Effects of structure on deformation and strength characteristics of transversely isotropic man-made geomaterials

OM Usoltseva[1], PA Tsoi[1,2] and VN Semenov[1]

[1]Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
[2]Novosibirsk State Technical University, Novosibirsk, Russia

E-mail: [1]usoltseva57@mail.ru

Abstract. The laboratory tests on uniaxial and triaxial (Karman scheme) compression of bedded specimens (made of equivalent man-made geomaterial, meta-siltstone and shale) has allowed deriving relations between the strength and deformation characteristics and the bedding angle of the specimens. The elasticity and strength are assessed in accordance with the theoretical model by Salamon–Tien and the Hoek–Brown failure criterion. For the bedded geomedia (man-made geomaterial), the Salamon–Tien model yields a satisfactory estimate of the elastic characteristics (elasticity modulus, Poisson's ratio). Based on the use of the Hoek–Brown criterion, the authors have derived a strength parameter independent of the lateral pressure.

Alternating strata of overburden rocks possess considerably anisotropic physical properties depending от structure and texture of material, bedding angle, thickness and strength of strata, their geometry etc. The review of the recent publications shows that the researchers pay attention to bedded rock mass and to development of deformation processes in them [1–5]. It is highlighted in the studies that the angle of bedding has much influence on deformation and strength characteristics of rock mass. The research keeps relevancy as there are very many kinds of rocks.

This study describes experimental testing of variation in deformation and strength characteristics of a stratified geomaterial and rocks (meta-siltstone and schist) under uniaxial compression and triaxial compression by epy Karman scheme.

The tests used Instron 8802 hydraulic press with the loading rate preset as yoke displacement. Deformation and strength characteristics of a geomaterial were estimated in accordance with the ASTM standards. The geomaterial specimens were manufactured as alternation of two layers of different composition:

layer 1: sand—30 g, cement—10 g, Neolit glue—4 g, water—2.5 g;

layer 2: sand—30 g; cement—5 g, Neolit glue—3.5 g, water 2.5 g.

The angle of bedding (angle between the axis of a cylindrical specimen and the normal to the plane of beds—isotropy) was $\Psi = 0$, 15, 30, 45, 60, 75, 90º. Specimens made of different materials before the tests are shown in the pictures in Figure 1.

The uniaxial and Kaman's triaxial compression tests involved lateral pressures of 3 and 6 MPa (not less than 3 specimens per test series). For each material, the curves of the limit strength σ_1, deformation modulus E, transversal deformation ν and the bedding angle Ψ were plotted (Figures 2–4).

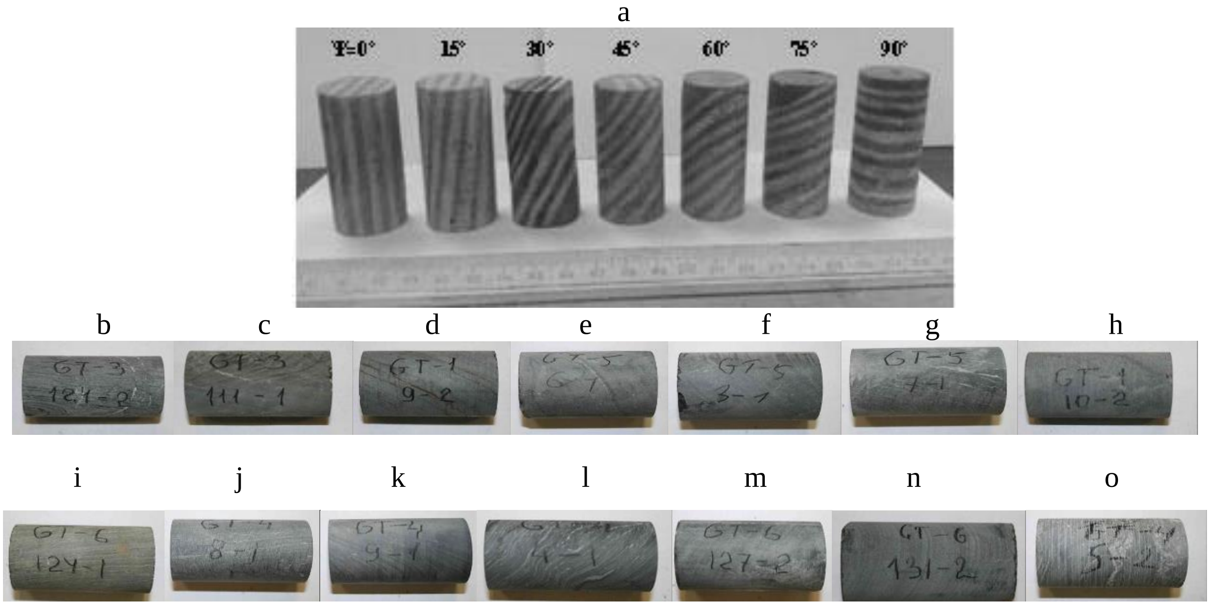

Figure 1. Pictures of specimens before the tests: (a) man-made geomaterial with Ψ = 0°, 15°, 30°, 0°, 45°, 60°, 75°, 75°, 90°; (b)–(h) siltstone with Ψ = 0°, 15°, 30°, 0°, 45°, 60°, 75°, 90°, respectively; (i)–(o) schist with Ψ = 0°, 15°, 30°, 0°, 45°, 60°, 75°, 90°.

