Building a Nomogram to Determine Drilling & Blasting Parameters in the Marginal Quarry Zone

S N Zharikov¹, V A Kutuev¹
¹Institute of mining of Ural branch of the Russian Academy of Sciences

E-mail: 333vista@mail.ru

Abstract. In the paper, blasting seismic survey results for some mine blocks are given. Issues of studying the wave propagation processes in the rock mass and solutions to them are described specifically for mining engineers with minor theoretical deviations and emphasizing maximum practical significance. The method developed by the Mining Institute of the Russian Academy of Sciences Ural Branch to determine protective measures against the effects of blasting on protected objects depending on the explosive weight in delay, soil factors, and the permissible seismic velocity is described. Based on previously identified patterns for various soils, dependencies between the rock mass properties and charge parameters have been built and summarized in a nomogram to simplify the corresponding determination of the technical explosion parameters. The advantage of this approach, in contrast to others, is the possibility of a quick multivariate evaluation, which is of great importance for the prompt elaboration of technical solutions. In the paper, the specifics of determining the drilling & blasting parameters when approaching the marginal quarry zone are partially discovered and promising areas in studying seismic phenomena in rocks and the blast seismic for the nearest future outlined.

1. Introduction
Over more than 14 years of activity at various enterprises of the Urals, Siberia, and Kazakhstan, the RD (Rock Destruction) Laboratory of the Mining Institute UB RAS has accumulated a significant amount of the blast seismic measurement data. The analysis of these materials has shown the deviations of the measured values from those previously calculated according to the methodological recommendations [1]. Further studying the deviation causes has led to the evaluation of the structural rock bedding features and allowed determining a relationship between the permissible seismic velocity and the strength characteristics of the rock mass at different weakening coefficients. The weakening coefficient itself is not a strictly determined parameter since there are no techniques to precisely describe the rock mass, so this value is approximately defined. Herewith, techniques are recently being developed to study rock fracturing, the research complexity is being reduced, and in the nearest future, evaluating the weakening coefficient will become easier. However, currently available general dependencies, which do not consider the rock mass structure or represent it as some homogeneous average medium, lead to a discrepancy between the actual and calculated values.

2. Theoretical Treatment
The patterns of the stress wave propagation in a rock mass are a consequence of the physical processes occurring at an explosion. The processes themselves occur at high speeds, which determines the
completeness of studying them. However, studying these processes by dividing into parts and the subsequent model representation when compared with practical data allows determining the specifics of their flow and explain the accompanying phenomena [2-13]. The most predictable is the detonation development and the shock wave propagation in pipes [3, 14]. In this regard, explosive processes are mathematically represented as those occurring in an ideal fluid. Solid and gaseous media are reduced to an ideal fluid through thermal conductivity [15]. The most difficult is studying explosion directly in an industrial environment. In mining and construction, large volumes of rocks of different strength, porosity, and structure are blasted. In [16], it is pointed out that the real rock mass state can be mathematically described only in approximation since the rock mass itself changes due to various processes caused by tectonics and man-made impact. In this regard, each industrial blast is unique. However, the consequences of each blast should be predictable for safety reasons, one way or another. Therefore, in the regulatory documents, the dependencies for calculating zones, which are safe for people and property by damaging factors are given. Herewith, this issue is not sufficiently covered in terms of blast seismic impact on buildings, structures, and other protected objects. It should be noted that people and animals, on the one hand, and buildings and structures, on the other hand, respond differently to the propagation of surface waves expressed in seismic vibrations. Therefore, the issue of ensuring the seismic safety of buildings, structures, and other industrial and cultural objects should be resolved considering the properties of soils in which these vibrations propagate.

The blast seismic effect is caused by the development of wave processes at the explosion and expressed in the surface vibrations. The soil vibration velocity at any point depends on the soil properties, the distance to the explosion, and the charge weight (for the bulk blast, the charge weight per delay). The below blast seismic effect aspects should be considered [4–8, 16].

At different distances to the explosion, the effect of soil properties and explosion parameters on the seismic velocity changes.

Rock masses of different structures respond differently to blasting. The seismic effect develops in them in different ways.

The air gap reduces the seismic effect. In this regard, the blast screening (by the fracture surface) prevents the development of critical strain manifestations (saves the soil stability) in the protected direction.

