocky formations	120	120	120
Rocky formations harder than average	Clay-sandy rocks with thicknesses between 10 and 15 m	200	300	250
Rocky formations below average hardness	Semi-hard and hard rocky formations	90	90	90

Rocky formations below average hardness	Clay-sandy rocks with thicknesses > 10-15 m	150	230	200

Table no. 18

Values of k_2

Location of the site to be protected	**k_2**
Behind the blasting lock	1.00
On the side of the block; the blasting direction is opposing the site	0.65
On the side of the block; the blasting direction is towards the site	0.85
Before the blasting block	0.70

Table no. 19

Values of k_3

Blasting conditions	**k_3**
Regular frontal workface	1.0
With a workface that has a free surface, delayed blasts, within a compressed environment etc.	2.0
In pillars with 4 to 5 free surfaces	0.5

Table no. 20

Values of k_5

r/l	**k_5**
0.2	0.70
0.4	0.75
0.7	0.85
1	0.90
2	0.95
3	0.98
4	1.00

Table no. 21

Values of k_6

Distance between the explosion and the site to be protected	**k_6**		
	2 borehole rows	**3 borehole rows**	**4 borehole rows**
10	1.30	1.35	1.45
100	1.15	1.30	1.40
500	1.00	1.02	1.05

Berta, G. (1990) has established a calculation formula of the oscillation velocity by starting with the formula of seismic energy that was presented under sub-chapter 1.4.:

$$\varepsilon_g = 4\pi^3 R^2 \cdot \rho_r \cdot C \cdot a^2 \cdot f^2 \cdot t_v \cdot 10^{-6} \quad \textbf{(31)}$$

Considering that ε_g represents 40% of the total energy of the explosion (η_g), the formula may be rewritten as follows:

$$\varepsilon_g = \eta_g \varepsilon \cdot Q = \eta_g \eta_1 \eta_2 \cdot \varepsilon \cdot Q \quad \textbf{(32)}$$

From (21) and (22) equations result:

$$a = \sqrt{\frac{\eta_g \eta_1 \eta_2 \cdot \varepsilon \cdot Q \cdot 10^6}{4\pi^3 R^2 \cdot \rho_r \cdot C \cdot a^2 f^2 \cdot t_v}} \quad \textbf{(33)}$$

Considering the fact that the significant duration of vibration is usually 5 cycles, the t_v time shall be:

$$t_v = 5T = \frac{5}{f} \quad \textbf{(34)}$$

and:

$$f = (K_f \cdot \log R)^{-1} \quad \textbf{(35)}$$

From formulas **(29), (30), (31)** result:

$$a = \sqrt{\frac{\eta_g \eta_1 \eta_2 \cdot \varepsilon \cdot Q \cdot K_f \cdot \log R \cdot 10^6}{20\pi^3 R^2 \cdot \rho_r \cdot C}} \quad \textbf{(36)}$$

Starting with $v = 2$ $a f$ and with formula (32) we obtain:

$$v = \frac{\sqrt{Q}}{\sqrt{\dfrac{\eta g \eta_1 \eta_2 \cdot \varepsilon \cdot 10^6}{5\pi \cdot K_f \cdot \rho_r \cdot C \cdot \log R}}} \quad \textbf{[m/s] (37)}$$

Awojobi et al.(1974) have proposed the following formula:

$$v = KQ^{0,55} (\frac{h}{r})^{0,1} \quad \textbf{(38)},$$

where:

h – the depth where the explosive load is detonated;

k – coefficient that depends on land conditions.

Langefors, U. proposes for the calculation of velocity the following formula:

$$v = K \sqrt{\frac{Q}{R^{\frac{3}{2}}}} \quad \textbf{(39)}$$

Mârza, V. and Pantea, A. have proposed a the following formula for the calculation of the total velocity:

$$V_T = 408 (\frac{\sqrt[3]{Q}}{r})^{\frac{3}{2}} \quad \textbf{(40)}$$

Sadovski, M.A.(1946) porposes formula:

$$v = k\sqrt{\frac{Q}{R^3}}\quad \textbf{(41)}$$

Particle oscillation velocity is a parameter accepted by many researchers as a main criterion to assess the seismic effect of explosions.
The formula **(41)** has been used by S.C. IPROMIN S.A. to conduct the seismic zoning of the perimeter. The average value of k was 30 and was established through experiments after conducting four explosions.
Considering the fact that the sites to be protected at Rosia Montana are shaky buildings and historic monuments, it is necessary for the maximum accepted velocity to be 3 mm/s, as provided under the DIN 4150/83, the German standard.
The maximum accepted loads are presented in the following table that may be blasted instantly at different distances from the sites to be protected from Rosia Montana Perimeter, calculated by using formula (41) for the velocity of 4 mm/s and k = 30.

Table no. 22

V = 4.0 mm/s; k = 30							
R [m]	100	150	200	250	300	400	500
Q [kg TNT]	178	600	1,422	2,778	4,800	11,378	22,222

R = distance between the explosion center and receptor;
Q = explosive quantity blasted instantly in TNT equivalent.

4.4.2. Calculation formulas for Travelling

In order to calculate the radial travel, one can use the following equation (I.C.I.,1972):

$$u = k_a \frac{\sqrt{Q}}{r}\quad \textbf{[mm] (42)},$$

where k_a is a coefficient that depends on the nature of rocks where the explosion is performed and the nature of rocks on which the facilities are placed on (v. table 15).

