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ANALYSIS OF A SIMPLIFIED MODEL FOR DETERMINING ROCK MASS OSCILLATION VELOCITY AT THE KOVILOVAČA OPEN PIT

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Abstract: *In mining, explosives are primarily used to obtain mineral raw material from hard rocks. Explosive charges with hundreds of kilograms per a drillhol and blasting with dozens and even hundreds of tonnes of an explosive are being apllied in the world nowdays. Such large quantities of an explosive can cause seismic shocks with the intensity that can have hazardous impact on the environment and result in moving of buildings. In order to protect the environment from shock when performing blasting it is necessary to define rock mass oscillation equation for each working site. This paper offers the analysis of the simplified model for defining parameters of the oscillation equation at the Kovilovača open pit, in eastern Serbia. On the basis of calculation on concrete example of mass blasting, it has been stated that the simplified model may be used in order to calculate rock mass oscillation velocity.*

Keywords: *blasting, oscillation velocity, rock mass oscillation equation, simplified model*

1. INTRODUCTION

During blasting operation, potential energy of explosive transformes into mechanical work. In the near of the blasting point, that energy destroys and crushes the rock mass. At a slightly greater distance that energy creates cracks and permanent deformations in the rock mass while at an even greater distance that energy transformes into elastic deformations. Seismic waves, that propagates through the rock mass, produces soil oscillation and oscillation of construction objects [1-3].

Parameter for estimating of the seismic action of blasting, that is commonly used, represents the rock mass oscillation velocity. As the relation between rock mass oscillation velocity and the basic parameters that influence its magnitude, most often is used the M.A. Sadovskii equation where oscillation velocity v is given in the form of:

$$v = K \cdot R^{-n}; \tag{1}$$

where R is reduced distance, that represents distance from the blasting site to monitoring site r, reduced to the total quantity of the explosive Q i.e., $R = \frac{r}{\sqrt[3]{Q}}$. Parameters K and n are conditioned by characteristics of the rock mass and blasting conditions. Thus, v is a decreasing and convex function of the variable R.

By applying the equation of rock mass oscillation while blasting, the determination of the rock mass oscillation velocity is made possible for each blast operation in advance, i.e. magnitude of shock.

2. RECORDING ROCK MASS OSCILLATION VELOCITY

Intensity of the shock is measured by instruments – seizmographs. Measuring of the rock mass oscillation velocity needed for this paper has been done by the instrument type Vibraloc, produced by the Swedish firm $ABEM$. From seismograph, maximum values for three oscillation velocity components can be recorded in directions X, Y and Z from the rectangular coordination system, as follows:

- v_t – rock mass oscillation velocity horizontal transversal component,
- v_v – rock mass oscillation velocity vertical component,
- v_l – rock mass oscillation velocity horizontal longitudinal component.

Based on that, maximum, i.e., resulting rock mass oscillation velocity v_r can be determined using following equation:

$$v_r = \sqrt{v_t^2 + v_v^2 + v_l^2} \; ; \tag{2}$$

3. ROCK MASS OSCILLATION VELOCITY EQUATION

Rock mass oscillation velocity equation defines velocity alteration of rock mass oscillation depending on distance, explosive amount, properties of rock material and blasting method. The equation, defined in this way, offers the possibility to determine the seismic effect of blasting towards a structure, whereby the connection between the rock mass oscillation velocity and consequences that can affect facilities, is used. The equation of M.A Sadovskii [4] is given in the form:

$$v = K \cdot R^{-n} = K \cdot \left(\frac{r}{\sqrt[3]{Q}} \right)^{-n} \; ; \tag{3}$$

where there are:
v – rock mass oscillation velocity $[cm/s]$
K – coefficient conditioned by rock mass characteristics and blasting conditions,
n – exponent conditioned by characteristics of rock mass and blasting conditions,
r – distance from the blasting site to the monitoring point $[m]$,
Q – total amount of explosive $[kg]$.
R – the reduced distance, given in the form $R = \frac{r}{\sqrt[3]{Q}}$.

