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Failure-plane angle in Bentheim sandstone subjected to true triaxial stresses: experimental results and theoretical prediction

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We conducted true triaxial tests in the high-porosity (n = 24%), quartz-rich (95%), Bentheim sandstone. An important objective was to investigate the dependence of failure-plane angle θ (angle between the normal to the plane and σ_1 direction) on the prevailing stress conditions. We employed two distinct loading paths, and seven σ_3 magnitudes (between 0 and 150 MPa). In tests using the common loading path, σ_2 and σ_3 were fixed, while σ_1 was raised monotonically to failure. In tests using the novel loading path (which facilitate comparison with theoretical predictions), σ_3 was fixed, and the Lode angle, Θ (= $\tan^{-1}$ [(σ_1 - 2σ_2 + σ_3) / $3^{0.5}$(σ_1 – σ_3)]) was kept constant by raising σ_1 and σ_2 simultaneously at a set ratio b [= ($\sigma_2 - \sigma_3$)/($\sigma_1 - \sigma_3$)] until failure occurred. Six stress ratios b (= 0, 1/6, 1/3, 1/2, 3/4, 1), i.e. six Θ (= $\tan^{-1}$ [(1-2b) / $3^{0.5}$]) values from +π/6 (axisymmetric compression) to –π/6 (axisymmetric extension) were used.

In axisymmetric common loading path tests, failure-plane angle θ generally declined as the applied $\sigma_3 = \sigma_2$ increased from about 80° at $\sigma_3 = \sigma_2$ = 0 MPa to 0° at $\sigma_3 = \sigma_2$ = 150 MPa (forming compaction bands). In tests where $\sigma_3 \neq \sigma_2$, the resulting failure-plane strike was consistently parallel to σ_2 direction. For low σ_3, θ typically rose by up to 12° as σ_2 rose from $\sigma_2 = \sigma_3$ to $\sigma_2 = \sigma_1$. However, the rise in θ with σ_2 tended to diminish at higher σ_3. A limiting case occurred at σ_3 = 150 MPa, where failure plane remained at 0°, regardless of the rise in σ_2. In the novel loading path tests, failure-plane angle θ declined monotonically for any given Lode angle Θ, from roughly 80° to 0°, as the mean stress at failure ($\sigma_{oct,f}$) rose from about 20 MPa to around 220 MPa; for a constant $\sigma_{oct,f}$, θ typically increased from 10° (at $\sigma_{oct,f}$ = 20 MPa) to 30° (at $\sigma_{oct,f}$ = 220 MPa) as Θ dropped from +π/6 ($\sigma_2 = \sigma_3$) to -π/6 ($\sigma_2 = \sigma_1$).

We compared the measured θ with that predicted using equation 28 in *Rudnicki* (2013), an extension of the Rudnicki and Rice (1975) prediction to include the third stress invariant Θ. (Space does not permit detailing the equation in this abstract.) The theory treats octahedral shear stress at failure ($\tau_{oct,f}$) and the resulting θ as dependent on $\sigma_{oct,f}$ and Θ. We used two series of the novel loading path tests: axisymmetric compression (Θ = +π/6) and pure shear (Θ = 0) to constrain that dependence. The failure conditions in the novel loading path tests were then simulated to compare the predicted failure-plane angles with the experimental results. The predictions were in general agreement with the experimental data, except when Θ = -π/6 ($\sigma_2 = \sigma_1$). In the common loading path tests, failure prediction replicated the general rise of the experimentally observed θ with σ_2 for a given σ_3,as well as the diminished rise at high σ_3 magnitudes.

The reasonable agreement between the predicted and the observed failure-plane angle demonstrated the applicability and the limitations of *Rudnicki*'s (2013) theory.