Table no. 23

Values of the site coefficient

Rock types where the explosion is performed	**Rock types from the building site**	**k_a**
Rocky formations	Rocky formations	0.57-1.15
Rocky formations	Clays	1.15-2.30
Clays	Rocky formations	1.15-2.30
Clays	Clays	2.30-3.40

4.4.3. Calculation formulas for Acceleration

For the calculation of the Acceleration, one may use an empiric formula proposed by (Hudson,1961):

$$a = 877{,}95\frac{Q^{\frac{3}{4}}}{r^2}\quad \textbf{(43)}$$

4.5. Norms and regulations on the seismic effect of explosions

The significant dynamic parameters of vibrations have been presented within the previous chapter associated with the vibrations produced by explosions and the relation existing between their levels and the buildings wear degree.
Considering these correlations, some countries have adopted several standards on the acceptable levels of the significant dynamic parameters associated with the oscillations produced by explosions.
The standard values under the German Standard DIN 4150/1983 are presented in table 24 and figure 8.

Table no. 24

Standard values of the oscillation velocity (mm/s) as per DIN 4150/1983

Structure Type	Measuring Point			
	Foundations			The floor of the highest level of a building
	< 10 Hz	10 - 50 Hz	50 - 100 Hz	Any frequency
1. office building or plant	20	20-40	40-50	40
2. residential building with plastered walls	5	5-15	15-20	15
3. historic buildings or other buildings that need careful attention	3	3-8	8-10	8
For frequencies > 100 Hz, higher levels may be accepted				

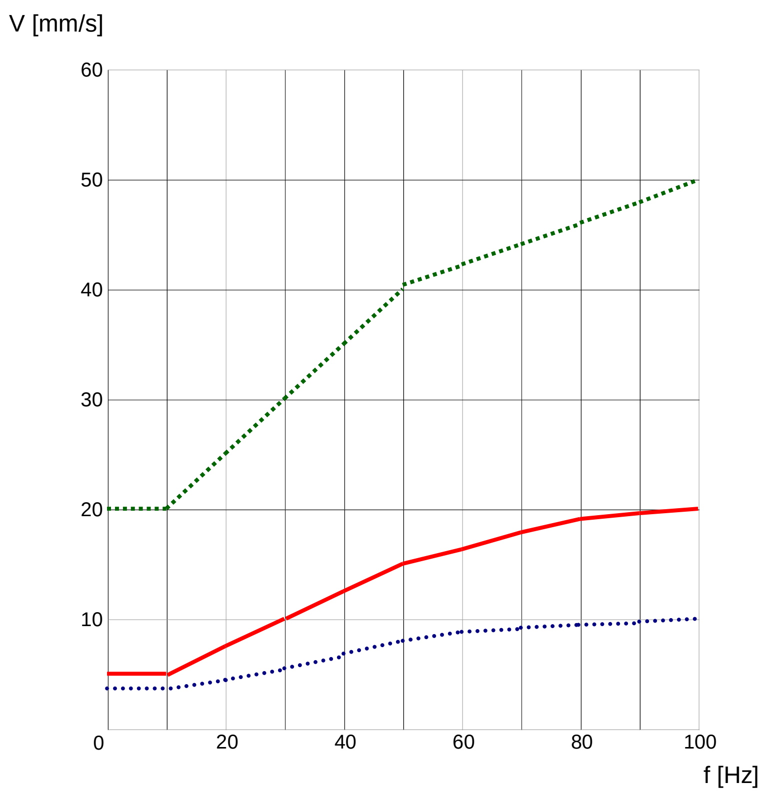

Figure no. 8 The accepted levels of the vibration velocity for different types of construction depending on the frequency, as defined under DIN 4150 Standard (Germany)

RI 8507 – 1980 Norm is used in USA, a norm prepared by Mines Office, which is presented in figure no. 9.

