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ANALYSIS OF ROCK MASS OSCILLATION LAW WITH REVIEW OF REDUCED DISTANCE

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ABSTRACT

Explosive energy, by its form, has destructive, devastating character, but nowadays the implementation of chemical explosive energy is highly advanced in order to meet human needs.

There have been developed numerous activities in the world whose work cannot be imagined without explosive energy implementation. Explosives are used in mining, primarily, for extracting of mineral raw materials from hard rocks. Nowadays explosive charges with hundreds of kilograms by a borehole and blasting with tens, even hundreds of tons are applied in the world.

Large explosive quantities can cause seismic wave shocks of such intensity that can have bad impact on the environment and cause moving of facilities.

For the evaluation and control of blasting seismic effects, as well as for its planning, the confirmation of soil oscillation law of the strike: the mine field - facilities that are to be protected, is required.

The analysis of two variants of soil oscillation law, by Russian and American authors was conducted on the example of the open pit Drenovac-Mionica.

KEY WORDS: explosion, rock decomposition, seismic effect, soil oscillation law.

1.0. INTRODUCTION

The development of manufacturing capacities has conditioned the use of large explosive quantities resulting in the increase of negative effects accompanying blasting operations. Negative effects of blasting imply, in addition to seismic effects of blasting, shock wave effect, air blast effect, dissipation of blasted rock mass, etc.

2.0 SOIL OSCILLATION LAW

To establish the correlation between the oscillation velocity and three basic parameters affecting its size: the explosive quantity, properties of rock material and the distance, there have been developed several mathematical models in the world. One of most frequently used models, i.e. equations, is the equation of Sadovski defining the law on velocity alteration of soil oscillation depending on the distance, the explosive quantity, and the way of blasting.

Therefore, more attention is paid to the study of these occurrences with the tendency for reducing them to permit boundaries.

One of the most frequently used equations is that by Professor M.A. Sadovski defining law on alteration of soil oscillation velocity depending on distance, explosive quantity, conditions of blasting operations, and geological characteristics of soil.

The law defined in this way offers the possibility to determine the seismic effect of blasting towards a facility or a settlement, whereby the connection, between the velocity of soil oscillation and consequences that can affect facilities, is used. The equation of M.A Sadovski is given in the form:

$$v = K \cdot R^{-n} \quad (1)$$

Where: v - is velocity of soil oscillation, cm/s

K, n - is a coefficient conditioned by soil characteristics and blasting conditions determined by terrain surveying,

R - is reduced distance.

$$R = \frac{r}{\sqrt[3]{Q}} \qquad (2)$$

As to the parameter of explosive quantity (Q) in the equation of Sadovski, we imply the overall explosive quantity in a mine series and thereby address to our regulations (*Collection of regulations in geology and mining- book 1. paragraph 9. Determination of safety zones, Article 10, p.393*) regulating*:*

On the occasion of the determination of safety zones, a single, at the same time detonating charge, namely by mines, is considered:

1. *in case of explosive initiation by electric detonators-all explosive charges initiated at the same time or whose deceleration time(detonation retardation)at mille second mine firing does not exceed 100 ms (mille seconds);*
2. *in case of explosive initiation by detonating fuse- all explosive charges of a mine series;*
3. *in case of blasting by laid boiler charges- the boiler charges with the length of 20 m.*

In western countries the following expression is used:

$$R = \frac{r}{\sqrt{Q_i}} \qquad (3)$$

Where:

Q_i - is the maximal explosive quantity initiated at the same time at one deceleration interval, whereby there must be a sufficient time interval between two successive initiations to prevent overlapping or meeting of waves (the USA regulations determine the minimal interval of 8 ms).

3.0 DEFINING OF STATISTICAL CRITERIA

Defining of statistical criteria for the assessment of the correlation equation reliability is calculated on the basis of results obtained by examinations. Methods of mathematical statistics are used for data processing, which depending on the kind of data, the way of their interpretation and wishful accuracy and reliability enable defining of alterations and the behaviour law of monitored occurrences.