The blast screening causes the wave reflection from the fracture surface (a cumulative effect is also possible), which leads to the redistribution of the blast energy for a destructive effect. A screen on one side of the blast increases energy spent on the rock shattering by about 10%.

Under the effect of a seismic wave, in block soils, in addition to block displacements, rotational phenomena occur leading to interblock motions.

Rock pressure affects the propagation of seismic waves. With an increase in rock pressure, the camouflage explosion effect decreases.

Studying the absolute fracture characteristics using a model medium is low informative due to the qualitative differences between real and model environments [4]. Therefore, the propagation of seismic waves in solid soil can be determined only in the approximation by averaged medium parameters. These include the longitudinal and transverse wave propagation velocities characterizing the medium strength properties and the dip direction of the major fracture systems characterizing the blocky structure. In this case, the effect of fracturing is reflected in the wave propagation velocity.

3. Data and Development of Nomogram
The data in Table 1 have been used as the basis for the nomogram development. The physical and mechanical properties are specified within the range of values and express all the variability of the rock mass state in-situ, the mining engineers deal with when arranging and performing mining operations. It should be noted that in this study, the blast impulse associated with the detonation characteristics of a specific explosive and transmitted to the rock mass was not specified, only weight was considered. Although the faulted rock mass may differently respond to the propagation of waves of different powers, depending on the load. Attention to this aspect is drawn in [17]. However, a general approach is the
most appropriate to consolidate the data and build the relationship, especially since the formula part can always be refined in the future. Partially, the errors have already been clarified when building the nomogram.

When analyzing the actual data of the blast seismic measurements obtained by the staff of the RD Laboratory of the MI UB RAS, the average deviations of the actual seismic velocity values from those calculated at various soil factors have been determined [1], on average, within 8.5 to 24.5 % (the minimum and maximum values correspond to K=650 and K = 200, respectively). On this basis, refining dependencies have been determined to calculate permissible seismic velocities depending on the physical and mechanical rock properties at various rock mass weakening coefficients. From the mining safety point of view, these results are of high importance. Based on the data in Table 1 and considering the refinements, a nomogram has been built, which is shown in Figure 1.

**Table 1. Rock Properties and Permissible Seismic Velocity.**

| Rock Group of Rocks | Compressive Strength, $\sigma_{\text{com}}$, MPa | Tensile Strength, $\sigma_t$, MPa | Density, $\gamma$, t/m$^3$ | Elasticity Modulus, E, GPa | Wave Velocity, $V_w$, m/s | Permissible Seismic Velocity, $v$, m/s | Propagation Coefficient, $\lambda$, units | Rock Mass Weakening Coefficient, $\gamma$, % |
|---------------------|---------------------------------|---------------------------------|---------------------|-----------------------------|------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Brown coals and... | from 30 to 400 | from 10 to 60 | from 1.5 to 6 | from 0.5 to 0.3 | from 5000 to 10 000 | from 10000 to 15 000 | $0.05 \leq \lambda \leq 0.1$ | $0.066 \leq \gamma \leq 0.05$ |
| Hard coals, weathered mudstones, very weak siltstones | 40 | 0.1 | 5 | 1.1 | 2.2 | 0.5 | 25 | 600 | 3,300 | 0.25 | 0.50.05 | 0.230.03 | 0.150.03 | 0.12 |
| Sandy shales, phosphorites, anthracites and other hard coals, dense siltstones, mudstones, Sulfide ores, serpentinites, peridotites, pyroxenites, carbonate-clayey shales, | 60 | 1.5 | 8 | 1.2 | 2.5 | 5 | 50 | 1,800 | 4,500 | 0.19 | 0.24 | 0.12 | 0.160.09 | 0.12 |
| Gypsum-anhydrites, clayey dolomites, siderites, Limestones, clayey shales, hornfelsed porphyrites, anhydrites, sandstones with clayey cements, | 80 | 2.5 | 11 | 2.5 | 2.7 | 15 | 65 | 2,500 | 4,900 | 0.5 | 0.14 | 0.280.09 | 0.190.07 | 0.14 |
| Description                                                                 | Density (g/cm³) | Compressibility (GPa) | Elastic Modulus (GPa) | Poisson's Ratio | Cohesion (MPa) | Cohesive Tensile Strength (MPa) |
|-----------------------------------------------------------------------------|-----------------|-----------------------|-----------------------|----------------|----------------|-------------------------------|
| gabbrororites, porous martites                                             | 40              | 5                     | 14                   | 2.6            | 25             | 100                           |
| Very dense fine-grained mudstones, apatite-nepheline ores, diabase         |                 |                       |                       |                |                | 3,000                         |
| porphyrites, sandy marble shales, gray sandstones                          |                 |                       |                       |                |                | 5,600                         |
| Limestones, magnetite-garnet skarns, ferruginous porous quartzites,         | 45              | 5.5                   | 15                   | 2.6            | 3              | 25                           |
| gabbrororites, serpentized peridotites, syenite porphyries, Epidotitized   |                 |                       |                       |                |                | 3,200                         |
| porphyrites, basalts, phosphorites, coarse and medium-grained granites,     | 50              | 6                     | 16                   | 2.7            | 3              | 30                           |
| diabases, pegmatites, skarns, coarse-grained gneisses and granodiorites,    |                 |                       |                       |                |                | 3,400                         |
| medium-grained syenites Garnet-biotite gneisses, granite-porphyries,       |                 |                       |                       |                |                | 5,900                         |
| semi-oxidized ferruginous quartzites, fine-grained sandstones, chalcopyrites | 55              | 6.5                   | 17                   | 2.7            | 3.1            | 35                           |
| granite-gneisses, garnet-magnetite skarns, siliceous marl, diabase         |                 |                       |                       |                |                | 3,600                         |
| porphyrites                                                                 |                 |                       |                       |                |                | 6,000                         |