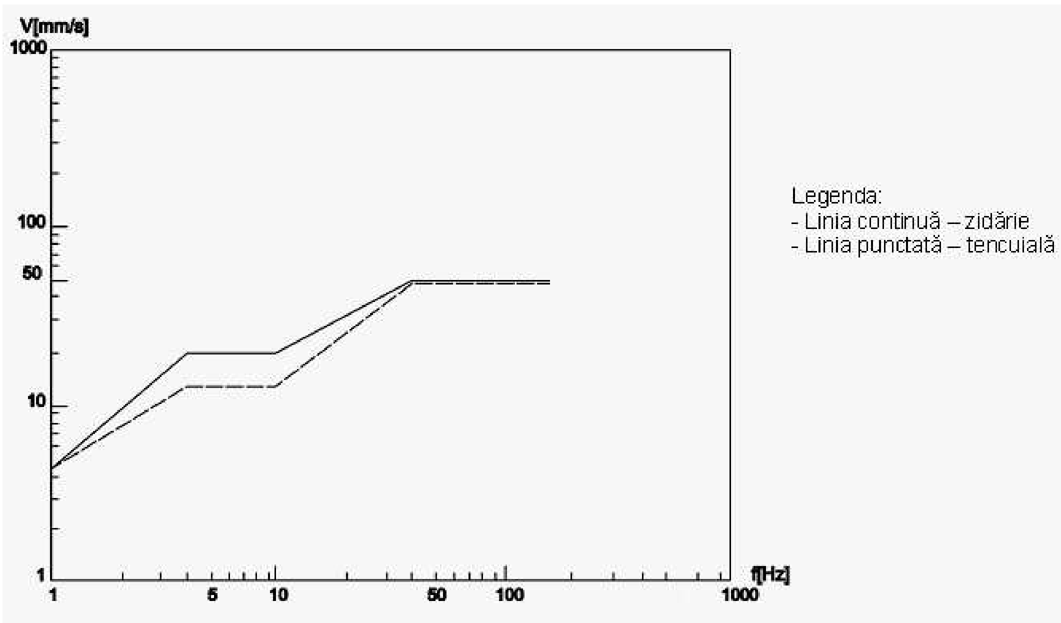

Figure no. 9 The accepted levels of the vibration velocity for different types of construction depending on the frequency, as defined under RI 8507 – 1980 Norm (USMB)

– For frequencies over 40 Hz: v = 50 mm/s;
– For frequencies between 5-10 Hz: v = 19 mm/s (masonry), v = 12,7 mm/s (plastering work);
– For frequencies between 10-40 Hz and < 5 Hz: values related to frequency, as presented in the figure.

The Swiss Standard in presented in the following table:

Table no. 25

Structure type	Frequency [Hz]	Velocity of the explosion vibration [mm/s]	Velocity of the traffic vibration [mm/s]
Steel or reinforced concrete structures (industrial bays, dams, bridges, towers with metallic structure, channels, tunnels)	10-60 60-90 10-30 30-60	30 30-40	12 12-18
Buildings with foundations, walls and floors made of concrete, buildings with concrete walls and masonry, underground rooms and tunnels with masonry	10-60 60-90 10-30 30-60	18 18-25	8 8-12
Building with masonry walls and wood ceilings	10-60 60-90 10-30	12 12-18	5 5-8

	30-60		
Historic monument buildings and other sites with sensitive structures	10-60 60-90 10-30 30-60	8 8-12	3 3-5

The Sweden Standard is presented in the following table:

Table no. 26

Standard values of the oscillation velocity, amplitude and acceleration for hard rock foundations, valid for a short duration of the blast

(Persson et al, 1980)

Structure Type	Maximum accepted values of the vibration parameters		
	Amplitude [mm]	Vibration Velocity [mm/s]	Acceleration [mm/s^2]
Reinforced concrete building	0.4	200	5
Apartments located at elevated heights in apartment buildings made of reinforced concrete or metallic structures		100	

Structure Type	Maximum accepted values of the vibration parameters		
	Amplitude [mm]	Vibration Velocity [mm/s]	Acceleration [mm/s^2]
Underground mining works (galleries, chambers workfaces) excavated in hard and very hard rocks, with 15-18 m opening	0.4	70-100	5
Regular blocks made of bricks or equivalent		70	
Concrete buildings		35	
Sweden National Museum (site with sensitive structures)		25	
IT Centre	0.1		2.5
Command Center (dispatch center)			0.5-2

There is no standard in Romania with respect to the accepted standards on the significant dynamic parameters of explosion vibrations and the calculations made for Rosia Montana Project considered the German Standard (table 24, figure 8), which is more restraining.

4.6. Assessment of the seismic effect of the aerial wave

The explosions carried out in plain air, on the earth surface or in cavities excavated in rocks with inappropriate packing or with no packing may produce powerful aerial shock waves.

The air vibrations are influence by the air conditions and land morphology.

The detonation of explosives in air or in not packed holes is accompanied by a rapid release of all gases, heat and light. The expanding gases determine the production of a pressure wave into the air, called aerial shock wave. This shock wave is characterized by a sudden increase of pressure over the value of the air pressure. This pressure increase is followed by a decrease, and that determines after a period of time, the positive stage of the pressure variation to be followed by a negative one, when the pressure becomes lower than the value of the air pressure. The overpressure is in general caused by one or several conditions:

- Detonation of explosive within open space;
- incorrect or insufficient packing;
- rapid expansion of gases;
- travel of the blasted material (piston effect);
- soil vibrations (vertical component).

The air overpressure is the result of the energy sent through the air with a frequency spectrum in general between 0.1 and 200 Hz. It has been estimated that the energy from this source reaches 38-39 % of the energy produced by explosion.

Due to the fact that human ear does not detect air vibrations with a frequency below 20 Hz, the overpressure energy may induce vibrations in the structure and the individuals present inside may not notice any “noise”. However, during explosion designing, the effects felt as “noises” are the ones causing more problems.

Noises, especially the unexpected ones, produce not only discomfort but, in many occasions, panic and involve complaints, damages claim or sometime requests to suspend works.

In fact it is very rare for the air overpressure to produce damages to structures, and in the exceptional cases when this has occurred the damage has been in fact window glass breaking or removal of the plastering works.

When the shock wave passes a certain point the air pressure in that point increases rapidly to a value over the environmental value (peak value), and then decreases to a lower value and in the end after a series of oscillations, the original level is reached.

The pressure variations may at any given time during the passage be measured and registered with microphones that are usually accompanied by measuring instruments placed to record vibration on soil.

The signal is simultaneously recorded with the three components of the vibration velocity. The peak value is measured in comparison with the air pressure.

