Strength and Microseismic Properties of Tuff Sandstone, Siltstone and Clayey Weathering Crust Under Shear Loading

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Abstract. The nature of changes of the parameters of microseismic emission signals (MSE) contains important information about the stage of the deformation process during the destruction of rocks under various types of loading, and can also give predictive estimates of the destruction of the massif. In this paper, the study of the MSE behavior is carried out signals under direct shear loading of samples from tuff sandstone, siltstone and clay crust weathering. The analysis of changes of the parameters of the MSE signals: the number, amplitude of acceleration and frequency at the pre-limit stage, the limit load and the post-peak stage of deformation is given.

1. Introduction
Rock mass is a substantially heterogeneous medium, it consists of blocks of different strengths separated by cracked surfaces, has voids, layers of low strength, etc. The destruction of rock massifs occurs mainly due to the displacement of its parts along weakened surfaces. A review of the literature shows that a large number of works are devoted to the study of the influence of various factors (type of loading, loading speed, humidity, boundary conditions, as well as the analysis of microseismic emission signals) on the strength and deformation properties of rocks joints under direct shear loading [1–9]. This work is devoted to the continuation of such researches. The main goal was to study the character of the parameters of the microseismic emission (MSE) signals arising in rock specimens under shear loading, depending on the roughness coefficient of the surfaces of rock joints.

2. Procedure of experiments, equipment and test specimens
Investigations of geomechanical properties of rock joints under direct shear loading were carried out according to the method of the International Society for Rock Mechanics ASTM D5607–08 [9] on multiparameter test complex based on the servohydraulic press Instron 8802. Specially designed additional device was used for realizing direct shear tests under boundary condition «constant normal load». The general view of the functional scheme of equipment for direct shear test under constant normal load is shown in Figure 1. The special device is fixed between the press grips (system of shear loading). It is the frame consisting of two parts into which a shear box is located. The shear box consists of two parts, in which the test sample is placed. The normal (pressing) force is created by the hydraulic cylinder, the force is controlled by an electronic pressure sensor. Encapsulating material for shear box was dental gypsum which strength limit under uniaxial stress was 70 MPa.
The complex for microseismic measurements «Pulse» of the company Bruel and Kjaer and accelerometers KD91 were used to measure the characteristics of MSE signals. The accelerometers were glued to the samples and were located in the gap between the two parts of the shear box.

Determination of shear strength of rock joints can follow two different types of procedures: single shear procedure and multi-stage shear procedure. Different values of constant normal force are applied to several samples in the case of single shear procedure. Three to five samples are used, selected from the same joint in the rock massif. If it is not possible to select several samples, a multi-stage shift is performed. Multi-stage shear procedure consists of testing of the same specimen repeatedly under different constant normal stresses. Three or four loading cycles were performed in each shear test.

![Figure 1. The functional scheme of equipment for direct shear test under constant normal loading.](image)

Three types of rock were chosen for the experiments: siltstone, tuff sandstone and clayey weathering crust. Preliminary tests were carried out on samples from these rocks under uniaxial compression and tensile (Brazil test). Sizes of specimens under uniaxial compression test were: diameter 30 mm and length 60 mm; under tensile test – diameter 30 mm and length 30 mm; under shear tests – diameter 100 mm and length 100 mm. Three or four loading cycles were performed at each shear test. The rate of shear loading was 0.1 mm/min. To prepare rock samples with joints cylindrical samples were previously divided into two parts by the split method (Brazil test). The surfaces of rock joints were digitized using EinScan 3-D scanner before testing. The surface roughness coefficients $JRC$ of the joints were calculated according to [10]. Samples of clayey weathering crust were tested under direct shear test as intact sample. Three or four samples were used for each type of test. Shear load, shear displacement (movement of the press beam), normal load and normal displacement are continuously recorded to the computer file during the test.
3. Results of experiments
Strength limits, deformation modulus and the coefficients of transverse deformation were determined at the uniaxial compression tests, strength limits were determined at the tensile tests for each type of rock. The cohesion and the internal friction angle have been determined. The test results are given in Table 1.