Easily fractured rocks

| Description                                                                 | Density (g/cm³) | Compressibility (GPa) | Elastic Modulus (GPa) | Poisson's Ratio | Cohesion (MPa) | Cohesive Tensile Strength (MPa) |
|-----------------------------------------------------------------------------|-----------------|-----------------------|-----------------------|----------------|----------------|-------------------------------|
| Limestones, magnetite-garnet skarns, ferruginous porous quartzites,         | 40              | 5                     | 14                   | 2.6            | 25             | 100                           |
| gabbrororites, porous martites                                             |                 |                       |                       |                |                | 3,000                         |
| Very dense fine-grained mudstones, apatite-nepheline ores, diabase         |                 |                       |                       |                |                | 5,600                         |
| porphyrites, sandy marble shales, gray sandstones                          | 45              | 5.5                   | 15                   | 2.6            | 3              | 25                           |
| Limestones, magnetite-garnet skarns, ferruginous porous quartzites,         |                 |                       |                       |                |                | 3,200                         |
| gabbrororites, serpentized peridotites, syenite porphyries, Epidotitized   | 50              | 6                     | 16                   | 2.7            | 3              | 30                           |
| porphyrites, basalts, phosphorites, coarse and medium-grained granites,     |                 |                       |                       |                |                | 3,400                         |
| diabases, pegmatites, skarns, coarse-grained gneisses and granodiorites,    |                 |                       |                       |                |                | 5,900                         |
| medium-grained syenites Garnet-biotite gneisses, granite-porphyries,       |                 |                       |                       |                |                | 3,600                         |
| semi-oxidized ferruginous quartzites, fine-grained sandstones, chalcopyrites | 55              | 6.5                   | 17                   | 2.7            | 3.1            | 35                           |
| granite-gneisses, garnet-magnetite skarns, siliceous marl, diabase         |                 |                       |                       |                |                | 6,000                         |
| porphyrites                                                                 |                 |                       |                       |                |                | 6,000                         |
|                          | Mineralogy                        | Width  | Height | Fracture | Width  | Height | Fracture | Width  | Height | Fracture | Width  | Height | Fracture | Width  | Height | Fracture |
|--------------------------|-----------------------------------|--------|--------|----------|--------|--------|----------|--------|--------|----------|--------|--------|----------|--------|--------|----------|
| Magnetite ores,          | Mineralized hornfelses,           | 150    | 7      | 18       | 2.7    | 3.1    | 4.0      | 115    | 3.80   | 6.100    | 0.23   | 0.320  | 0.15     | 0.210  | 0.12   | 0.16     |
|                          | pyrrhotines,                      |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | garnet skarns,                    |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | labradorites,                     |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | silicified sandstones,            |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | garnet magnetite skarns,          |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | porous basalt,                    |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
| Fine-grained granites,   | granite gneisses,                 |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | quartzites,                       |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | diorites,                         |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | porphyrites,                      |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | dolerites,                        |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | medium-grained basalts,           |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | granodiorites,                    |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
