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Estimation of Rock Mass Strength in Open-Pit Mining

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The paper presents results of an experimental study on strength characteristics of the rock mass as applied to the assessment of open-pit slope stability. Formulas have been obtained that describe a correlation between ultimate and residual strength of rock samples and residual shear strength along the weakening surface. A new method has been developed to calculate residual interface strength of the rock mass basing on data from the examination of small-scale monolith samples with opposing spherical indentors. A method has been proposed to estimate strength characteristics (structural weakening coefficients and internal friction angles) of the fractured near-slope rock mass. The method relies on test data from shattering small-scale monolith samples with spherical indentors, taking into account contact conditions along the weakening surface, and can be applied in the field conditions. It is acceptable to use irregular-shaped samples in the tests.

Key words: open-pit slope stability; near-slope rocks mass; geomechanical model; structural weakening coefficient; laboratory tests; strength certificate of rocks; residual strength; contact conditions

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Introduction. In the assessment of open-pit slope stability initial data is represented by physical and mechanical properties of the rock mass [12, 13]. However, in the field conditions their estimation turns out to be very labour-intensive, obtained results are difficult to interpret for high slopes. Hence, initial data is determined by adjusting results of laboratory tests for empirical dependencies that take into account specific characteristics of the structurally faulted rock mass. In Russia this phenomenon is described by a term «structural weakening coefficient» [2, 3, 5], foreign researchers utilize rating indicators [10]. A lot of attention is given to the characteristics of contacts between the fractures, especially to surface irregularities of the fractures with a regard to their extension [6-8].

At the same time with the development of computers and specialized software, aimed at stability estimation of open-pit slopes, practical calculations actively incorporate methods, which allow for more complete and detailed consideration of the structural composition of the near-slope rock mass.

Combined application of empirical dependencies with a regard to scale effect and modelling of the slopes with a detailed structural composition can lead to double counting of rock mass faults. On the other hand, an approach when the scale effect is estimated using numerical modeling is gaining ground [4, 15, 16].

Therefore, it is a promising solution to use hierarchical block models of the rock mass based on separate estimation of shear strength along the contacts of rock blocks and the strength of blocks themselves. As the lower strength limit of the fractured rock it is acceptable to consider residual strength of the rock mass [14].

Currently full assessment of rock mass strength (certificates of ultimate and residual strength of the rock mass and contacts along the weakening surfaces) involves numerous tests using complex high-rigidity loading devices and shearing equipment; it is often limited by the capacity of experimental machinery or lack of samples. In this context the relevance of the task to develop simplified meth-

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ods of rock mass strength estimation, which would also be available in the field, becomes obvious. The main focus of the paper is set on calculation methods of plotting strength certificates of the rock mass, basing on the results of shattering the samples with spherical indentors – not only simplifying the tests, but significantly increasing their descriptiveness.

Calculation method of plotting rock strength certificate. As a basic test method to estimate rock mass strength, it was decided to use improved loading of the sample with spherical indentors, invented at Saint-Petersburg Mining University [1].

The main idea of the method lies in testing the sample with axial load from two steel balls until the former gets shattered, identification of the destruction power *P*, measurement of the breakage surface area *S* and surface areas in the shattered rock zones at the contact with indentors F_1 and F_2, out of which the greatest – *F* – is selected (Fig.1). In accordance with the obtained experimental data, a pattern of sample destruction is accepted, which describes mechanical behaviour of the rock mass under complex heterogeneous stress state. At the moment of shattering, three various mechanisms of destruction get activated in the sample: «quasi-plastic» behaviour in the proximity of indentors and mechanisms of breakage and shearing at the boundaries.

