YER OSTI KO'MIR GAZLASHTIRISHDA GEOMEXANIK JARAYONLAR VA ISSIQLIK TA'SIRINING JINS MASSIVI HOLATIGA TA'SIRI

Saitov Dilshod Tohir O'g'li
E-mail: [saitovdilshodbek@gmail.com]

Annotatsiya. Maqolada yer osti ko'mir gazlashtirish (YOKG) jarayonida yuzaga keladigan geomexanik jarayonlar va issiqlik ta'sirining jins massivi holatiga ta'siri tahlil qilinadi. Termo-gidro-mexanik (TGM) bog'langan jarayonlarning nazariy asoslari — issiqlik o'tkazuvchanlik, termoelastiklik va poroelastiklik — tizimlashtirilgan. Analitik modellar asosida gazlashtirish kamerasi atrofida harorat maydoni, termik kuchlanishlar, jins mustahkamligining pasayishi, g'ovak bosimining termik ortishi va kamera shifi turg'unligi zaxira koeffitsiyenti baholangan. Hisoblashlar adabiyotlarda keng uchraydigan shartli parametrlar bilan bajarilgan; natijalar tendensiya va tartib jihatidan baholash xususiyatiga ega. Modelga ko'ra 180 sutkada isish zonasi kamera devoridan taxminan 9 m gacha tarqaladi, 600 °C da mustahkamlik dastlabki qiymatning taxminan 60 % igacha pasayadi, 200–300 m chuqurliklarda turg'unlik zaxirasi 450–600 °C oralig'ida birdan kamayadi.

Kalit so'zlar: *yer osti ko'mir gazlashtirish, geomexanika, termoelastiklik, poroelastiklik, termik kuchlanish, jins mustahkamligi, turg'unlik, yer yuzasining cho'kishi.*

Abstract. The paper examines geomechanical processes and the effect of heat on rock mass behaviour during underground coal gasification (UCG). The theoretical basis of coupled thermo-hydro-mechanical (THM) processes is summarised, and analytical models are used to estimate the temperature field, thermal stresses, strength degradation, thermally induced pore-pressure build-up and the roof stability factor around a gasification cavity. Calculations use typical

literature-based parameters and are intended to show trends rather than site-specific values. **Keywords:** *underground coal gasification, geomechanics, thermoelasticity, poroelasticity, thermal stress, rock strength, stability, subsidence.*

1. KIRISH

Yer osti ko'mir gazlashtirish (YOKG) — ko'mir qatlamini yer ostida to'g'ridan-to'g'ri yoqilg'i gaziga (sintez-gaz: H_2, CO, CH_4, CO_2) aylantirishga asoslangan texnologiya bo'lib, an'anaviy ochiq va shaxta usulida qazib olish iqtisodiy jihatdan maqbul bo'lmagan, chuqur yoki murakkab geologik sharoitdagi zaxiralarni o'zlashtirish imkonini beradi (Bhutto va boshq., 2013; Shafirovich & Varma, 2009). Texnologiyaning tarixiy tajribasi, jumladan O'zbekistondagi Angren stansiyasi, adabiyotda dunyodagi eng uzoq davom etgan sanoat tajribalaridan biri sifatida qayd etiladi (Perkins, 2018a; Khadse va boshq., 2007).