Some of basic statistic parameters to be used in this paper are:

*Arithmetic mean:

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \ldots + x_N}{N} = \frac{\sum x_i}{N} \qquad (7)$$

There are two parameters (K) and (n) in the equation (1) which should be determined for a specific blasting environment and with specific blasting conditions. The smallest square method is mainly used to obtain the parameters (K) and (n) which represents a common model. The equation (1) uses logarithms and is reduced to the following form:

$$\log v = \log K - n \log R \qquad (4)$$

By introducing of the replacement: v = y; K = a; R = x; n = b; the equation gets the following form:

$$\log a - b \log x = \log y \qquad (5)$$

The normal equation system for finding parameters (a) and (b) in this case is

$$\begin{aligned} N \log a - b \sum_{i=1}^{N} \log x_i &= \sum_{i=1}^{N} \log y_i \\ (\log a) \sum_{i=1}^{N} \log x_i - b \sum_{i=1}^{N} (\log x_i)^2 &= \sum_{i=1}^{N} \log x_i \cdot \log y_i \end{aligned} \qquad (6)$$

Where:

N - is the number of carried out surveys.

On the basis of the calculated law by the formula (1), we are able to construct an approximate curve correlating the obtained results depending on the explosive quantity, distance, the blasting environment, and blasting conditions. Thus calculated law enables us to make a prognosis, in advance, of the oscillation velocity for each blasting, namely to predict the degree of shock wave intensity caused by blasting. In this way, blasting is, as regards, seismic effect under control, which at the same time gives opportunity not only to control shock waves but to plan them in advance as well.

where:

x_1, $x_2 \ldots x_N$ - are values of results of particular examinations,

N - is number of results, surveys, (samples).

* Mean absolute abberation:

$$\sigma_0 = \frac{\sum \left| x_i - \bar{x} \right|}{N} \qquad (8)$$

where: $\left| x_i - \bar{x} \right|$ - are absolute values of abberation.

* Variance:

$$\sigma^2 = \frac{\sum \left(x_i - \bar{x} \right)^2}{N} = \frac{1}{N} \Sigma x_i^2 - \bar{x}^2 \qquad (9)$$

3.1 Criteria for Testing of Approximate Curve Mathematical Form

To avoid subjective decisions while adopting the curve mathematical form y = y(x), which will appriximate values obtained by research, *the linear correlation coefficient* is used

$$k = \frac{\mu_{11}}{\sigma_x \cdot \sigma_y} = \frac{\Sigma(x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2 \cdot \Sigma(y_i - \bar{y})^2}} \qquad (10)$$

if supposed linear dependency between x_i and y_i is in question, as the assessment of the degree of linear connection. If dependency is curvilinear, the *curvilinear dependency index* is used.

$$\rho = \sqrt{1 - \frac{\Sigma(y_i - y(x_i))^2}{\Sigma(y_i - \bar{y})^2}} \qquad (11)$$

The assessment of correlation degree of two variables is given in the following survey:

0,0 < ρ < 0,2 - none or highly poor correlation
0,2 < ρ < 0,4 - poor correlation
0,4 < ρ < 0,7 - significant coorelation
0,7 < ρ < 1,0 - strong or highly strong correlation

This criterion is used if the number of data is N ≥ 10.

For the evaluation of the convenience degree of the selected curve, in mathematical statistics, in addition to the stated criterion, the criterion "3S" is used. This criterion uses the squares of differences between data obtained by the experiment for y_i and data calculated by the smallest square method of established dependency between x and y. If those differences are one after another ε_1, ε_2 ... ε_N, then it is:

$$S = \sqrt{\frac{\varepsilon_1^2 + \varepsilon_2^2 + ... + \varepsilon_N^2}{N}} \qquad (12)$$

According to this criterion, for the evaluation of convenience of the obtained functional correlation, the following relations are valid:

- If it is $|\varepsilon_{max}| > 3S$, the obtained functional correlation is rejected as unfavourable,
- If it is $|\varepsilon_{max}| < 3S$, the functional correlation is accepted as a good one.

4.0 RESULTS OF EXAMINATIONS AT OPEN PIT "DRENOVAC" – MIONICA

The open pit Drenovac is of elevated type situated almost at the very top of the hill of the same name. The altitude difference of the deposit is about 70 m from the elevation 440-520.There is a diabase - chert formation in the floor of limestone, approximately at the elevation of 438 m.

The limestone is of fissure porosity as stated by mapping of both the terrain and test bore holes. The length of cores is from 30 to 40 cm. Joints are mostly filled with calcite, and to a lesser extent they are filled with limonite debris, namely limonite dross. While drilling, circulation loss-water was insignificant, which points to low effective porosity of limestone.

Limestone is a firm petrified environment. It is tectonically undamaged thus it represents a unique monolithic mass. The present joints impact insignificantly on physico-mechanical characteristics and have the following values:

- volume mass, kN/m³, 2,68
- porosity, % ,0,7-1,5
- cohesion, MPa, 0,25
- uniaxial strength
- in dry state MPa,120-134
- in watersaturated state,83-129
- angle of internal friction,°, 41.