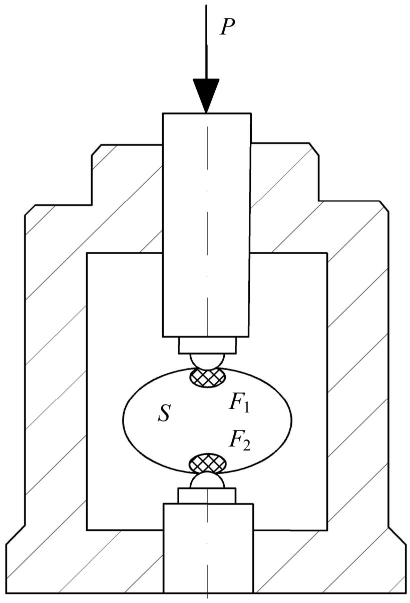

Fig.1. Configuration of sample loading with spherical indentors

The basic method of plotting rock mass strength certificate implies the calculation of coordinates for characteristic points of Mohr's envelope and strength certificate parameters using functional characteristics, which define rock mass destruction. Straining σ_t and compressing *p* components of the ultimate shear resistance C_0 in the absence of normal stress have been accepted as such.

In the system of Mohr's coordinates it is proposed to approximate the envelope of stress circles with straight intervals corresponding to persistent forms of destruction – breakage, shear, «quasi-plastic» behaviour under high uneven 3D compression – and transition curve sections, whose destruction form is stochastic by nature (Fig.2, line 1).

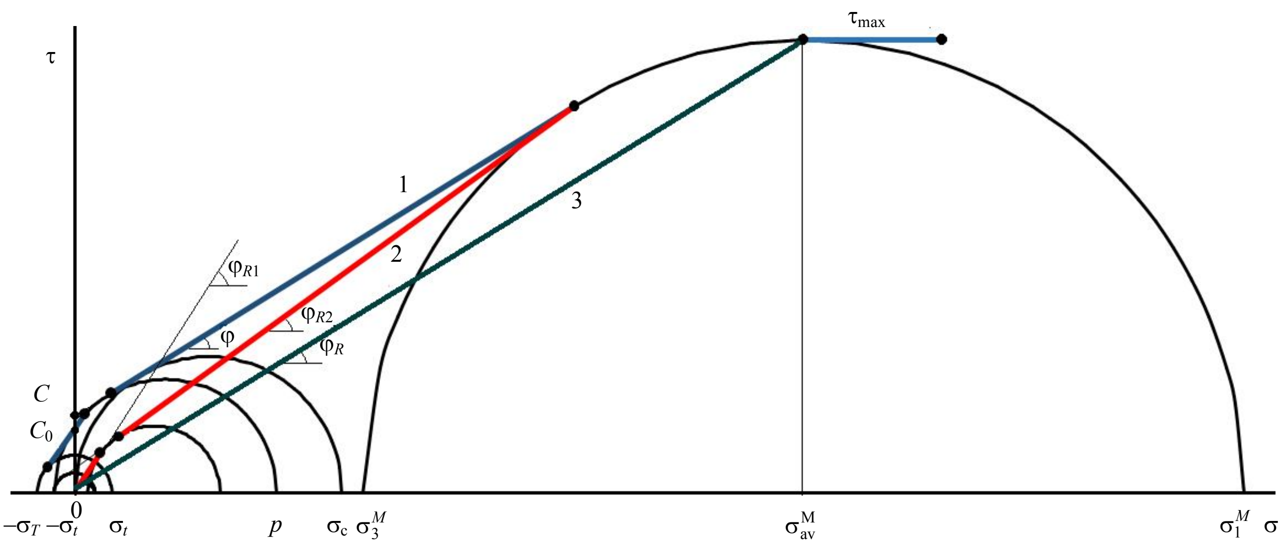

Fig.2. Plotting certificates of ultimate (1) and residual (2) rock mass strength and certificate of residual (3) strength of the natural contact in the sample

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The straight interval of Mohr's circle envelope, corresponding to shear destruction, is characterized by relative adhesion C and internal friction angle φ.

The method allows to estimate all strength parameters – from 3D tension strength σ_{3T} to maximum shear force τ_{max}.