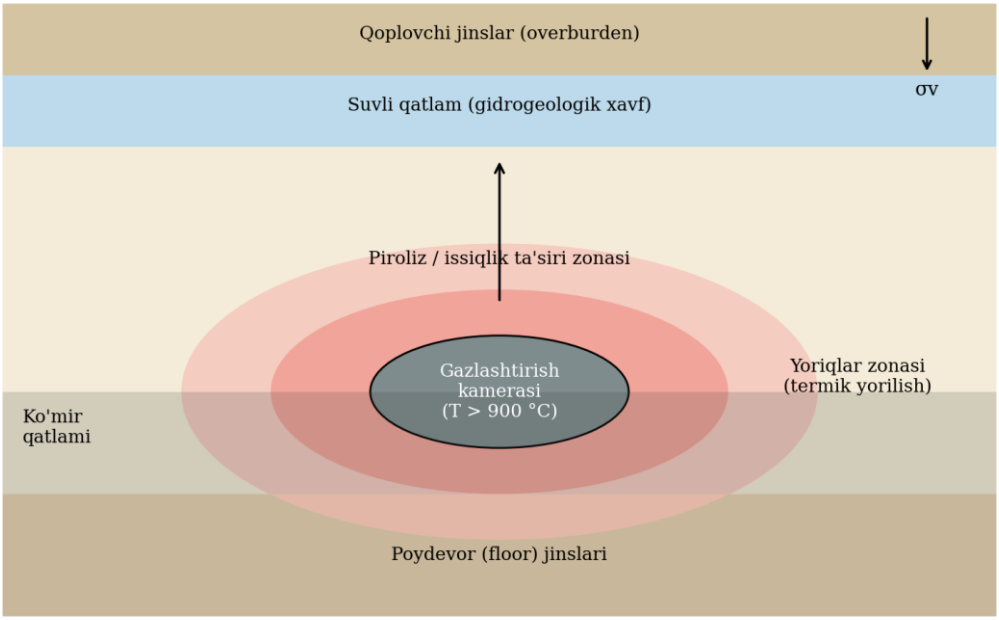
Gazlashtirish jarayonida kamera ichida harorat 900–1200 °C ga yetadi, ko'mir qatlami chiqib ketgach hosil bo'lgan bo'shliq atrofidagi jinslar keskin isiydi, qurishadi va shikastlanadi. Bu jarayon massivning dastlabki kuchlanish-deformatsiya holatini o'zgartiradi, qoplovchi jinslarning turg'unligiga, yer yuzasining cho'kishiga hamda yer osti suvlarining ifloslanish xavfiga bevosita ta'sir qiladi (Younger, 2011; Kapusta & Stańczyk, 2011). Shu sababli YOKG loyihalarining xavfsizligi va samaradorligi geomexanik jarayonlarni to'g'ri baholashga bog'liq.

Geomexanik nuqtai nazardan YOKG murakkab, chunki bir vaqtda issiqlik uzatilishi (T), g'ovak muhitdagi suyuqlik va gaz oqimi (H) hamda jins deformatsiyasi (M) o'zaro bog'liq kechadi (Rutqvist & Stephansson, 2003). Bunday bog'langan jarayonlarni tavsiflashda Terzaghi (1943) va Biot (1941, 1956) tomonidan asos solingan konsolidatsiya va termoelastiklik nazariyalari, keyinchalik Coussy (2004) va Wang (2000) tomonidan rivojlantirilgan poromexanika qo'llaniladi.

Maqolaning maqsadi — YOKG kamerasi atrofida issiqlik ta'siri ostida yuz beradigan asosiy geomexanik jarayonlarni nazariy jihatdan tizimlashtirish va analitik modellar yordamida ularning miqdoriy tendensiyalarini baholashdir. Maqsadga erishish uchun quyidagi vazifalar qo'yildi: (i) isish zonasining kengayish dinamikasini aniqlash; (ii) termik kuchlanishlarni hisoblash; (iii) haroratga bog'liq mustahkamlik pasayishini modellashtirish; (iv) termik g'ovak bosimi ortishining xavfini baholash; (v) kamera shifi turg'unligi zaxira koeffitsiyentini chuqurlik va haroratga bog'liq holda aniqlash.

2. NAZARIY ASOSLAR

YOKG kamerasi atrofidagi jarayonlarning umumiy sxemasi 1-rasmda keltirilgan. Kamera atrofida markazdan chetga qarab yuqori haroratli gazlashtirish zonasi, piroliz va issiqlik ta'siri zonasi hamda termik yorilish natijasida hosil bo'lgan yoriqlar zonasi shakllanadi. Qoplovchi jinslar ustida suvli qatlam mavjud bo'lsa, yoriqlar rivojlanishi gidravlik bog'lanish xavfini oshiradi.



