DOI:10.18454/PMI.2017.1.51

UDC 624.12

RESEARCH OF COMPRESSION STRENGTH OF FISSURED ROCK MASS

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The article examines a method of forecasting strength properties and their scale effect in fissured rock mass using computational modelling with final elements method in ABAQUS software. It shows advantages of this approach for solving tasks of determining mechanical properties of fissured rock mass, main stages of creating computational geomechanic model of rock mass and conducting a numerical experiment. The article presents connections between deformation during loading of numerical model, inclination angle of main fracture system from uniaxial and biaxial compression strength value, size of the sample of fissured rock mass and biaxial compression strength value under conditions of apatite-nepheline rock deposit at Plateau Rasvumchorr OAO «Apatit» in Kirovsky region of Murmanskaya oblast.

We have conducted computational modelling of rock mass blocks testing in discontinuities based on real experiment using non-linear shear strength criterion of Barton – Bandis and compared results of computational experiments with data from field studies and laboratory tests. The calculation results have a high-quality match to laboratory results when testing fissured rock mass samples.

Key words: fissured rock mass, final elements method, strength anisotropy, scale effect, fractures

How to cite this article: Protosenya A.G., Verbilo P.E. Research of Compression Strength of Fissured Rock Mass. Zapiski Gornogo Instituta. 2017. Vol. 223, p. 51-57. DOI: 10.18454/PMI.2017.1.51

Introduction. The rock mass strength is one of the most significant properties in designing underground structures in ground or rock [5]. The fissured rock mass due to different fractures is inhomogeneous anisotropic medium with a certain structure. It is explained by significant influence on deformation and strength properties of fissures [9-11]. Any structural or geological peculiarity, which influence rock mass homogeneity, can be considered as a fault. Geometrical properties of such faults (frequency, orientation, degree of interrelationship, surface roughness, length) significantly influence strength and deformation properties of fissured rock mass.

The structure of rock has great practical significance because it influences discontinuity, inhomogeneity, anisotropy and stress state of rock mass and its physical-mechanic properties. When examining the rock mass, we can find some structural regularity patterns. With smaller scale these regularities will change from one type of homogeneity to another. Therefore, the type of homogeneity and mechanic properties of the examined part of the rock change with a scale of investigation. It is possible to single out such areas in rock mass under constant bounding conditions, their further zooming will not influence strength and deformation properties and this rock mass volume can be considered as representational [1]. The use of continuum mechanics methods is valid to be used to solve geomechanic tasks for this rock mass volume. The fundamental task of geomechanic is studying limits of homogeneity.

Methods for identifying mechanic properties of rock mass are divided into direct and indirect. The direct methods [6, 7] are used in field tests and laboratories, where rock mass is loaded with press equipment and its uniaxial compression strength is defined. Laboratory or field tests for rock and rock mass are the most accurate tools for determining mechanical properties, but laboratory tests with big and fissured samples have some difficulties and are very expensive. Another way of identifying strength and deformation properties of rock mass is indirect methods [3], which include empirical, analytical and computational tools.

The empirical method for determining mechanic properties of rock mass is based on pastime tasks, which is widely used in designing tunnels with rock mass classification systems. The main disadvantage of this method is lack of mathematical framework for creating geomechanic model. Currently Russian industry uses empirical coefficient of structural weakening based only on one parameter – distance between fractures to calculate strength and deformation properties of fissured rock mass. In most cases this method is not scientifically valid, hence, can lead to obtaining inaccurate results.

The analytical methods are applicable for geomechanic tasks, but when used for identification of mechanic parameters of rock mass they do not give solutions for medium with complex system of fractures and solid rock.

The development of computer technologies significantly advanced computational methods for determining strength and deformation properties of fissured rock mass. Due to several uncertainties of moving from rock mass test results to its physical-mechanic properties and complex structure of fissured rock mass, the development of computational methods and their integration with existing analytical tools for solving tasks of identifying impact degree on mechanic properties of rock mass and scale effect is a subject of fundamental researches. The main advantage of computational method is a possibility of creating geomechanic model of rock mass taking into consideration fracture system and interaction between discontinued rock blocks [7]. Final elements method is one of the most common computational tools for identifying mechanic properties of fissured rock mass, since it enables modelling of fractures and considering interaction conditions of discontinued rock blocks [11].