Calculation method of plotting residual rock strength certificate. Basing on the results of comparative tests, where rock mass samples were subject to shattering by indentors and Carman-scheme volume compression in controlled deformation mode, as an improvement of the basic method a calculation method of plotting residual strength certificate, using data from examinations of monolith samples with spherical indentors, has been developed [11].

Plotting residual strength certificate in the system of Mohr's coordinates is also performed by approximating the envelope of stress circles with straight-line intervals, corresponding to persistent forms of destruction, and transition curve sections, whose destruction form is stochastic by nature (Fig.2, line 2). Envelope section of residual strength, characterizing shear destruction, approximates a straight-line interval tangent to the Mohr's circle, corresponding to residual value of simple shear strength at the stress level of $\{-\sigma_t; \sigma_t\}$ and maximum stress $\{\sigma_3^M; \sigma_1^M\}$, corresponding to the equality of ultimate and residual strength at maximum shear force τ_{max}; σ_R, numerically equal to the absolute value of average tension stress σ_t in case of indentor shattering, is taken as a limit of residual strength under linear compression [9].

Calculation method of residual rock strength parameters determination for the shear along the weakening surface. At Saint-Petersburg Mining University a set of experiments has been performed to define ultimate and residual strength of the rock mass for the cases of volume compression, shearing compression along the weakening surfaces, as well as calculations of tests with spherical indentors. Volume compression and shearing tests were carried out on samples with natural and artificial (saw-cut) weakening surfaces.

Then experimental data on shearing compression along the weakening surfaces (natural and saw-cut) was plotted on Mohr's diagram and compared to the envelopes of ultimate and residual stresses, plotted using data from sample examination with spherical indentors.

As a typical example, the paper presents examination results of volume compression in controlled deformation mode performed in the stabilometer BV-21 and shattering of the marble sample with spherical indentors. Volume compression was performed both on monolith samples and specimen saw-cut at 45 and 60° to the axis (plotting of strength certificates taking into account orientation of weakening surfaces has been performed using the method of G.N. Kuznetsov).

Certificate parameters of ultimate and residual strength of the marble, plotted using results of spherical indentor examinations, are presented in Tables 1 and 2.

It has been identified that shear rock strength along the contacts is the smallest of compared parameters. With rising ultimate stresses, corresponding to the shearing mechanism of destruction, the difference between the strength of continuous contacts and residual strength of the shattered rock increases (Fig.3).

Results of comparison between ultimate and residual strength of the monolith rock, obtained in volume tests, and estimated parameters, calculated using results of spherical indentor tests, demonstrate the applicability of calculating ultimate and residual strength using straight-line approximation of the envelope segment, corresponding to the shearing mechanism of destruction.

For a wide-range comparison, the ultimate stresses (up to the level of maximum shear force τ_{max}) in the ultimate and residual strength certificate of marble samples, residual shear stress along

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the saw-cut surfaces and similar strength certificates, calculated using piecewise-linear approximation of the limit envelope of monolith rock, are graphically presented in the system of Mohr's coordinates (Fig.4).

Table 1

Calculated parameters of marble strength

σ_t, MPa	p, MPa	σ_T, MPa	C_0, MPa	σ_c, MPa	φ_0, degree	C, MPa	φ, degree	τ_{max}, MPa	σ_3^M, MPa	σ_1^M, MPa
3.40	97.10	6.56	18.16	115.26	68.8	24.9	43.2	648.8	271.9	1569.4
5.74	103.83	10.88	24.41	128.25	63.5	31.1	38.3	428.3	223.9	1080.5
3.72	77.34	7.10	16.96	94.30	65.3	22.1	39.8	369.6	181.1	920.3
3.28	90.95	6.33	17.27	108.21	68.5	23.6	42.9	588.4	250.4	1427.3
5.36	114.34	10.23	24.75	139.08	65.6	32.4	40.1	561.5	271.8	1394.8
3.03	64.62	5.80	14.00	78.62	65.6	18.3	40.1	316.6	153.4	786.6
4.20	84.28	7.99	18.80	103.09	64.9	24.4	39.4	388.3	193.4	970.1
3.80	86.65	7.27	18.14	104.79	66.4	24.0	40.8	456.7	214.1	1127.5
4.29	95.49	8.20	20.23	115.72	66.1	26.6	40.6	490.6	232.7	1213.8
6.54	129.39	12.45	29.09	158.48	64.7	37.6	39.3	586.8	294.3	1467.9
4.61	86.46	8.75	19.96	106.42	64.0	25.6	38.7	370.5	190.5	931.6
Average value		8.32	20.16	113.8	65.7	26.4	40.3	473.3	225.2	1171.8