Table 1. Results of uniaxial compression and tensile tests of samples from siltstone, tuff sandstone and clayey weathering crust

| Short lithological description of rock | Strength limit, MPa | Deformation modulus, GPa | Coefficient of transverse deformation | Cohesion C, MPa | Internal friction angle $\phi$, degree |
|----------------------------------------|---------------------|-------------------------|---------------------------------------|----------------|--------------------------------------|
|                                       | Uniaxial compression | Tensile                 |                                       |                |                                      |
| Siltstone                              | 94.7                | 21.2                    | 25.4                                  | 0.164          | 22.8                                 | 51                                   |
| Tuff sandstone                         | 76.7                | 19.3                    | 19.3                                  | 0.155          | 18.5                                 | 37                                   |
| Clayey weathering crust                | 0.26                | 0.14                    | 0.013                                 | 0.340          | 0.07                                 | 22                                   |

The results of experiments under shear loading of samples of siltstone, tuff sandstone and clayey weathering crust are shown in Table 2.

Table 2. Results of direct shear tests of samples from siltstone, tuff sandstone and clayey weathering crust

| Short lithological description of rock | Loading stage | Shear strength, MPa | Normal stress, MPa | Cohesion C, MPa | Internal friction angle $\phi$, degree |
|----------------------------------------|--------------|---------------------|--------------------|----------------|--------------------------------------|
| Siltstone, $JRC=7.1$                   | 1            | 7.83                | 1                  | 3.74           | 36                                   |
|                                       | 2            | 8.35                | 2                  |                |                                      |
|                                       | 3            | 9.92                | 3                  |                |                                      |
| Siltstone, $JRC=1.8$                   | 1            | 4.36                | 1                  | 1.98           | 29                                   |
|                                       | 2            | 5.92                | 2                  |                |                                      |
|                                       | 3            | 6.34                | 3                  |                |                                      |
| Tuff sandstone, $JRC=2.6$              | 1            | 4.78                | 1                  | 1.93           | 30                                   |
|                                       | 2            | 6.45                | 2                  |                |                                      |
|                                       | 3            | 7.7                 | 3                  |                |                                      |
| Tuff sandstone, $JRC=0$                | 1            | 2.47                | 1                  | 0.96           | 24                                   |
|                                       | 2            | 3.56                | 2                  |                |                                      |
|                                       | 3            | 4.67                | 3                  |                |                                      |
| Clayey weathering crust                | 1            | 0.06                | 0.015              | 0.063          | 20                                   |
|                                       | 2            | 0.066               | 0.03               |                |                                      |
|                                       | 3            | 0.075               | 0.045              |                |                                      |
|                                       | 4            | 0.079               | 0.06               |                |                                      |

The value of cohesion coefficient is $C=22.8$ MPa and the angle of internal friction is equal to $\phi=51^\circ$ obtained by the results of compression and tensile tests of siltstone samples. Under direct shear tests, the values of the cohesion and internal friction angles are $C=3.74$ and $\phi=36^\circ$ for samples with $JRC=7.1$ and $C=1.98$ MPa and $\phi=29^\circ$ – with $JRC=1.8$. Cohesion coefficient decreases by $6\div12$ times and internal friction angle – by $1.4\div1.8$ times depending on the value of $JRC=1.8$ and 7.1 accordingly.
For samples of tuff sandstone, the values of cohesion and internal friction angle are \( C = 18.5 \text{ MPa} \) and \( \phi = 37^\circ \) obtained by the results of uniaxial compression and tensile tests. Under shear loading, \( C = 1.93 \text{ MPa} \) and \( \phi = 30^\circ \) at the roughness value \( JRC = 2.6 \) and \( C = 0.96 \text{ MPa} \) and \( \phi = 24^\circ \) at \( JRC = 0 \).