A significant property of the equation of rock mass oscillation velocity depending on the reduced distance is as follows: if the reduced distance R from any level is increased (decreased) by 1%, the rock mass oscillation velocity v will decrease (increase) by approximately $n\%$ [5].

The Sadovskii equation is determined based on test blasting for the concrete working environment.

3.1 Rock mass oscillation velocity equation derivation

The equation of Sadovskii was derived from the condition: if the radius of charge r_0 and distance from the blasting site to the monitoring point r increase in the same or approximately the same ratio, the rock mass oscillation velocity v remains the same [6].

Here we cite second way of rock mass oscillation velocity equation derivation. If, in blasting in the specific environment, the relative increment in rock mass oscillation velocity and relative increment of reduced distance are monitored, then it can be seen that their relations at various levels have approximately the same value which will be marked $-n$ meaning that:

$$\frac{\frac{\Delta v}{v}}{\frac{\Delta R}{R}} \approx -n\,; \tag{4}$$

Thereby, it can be considered that:

$$\lim_{\Delta R \to 0} \frac{\frac{\Delta v}{v}}{\frac{\Delta R}{R}} \approx -n \quad \text{which means that is:} \ \frac{\frac{\Delta v}{v}}{\frac{\Delta R}{R}} \approx -n\ ; \tag{5}$$

Equation (5) can be written in the form: $\frac{\Delta v}{v} \approx -n \cdot \frac{\Delta R}{R}$, whereby integration, it is obtained:

$$\int \frac{\Delta v}{v} \approx -n \cdot \int \frac{\Delta R}{R}, \text{ respectively: } \log v = \log R^{-n} + \log C\,; \tag{6}$$

where C is a constant of integration.

Equation (6) can be written in the form:

$$\log v = \log C \cdot R^{-n}\,; \tag{7}$$

4. MODELS FOR DETERMINING PARAMETERS FOR ROCK MASS OSCILLATION EQUATION

In the Equation (1) two parameters appear, K and n, which need to be determined for a specific work environment and specific blasting conditions. It is possible to determine the parameters K and n in many ways, i.e., models, using the values obtained by experimental measurements [6].

Model 1 – Determining the parameters by applying the least square method.
The Least Square Method is mainly used to obtain the parameters K and n which represents a common model.

Model 2 – Determining the parameters through the application of quotient of products of the same number of reduced distances and oscillation velocities.
According to this model, determination of the parameter n is based on the quotient of the product of equal number of experimental data of the rock mass oscillation velocity v, using the oscillation velocity equation. In this way, first, we determine the parameter n, and then, when the parameter n found, we determine the parameter K from the rock mass oscillation equation.

Model 3 – Determining parameters by applying Lagrange's theorem.
In the rock mass oscillation velocity equation (1), parameter n may be determined by consecutive approximations with applying Lagrange's theorem.

Model 4 – Determining parameters by applying quotient of relative increments oscillation velocity and reduced distances.

Beginning with the rock mass oscillation velocity equation (1), which is derived in a different way, where parameter K, that appeared as the integration constant, we can determine from the conditions (initial condition) that for $R = R_1$ we get $v = v_1$. Parameters will be determined by applying experimental data of pairs $(R_i, v_i), i = 1,2,..., N$, provided that the curve of the rock mass oscillation velocity passes through the point $M_1(R_1, v_1)$.

Model 5 – Simplified model defining parameters adopting the values of parameter n
Earlier numerous explorations have shown that the value of parameter n ranges mostly in the interval from 1 to 3, most frequently in the interval from 1 to 2. Taking into consideration the characteristic of the rock mass oscillation equation as well as the values of parameter n, which is mostly in the interval from 1 to 2, we can accept that it is $n = 1.5$, which means that rock mass oscillation equation is reduced to the relation [6]:

$$v = K \cdot R^{-1.5}; \tag{8}$$

From equation (8) for K we get:

$$K = v \cdot R^{1.5}; \tag{9}$$

For finding parameter K are used data for pairs $(R_m, v_m), m = 1,2,..., N$, from the table of experimental data, thus we arrive at:

$$K_1 = v_1 \cdot R_1^{1.5}, K_2 = v_2 \cdot R_2^{1.5} ... K_N = v_N \cdot R_N^{1.5}; \tag{10}$$

however, for parameter K we take its arithmetical mean value.