| Ferruginous quartzites,  | gabbro-diabases,                  |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | hornfels-quartz breccias,         |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | fine-grained gneisses and         |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | granites,                         |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | pyroxene-garnet skarns,           |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
| Gabbro-granites,         | ferruginous quartzites,           |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | quartz porphyries,                |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | urites,                           |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | dense andesites,                  |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | mineralized sandstones,           |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | dense jaspers,                    |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | greisens                         |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
| Barren quartzites,       | skarns,                           |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | quartz jaspilites,                |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | fine-grained gabbros,             |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | dense albitophyres,               |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
|                          | syenite-porphyries,               |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
| Labradoritic basalts,    | ferruginous                       |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
| Average                  |                                  |        |        |          |        |        |          |        |        |          |        |        |          |        |        |          |
| Hardly fractured rocks | Very hardly fractured rocks |
|------------------------|----------------------------|
| hornfelses, fine-grained magnetite-hematite ores | hornfelses, fine-grained magnetite-hematite ores |
| Scantolitic skarns, diorite-porphyrites, andesitic porphyrrites, pyroxene-skarned hornfelses, biotite, biotite-garnet and pyroxene silicified gneisses | Scantolitic skarns, diorite-porphyrites, andesitic porphyrrites, pyroxene-skarned hornfelses, biotite, biotite-garnet and pyroxene silicified gneisses |
| 160 240 18 30 2.8 3.4 70 145 5,000 6,600 | 160 240 18 30 2.8 3.4 70 145 5,000 6,600 |
| Siliceous skarns, diorite porphyrites, pyroxene-skarned hornfelses, nephrites, albitophyres, highly silicified fine-grained, very dense jespilites, fine-grained basalts, very dense andesites | Siliceous skarns, diorite porphyrites, pyroxene-skarned hornfelses, nephrites, albitophyres, highly silicified fine-grained, very dense jespilites, fine-grained basalts, very dense andesites |
| 190 280 20 35 2.8 3.7 85 180 5,500 7,000 | 190 280 20 35 2.8 3.7 85 180 5,500 7,000 |
| Very dense confluent microquartzites, intensely silicified skarns, confluent quartz, unaltered confluent andesites, jaspilites, basalts, flint, microgranites, unaltered hematite-confluent iron ores | Very dense confluent microquartzites, intensely silicified skarns, confluent quartz, unaltered confluent andesites, jaspilites, basalts, flint, microgranites, unaltered hematite-confluent iron ores |
| 225 450 25 50 2.8 4.7 100 230 6,000 8,000 | 225 450 25 50 2.8 4.7 100 230 6,000 8,000 |
4. Discussion of the Results
The nomogram allows determining the permissible seismic velocity characterizing the object's seismic stability based on the known longitudinal wave propagation velocity in the rock mass and the estimated weakening coefficient. Then, depending on the distance to explosion and soil conditions, the safe...
explosive weight per delay is determined. When reversely moving along the nomogram, the shear strain and elastic zones can be determined, beyond which residual strains are excluded. On a separate plot, the fracture zone can be determined depending on the explosive weight per delay.

5. Conclusion
Based on the data on the physical and mechanical rock properties and the seismic vibration propagation in them at bulk blasts, a nomogram has been built to determine the restrictions on the charge weight per delay, which ensure the seismic safety of the protected objects. The nomogram also allows promptly evaluating the blast consequences and the man-made fault zone for the option selected. The nomogram is based on the method developed by the MI UB RAS according to the fundamental seismic wave propagation principles.

6. Further Research
Further research in the field of the blast seismic effect is associated with the development of physical ideas about the blast, mathematical methods for describing the rock mass state, and techniques for studying the strength characteristics and structure of rocks.

To improve the nomogram developed, the relationship between the permissible seismic velocity and the structural weakening of rocks in the mass should be refined. To do this, the appropriate development of the express determination of rock properties in-situ is required.

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