1-rasm. Yer osti gazlashtirish kamerasi atrofidagi zonalar sxemasi (sxematik, masshtabsiz)

2.1. Issiqlik uzatilishi

Jins massivida issiqlik asosan o'tkazuvchanlik (kondaksiya) orqali tarqaladi. Issiqlik o'tkazuvchanlikning umumiy tenglamasi quyidagicha yoziladi (Carslaw & Jaeger, 1959):

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + Q (1)$$

bu yerda ρ — jins zichligi (kg/m³), c — solishtirma issiqlik sig'imi (J/(kg·K)), λ — issiqlik o'tkazuvchanlik koeffitsiyenti (Vt/(m·K)), T — harorat (°C), Q — hajmiy issiqlik manbai (Vt/m³), t — vaqt (s). Kamera devori sirt harorati T_s doimiy deb qabul qilinsa, yarim cheksiz muhit uchun bir o'lchamli analitik yechim quyidagi ko'rinishga ega bo'ladi:

$$T(x,t) = T_0 + (T_s - T_0) \cdot erfc\left(\frac{x}{2\sqrt{\alpha t}}\right) (2)$$

$$\alpha = \frac{\lambda}{\rho c} (3)$$

bu yerda T_0 — massivning boshlang'ich harorati, x — devordan masofa (m), α — haroratli o'tkazuvchanlik (temperaturoprovodnost) koeffitsiyenti (m²/s), erfc — qo'shimcha xato funksiyasi. (2) ifodadan isish zonasining chuqurligi vaqt kvadrat ildiziga proporsional ekanligi, ya'ni $x \sim \sqrt{(\alpha t)}$ kelib chiqadi. Bu qonuniyat YOKG kamerasi atrofida isish zonasining vaqt o'tishi bilan sekinlashib kengayishini tushuntiradi.

2.2. Termoelastik kuchlanishlar

Jins isiganda erkin termik kengayish chegaralangan bo'lsa, unda siquvchi kuchlanish hosil bo'ladi. To'liq cheklangan tekis kuchlanish holatida bunday kuchlanish ifodasi Timoshenko va Goodier (1970) bo'yicha quyidagicha yoziladi. Real sharoitda cheklanish to'liq bo'lmagani uchun ξ ($0 < \xi \leq 1$) cheklanish koeffitsiyenti kiritiladi:

$$\sigma_{th} = -\xi \frac{E \alpha_T \Delta T}{1 - \nu} (4)$$

bu yerda E — Yung moduli (MPa), α_T — chiziqli termik kengayish koeffitsiyenti (1/K), ν — Puasson koeffitsiyenti, $\Delta T = T - T_0$. Termik kuchlanish

massivdagi tabiiy kuchlanishlarga qo'shilib, kamera atrofida siqilish va cho'zilish zonalarini qayta taqsimlaydi; sovish yoki notekis isish tufayli cho'zuvchi kuchlanishlar paydo bo'lib, termik yoriqlar hosil bo'lishiga olib keladi (Najafi va boshq., 2014).

2.3. Poroelastik bog'lanish va termik bosimlanish

G'ovakli, suv bilan to'yingan jinslarda deformatsiya samarali kuchlanish orqali boshqariladi. Terzaghi (1943) va Biot (1941) bo'yicha samarali kuchlanish tensori:

$$\sigma' = \sigma - \alpha_B p\, I \quad (5)$$

bu yerda σ — to'liq kuchlanish tensori, p — g'ovak bosimi, α_B — Biot koeffitsiyenti, I — birlik tensor. Suyuqlik massasi saqlanish tenglamasi issiqlik bilan bog'langan holda quyidagi ko'rinishda ifodalanadi (Coussy, 2004; Wang, 2000; Detournay & Cheng, 1993):

$$\frac{1}{M}\frac{\partial p}{\partial t} + \alpha_B \frac{\partial \varepsilon_v}{\partial t} - \nabla \cdot \left(\frac{k}{\mu}\nabla p\right) = \Gamma \frac{\partial T}{\partial t} \quad (6)$$

bu yerda M — Biot moduli, ε_v — hajmiy deformatsiya, k — o'tkazuvchanlik (m^2), μ — suyuqlikning dinamik qovushqoqligi (Pa·s), Γ — issiqlik-gidravlik bog'lanish koeffitsiyenti. Tenglamaning o'ng tomoni haroratning o'zgarishi g'ovak suyuqligi bosimiga ta'sir etishini ifodalaydi. Suv minerallar skeletiga qaraganda ancha ko'proq kengayadi, shuning uchun past o'tkazuvchanlikli jinslarda (drenaj sekin) isish g'ovak bosimining keskin ortishiga olib keladi. Bu hodisa «termik bosimlanish» deb ataladi (Palciauskas & Domenico, 1982; McTigue, 1986). Drenajsiz sharoitda bosim ortishi $\Delta p = \Lambda \Delta T$ ko'rinishida yoziladi, bunda (Rice, 2006):

$$\Lambda = \frac{\lambda_f - \lambda_n}{\beta_f + \beta_n} \quad (7)$$

bu yerda λ_f — suyuqlikning hajmiy termik kengayish koeffitsiyenti, λ_n — g'ovak hajmining termik kengayishi, β_f — suyuqlik siqiluvchanligi, β_n — g'ovak

fazosining siqiluvchanligi. Λ qiymati qattiq, past g'ovakli jinslarda yuqori bo'ladi, shu sababli bunday jinslarda xavf eng katta.