Measurements of seismic shock waves at open pit *Drenovac* were carried out while blasting carried out for the sake of deposit exploitation.

4.1. Calculation of Soil Oscillation Law According to Russian Authors

Values of overall explosive quantity by blasting (Q_{uk}), distance from the blasting site to the place of observation (r), namely reduced distances (R), as well as resulting oscillation velocities (v_{res}) are presented in Table 1.The record of soil oscillation velocity for blasting number 1 - measuring point 3 is shown in Fig.1

Table 1 Values of oscillation velocities

No	Blasting No	Measuring point	r (m)	Q_{uk} (kg)	R	Resulting soil oscillation velocity, v_{res} (cm/s)
1	I	MM – 2	383,87	661,4	44,0585	0,1643
2	I	MM – 3	250,49	661,4	28,7499	0,7616
3	I	MM – 5	647,42	661,4	74,3073	0,1446
4	II	MM – 1	605,54	1980,6	48,2182	0,1100
5	II	MM – 2	334,15	1980,6	26,6078	0,2081
6	II	MM – 3	256,71	1980,6	28,4042	1,3031
7	II	MM – 6	527,05	1980,6	41,9681	0,2943
8	III	MM – 1	616,35	915,3	63,4804	0,1482
9	III	MM – 2	250,14	915,3	25,7629	0,9392
10	III	MM – 3	412,66	915,3	42,5015	0,8247
11	III	MM – 5	714,10	915,3	73,5481	0,2045
12	III	MM – 6	541,13	915,3	55,7332	0,3454
13	III	MM – 7	530,89	915,3	54,6785	0,3326
14	IV	MM – 1	723,77	745,0	79,8390	0,1221
15	IV	MM – 2	410,33	745,0	45,2635	0,2844
16	IV	MM – 3	223,89	745,0	24,6973	0,7511
17	IV	MM – 5	644,64	745,0	71,1102	0,3035
18	IV	MM – 7	426,38	745,0	47,0339	0,3701
19	V	MM – 1	737,38	1895,0	60,0667	0,0948
20	V	MM – 3	210,96	1895,0	17,1847	1,4996
21	V	MM – 7	422,53	1895,0	34,4192	0,5254
22	VI	MM – 3	231,44	1774,4	19,1171	1,4768
23	VI	MM – 5	650,53	1774,4	53,7341	0,1165
24	VI	MM – 6	640,06	1774,4	52,8693	0,2393
25	VI	MM – 7	425,36	1774,4	35,1350	0,6316
26	VII	MM – 3	333,13	1988,6	26,4910	0,9268
27	VII	MM – 6	530,48	1988,6	42,1845	0,2623
28	VII	MM – 7	415,31	1988,6	33,0260	0,6618
29	VIII	MM – 1	609,20	600,0	72,2286	0,1034
30	VIII	MM – 3	387,35	600,0	45,9254	0,8878
31	VIII	MM – 6	532,35	600,0	63,1171	0,1607
32	VIII	MM – 7	493,85	600,0	58,5524	0,2327

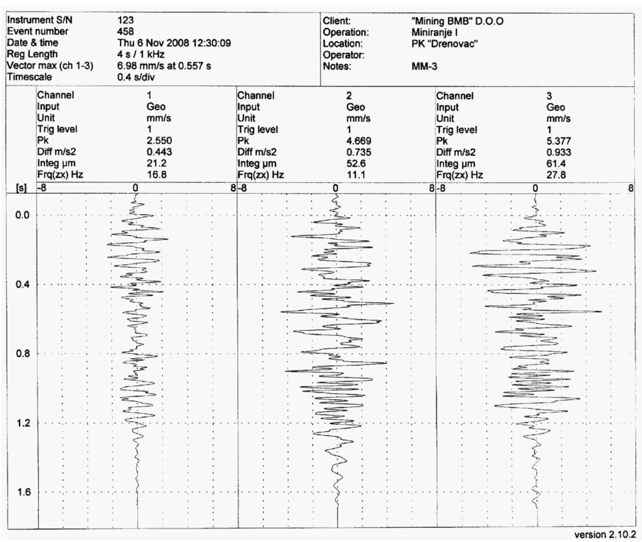

Figure 1 Image of soil oscillation velocity for blasting I-MM3

On the basis of results presented in Table 2, by the application of the smallest square method, the soil oscillation law is calculated by the formula (1).The calculation of the curve is carried out for values of reduced distances from R = 17.1847 to R = 79.8390 and thereby the soil oscillation equation was determined in the form:

$$v_1 = 166,3916 \cdot R^{-1,6433} \qquad (13)$$

Graphic survey of soil oscillation law is shown in Figure 2.