Table 2

Calculated parameters of residual marble strength

σ_t, MPa	p, MPa	Shear along the breakage surface			Shear along the natural fracture			Shear along the flat (saw-cut) surface		
		C_{R2}, MPa	C_{R2}/C	φ_{R2}, degree	C_R, MPa	C_R/C	φ_R, degree	C_{SR}, MPa	C_{SR}/C	φ_{SR}, degree
3.40	97.10	3.39	0.136	44.5	0.50	0.020	35.2	0	0	35.2
5.74	103.83	5.74	0.185	40.4	0.99	0.032	33.3	0	0	33.2
3.72	77.34	3.72	0.168	41.6	0.61	0.028	33.9	0	0	33.8
3.28	90.95	3.28	0.139	44.2	0.49	0.021	35.1	0	0	35.0
5.36	114.34	5.36	0.166	41.9	0.88	0.027	34.0	0	0	33.9
3.03	64.62	3.03	0.166	41.9	0.50	0.027	34.0	0	0	33.9
4.20	84.28	4.20	0.172	41.3	0.70	0.029	33.7	0	0	33.7
3.80	86.65	3.80	0.158	42.5	0.61	0.025	34.3	0	0	34.2
4.29	95.49	4.29	0.161	42.3	0.69	0.026	34.2	0	0	34.1
6.54	129.39	6.54	0.174	41.2	1.10	0.029	33.7	0	0	33.6
4.61	86.46	4.61	0.180	40.7	0.79	0.031	33.4	0	0	33.4
Average value		4.36	0.164	42.0	0.71	0.027	34.1	0	0	34.0

It has been identified that in the stress range, corresponding to shearing mechanism of destruction, it is acceptable to approximate the envelope of residual strength for flat homogenous contacts (saw-cut surfaces) with a straight-line interval, which in the diagram, plotted in Mohr's coordinates, connects the dots corresponding to residual shear strength along the surfaces of structural weakening in case of linear compression and the stresses reaching maximum shear force τ_{max} (Fig.4).

Hence, results of performed tests demonstrate that the approach, earlier utilized to develop the method of plotting residual strength certificate basing on data from examinations of monolith samples with spherical indentors, can also be used to estimate the parameters of residual shear strength along the weakening surfaces.

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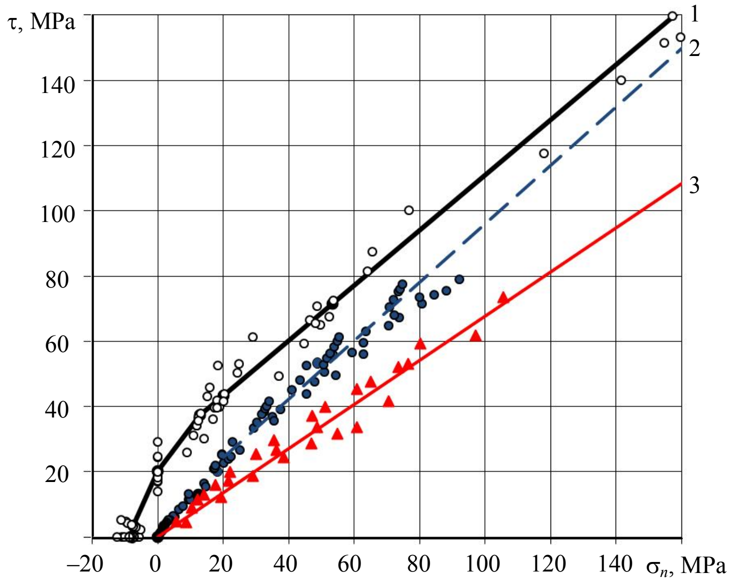