The following figures represent a series of values of the shock waves that may be encountered, together with their potential effects:

– 21,000 Pa – causes damages to structures;
– 7,000 Pa – window glasses are breaking;
– 2,100 Pa – window glasses made from glass plates may broke;
– 210 Pa – no damage;
– 21 Pa – personal discomfort;
– 14 Pa – the china and windows are vibrating;
– $2*10^{-5}$Pa – audible threshold.

The practice directly relates the pressure to acoustic effects, i.e. we are dealing with a wide range of values. This is a consequence of the fact that the ear is answering in a logarithmic manner to pressure changes.

The pressure peaks are defined through the following formula

$$PDB(dB) = 20 \cdot \lg \frac{p}{p_0} \quad \textbf{(44)},$$

where

PDB (dB) – pressure peak, on a decibels scale
P – measured overpressure (Pa)
p_0 – $2*10^{-5}$ Pa – audibility threshold (value accepted conventional as reference pressure).

The variation of the overpressure SP during the positive stage is expressed by the following relation:

$$SP(T) = SP_0(1 - \frac{t}{t_{os}})e^{\frac{-t}{t_{os}}} \quad \textbf{(45)},$$

where:

SP_0 – value of the maximum overpressure;
t_{os} – the time of the positive stage of the overpressure;

t – the time measured since the occurrence of the shock wave.

Several formulas are to be used to calculate SP_0 as proposed by:

- Naumenko and Petrovski:

$$SP_0 = 10^6 (\frac{Q}{10^8})^{\frac{2}{3}} (\frac{400}{r})^2 \text{ [dyn/cm}^2\text{] (46)}$$

- Sadovski:

$$SP_0 = 10^6 (\frac{0,76}{r} + \frac{2,55}{r^2} + \frac{6,5}{r^3}) \text{ [dyn/cm}^2\text{] (47)}$$

- Henrych:
  - for $0.05 < \underline{r} = rQ^{1/3} \leq 0.3$ m/kg$^{1/3}$

$$SP_0 = 10^6 (\frac{14,0717}{\underline{r}} + \frac{6,5397}{\underline{r}^2} - \frac{0,3572}{\underline{r}^3} + \frac{0,0625}{\underline{r}^4}) \text{ [dyn/cm}^2\text{] (48)}$$

  - for $0.3 < \underline{r} = rQ^{1/3} \leq 1.0$ m/kg$^{1/3}$

$$SP_0 = 10^6 (\frac{6,1938}{\underline{r}} - \frac{0,3262}{\underline{r}^2} + \frac{2,1324}{\underline{r}^3}) \text{ [dyn/cm}^2\text{] (49)}$$

  - for $1.0 \leq \underline{r} = rQ^{1/3} \leq 10.0$ m/kg$^{1/3}$

$$SP_0 = 10^6 (\frac{0,622}{\underline{r}} + \frac{4,05}{\underline{r}^2} + \frac{3,29}{\underline{r}^3}) \text{ [dyn/cm}^2\text{] (50)}$$

The propagation velocity of the aerial shock wave may be calculated by using the following formula:

$$V_0 = V_s (1 + \frac{6SP_0}{7P_{atm}}) = 340\sqrt{1 + 0,0857 \cdot SP_0} \text{ [m/s] (51)},$$

where:

V_s = 340 m/s sound speed;
P_{atm} = 10 N/cm^2 air pressure.

The propagation velocity is usually slower than the seismic wave velocity through the rocks. That is why the aerial shock wave is reaching a construction after the main body of the seismic wave has already passed the respective construction.
Due to the overpressure, i.e. due to the “blast blow”, the air masses are traveling in opposite directions and that results in powerful winds that are accompanying the shock wave.
The effect produced by these winds is called dynamic pressure - P_d, which is expressed as follows:

$$P_d = \rho_a V_v^2 \text{ (52)},$$

where:

ρ_a – air density;

V_v – velocity of the wind accompanying the shock wave.

The timely variation of the dynamic pressure is expressed as follows:

$$P_d = P_{d,0}(1-\frac{t}{t_{od}})e^{\frac{-2t}{t_{od}}}$$ **(53),**

where:

$P_{d,0}$ is the maximum dynamic pressure,
t_{od} is the duration of the positive stage of the dynamic pressure

The sizes of $P_{d,0}$ and t_{od} are calculated with the help of the following equations:

$$P_{d,0} = 3\cdot 10^6(\frac{Q}{10^8})^{0,424}\cdot(\frac{500}{r})^{1,272}$$ **[din/cm²] (54)**

$$t_{od} = 1,5B\cdot 10^{-3}\sqrt{Q}$$ **[m] (55)**

The experimental researches aimed at the destructive effects of an aerial wave are summarized in table 27.