2.4. Termik shikastlanish va mustahkamlik mezonlari

Yuqori harorat ta'sirida minerallarning kengayishi, g'ovak suvining chiqib ketishi, kristalli panjara o'zgarishlari (masalan, kvarsning α–β o'tishi 573 °C atrofida) va mikroyoriqlar hosil bo'lishi jinslarning mustahkamligi va elastiklik modulining pasayishiga olib keladi (Heuze, 1983; Zhang va boshq., 2009; Sirdesai va boshq., 2017). Bu o'zgarishlarni termik shikastlanish parametri D(T) orqali ifodalash qulay. Quyida Weibull ko'rinishidagi empirik bog'lanish qabul qilindi:

$$\sigma_c(T) = \sigma_{c0}[1 - D_\sigma(T)],\ D_\sigma(T) = 1 - exp\left(-[(T - T_0)/T_{ref}]^m\right) \quad (8)$$

bu yerda σ_{c0} — oddiy haroratdagi bir o'qli siqilish mustahkamligi, T_{ref} va m — tajriba ma'lumotlariga moslanadigan parametrlar. Elastiklik moduli ham xuddi shunday $E(T) = E_0[1 - D_E(T)]$ shaklida ifodalanadi. Massivning chegaraviy holati Mohr–Coulomb mezoni bilan baholanadi (Jaeger va boshq., 2007):

$$\sigma_{1'} = \sigma_c + \sigma_{3'}\frac{1 + sin\,\varphi}{1 - sin\,\varphi} \quad (9)$$

bu yerda σ_1' va σ_3' — eng katta va eng kichik samarali bosh kuchlanishlar, φ — ichki ishqalanish burchagi. Yoriqli massivlar uchun Hoek–Brown mezoni ham keng qo'llaniladi (Hoek & Brown, 1980; Brady & Brown, 2004). Kamera shifi turg'unligini baholash uchun zaxira koeffitsiyenti kiritiladi:

$$FS = \frac{\sigma_c(T)}{k \cdot \gamma \cdot H + \sigma_{th}(T)} \quad (10)$$

bu yerda H — chuqurlik (m), γ — jinslarning hajmiy og'irligi (MN/m³), k — kamera atrofidagi kuchlanish konsentratsiyasi koeffitsiyenti. FS < 1 bo'lsa, shifda yemirilish (qulash) ehtimoli yuqori hisoblanadi. Qoplovchi jinslar og'irligidan tushadigan $\sigma_v = \gamma H$ vertikal kuchlanish Zoback (2007) va Fjær va boshq. (2008) asarlarida bayon etilgan tartibda baholanadi.

3. USLUB VA DASTLABKI MA'LUMOTLAR

Tadqiqot analitik modellashtirishga asoslangan: harorat maydoni (2)-tenglama, termik kuchlanish (4)-tenglama, g'ovak bosimi (7)-tenglama va turg'unlik zaxirasi (10)-tenglama orqali hisoblangan. Hisoblashlar Python (NumPy, SciPy, Matplotlib) muhitida bajarilgan. Kirish parametrlari qumtosh–alevrolit turidagi qoplovchi jinslar uchun adabiyotlarda keng uchraydigan oraliqlardan tanlandi (Jaeger va boshq., 2007; Fjær va boshq., 2008) va 1-jadvalda keltirilgan.