Fig.3. Experimental data for plotting ultimate (1) and residual (2) strength certificates of the samples and residual (3) strength certificate along the contacts in the marble

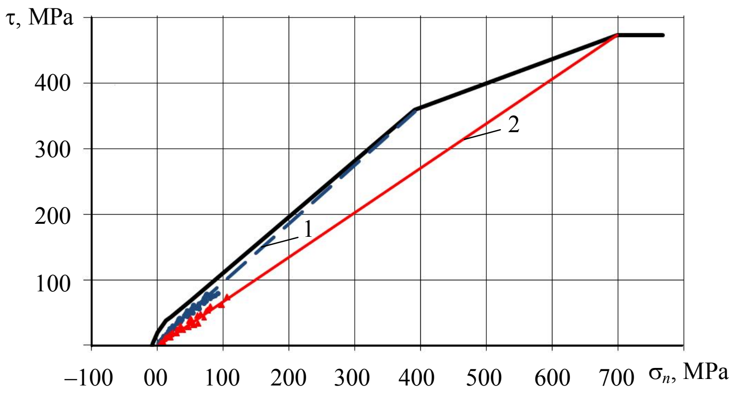

Fig.4. Plotting estimation certificates of residual strength for shattered samples (1) and weakening surfaces (2) in the marble

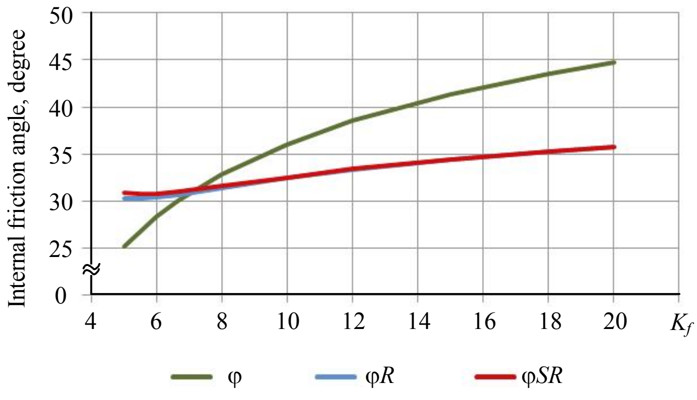

Fig.5. Dependency of ultimate and residual angles of internal friction from rock fragility

At the foundations of the method lies Mohr-coordinate approximation of residual strength envelope for homogenous rock contacts with straight-line intervals corresponding to the shearing mechanism of destruction and stresses reaching the level of maximum shear force τ_{max}. In the Mohr diagram, a straight-line interval of the envelope for residual shear strength along natural fractures passes through the boundary points with coordinates $\{\sigma_n; \tau\}$, $\{\sigma_t/2; \sigma_t/2\}$ and $\{\sigma_{av}^M; \tau_{max}\}$, corresponding to maximum tangent stress in the shattered rock in case of linear compression σ_c and maximum shear force τ_{max}. A similar interval of the envelope for residual shear strength along the flat saw-cut surfaces passes through the origin of coordinates (see Fig.2, line 3).