Table no. 27

Probable deteriorations associated with the values of overpressure created by the aerial shock wave

Overpressure		**Noticed deteriorations**
[10^4 x dyn/cm^2]	**[Db]**	
<1.5	<153	Shaking mobile windows, deterioration of some poorly pre-stressed and installed window glasses
≈5	≈165	Deterioration threshold of the window frames properly installed
7-14	167-173	Some of the window glasses are deteriorated (broken)
14-21	173-176	Minor deteriorations occurred at the plastered walls, all window glasses are broken
>21	>176	Cracks in the masonry, all window glasses are broken

From the data presented under table 27, it results the fac that the most serious damages produced by an aerial shock wave if no protection measures are taken are the occurrence of cracks in the masonry and that the window glasses are broken.
In case of Rosia Montana, following the protection measures taken by using special blasting technologies, the calculated overpressure is 2.7 x 10^4 x dyn/cm^2, for a distance of 100 m between the blast center and the site to be protected.
This is encountered at the following sites: Piatra Corbului, Simeon Balint's grave and 4 monument houses located around the current Mayoralty.

5. Control and Monitoring of the seismic effect of explosions

It is necessary to record the seismic waves produced by explosions in order to assess their seismic effect.

5.1. Devices used to record explosion vibrations

The seismograph (seismometer) is a special seismic instrument that is used to measure the seismic waves.
A mobile seismograph has at least three channels allowing the record of three orthogonal directions: radial – towards the blasting point; tangential – perpendicular on horizontal plant onto the radial direction, and vertical – perpendicular on the other two directions.

The seismograph is usually consisting of three blocks:

- seismic transducers block;
- amplifier block
- command and record block.

Usually, the amplifier and the command-record blocks are built together and are known as the central unit. Some seismographs these three blocks are placed under the same casing.

5.1.1. Seismic Transducer

There are three types of seismic transducers:

- a motion transducers
- a velocity transducer (geophone)
- acceleration transducer

5.1.2. Mobile Seismographs

Today, there are many companies that manufacture mobile seismometers capable to record the seismic oscillations produced by explosions.
The transducers most widely used are the velocity and acceleration transducers.
The most modern seismometers are provided with transducers (microphones) for the aerial shock wave. The data are registered on a magnetic support and the data may be sent to remote locations.
The data are registered on magnetic support. Some seismometers are provided with a modem that allows data tro be sent to remote locations.
The onsite measurements need to be made at soil level and not in the constructions, in order to avoid the effects from the great variety of constructions, which answer to ground movement in a different manner.
The seismic records need to be made on three directions: one vertical and two horizontal. One of the horizontal directions needs to be radial and the other one transversal onto the direction blast center-measuring point.
Upon placing on site the seismometers, the most representative locations are to be selected for the proposed research, which will allow the performance of a more complex study on the variation of the measured parameters depending on distance and direction relative to the blast location.
In the case of Rosia Montana Project, the seismic effect of the blasting operations is to be monitored during the mining operation development.
Considering the fact that blasting is to be developed away from the sites to be protected, and the distance shall decrease in time, the seismic effects shall be thoroughly studied within the monitoring program so as the blasting technology may adapt in order to have hazards equal to zero.
Initially, the sites closer to the center of the first blasts are Piatra Corbului and Taul Gauri, which shall be located at distances longer than 500 m and the rest of the sites shall be located at distances longer than 1,000 m.
Practically, this is the situation in which the monitoring program shall be launched through which a seismometer shall be installed at each site to record the parameters of the seismic wave generated by blasting.
The seismometers shall be provided with three converters placed on the three orthogonal directions to send the data to remote locations.
We would like to propose that the seismometers selected for this job to be one of the seismometers presented in the Annexes or others that will present the same performances or better.
The seismometers shall operate continuously and therefore they need to be supplied with adequate power supply units. All data recorded by the fixed seismometers shall be inputted and process and the significant dynamic parameters would be subsequently established for the explosion.
Moreover, relative to these seismometers placed at the sites to be protected, a mobile seismometer would be required, with at least 6 channels to record on different directions and in areas as close as possible to the explosion center.
Based on the parameters of the seismic wave, determined through the monitoring performed with the fixed and mobile seismometers, the blasting operations shall be altered if necessary.
A monitoring network of seismometers made by INSTANTEL is presented in figure no. 10.