Research methodology. Creation of computational model of scaled inhomogeneous rock mass requires identifying and analyzing types of fracture patterns according to their engineering-geological data, which reflect peculiarities of rock mass structure and determine block shapes. The elementary block is a block which matches conditions of quasi-discontinuity and quasi-homogeneity. The mechanic behavior of elementary block is most accurately described with laboratory compression test results at press equipment. In computational model the rock mass behavior inside elementary block is described with results of laboratory tests, which is done with creating a model of rock mass and its subsequent adjustment till it provides qualitative results matching the those measured during laboratory tests within the limit of their permissible variation. Mechanic behavior of rock mass in computational model will match the real one if the obtained result is similar to test results. The rock mass has several types of fracture and fault system. Each type has finite number of structures of previous level, which lead to meeting requirements of quasi-discontinuity and quasi-homogeneity when doing calculations for each level. This requirement is explained by necessity to exclude influence of scale effect on a final result.

The further development of geomechanic computational model requires similar series of computational experiments of modelling interaction of discontinued rock blocks along their boundaries until having results, which will not differ qualitatively from laboratory results of direct shear tests. This stage is the most important since conducted researches of rock mass testify that fractures, as a key factor, greatly influence qualitative value of mechanic properties of rock mass.

Basing on the given stages the general geomechanic model of rock mass is built, it considers rock blocks behavior and their shear interaction during loading. The changes of computational model sizes enable valid calculation of scale effect. The model allows conducting computational experiments with systems of different fracture types.

Computational modelling of blocks interacting on their joints. The main reason of failures and weakening of fissured rock mass is presence of fractures [3], the shear happens at their edges. Therefore, the constitutive properties of rock mass in inhomogeneous fracture system are not rock mass properties but mechanic properties of fractures and their pattern.

The shear fracture tests may provide over-stated values of cohesion, when fractures with most rough surfaces have insignificant friction [8], but they have high internal friction angle with low stress. The rock mass behavior on joint boundaries of blocks was described by Barton in [3, 4], where he developed empirical criterion for shear strength:

$$\tau_{\text{пр}} = \sigma_n \operatorname{tg}\left(JRC \lg \frac{JCS}{\sigma_n} + \varphi_{\text{ост}} \right),$$

where JRC – joint roughness coefficient; JCS – joint wall compression strength, MPa; σ_n – normal active stress, MPa; $\varphi_{\text{ост}}$ – basic friction angle, degrees.

The experimental tools provided the following values of shear strength of joint blocks at deposit of Plateau Rasvumchorr: internal friction angle 27 degrees, cohesion 795 Pa, joint wall compression strength 200 MPa, joint roughness coefficient 18.

To validate the offered computational model of blocks interaction we have conducted two-staged computational experiments: at the first stage, we gave normal load to upper surface of the model, at the second – moved the upper block along the lower one. For each computational experiment we changed vertical load with a range of 0-3.5 Mpa with a step of 0.5 Mpa. The results of computational experiment are shown at Fig.1, their comparison to laboratory test results is at Fig.2. The analysis of the given data says that used non-linear criterion of shear strength for joint blocks of rock mass can be implemented in software package ABAQUS, the error of results is not higher than 0.5 %.

Research of anisotropy of compression strength of fissured rock mass. Basing on results of laboratory tests of rocks from Plateau Rasvumchorr deposit we have identified their physical-mechanical properties. After the test we have the following rock properties: density 2760 kg/m^3, uniaxial compression strength 200.8 MPa, tensile strength 14.2 MPa, rock hardness coefficient 14.9, elasticity module 105 GPa, Poisson coefficient 0.26, cohesion 30.9 MPa and internal friction angle 57.4 degrees. Based on testing of rocks from earth bore holes, it was determined that strength of rock mass mostly does not change with depth. It should be noted that resistance to shear was defined in slanting shear tests.

To examine anisotropy of compression strength of fissured rock mass we have performed modelling of uniaxial and biaxial compression tests (Fig.3) of rock samples with changing inclination angle of the main fracture system to horizontal plane. The side load varied from 0 to 30 MPa with a step of 10 MPa. To study the anisotropy of uniaxial compression strength of rock mass we have built models with inclination angles of the main fracture system to horizontal plane of 0, 30, 45, 60, 90 degrees.

After conducting virtual tests, we have analyzed the results, built graphs of dependencies between relative stress values and relative deformation of computational model of rock mass with inclination angle of fractured plane of 45 degrees to horizontal plane (Fig.4) and relative value of compression strength limit and angle of fractured plane to horizontal plane (Fig.5). As we can see, the orientation of fracture system in rock mass has significant influence on its strength and deformation properties, and process of deformation and failure of rock mass in stress state has a form of shear and tear, which is confirmed by experimental data [2].