Formulas have been proposed to calculate main parameters of residual rock mass strength certificates (residual shear adhesion and corresponding angles of internal friction) for various contact conditions using data from spherical indentor tests:

• for shearing along natural fractures and normal stresses in the interval from $\sigma_t/2$ to $(\sigma_{av}^M - \tau_{max}\cos\varphi)$:

$$\mathrm{tg}\varphi_R = \frac{\tau_{max} - \frac{\sigma_t}{2}}{\sigma_{av}^M - \frac{\sigma_t}{2}} = \frac{K^2 - 3K + 6\sqrt{K} - 2}{K^2 + 2K\sqrt{K} - K - 2\sqrt{K} - 2}; \quad (1)$$

$$C_R = \frac{\sigma_t}{2}(1 - \mathrm{tg}\varphi_R) = \sigma_t\sqrt{K}\frac{K + \sqrt{K} - 4}{K^2 + 2K\sqrt{K} - K - 2\sqrt{K} - 2}; \quad (2)$$

$$\frac{C_R}{C} = \frac{2\sqrt[4]{K}(K + \sqrt{K} - 4)}{(1+\sqrt{K})(K^2 + 2K\sqrt{K} - K - 2\sqrt{K} - 2)}; \quad (3)$$

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• for shearing along flat saw-cut surfaces and normal stresses in the interval from 0 to σ_{av}^{M}:

$$\mathrm{tg}\varphi_{SR} = \frac{\tau_{\max}}{\sigma_{\text{av}}^{M}} = \frac{K^2 - 3K + 6\sqrt{K}}{K^2 + 2K\sqrt{K} - K - 2\sqrt{K}}; \quad (4)$$

$$C_{SR} = 0; \quad (5)$$

$$\frac{C_{SR}}{C} = 0. \quad (6)$$

For estimation purposes the fragility coefficient was taken as $K = p/\sigma_t$.

The method of strength estimation for structurally faulted rock mass. The study examines a dependence of structural weakening parameters – residual angles of internal friction along the contacts (φ_R and φ_{SR}) and residual adhesion (C_R/C) – from rock fragility (fragility coefficient $K_f = \sigma_c/\sigma_T$, where σ_c, σ_T – compression and tension strength limits, respectively) and contact conditions.

With rising fragility increases the value of internal friction angles along rock contacts (from 30 to 36° at K_f = 5-20). At the same time φ_R and φ_{SR} are very close to each other (Fig.5). Hence, irregularity of contact surfaces has practically no influence on this parameter of strength certificates.

Residual angles of internal friction along the contacts φ_R and φ_{SR} are slightly lower than the same angles of internal friction φ for more fragile rocks ($K_f > 7$), whereas for less fragile rocks there is a reverse trend: $\varphi_R > \varphi$. For the majority of actual mineral rocks (K_f = 6-10) the difference on the average amounts to 2° and does not exceed 6 %.

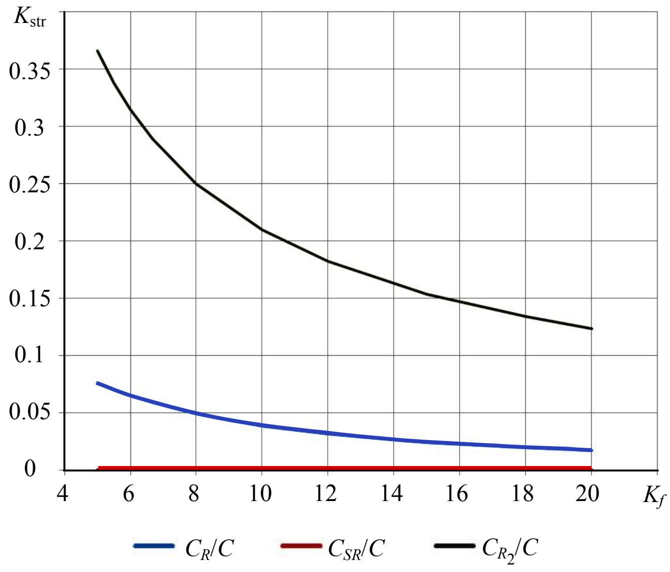

Fig.6. Dependence between strength characteristics of structural weakening and rock fragility