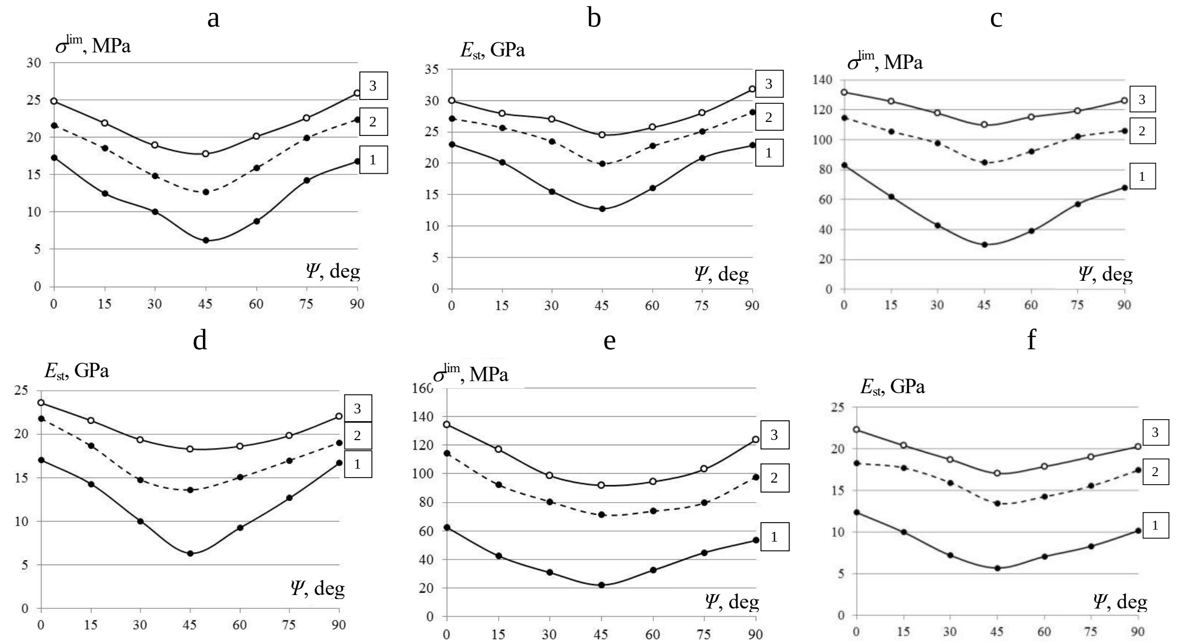

Figure 2. Limits strengths and deformation modulus versus bedding angles Ψ: (a) and (b) man-made geomaterial; (c) and (d) meta-siltstone; (e) and (f) schist under uniaxial compression (1), triaxial compression with the lateral pressure of 3 MPa (2) and 6 MPa (3).

The test data analyses show that the stratification essentially affects deformation and strength characteristics of the man-made material and rock specimens both under the uniaxial and triaxial compression. The strength is the lowest when $\Psi = 45°$ in all tests. The ratio of the strength limits at $\Psi = 90°$ and 0° makes:

Man-made geomaterial—2.79 under uniaxial compression,
1.78 under triaxial compression by the lateral pressure of 3 MPa and
1.45 under triaxial compression with the lateral pressure of 6 MPa;
Meta-siltstone— 2.74, 1.35 and 1.2;
Schist— 2.82, 1.6 and 1.46.

a b c d

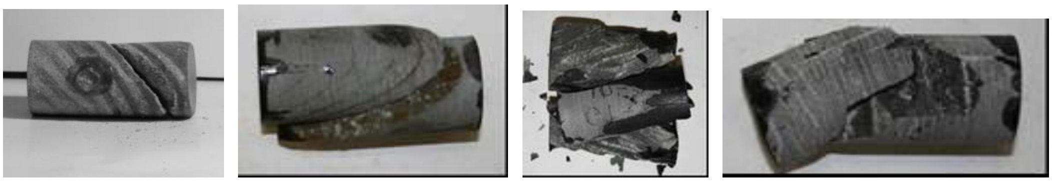

Figure 3. Specimens after the tests: $\Psi = 45°$—(a) man-made geomaterial; (b) meta-siltstone; $\Psi = 90°$—(c) meta-siltstone, (d) schist.