On the basis of obtained equation (13) of the soil oscillation, it is possible to calculate values of soil oscillation velocity for corresponding reduced distances. In Table 2, there is presented the survey of reduced distances (R), recorded soil oscillation velocities (v_i), as well as the difference between recorded and calculated soil oscillation velocities.

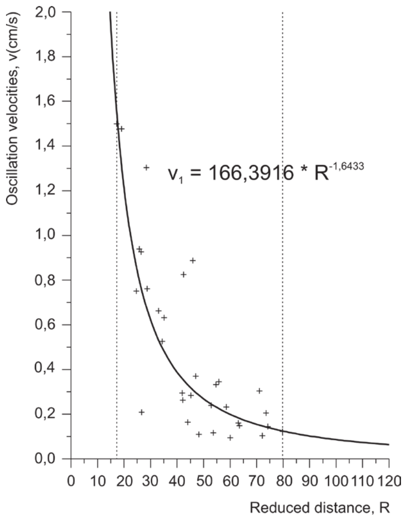

Figure 2 Graphic survey of soil oscillation law curve in OP Drenovac by Russian authors

Table 2. Values from survey for soil oscillation velocities

No	Reduced distance (R)	Recorded oscillation velocity, v_r (cm/s)	Calculated oscillation velocity, v_i (cm/s)	Velocity difference, $v_r - v_i$
1	44,0585	0,1643	0,3307	-0,1664
2	28,7499	0,7616	0,6670	0,0946
3	74,3073	0,1446	0,1401	0,0045
4	48,2182	0,1100	0,2852	-0,1752
5	26,6078	0,2081	0,7576	-0,5495
6	28,4042	1,3031	0,6804	0,6227
7	41,9681	0,2943	0,3583	-0,0640
8	63,4804	0,1482	0,1815	-0,0333
9	25,7629	0,9392	0,7988	0,1404
10	42,5015	0,8247	0,3509	0,4738
11	73,5481	0,2045	0,1425	0,0620
12	55,7332	0,3454	0,2248	0,1206
13	54,6785	0,3326	0,2319	0,1007
14	79,8390	0,1221	0,1245	-0,0024
15	45,2635	0,2844	0,3164	-0,0320
16	24,6973	0,7511	0,8562	-0,1051
17	71,1102	0,3035	0,1506	0,1529
18	47,0339	0,3701	0,2971	0,0730
19	60,0667	0,0948	0,1987	-0,1039
20	17,1847	1,4996	1,5539	-0,0543
21	34,4192	0,5254	0,4963	0,0291
22	19,1171	1,4768	1,3043	0,1725
23	53,7341	0,1165	0,2387	-0,1222
24	52,8693	0,2393	0,2451	-0,0058
25	35,1350	0,6316	0,4798	0,1518
26	26,4910	0,9268	0,7631	0,1637
27	42,1845	0,2623	0,3552	-0,0929
28	33,0260	0,6618	0,5311	0,1307
29	72,2286	0,1034	0,1468	-0,0434
30	45,9254	0,8878	0,3089	0,5789
31	63,1171	0,1607	0,1832	-0,0225
32	58,5524	0,2327	0,2073	0,0254

A statistical analysis was carried out on the basis of data presented in Table 2.
The arithmetic mean of recorded values of soil oscillation velocities, on the basis of the formula (7) amounts:

$\overline{v_{r1}} = 0,4822$.

The variance of recorded values of the soil oscillation velocities, on the basis of the formula (9) amounts: $\sigma^2_{vr1} = 0,1625$.

The index of curveline dependence between reduced distance (R) and soil oscillation velocity (v) on the basis of the formula (11) amounts: $\rho_1 = 0,8380$.

On the basis of the index value of curveline dependence (ρ_1), it can be stated that between two variables, i.e. the reduced distance (R) and the soil oscillation velocity (v), there is *highly tight correlation*, given in the formula (13). To evaluate the degree of convenience and accuracy.

Of the selected curve, in addition to the stated criterion, i.e. the index of curveline dependence (ρ_1), the criterion "3S" has been taken into account as well.