The results of modelling (see Fig.4) confirm that increase of load lead to solidification of rock mass and increase of hardness. During deformation happen minor shears leading to formation of micro rapture fractures. As soon as tangential stress of micro areas reaches its critical values, a shear happens which causes separation fractures [2]. These shears lead appear all through rock mass and lead to larger scale model, i.e. show dilatancy effect. Then shear deformation cause formation of cavings and increase of mass volume. These processes define value of strength limit of rock mass. Therefore, in the initial stage of loading the deformation of rock mass has linear character. When reaching the limit of elasticity there are irreversible deformations, which continue to happen up to achieving the strength limit, which equals maximum load. At this stage rock mass has shears of joint blocks and a main fault plane is formed.

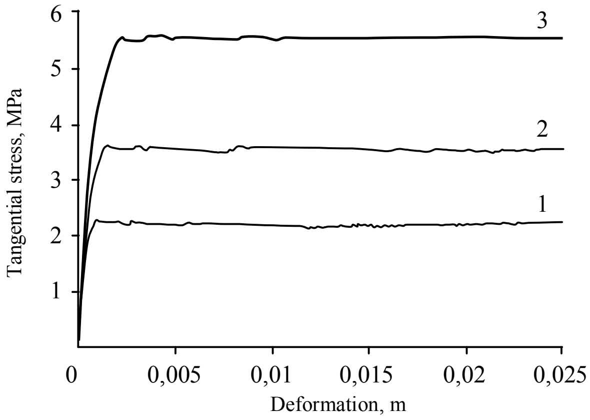

Fig.1. Results of computational experiment for shear movement of joint blocks of rock mass with different values of normal stress
σ_n = 1 MPa (1); 2 MPa (2); 3,5 MPa (3)

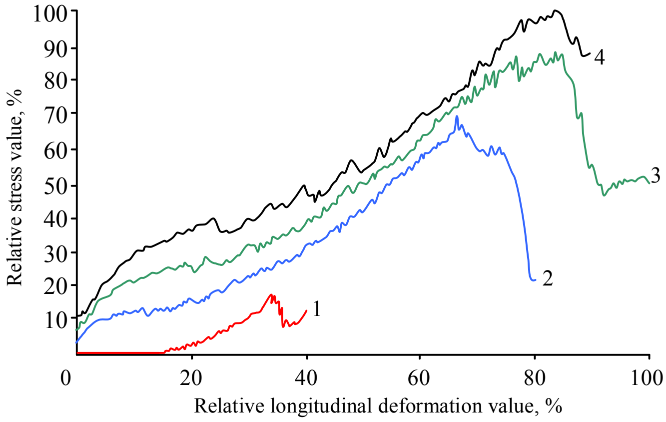

Fig.4. Graphs of dependencies between relative stress values and relative deformation of rock mass
σ_2 = 0 MPa (1); 10 MPa (2); 20 MPa (3); 30 MPa (4)

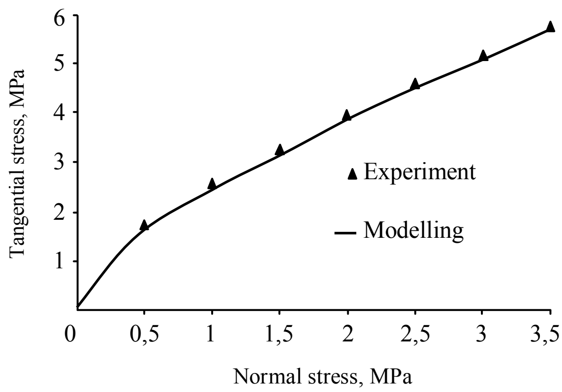

Fig.2. Rock mass blocks strength portfolio with regard to joints

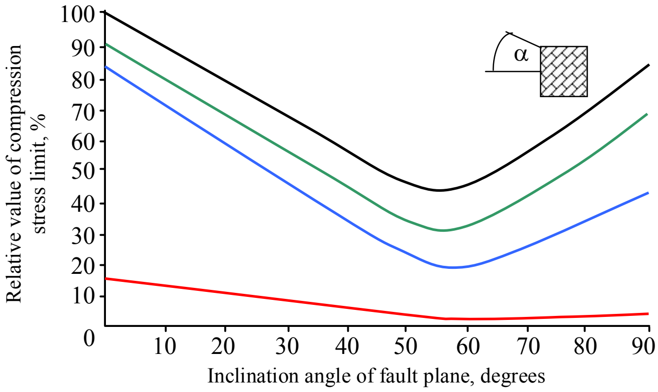

Fig.5. Graphs of dependencies of relative compression strength value and fault plane angle to horizontal plane at different side loads
σ_2 = 0 MPa (1); 10 MPa (2); 20 MPa (3); 30 MPa (4)