In this way the model for solving rock mass oscillation equation has been simplified by adopting the value of parameter n.

On the basis of the calculated rock mass oscillation equation using formula (1), using various earlier mentioned models, we are able to construct the approximate curve. This curve correlates the received results of the oscillated velocities depending on applied quantity of explosive, distance from the blasting site to the monitoring place, characteristics of the working environment and conditions of blasting.

5. DEFINING STATISTICAL CRITERIA

For the above-mentioned models 1 – 5, on the basis of experimental data, we can get equations that can give us the rock mass oscillation velocities v depending on the reduced distance R.

In order to evaluate the degree of connection between the registered (measured) and calculated rock mass oscillation velocities in this paper we used the coefficient of linear correlation r_p [7] between the logarithms of reduced distances R and logarithms of oscillation velocities v. Coefficient of linear correlation r is also used in order to evaluate the degree of connection between values of obtained parameters n and K for models 1 – 5.

Besides, in order to evaluate the degree of connection between the reduced distances R and oscillation velocities v we used index of the curved dependency ρ [7].

In order to make sure that the conclusions we reach based on the sample concerning the characteristics of the basic data set are credible, the sample needs to be representative. The sample shall be representative, if it is, by its structure, similar to the basic set [8].

6. REVIEW OF MASS BLASTING AT THE KOVILOVAČA OPEN PIT

6.1 General characteristics of the Kovilovača open pit

Measurements are performed at the mass or stratified limestone [9]. The physical – mechanical characteristics of the working environment are:

- angle of internal friction $\varphi = 31°35'$,
- cohesion $C = 138.33\left[kN/m^2\right]$,
- volume weight $\gamma = 26.26\left[kN/m^3\right]$,
- compressive strength $\sigma_p = 80.808\left[MPa\right]$,
- tensile strength $\sigma_z = 7.590\left[MPa\right]$,
- velocity of longitudinal elastic waves $c_p = 6661.00\left[m/s\right]$,
- velocity of transverse elastic waves $c_s = 2852.67\left[m/s\right]$,
- dynamic elasticity modulus $E_{din} = 62.46\left[GN/m^2\right]$,
- dynamic Poisson's ratio $\mu_{din} = 0.39\left[GN/m^2\right]$.

6.2 Method of blasting in the open pit Kovilovača

Measurements of seismic shocks in the open pit Kovilovača were performed during blasting, conducted for the purpose of deposit exploitation [9]. Two blasting operations were performed.

Balkanit 60/1500, detonex 65/1500 and ANFO 70/1500 were used as explosives. Activation of explosives in the borehole was performed using nonel detonators with retardations of 500 ms in the borehole, while the retardation between boreholes on the surface was 25 ms and 42 ms. Activating of nonel tube was performed using electric detonator.

Basic data related to the number of boreholes N_b, the overall explosive amount Q_{uk}, the maximal exsplosive amount by deceleration interval Q_i, overall borehole depth L_{uk}, and average stemming length $L_{p\check{c}}$, are presented in Table 1.

Table 1. *Review of blasting parameters at the Kovilovača open pit*

Blasting	N_b	Q_{uk} [kg]	Q_i [kg]	L_{uk} [m]	$L_{p\check{c}}$ [m]
1	34	3 623.0	108.0	842.0	2.2
2	36	3 264.0	92.0	918.0	2.2

6.3 Calculation of rock mass oscillation equation parameters at the Kovilovača open pit

Values of distance from the blasting site to the place of observation r, total quantity of explosive Q, calculated values of reduced distances R, registered values of rock mass oscillation velocities per components v_v, v_t, v_l and resulted rock mass oscillation velocities v_r for blasting I – II, at the total of ten measured points MP, are presented in Table 2.