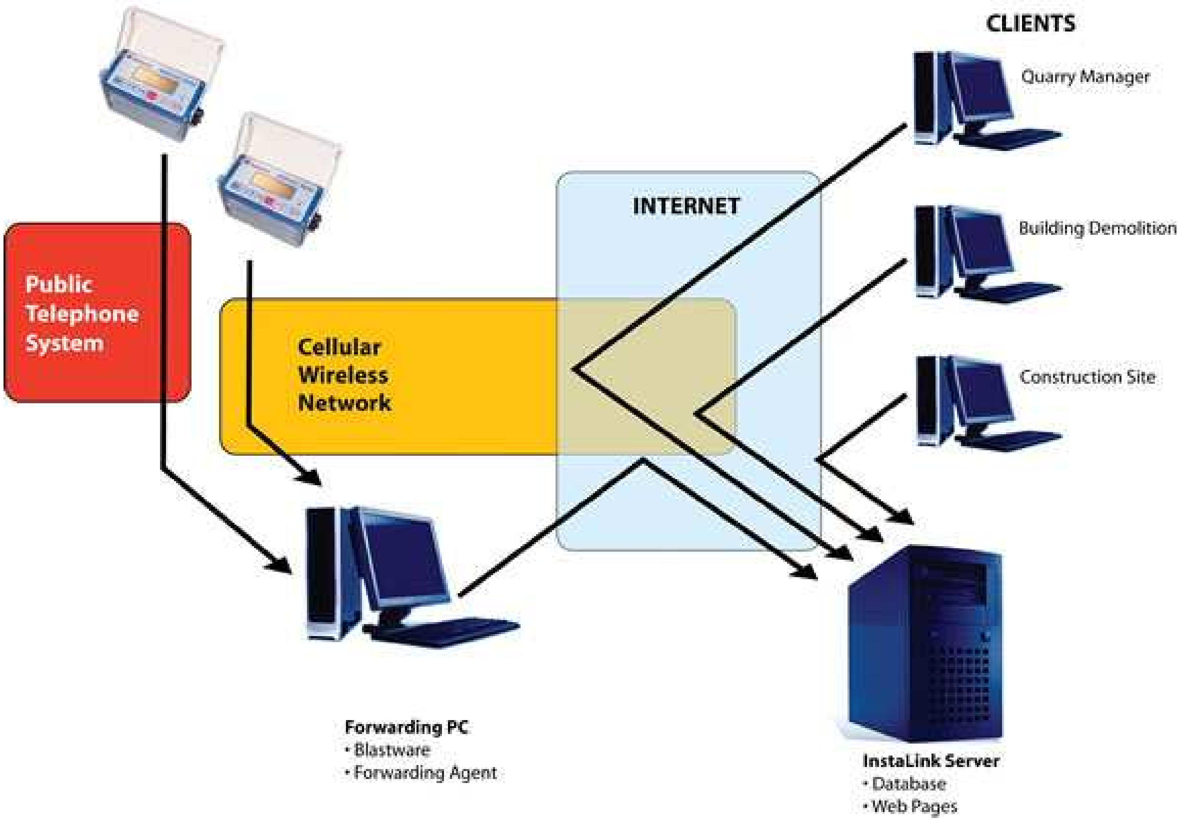

Figure no. 10

Please find below several types of seismometers.

5.2. Types of Seismographs (seismometers)

5.2.1. BLASTMATE Seismograph

The Blastmate Seismographs are ones of the most viable apparatuses for monitoring the vibrations produced during explosions.

These devices are designed and built in accordance with the requirements of International Association of Engineers on the performances of seismographs used to monitor explosions.

Figure no. 11

5.2.2. VIBRACORD DX Seismograph

The family of vibration measuring instruments Vibracord DX is used in construction work, mining, blasting, demolition or other works where vibrations cannot be completely avoided. To exclude any damage or risk, measurement and analysis of these vibrations are required.

Figure no. 12

One of the devices used to measure vibrations is VIBRACORD DX Digital Vibration Meter. The device is delivered with two different frequencies: 315 Hz (DIN 45669); 2-250 Hz.

5.2.3. ETNA Seismograph

Etna accelerograph is designed and built by the manufacturer most renowned of seismology equipments in the world, (KINEMETRIKS, USA) and is aimed at acquiring and recording acceleration data during strong earthquakes. Etna combines the most recent achievements within the fields of digital recording, programmed resources, telecommunications, and materials strength etc., based on Kinemetrics' Altus technology.

Figure no. 13

ETNA Accelerometer presents several advantages:

- it is a triaxial and digital recording device;
- includes an triaxial intern accelerometer (EpiSensor), which allows recording of the oscillation acceleration on three directions (N-S, E-V and vertical);
- measures acceleration on a wide dynamic range (108 dB) and wide frequency response (0-80 Hz);
- it has an incorporated PCMCIA module, with PC Memory Card slot (16 MB);
- it is provided with a software that allows rapid data analysis, simultaneously inputting and reading of recorded data;
- due to the permanent direct link through a special antenna with Earth's artificial satellites, it ensures the possibility to exactly pinpoint in space (the geographical coordinates and altitude), with an error of up to 25 m;
- ensures synchronization of the inner timer with the universal time (Universal Time Clock) (with an error of up to ±5 microseconds), through a GPS incorporated system and Earth's artificial satellites;
- allows remote control and auto-diagnosis;
- the records may be automatically read by connecting the device to a mobile computer;
- the data may be remotely accessed through the internal modem of the accelerator by using the electronic key of the software;
- it is provided with an internal battery that provides if necessary up to 72 hrs of operation.

The device operates as follows: the sensors detect the velocity or the acceleration of the base (the ground), permanently verifying if the signals observe the seismic criteria for the determination of the event. The signals meeting these criteria are recorded as event data on the PCMCIA memory card. The events recorded may be automatically sent through a modem via connection with a laptop or by copying the PCMCIA memory card. Based on these measurements, the regional geological researches as well as data on the previous seismic activity, the seismic zoning map is prepared for the territory covered by a country, representing the seismic intensity in degrees, and the seismic hazard maps on which the lines represent the level of the potential maximum acceleration.

5.2.4. TDL Seismograph

The TDL Seismographs are the new generation of mobile digital seismic recorders developed by the Zhuhai Taide Enterprise Co., Ltd., which are designed on the basis of TDE-324CI seismic data acquisition recorder, in compliance with the technical specifications of the China Earthquake Administration.

Figure no. 14

The technical sheets of some seismographs are presented in the annexes enclosed to this documentation.