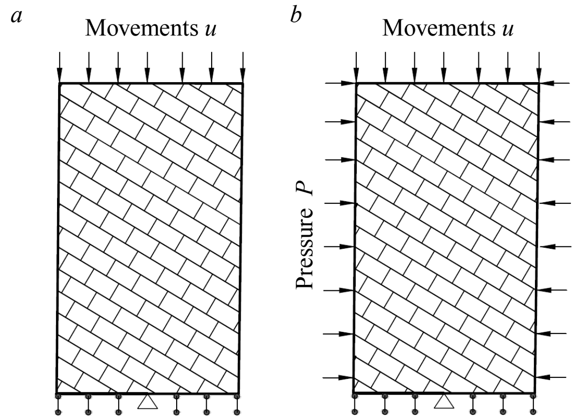

Fig.3. Loading patterns in computational experiments: *a* – uniaxial compression test, *b* – biaxial compression

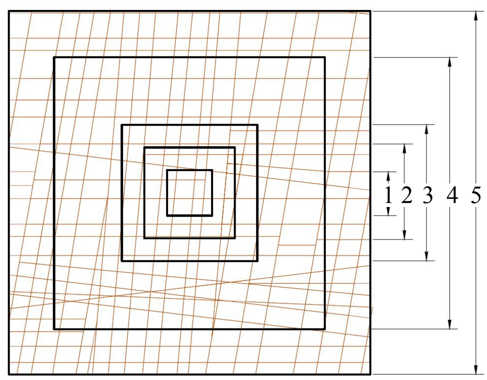

Fig.6. Sizes of fissured rock mass during identification of scale effect

After going above the maximum value there appears out-of-limit stress, which continues up to reaching a limit of residual strength. As a result, rock mass fails along the formed main fault plane, where maximum tangential stress arise.

The maximum value of uniaxial compression Strength is in a model of rock mass with inclination angle of 0 degrees to horizontal plane (Fig.5). When the angle increases the strength

DOI:10.18454/PMI.2017.1.51

limit gradually decreases and can be expressed as a linear function. The most difference of uniaxial compression strength has a model of rock mass with inclination angle of 55 degrees, which is true to a studied fracture system. The following increase of inclination angle of fracture system to a horizontal plane is accompanied by gradual increase of rock mass strength in case of uniaxial and biaxial compressions.

Research of scale effect. The blocked Khibinsky rock mass was selected for computational experiments, according to results of detailed study and fracture mapping of surficial and average depth horizons there have been identified four main fracture systems. For modelling we have chosen a section of apatite urtites, which has homogeneous blocks with sizes from 0.3×0.4×0.6 to 0.7×0.4×0.5 m. The average dip angle of fractured plane is 85 degrees, fractures are well-defined, even, oriented in meridian direction, average frequency is 0.8 pcs./m, single fractures 1-5 pcs./m, series of 5-20 pcs./m, fracture length of this system is above 60 m. The size of fractured rock mass model for scale effect experiments varies from 1 to 8 m (Fig.6).

In all computational experiments we used two axis system of loading, similar to a pattern at Fig.5. To create a load pattern the bearing plane of finite elements model was fixed in vertical direction and deformation of model was done due to vertical movements u, applied to top absolutely fixed plane. The value of aside loads is 10 MPa.

During deformation of block mass there appear a lot of different shear planes, which cause volume increase, inclination of fault plane from areas of maximum tangential stresses. With increase of vertical load the distance between fault planes decrease and as soon as tangential stresses of these planes reach critical values a shear happens, which lead to separation along vertical plane or increases stress in joint block. As a result, during redistribution of stresses happens formation of main fault plane, which visually resembles a ladder with steps of rock mass blocks. Macroscopically this surface could be visualized as rough fault plane, along which a part of rock mass model moves relative to another one. The created fault becomes a reason of model volume increase. Therefore, steplike deformation graph can be explained by a process of deformational solidification of a model at joint planes due to inhomogeneous distribution of fractures.