Table 2. Review of blasting parameters and measurement results

No	MP	r [m]	Q [kg]	R	v_v [cm/s]	v_t [cm/s]	v_l [cm/s]	v_r [cm/s]
1	MP1	335.0	3.623.0	21.8117	0.1460	0.0517	1.2000	1.2100
2	MP3	850.0	3.623.0	55.3430	0.0138	0.0270	0.0617	0.0687
3	MP5	830.0	3.264.0	55.9536	0.0206	0.0133	0.0407	0.0475
4	MP9	855.0	3.264.0	57.6390	0.0200	0.1070	0.0245	0.1116
5	MP3	860.0	3.264.0	57.9760	0.1400	0.1010	0.1830	0.2516
6	MP10	880.0	3.264.0	59.3234	0.0729	0.0936	0.0156	0.1197
7	MP10a	885.0	3.264.0	59.6614	0.0134	0.1530	0.0426	0.1594
8	MP7	950.0	3.623.0	61.8540	0.0222	0.0422	0.0623	0.0785
9	MP7	960.0	3.264.0	64.7174	0.0174	0.0477	0.0708	0.0871
10	MP6	965.0	3.264.0	65.0545	0.0045	0.0337	0.0555	0.0651
11	MP6a	970.0	3.264.0	65.3916	0.0202	0.0568	0.0711	0.0932
12	MP8	1155.0	3.623.0	75.2014	0.0327	0.0317	0.0246	0.0518

Based on data given in Table 2, the rock mass oscillation equation is calculated by the formula (1) – for the models 1 – 5. The calculation of the curve was carried out for values of reduced distances from $R = 21.8117$ to $R = 75.2014$. Thus, curve parameters were calculated enabling us to determine the equation of rock mass oscillation for models 1 – 5 in the form of:

- **Model 1**

$$v_1 = 2131.52 \cdot R^{-2.4410}; \tag{11}$$

thus between $\log v$ and $\log R$ we get linear dependency that is expressed by equation (11) with the coefficient of linear dependency $r_{\log}$ which is: $r_{\log} = -0.8613$.

Graphic review of the rock mass oscillation equation is shown in figure 1.