The values of cohesion and the internal friction angle for samples of clayey weathering crust obtained by uniaxial compression, tensile tests and direct shear tests differ by 10%.

The method of recording of microseismic emission signals was used for monitoring of deformation process of rock joints under shear loading. Figure 2 demonstrates the results of experiment of siltstone sample with the value surface roughness \( JRC = 7.1 \) under direct shear on the first stage of loading: the diagram \( \tau/\tau_{\text{max}} - t \), where \( \tau \) is the shear stress, \( \tau_{\text{max}} \) is the ultimate shear strength, \( t \) is the current test time; diagram \( N - t \), where \( N \) is the number of MSE events summed up over an interval of 10 seconds and the parameters of some characteristic MSE signals – the dependence of acceleration \( a \) on test time and the dependence of spectral density \( k \) on frequency \( f \).

![Figure 2](image_url)

**Figure 2.** The results of experiment of siltstone sample with the value surface roughness \( JRC = 7.1 \) under direct shear on the first stage of loading: the diagram \( \tau/\tau_{\text{max}} - t \) – a; the diagram \( N - t \) – d; the parameters of the MSE signals: the dependence of acceleration \( a \) on test time – b, e, g and the dependence of spectral density \( k \) on frequency \( f \) – c, f, h.
It can be seen from Figure 2a, d that MSE signals begin to occur at the load of 0.3÷0.4 of the ultimate shear strength. Their number is \( N = 15 \div 20 \) at the point A and it increases to 30÷40 at the point B. The maximum acceleration amplitude is 0.12 m/s\(^2\) and the frequency spectrum band is 5÷28 kHz. The shift along the cut-off boundary is accompanied by the destruction of sharp edges of the surface, which results in a wide band of the frequency spectrum and the presence of high–frequency harmonics. The largest number of signals is observed at peak load and remains significant up to the residual strength section. The maximum amplitude of the MSE acceleration signal had increased to 0.35 m/s\(^2\) at point B. The type of analog signal indicates the resonant frequency equal to 18 kHz. The signal amplitude decreased to 0.08 m/s\(^2\) at the post-peak section of the diagram \( \tau / t_{\text{max}} - t_n \), and the frequency spectrum band changed to 10÷18 kHz. It can be concluded that the destruction of the highest irregularities of the surface is accompanied by the highest amplitude values. With further loading, the movement of parts of the sample occurs due to the disruption of lower irregularities of the surface, which corresponds to lower values of amplitudes.

Shear tests of siltstone samples with surface roughness of \( JRC = 1.8 \) demonstrated analogous patterns of changes of the characteristics of the MSE signals described above but ones were more weakly expressed.

The dependence of shear stress \( \tau \) on current experiment time \( t \) and dependence of number of MSE signals \( N \) summarized over interval of 10 seconds on time \( t \) in accordance with the diagram \( \tau - t \) is shown in Figure 3a, c for clayey weathering crust sample and in Figure 3b, d – for tuff sandstone sample at the first stage of shear loading.

![Figure 3](image-url)

**Figure 3.** Number of MSE signals \( N \) summarized over interval of 10 seconds – a and b; diagram \( \tau - t \) – c and d; for clayey weathering crust sample – a and c; for tuff sandstone sample with the value surface roughness \( JRC = 2.6 \) – b and d.

The first MSE signals appear at values of shear stresses of 0.02 MPa (Figure 3a, c) for clayey weathering crust sample which is 30% of ultimate shear strength value (0.06 MPa). The number of signals is insignificant, the acceleration amplitude is 0.02÷0.05 m/sec\(^2\), broadband frequency is 2÷32 kHz. At stress values close to the shear strength, the number of signals increases significantly (to 25–30), acceleration amplitude increases to 0.27 m/sec\(^2\), their energy increases, the frequency spectrum is narrowed and shifted to low frequencies, up to \( f \approx 12 \div 15 \) kHz. The sample begins to break down. Then, at approximately constant shear stress, the shear strain increases, the sample is broken into two parts, which move one relatively the other. At this stage of the deformation process, MSE signals are
recorded, the number of which is less than in the vicinity of the peak load. Values of MSE signal amplitudes are less than the amplitudes of MSE signals before strength limit.