Experiments proved that geometrically similar and dimension diverse areas of one and the same rock mass studied in similar conditions demonstrate different mechanic properties, which are functions of area size [1] and confirmed by computational experiments, results presented at Fig.7. The graph shows dependencies of relative stress value from deformation load of computational models of fissured rock mass. The maximum stress value is a limit of strength model of a 1×1 m block. The graph shows influence of rock mass sizes on value of compression strength limit and proves presence of scale effect.

During analysis we observed reduction of strength changes speed when sizes increase, i.e. it could be assumed that with further enlargement of model sizes the increase of strength value will stop. This assumption is confirmed with researches of fractures influence rock mass strength (Fig.8) [7]. To make a qualitative comparison of compression strength values of fissured rock mass sample and its sizes dependency curves, we have made a comparison of (see Fig.6) results of computational experiments of this article with results from article [7].

Conclusion. We have studied computational method of identifying strength properties of fissured rock mass using final elements method. We have conducted computational experiments for rock mass of a given stable size and different side loads and fault plane angles to examine anisotropy of compression strength, and found a dependency between uniaxial and biaxial compression strength value and directions of side loads on a rock mass sample. The results have been compared to similar researches of fissured rock mass [9, 10, 12] with computational modelling based on experiments data from laboratory tests of rock mass samples. The obtained results have qualitative match with experimental data [2]. Experimental results show that structural disturbances of rock mass (fractures) significantly influence rock mass strength properties, which depend on direction of applied load in relation to main fracture system [9, 10, 12].

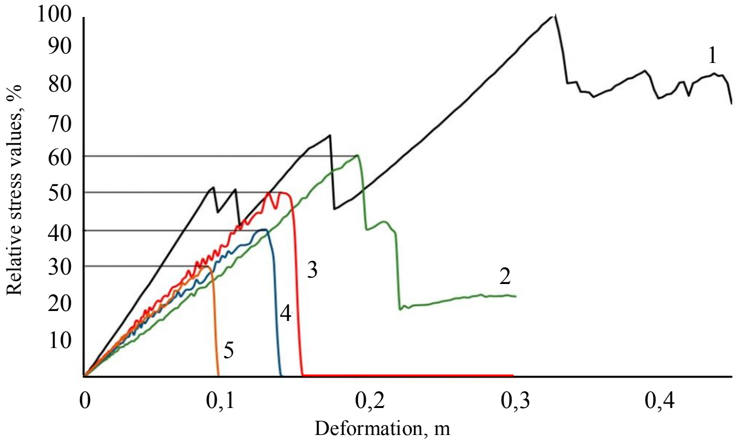

Fig.7. Graphs of deformation of fissured rock mass models in tests for uniaxial and biaxial compression with side load of 10 MPa
Size: 1 – 1×1; 2 – 2×2; 3 – 3×3; 4 – 6×6; 5 – 8×8 m

Anisotropy of strength is a key feature of fissured rock mass, which is explained by presence of defects in a form of fractures. The quantitative value of this anisotropy can be obtained by finite elements method, which could be a significant stage of underground structures design.

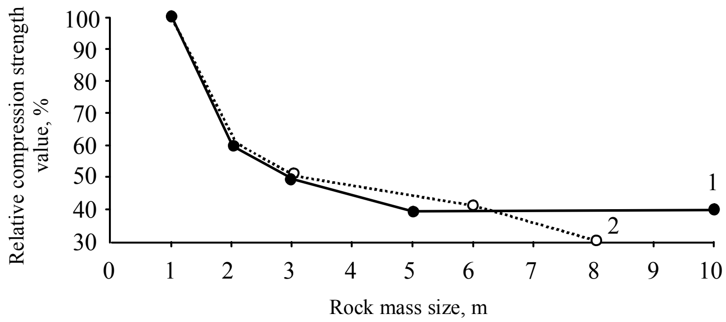

Fig.8. Qualitative comparison of experiment (1) and computation (2) results

Therefore, application of computational methods enables solving complex tasks and connect scientific achievements with rapidly advancing computer technology. When a big-sized fissured rock mass sample cannot be examined in laboratory settings, application of computational tools, in this case final elements method, enables studying fractures and obtain mechanic properties of rock mass in relation to direction of applied load to a main fault plane. Computational experiments with models of fissured rock mass of different sizes provide a possibility to identify valid limits of homogeneity and scale effect.

The article describes an approach to determine scale effect in fissured rock mass using the FEM implemented in software package Abaqus. The computational experiments have been conducted with models of fissured rock masses of different sizes and helped to identify scale effect of biaxial compression strength of rock mass.

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The article was accepted for publication on 11 August, 2016.