According to the obtained data in Table 2, maximal difference between recorded and calculated soil oscillation velocities $(\varepsilon_{max}) = \max|\varepsilon_i|$, amounts: ε_{max} = 0,6227; S = 0,2200; 3S = 0,6600.
As ε_{max} < 3S, the supposed functional correlation is accepted as a good one.

4.2. Calculation of Soil Oscillation Law According to American Authors

Values of maximal explosive quantity by the deceleration interval (Q_i), the distance from the blasting site to the observation point (r), namely reduced distances (R), as well as resulting oscillation velocities (v_{res}) are presented in Table 3.

Table 3. Values of maximal explosive quantity

No	Blasting No	Measuring point	r (m)	Q_i (kg)	R	Resulting soil oscillation velocity v_{res} (cm/s)
1	I	MM – 2	383,87	36,2	63,8014	0,1643
2	I	MM – 3	250,49	36,2	41,6328	0,7616
3	I	MM – 5	647,42	36,2	107,6048	0,1446
4	II	MM – 1	605,54	71,2	71,7634	0,1100
5	II	MM – 2	334,15	71,2	39,6006	0,2081
6	II	MM – 3	256,71	71,2	30,4231	1,3031
7	II	MM – 6	527,05	71,2	62,4614	0,2943
8	III	MM – 1	616,35	66,2	75,7528	0,1482
9	III	MM – 2	250,14	66,2	30,7436	0,9392
10	III	MM – 3	412,66	66,2	50,7181	0,8247
11	III	MM – 5	714,10	66,2	87,7668	0,2045
12	III	MM – 6	541,13	66,2	66,5078	0,3454
13	III	MM – 7	530,89	66,2	65,2493	0,3326
14	IV	MM – 1	723,77	47,0	105,5727	0,1221
15	IV	MM – 2	410,33	47,0	59,8528	0,2844
16	IV	MM – 3	223,89	47,0	32,6577	0,7511
17	IV	MM – 5	644,64	47,0	94,0304	0,3035
18	IV	MM – 7	426,38	47,0	62,1939	0,3701
19	V	MM – 1	737,38	60,5	94,8012	0,0948
20	V	MM – 3	210,96	60,5	27,1220	1,4996
21	V	MM – 7	422,53	60,5	54,3225	0,5254
22	VI	MM – 3	231,44	85,2	25,0737	1,4768
23	VI	MM – 5	650,53	85,2	70,4770	0,1165
24	VI	MM – 6	640,06	85,2	69,3427	0,2393
25	VI	MM – 7	425,36	85,2	46,0826	0,6316
26	VII	MM – 3	333,13	54,2	45,2495	0,9268
27	VII	MM – 6	530,48	54,2	72,0559	0,2623
28	VII	MM – 7	415,31	54,2	56,4122	0,6618
29	VIII	MM – 1	609,20	32,0	107,6924	0,1034
30	VIII	MM – 3	387,35	32,0	68,4745	0,8878
31	VIII	MM – 6	532,35	32,0	94,1071	0,1607
32	VIII	MM – 7	493,85	32,0	87,3012	0,2327

On the basis of results presented in Table 3, by the application of the smallest square method, soil oscillation law is calculated by the formula (1). The curve calculation was carried out for values of reduced distances from R = 25.0737 to R = 107.6924 and thereby the equation of soil oscillation was determined in the form:

$$v_2 = 364,4826 \cdot R^{-1,7033} \qquad (14)$$

Graphic survey of soil oscillation law is shown in Figure 3.

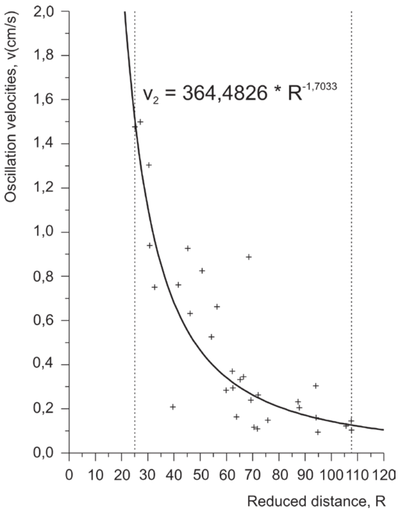

Figure 3 Graphic survey of curve of soil oscillation velocity in OP Drenovac

On the basis of the obtained equation (14) of soil oscillation, it is possible to calculate values of soil oscillation velocity for corresponding reduced distances.

In Table 4, there is shown the survey of reduced distances (R), recorded velocities of soil oscillation (v_r), calculated oscillation velocities (v_i), as well as the difference between the recorded and calculated soil oscillation velocities.