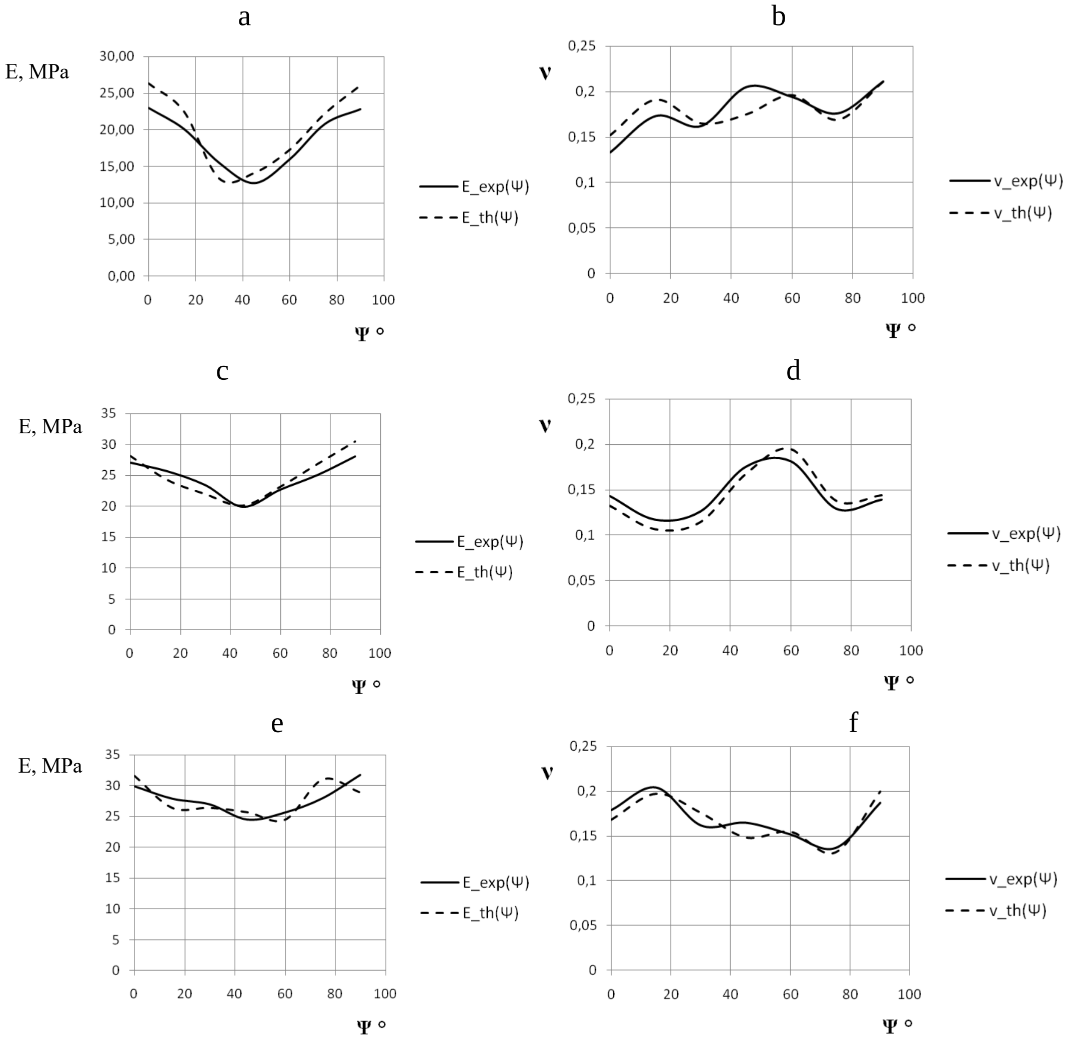

Figure 4. Experimental (solid) and theoretical (dashed) curves of deformation modulus E and Poisson's ratio ν and angle of bedding Ψ for: (a) and (b) uniaxial compression; (c) and (d) triaxial compression with the lateral pressure of 3 MPa; (e) and (f) triaxial compression with the lateral pressure of 6 MPa.

The E–Ψ curves behave the same way as with the limit strength. The deformation modulus acquires the least value when $\Psi = 45°$ in all tests. The ratios of the deformation moduli at $\Psi = 90°$ and 0° make:

Man-made geomaterial—1.81 under uniaxial compression,
1.41 under triaxial compression by the lateral pressure of 3 MPa and
1.29 under triaxial compression with the lateral pressure of 6 MPa;
Meta-siltstone— 2.68, 1.6 and 1.29;
Schist— 2.17, 1.35 and 1.31.