6. Methods used to mitigate the seismic effect of explosions

6.1. Groups of explosions

The amplitude of the seismic waves produced by a concentrated explosion within one single cavity may be expressed by the following equation:

$$A_{\Sigma} = k_1 Q^Q \quad \textbf{(56)}$$

If the load is represented equally within the cavities, the amplitude of the oscillation produced by one single explosion from the group shall be:

$$An = nk_1 (\frac{Q}{n})^q \quad \textbf{(57)}$$

From equations (51) and (52) it results:

$$k_n = \frac{A_n}{A_{\Sigma}} ... n^{1-q} \quad \textbf{(58)},$$

which is the amplitude characteristic of the explosions group.
In order to mitigate the seismic effect, the total quantity of explosive is divided and detonated at different times (delays) between the blasting stages, being equal to milliseconds.
The size of the delay interval and the number of blasting stages need to be selected in such a manner so as the seismic oscillations generated by each stage to be in anti-phase with the precedent stages, so as the amplitude of the resulting wave to be minimal.
Depending on their seismic effect, the blasting operations may be ranked in decreasing sequence as follows:

- instant explosions;
- micro-delayed explosions with extensive blasting effect;
- macro-delayed explosions (with gaps between blasting stages of 1-2 second or higher);
- micro-delayed explosions with a delay gap lower than the time required by the material to separate itself from workface.

The seismic oscillation produced by explosion is usually short and in many cases only three or four of its cycles present higher amplitudes than half of the maximum amplitude.
That means that at time delays longer than 3-4T (T – oscillation period), the sum of the effects shall be minimal.
If the delay interval is shorter (micro-delayed explosion) there is a possibility for the oscillations resulted from different blasts in the group to sum up and to increase the seismic effect. That is why the interval must be selected in such a manner so as the oscillations sum to lead to a resulting oscillation of an amplitude as low as possible, i.e. to be a sum conducted in anti-stage.
The maximum interference effect is obtained when the delay interval is equal to the predominant oscillation period or with an integral multiple thereof, i.e.:

t = nT; n = 1, 2, 3, ...

If n > 3, the resulting oscillation is lower than the oscillation produced by the instant detonation of the entire load.
If n < 3, the oscillation may be summed during the stage and the resulting is almost equal to the oscillation produced by the instant detonation of the entire load.
If n = 1/2, 3/2, 4/2 ... (i.e. n is uneven multiple of semi-periods), there is a chance that the oscillations would sum up in anti-stage.

If n > 7/2, then the situation is like n > 3 situation when the sum is not made either during the stage or the anti-stage, but occurs a so-called “head-to-head” placement of the oscillations generated by the explosions of each blasting stage.
Another way to establish the optimum interval for delaying a blasting stage is given by the following relation: Ht = kT, where H is the number of delay steps.
If H is an integer number, and k must be an integer number, then the k/H ratio must not be an integer number.
In the case of Rosia Montana Project, the detonation shall be performed in micro-delayed stages so as to mitigate the seismic effect of the explosions and the oscillations shall sum up in anti-stage.

6.2. Ignition Method

The ignition of the explosions is performed by using detonating wires or electrical caps.
The experiments have shown that the micro-delayed explosions ignited with electrical caps have generated seismic waves of lower amplitudes than the ones ignited with detonating wires.

6.3. Creation of free surfaces

When the blast hole is close to a free surface, the fractures system around the hole is greatly impacted by its presence, due to the fact that the pressure longitudinal wave is converted into a reflected tension wave and reflected shearing wave upon encountering a free surface.
Thus, it is necessary for the explosion to be performed towards a free surface in order to allow the rock to swallow and to prevent the explosion “to freeze” or “to suffocate”.

6.4. Pre-splitting and smoothing explosions

These explosions are used to mitigate the seismic effect. The breaking mechanism for these explosions is almost identical.
In the case of simultaneously detonation from two holes, the tension stresses induced by the explosions are amplified that are resulting an increased tension stress, acting perpendicularly on the line that connects the two holes and results in an increase of the fissurations along this line.
The adequate selection of the distance between holes and the loading density may lead to the formation of a fracture with no regularities that is propagating from one hole to another.
The loading density may be adjusted by decoupling the load in every hole. The decoupling is obtained by making a load with a diameter smaller than the hole diameter, so as a ring area filled with air is created around the load. This area filled with air is absorbing some of the initial explosion energy and mitigates the size of the impact produced by the high initial pressure, which is responsible with rock breaking in the immediate vicinity of the rock.
When these conditions of simultaneously detonation of holes, at low distance with decoupled loads are met, the fissured may propagate at low loading densities, mitigating greatly the deterioration of the rocks located around the hole.
Smoothing explosion requires several parallel holes to be drilled at low distances from each other and placed along the final outline of the excavation, their loading with decoupled loads of low density and their simultaneously detonation after detonating the holes placed in the workface. The distance between holes in this case is 15-18 time higher than the hole diameter, and the distance until reaching the free surface created by detonating the blasting holes is approx. 1.2-1.3 times higher than the distance between holes.
The pre-splitting explosion is different than smoothing explosion by the fact that the blasting holes are closer and their detonation is simultaneously performed before the main explosion. In this manner a pre-splitting fissure is created before the main explosion. This fissure limits the propagation of the fissures from the main explosion due to the fact that it allows the ventilation that expands from the main load. In the case of pre-splitting, there are not free surfaces to relieve stresses occurred *in situ* alike in the case of smoothing explosion.
The pre-splitting is used in the bench mining works, where more space is available to conduct different stages of the blasting procedure.
The distance between the holes is 8-12 times the hole diameter.
The pre-fissuration explosion is applied also to mitigate the seismic effect of explosions on surface constructions. In this case, the pre-fissuration holes are performed within a quasi-circular outline around the main explosion, within the side where the site to be protected is located so as the fissures to mitigate the seismic waves generated by the main explosion.