Table 4. Soil oscillation velocity in OP Drenovac according to American authors

No	Reduced distance (R)	Recorded oscillation velocity, v_r (cm/s)	Calculated oscillation velocity, v_i (cm/s)	Velocity difference, $v_r - v_i$
1	63,8014	0,1643	0,3073	-0,1430
2	41,6328	0,7616	0,6358	0,1258
3	107,6048	0,1446	0,1261	0,0185
4	71,7634	0,1100	0,2515	-0,1415
5	39,6006	0,2081	0,6923	-0,4842
6	30,4231	1,3031	1,0848	0,2183
7	62,4614	0,2943	0,3186	-0,0243
8	75,7528	0,1482	0,2293	-0,0811
9	30,7436	0,9392	1,0656	-0,1264
10	50,7181	0,8247	0,4542	0,3705
11	87,7668	0,2045	0,1785	0,0260
12	66,5078	0,3454	0,2863	0,0591
13	65,2493	0,3326	0,2957	0,0369
14	105,5727	0,1221	0,1303	-0,0082
15	59,8528	0,2844	0,3426	-0,0582
16	32,6577	0,7511	0,9614	-0,2103
17	94,0304	0,3035	0,1587	0,1448
18	62,1939	0,3701	0,3209	0,0492
19	94,8012	0,0948	0,1565	-0,0617
20	27,1220	1,4996	1,3192	0,1804
21	54,3225	0,5254	0,4041	0,1213
22	25,0737	1,4768	1,5080	-0,0312
23	70,4770	0,1165	0,2594	-0,1429
24	69,3427	0,2393	0,2666	-0,0273
25	46,0826	0,6316	0,5348	0,0968
26	45,2495	0,9268	0,5517	0,3751
27	72,0559	0,2623	0,2498	0,0125
28	56,4122	0,6618	0,3789	0,2829
29	107,6924	0,1034	0,1260	-0,0226
30	68,4745	0,8878	0,2724	0,6154
31	94,1071	0,1607	0,1585	0,0022
32	87,3012	0,2327	0,1801	0,0526

A statistical analysis was carried out on the basis of data in Table 4.
The curveline dependency index between the reduced distance (R) and soil oscillation velocity (*v*), on the basis of the formula 11, amounts: $\rho_2 = 0{,}8703$.

On the basis of the value of curveline dependency index, it can be stated that between two variables, i.e. reduced distance (R) and the soil oscillation velocity (*v*), there exists *highly tight connection* given in the formula (14). For the evaluation of both convenience and accuracy levels of the selected curve, in addition to the stated criterion, i.e. the curveline dependency index,(ρ_2), the criterion "3S" was taken into account as well.

According to the data presented in Table 4, maximal difference between recorded and calculated soil oscillation velocities $(\varepsilon_{max}) = \max|\varepsilon_i|$, amounts: $\varepsilon_{max} = 0{,}6154$; S = 0,1985; 3S = 0,5955.
As $\varepsilon_{max} > 3S$, the supposed *functional correlation is rejected as unfavourable.*

5.0 CONCLUSION

The statistical analysis of data was conducted on the basis of recorded and calculated soil oscillation velocities according to Russian and American authors. For the evaluation of both convenience and accuracy levels of the selected curve, in addition to the curve line dependency index (ρ), the criterion "3S" was taken into account as well.

On the basis of the values *of curve line dependency index* between recorded and calculated soil oscillation velocities according to both Russian and American authors, it can be stated that between two variables, i.e. the soil oscillation velocity (*v*) and the reduced distance (R) there exists a *highly strong correlation* in both cases.

On the basis of "3S"criterion, according to the obtained data for the calculation by Russian authors, as $\varepsilon_{max} < 3S$, the supposed functional *correlation is accepted as a good one.* According to the obtained data for the calculation by American authors, as $\varepsilon_{max} > 3S$, *the supposed functional correlation is rejected as the unfavourable one.*

Based on the obtained data of statistical analysis, it can be stated that there is a highly strong correlation between soil oscillation velocity (*v*) and the reduced distance (R), but the Russian method provides results closer to the values of the measured ones, i. e. recorded soil oscillation velocities.

Additionally, it is sometimes hard to determine on a velosigram which peak in the oscillation curve, by oscillation velocity components, corresponds to the given deceleration, i.e. specific explosive quantity for the given deceleration, as existing instruments cannot separate that. Therefore, in our practice, the priority is given, however, to the Russian method of reduced distance determination.

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