No clear regular pattern of change due to the bedding angle is observed for the coefficient of transversal deformation.

After examining damage of the test specimens, the conclusion is drawn that at $\Psi = 90°$ the damage zone contains a few main cracks; i.e. there is the longest line of fracture, which is consistent with the maximum values of the limit strength. When $\Psi = 45°$ failure propagates alone a line inclined at an angle of 35–55° to the specimen axis, as a rule (Figure 3).

The experimental characteristics of elasticity of the man-made geomaterial were compared with the theoretical values obtained using the Tien–Salamon equation. Assuming the deformation modulus and the transverse deformation coefficient as the elasticity modulus and Poisson's ratio, respectively, allows their assessment by the Tien–Salamon theory [6, 7]

$$\nu = \frac{\sum_{i=1}^{n} \frac{\lambda_i \nu_i E_i}{1-\nu_i^2}}{\sum_{i=1}^{n} \frac{\lambda_i E_i}{1-\nu_i^2}}, \quad (1)$$

$$E = \left(1-\nu^2\right)\sum_{i=1}^{n} \frac{\lambda_i E_i}{1-\nu_i^2}, \quad (2)$$

$$\lambda_i = \frac{H}{\sqrt[3]{V_i}}, \quad (3)$$

where λ_i is the dimensionless coefficient of volume for an i-th layer; V_i is the volume of an i-th layer; H is the layer thickness; ν_i and E_i are Poisson's ratio and elasticity modulus of an i-th layer; ν, E are Poisson's ratio and elasticity modulus of the whole specimen.

The maximum error of the estimate was not higher than 14.5%, which proved applicability of the proposed theoretical model for satisfactory assessment of elastic parameters of layered geomaterials.

For the man-made geomaterial, meta-siltstone and schist, the strength characteristics $m_{(0°)}$, $m_{(90°)}$ as per the Hoek–Brown criterion [8, 9] were calculated using the formulas below

$$m_{(0°)} = \frac{(\sigma_{1(0°)} - \sigma_3)^2 - \sigma_{c(0°)}^2}{\sigma_3 \cdot \sigma_{c(0°)}}, \quad (4)$$

$$m_{(90°)} = \frac{(\sigma_{1(90°)} - \sigma_3)^2 - \sigma_{c(90°)}^2}{\sigma_3 \cdot \sigma_{c(90°)}}, \quad (5)$$

$$m_{(0°)} = \frac{\frac{2\cdot(\sigma_{1(90°)} - \sigma_3)}{(\sigma_{1(30°)} - \sigma_3)} - \frac{1}{8} - \frac{(\sigma_{1(90°)} - \sigma_3)}{(\sigma_{1(0°)} - \sigma_3)}\cdot\frac{9}{8}}{\frac{9}{16}\cdot\frac{(\sigma_{1(90°)} - \sigma_3)}{(\sigma_{1(0°)} - \sigma_3)}}, \quad (6)$$

where $\sigma_{c(0°)}$, $\sigma_{c(90°)}$ are the limit strengths under uniaxial compression and bedding angles of 0° and 90°; $\sigma_{1(0°)}$, $\sigma_{1(30°)}$, $\sigma_{1(90°)}$ are the limit strengths under triaxial compression with the lateral stress σ_3 and bedding angles of 0, 30 and 90°. The table gives the calculation results.

Input and calculated criteria of failure by Hoek–Brown.

σ_3, MPa	$\sigma_{c(0°)}$, MPa	$\sigma_{c(90°)}$, MPa	$\sigma_{1(0°)}$, MPa	$\sigma_{1(30°)}$, MPa	$\sigma_{1(90°)}$, MPa	$m_{(0°)}$	$m_{(90°)}$	n	n_{av}
Man-made geomaterial									
3	17.3	16.8	22.6	14.8	22.4	1.63	1.86	2.76	2.59
6	17.3	16.8	25.8	18.9	25.2	0.89	0.85	2.42	
Meta-siltstone									
3	82.9	68.2	114.7	97.7	106.1	22.53	29.21	1.46	1.39
6	82.9	68.2	131.8	117.7	126.3	18.0	24.0	1.32	
Schist									
3	62.5	53.4	114.1	80.5	97.7	45.0	38.18	12	2.06
6	62.5	53.4	134.4	98.6	123.7	33.54	34.33	2.01	

Finally, the accomplished experimental research confirms that deformation and strength characteristics of an anisotropic stratified geomedium greatly depend on the medium structure. Anisotropy of rocks should be taken into account to avoid significant errors in calculation of stress state of rocks. The theoretical model of Tien–Salamon offers a satisfactory estimate of elastic parameters of bedded geomedia (elasticity modulus, Poisson's ratio). The strength parameter n_{av} calculated using the Hoek–Brown criterion of failure is independent of the value of lateral pressure.

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