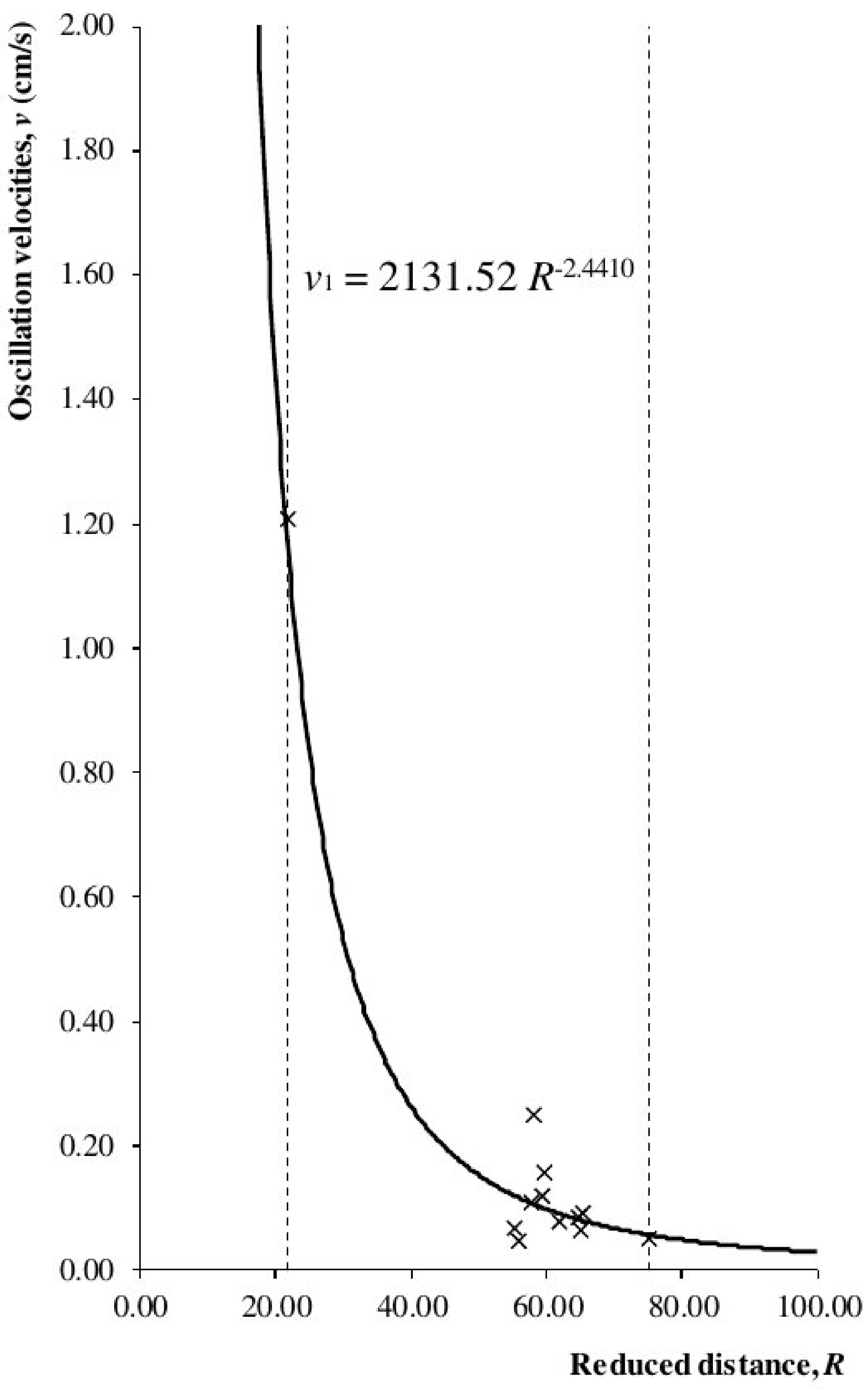

Figure 1. Graphic review of oscillation velocity and reduced distance at the Kovilovača open pit

- **Model 2**

$$v_2 = 13.3219 \cdot R^{-2.1351}; \tag{12}$$

- **Model 3**

$$v_3 = 38.9387 \cdot R^{-1.4227}; \tag{13}$$

- **Model 4**

$$v_4 = 2571.7694 \cdot R^{-2.4854}; \tag{14}$$

- **Model 5**

$$v_5 = 52.6399 \cdot R^{-1.5}; \tag{15}$$

On the basis of the obtained equations for rock mass oscillation (11), (12), (13), (14) and (15) it is possible to calculate values of rock mass oscillation velocities for the corresponding reduced distances for models 1 – 5.

In table 3, the review of reduced distances R, registered rock mass oscillation velocities v_r is given, as well as calculated rock mass oscillation velocities from v_{i1} to v_{i5}, for models 1 – 5.

Table 3. *Review of registered and calculated rock mass oscillation velocities for models 1-5*

No	R	v_r [cm/s]	v_{i1} [cm/s]	v_{i2} [cm/s]	v_{i3} [cm/s]	v_{i4} [cm/s]	v_{i5} [cm/s]
1	21.8117	1.2100	1.1507	0.4027	0.4851	1.2100	0.5168
2	55.3430	0.0687	0.1185	0.1400	0.1290	0.1196	0.1279
3	55.9536	0.0475	0.0904	0.1382	0.1270	0.1164	0.1258
4	57.6390	0.1116	0.1073	0.1337	0.1217	0.1081	0.1203
5	57.9760	0.2516	0.1058	0.1328	0.1207	0.1065	0.1192
6	59.3234	0.1197	0.1001	0.1294	0.1168	0.1006	0.1152
7	59.6614	0.1594	0.0987	0.1285	0.1159	0.0992	0.1142
8	61.8540	0.0785	0.0904	0.1234	0.1101	0.0907	0.1082
9	64.7174	0.0871	0.0809	0.1172	0.1032	0.0811	0.1011
10	65.0545	0.0651	0.0799	0.1165	0.1025	0.0800	0.1003
11	65.3916	0.0932	0.0789	0.1158	0.1017	0.0790	0.0995
12	75.2014	0.0518	0.0561	0.0988	0.0834	0.0558	0.0807

In table 4, review of reduced distances R, registered rock mass oscillation velocities v_r is given as well as the differences between registered and calculated oscillation velocities for models 1 – 5.

