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Research article

Rock strength degradation induced by salt precipitation: A new mechanical mechanism of sand production in ultra-deep fractured tight sandstone gas reservoirs

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APPENDIX

The critical sand production pressure drop based on M-C strength criterion can be calculated by [1,2]:

$$\Delta p_c = p_0 - \frac{\frac{2\sigma_v\mu + (1-2\mu)\beta p_0}{1-\mu}\sin\varphi + 2S_0\cos\varphi - \frac{2\sigma_v\mu}{1-\mu} - \frac{1-2\mu}{1-\mu}\beta p_0}{\frac{1-2\mu}{1-\mu}\beta - 2 + \frac{\sin\varphi}{1-\mu}\beta} \tag{A.1}$$

Where Δp_c is critical sand production pressure drop, Mpa; p_0 is pore pressure, Mpa; σ_v is the vertical wellbore stress, Mpa; μ is Poisson's ratio; β is Biot coefficient; θ is the angle coordinates in a cylindrical coordinate system, which is the angle between maximum horizontal principal stress, rad; S_0 is rock joint cohesion, Mpa; φ is internal friction angle, rad. The critical production pressure drop based on D-P strength criterion method can be calculated by Lou et al. [3]:

$$\Delta p_c = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{A.2}$$

and $A=\beta^2\left(6-\frac{24\tan^2\varphi}{3+4\tan^2\varphi}\right)\left(\frac{1-2\mu}{1-\mu}\right)^2-18\beta\frac{1-2\mu}{1-\mu}+18$

$$B=6\left(\beta\frac{1-2\mu}{1-\mu}-2\right)\left(2p_0-3\sigma_v+\sigma_h\right)+6\left(\beta\frac{1-2\mu}{1-\mu}-1\right)\left[p_0-\sigma_H-2\mu\left(\sigma_v-\sigma_h\right)\right]$$

$$+6\left[3\sigma_v-\sigma_h-p_0-\sigma_H-2v\left(\sigma_v-\sigma_h\right)\right]+\beta\frac{24\left(1-2\mu\right)\tan\varphi}{\left(1-\mu\right)\sqrt{9+12\tan^2\varphi}}$$

$$\left\{\frac{1.5\sigma_c\left(\sqrt{\tan^2\varphi+1}-\tan\varphi\right)}{\sqrt{9+12\tan^2\varphi}}+\frac{3\tan\varphi}{\sqrt{9+12\tan^2\varphi}}\left[3\sigma_v-\sigma_h+\sigma_H+2v\left(\sigma_v-\sigma_h\right)\right]\right\}$$

$$C=3(2p_0-3\sigma_v+\sigma_h)^2+3\left[p_0-\sigma_H-2\mu\left(\sigma_v-\sigma_h\right)\right]^2+3\left[3\sigma_v-\sigma_h-\sigma_H-2\mu\left(\sigma_v-\sigma_h\right)-p_0\right]^2$$

$$-\frac{13.5\sigma_c^2\left(\sqrt{\tan^2\varphi+1}-\tan\varphi\right)^2}{3+4\tan^2\varphi}-\frac{6\tan^2\varphi}{3+4\tan^2\varphi}\left[3\sigma_v-\sigma_h+\sigma_H+2\mu\left(\sigma_v-\sigma_h\right)\right]^2$$

$$-\frac{18\tan\varphi\sigma_c\left(\sqrt{\tan^2\varphi+1}-\tan\varphi\right)}{3+4\tan^2\varphi}\left[3\sigma_v-\sigma_h+\sigma_H+2\mu\left(\sigma_v-\sigma_h\right)\right]$$

where: σ_H is the maximum horizontal principal stress, MPa; σ_h is the minimum horizontal principal stress, MPa; σ_c is the uniaxial compressive strength，MPa. The critical production pressure drop based on C-Index method can be calculated by Xiong and Pan [4]:

$$\Delta p_c = \frac{\sigma_c - \frac{2\mu}{1-\mu}(\overline{\rho_r} g H_w \times 10^{-6} - p_0)}{2} \tag{A.3}$$

where $\overline{\rho_r}$ is the average density of the overburden rock, kg/m^3; H_w is the depth of the formation, m.

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