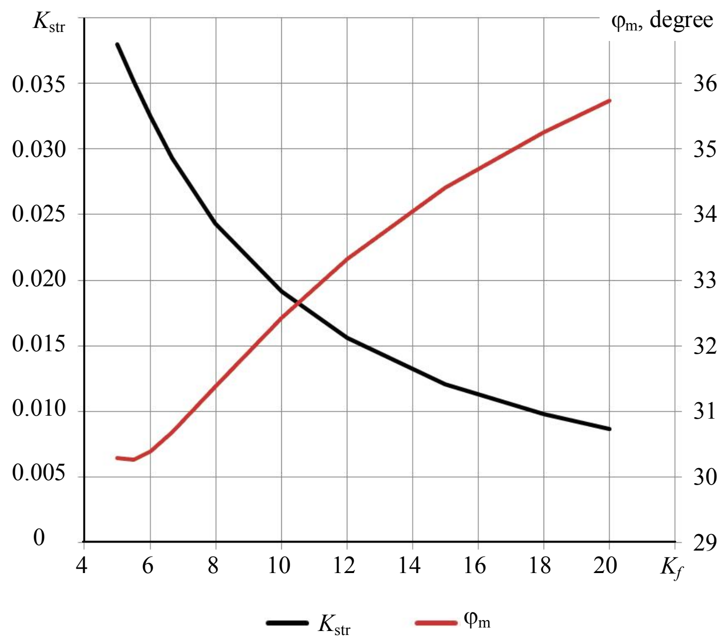

Fig.7. Dependence of structural weakening coefficient K_{str} and internal friction angle φ_m from rock fragility

Minimum values of residual adhesion for natural contacts C_R/C are significantly lower (by factor of 5-7) than the same values for rock samples C_{R_2}/C (Fig.6).

Natural fractures in the rock mass always have irregularities due to the composition of formation rocks. Therefore, in the estimation of rock mass strength it is proposed to take the lowest values of strength characteristics as arithmetic average of strength characteristics of structural weakening along irregular natural and flat contacts – C_R/C and C_{SR}/C. In order to calculate K_{str} using data from spherical indentor tests, the following formula has been proposed:

$$K_{\text{str}} = \frac{C_R}{2C} = \frac{\sqrt[4]{K}(K + \sqrt{K} - 4)}{(1 + \sqrt{K})(K^2 + 2K\sqrt{K} - K - 2\sqrt{K} - 2)}. \quad (7)$$

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Taking into account correlation between relative adhesion and internal friction angles, as a benchmark in the stability estimations of open-pit edges and natural slopes, along with the value of K_{str}, calculated using formula (7), it is recommended to utilize residual internal friction angle in the shear along natural fractures φ_R, calculated using formula (1).

In the absence of reliable data on isotropic open-pit slopes, basing on the performed examinations it is proposed to perform benchmark estimation using structural weakening coefficient K_{str} for adhesion and internal friction angle φ_m of the fractured near-slope rock mass depending on the fragility of the rock (Fig.7).

Data on strength characteristics of the rock mass, estimated according to the proposed method without detailed investigation of weakening surface specifics, is preliminary by nature and is associated with early stages of object examination.

Calculated values of rock mass strength characteristics need to be specified with the accumulation of data on actual parameters of weakening surfaces in the natural conditions and in the process of additional tests.

Described method is applicable in the field with the use of a technically simple loading device. It is acceptable to use irregular-shaped samples in the tests.

Conclusions

1. Authors present a calculation method to estimate residual rock mass strength in the shear along the contact surfaces basing on data from the examination of small-scale monolith samples with opposing spherical indentors.

2. Authors propose a method to calculate strength characteristics (structural weakening coefficient for adhesion and internal friction angles) of the fractured near-slope rock mass.

3. Authors formulate recommendations, according to which, when the open-pit slope is considered a solid isotropic mass, it is suggested to carry out benchmark estimations using internal friction angle and adhesion (adjusted for structural weakening coefficient) judging from the dependency presented in Fig.7, and when the open-pit slope is regarded in terms of hierarchal block composition, initial data should be considered in the interval between strength characteristics along the rock contacts and residual strength of the rock mass (see Fig. 5 and 6).

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