For tuff sandstone sample with the value surface roughness $JRC = 2.6$, first MSE signals began to appear almost from the beginning of the loading process (Figure 3b, d), the number of signals for tuff sandstone sample is much larger than the number of signals for clayey weathering crust sample. The acceleration magnitude is $a = 0.06 \div 0.09$ m/sec$^2$, broadband frequency is $5 \div 28$ kHz. The number of signals has significantly increased to $N = 30 \div 50$, the frequency spectrum has narrowed to $15 \div 20$ kHz, acceleration amplitude has also increased to $a = 0.16$ m/sec$^2$ at values of shear stresses close to ultimate shear strength $\tau_{max} = 4.78$ MPa. During the post-peak stage of loading, large number of MSE signals are observed. It should be noted that each surge of number of MSE signals corresponds to abrupt decreasing of shear stress and slipping of one part of the sample by another.

Insignificant number of MSE signals was recorded under the shear stress test of tuff sandstone sample (surface roughness 0), while the surge of number of MSE signals during post-peak loading was not particularly pronounced, but still corresponded to shear stress decreasing.

4. Conclusions

In this study, the comparative analysis of the strength properties of siltstone, tuff sandstone and clayey weathering crust was carried out under three types of loading: uniaxial compression, tensile (Brazil test) and direct three-stage shear loading at constant normal load according to ASTM D 5607 standard. The test results demonstrated that the values of the coefficients of cohesion and the angle of internal friction obtained from tests under uniaxial compression and tensile exceed similar characteristics under direct shear loading by $6 \div 12$ times and $1.4 \div 1.8$ times for siltstone, by $9 \div 19$ times and $1.2 \div 1.5$ for times tuff sandstone respectively, depending on the roughness coefficient $JRC$. Higher values of the roughness coefficient correspond to higher values of cohesion and the angle of internal friction. The coefficient of cohesion and the angle of internal friction according to compression and tensile tests exceed similar characteristics under direct shear loading by about 10\% for the clay crust of weathering,

Analysis of the characteristics of the MSE signals obtained under the most dangerous type of loading rock mass – direct shear loading allowed to identify the following patterns. The first MSE signals appear at values of shear stress $0.2 \div 0.4$ of ultimate shear strength, the number of signals is insignificant, the acceleration amplitude is not high $a = 0.1 \div 0.15$ m/sec$^2$, broadband frequency is $f = 2 \div 32$ kHz.

At stress values close to the ultimate shear strength, the number of signals increases significantly, acceleration amplitude and its energy increases, the frequency spectrum is narrowed and shifted to low frequencies, up to $f = 15 \div 18$ kHz. The largest values of the acceleration amplitude correspond to the cuts of high irregularities of the surface, and further, the shift occurs already due to the destruction of low irregularities of the surface that correspond to lower values of amplitudes. The effect of the surface roughness coefficient $JRC$ of rock joints on the parameters of the MSE signals is that the nature of the change of the MSE signals is more contrasting for samples with higher values of $JRC$.

The post-peak stage of shear deformation is accompanied by significant seismic activity, each spike of the number of MSE signals corresponds to a sharp decrease of shear stress and sliding of one part of the sample by another.

It should be noted that the MSE signals with the highest amplitude value and the lowest frequency value were recorded at the moment preceding the breakdown of high surface irregularities, the sharp decrease of shear stress and the transition to the post-peak section of the stress-strain diagram, which can be a diagnosis of the onset of fracture of rock mass.

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