Table 4. *Review of differences between registered and calculated rock mass oscillation velocities for models 1-5*

No	R	v_r [cm/s]	$v_r - v_{i1}$	$v_r - v_{i2}$	$v_r - v_{i3}$	$v_r - v_{i4}$	$v_r - v_{i5}$
1	21.8117	1.2100	0.0593	0.8073	0.7249	0.0000	0.6932
2	55.3430	0.0687	-0.0498	-0.0713	-0.0603	-0.0509	-0.0592
3	55.9536	0.0475	-0.0679	-0.0907	-0.0795	-0.0689	-0.0783
4	57.6390	0.1116	0.0040	-0.0221	-0.0101	0.0035	-0.0087
5	57.9760	0.2516	0.1458	0.1188	0.1309	0.1451	0.1324
6	59.3234	0.1197	0.0196	-0.0097	0.0029	0.0191	0.0045
7	59.6614	0.1594	0.0607	0.0309	0.0435	0.0602	0.0452
8	61.8540	0.0785	-0.0119	-0.0449	-0.0316	-0.0122	-0.0297
9	64.7174	0.0871	0.0062	-0.0301	-0.0161	0.0060	-0.0140
10	65.0545	0.0651	-0.0148	-0.0514	-0.0374	-0.0149	-0.0352
11	65.3916	0.0932	0.0143	-0.0226	-0.0625	-0.0398	-0.0603
12	75.2014	0.0518	-0.0043	-0.0470	-0.0316	-0.0040	-0.0289

Based on data from table 4, a statistical analysis has been done and following values have been obtained. The curved line dependency index ρ between the reduced distance R and rock mass oscillation velocity v:

- **model 1:** $\rho_1 = 0.9843$ for total of 12 data
  (there is a strong correlation between R and v, given in the Equation (11)).
- **model 2:** $\rho_2 = 0.8487$ for total of 11 data
  (there is a strong correlation between R and v, given in the Equation (12)).
- **model 3:** $\rho_3 = 0.8513$ for total of 11 data
  (there is a strong correlation between R and v, given in the Equation (13)).
- **model 4:** $\rho_4 = 0.9852$ for total of 12 data
  (there is a strong correlation between R and v, given in the Equation (14)).
- **model 5:** $\rho_5 = 0.8537$ for total of 11 data
  (there is a strong correlation between R and v, given in the Equation (15)).

Based on the obtained values for parameters n and K in the rock mass oscillation equations, by application of the mentioned five models, the linear dependency between n and K form has been determined.

$$K = 1996.4739 \cdot n - 2625.7860; \tag{16}$$

With coefficient of the linear dependency which is: $r_p = 0.974$.

Based on the values of the coefficient of linear dependency r_p between parameters n and K for all five models, we can say that there is a strong correlation between parameters n and K.

7. CONCLUSION

In this paper, parameters n and K from Sadovskii's equation were determined in five ways – models in the given work environment. Their corresponding functions have been obtained presenting rock mass oscillation velocities of the depending on a reduced distance. The calculated corresponding indexes of the curved line correlation point out that there is a rather strong curved line relationship between a reduced distance and the rock mass oscillation velocity expressed in the obtained functions.

The relation between parameters K and n has been obtained in this study. This relation made it possible to find the value of the second parameter for the given determined value of one parameter. In practice it is simpler to determine the value of the parameter K in advance for an adopted value of the parameter n in the interval from 1 – 2, as has been applied in model 5. In this way, a new simplified formula has been obtained for determining the rock mass oscillation velocity equation in which only parameter K is calculated.

Linear dependency with highly strong correlation has been obtained between registered and calculated values of rock mass oscillation velocities. On the basis of the obtained coefficients of the linear dependency, we can conclude that all five models can be used for calculating the rock mass oscillation velocity.

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