Conclusions

This study is a theoretical analysis of the seismic waves produced by the blasting explosions, considering their generation, propagation, mitigation and effects.
The theoretical and experimental researches conducted in time on the blasting procedures that are using explosives have lead to a better knowledge of the phenomena that are taking place, and the possibility of making mathematical models of the processes that are to be generated by the blasting operations and the interactions between the energy generated by explosions and the rock, together with the secondary effects (seismic vibrations) that are impacting the different civil and industrial constructions.
The results of these researches have been used also in the case of Rosia Montana Perimeter, and the performed theoretical analysis was aimed mainly at:

- the establishment of a blasting technology that will use explosives in order to ensure the designed operational capacity, the breaking of the mining mass down to values of maximum 400 mm, confining the material projection of the blasted material;
- the identification of several options of blasting technologies that are using explosives placed in boreholes that may be applied near the cultural heritage sites present within the vicinities of the Rosia Montana Pits;
- the theoretical quantification of the seismic effects generated by the blasting operations on the cultural heritage sites, the oscillation velocity of the material particle at the level of the respective constructions, so as this parameter to be monitored during mining operations stage and, depending on the results of these measurements, the blasting technologies to be adapted before any deteriorations and damages are produced that will impact the integrity of the sites that need to be protected.

The theories considered are tailored to meet the specifics of Rosia Montana Mine Site, aimed at establishing the protection modalities for the following protected areas:

- ✓ *Piatra Corbului Protected Area (surface and underground),*
- ✓ *PUZ CP area and Catalina-Monulesti,*
- ✓ *Carpeni Protected Area (surface and underground),*
- ✓ *Taul Gauri Protected Area (surface),*
- ✓ *Orlea underground galleries,*
- ✓ *Greek-Catholic Church and its Parish House,*
- ✓ *Simeon Balint's grave,*
- ✓ *4 monument houses located around the current Mayoralty.*

The mining activity at Rosia Montana shall be conducted by applying blasting technologies with explosives placed in cylindrical boreholes.
Four options have been established for the blasting technology and their effects have been quantified in theory.
The detonation of the explosive loads shall produce seismic vibrations that will propagate within the adjacent environment to the explosions and they may produce damages to the area's heritage sites.
The oscillation velocity is the significant dynamic parameter of the seismic vibration based on which the destructive effect of explosives is assessed.
Following the researches that were conducted within this field worldwide, correlations have been made between the oscillation velocity and the blasted explosive quantity.
Based on these correlations, several norms and standards on the accepted oscillation velocity values have been established in several countries, so as to ensure the seismic protection of sites located within the explosions impact area.
The most restrictive European standard for this field is the German Standard entitled DIN 4510, where the maximum accepted values of the oscillation velocity are comprised between 0.3 cm/s (in the case of historic buildings) and 2.0 cm/s (in the case of offices and industrial structures).
The sites from Rosia Montana Perimeters for which blasting technologies have been established so as to remove the risks of producing deteriorations or damages are as follows:

- ✓ Very sensitive buildings with an elevated seismic risk *(Greek-Catholic Church and its Parish House, monument houses located around the current Mayoralty);*
- ✓ constructions *(Simeon Balint's grave, Taul Gauri Protected Area);*

- ✓ natural monuments (*Piatra Corbului Protected Area);*
- ✓ ancient mining works (*Catalina-Monulesti Area, Orlea underground galleries, Carpeni Protected Area).*

The condition that maximum oscillation velocity accepted near the site to be protected is maximum 0.2 cm/s has been adopted.

In the case of natural monuments and the ancient mining works, the maximum oscillation velocity has been established at 0.4 cm/s.

From the analysis, it has resulted that the classical blasting technology that is using explosives placed in boreholes to blast the mining mass may be applied for distances of maximum 300 m away from the closest construction.

At distances lower than 300 m, the options described within this paper may be used, the seismic effect on the sites that need to be protected being quantified through the oscillations velocity of the material particle at the level of foundations, being at maximum 0.2 cm/s in the case of very sensitive buildings with an elevated seismic risk *(Greek-Catholic Church and its Parish House, monument houses located around the current Mayoralty)* and the constructions of special value *(Simeon Balint's grave, Taul Gauri Protected Area)* or maximum 0.4 cm/s in the case of the natural monuments (*Piatra Corbului Protected Area)* or the ancient mining works (*Catalina-Monulesti area, Orlea underground galleries, Carpeni Protected Area).*

A permanent system of seismic surveillance of the abovementioned oscillations is proposed to be implemented so as to experimentally check the results of the theoretical studies on the establishment of the blasting technologies to be applied within Rosia Montana Perimeter.

Depending on the results of the measurements to be conducted even from the first stages of development of the Rosia Montana pits when the activity is developed within the area of minimum risk, the proposed blasting technologies may be tailored before producing any deteriorations or damages that will impact the integrity of the cultural heritage sites so as the risks associated with the sites to be protected are reduced to a minimum level.

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FINAL PAGE

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