1-jadval. Modelda qabul qilingan kirish parametrlari

Parametr	Qiymat	Izoh
Kamera devori harorati T_s	1000 °C	Gazlashtirish zonasi
Boshlang'ich harorat T_0	25 °C	Sayoz chuqurliklar uchun shartli
Haroratli o'tkazuvchanlik α	$0{,}7\cdot10^{-6}$ m²/s	Cho'kindi jinslar oralig'i
Yung moduli E_0	12 GPa	Qumtosh–alevrolit
Termik kengayish α_T	$8\cdot10^{-6}$ 1/K	Qumtosh uchun tipik
Puasson koeffitsiyenti ν	0,25	—
Cheklanish koeffitsiyenti ξ	0,4	Qisman cheklangan
Siqilish mustahkamligi σ_{c0}	45 MPa	Oddiy sharoitda
Hajmiy og'irlik γ	0,025 MN/m³	Qoplovchi jinslar
Konsentratsiya koeffitsiyenti k	2,5	Kamera burchagi/shifi
Weibull parametrlari (σ_c)	T_{ref} = 900 °C; m = 1,5	Empirik, tendensiyani aks ettiradi
Weibull parametrlari (E)	T_{ref} = 750 °C; m = 1,4	Empirik, tendensiyani aks ettiradi

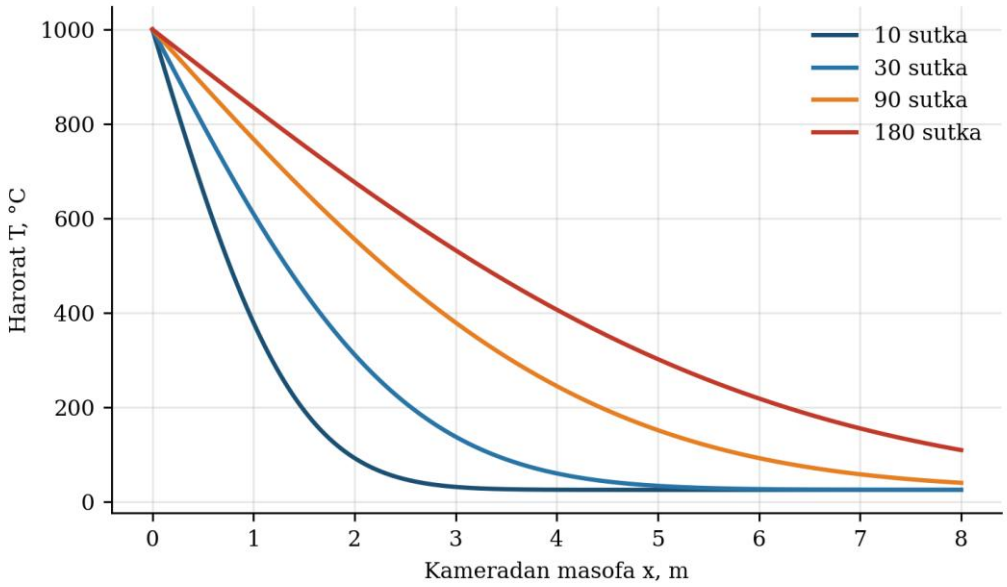
Modelning chegaralari: jins bir jinsli va izotrop, xossalari harorat bo'yicha faqat D(T) orqali o'zgaradi, termik kengayish koeffitsiyenti haroratga bog'liq emas, ko'mirning yonishi va gaz oqimi alohida hisoblanmagan, yoriqlar aniq

modellashtirilmagan. Shu sababli natijalar aniq obyekt uchun loyihaviy qiymat emas, balki tendensiyalarni baholash vositasi sifatida qaraladi. Aniq obyekt uchun laboratoriya sinovlari va bog'langan TGM sonli modellash (masalan, Rutqvist va boshq., 2002) talab etiladi.

4. NATIJALAR VA MUHOKAMA

4.1. Harorat maydonining rivojlanishi

2-rasmda 10, 30, 90 va 180 sutkadan keyingi harorat taqsimoti ko'rsatilgan. Isish zonasi vaqt o'tishi bilan kengayadi, biroq tezligi kamayadi: 10 sutkada 5 % ΔT chegarasi devordan taxminan 2,2 m da, 180 sutkada esa taxminan 9,1 m da joylashadi (2-jadval). Bu natija (2)-tenglamadagi $x \sim \sqrt{t}$ qonuniyatiga mos keladi. Demak, kameraning ishlash muddati ikki baravar oshishi isish zonasi qalinligini faqat taxminan 1,4 marta oshiradi.



2-rasm. Kamera devoridan jinsga issiqlik tarqalishi T(x,t)

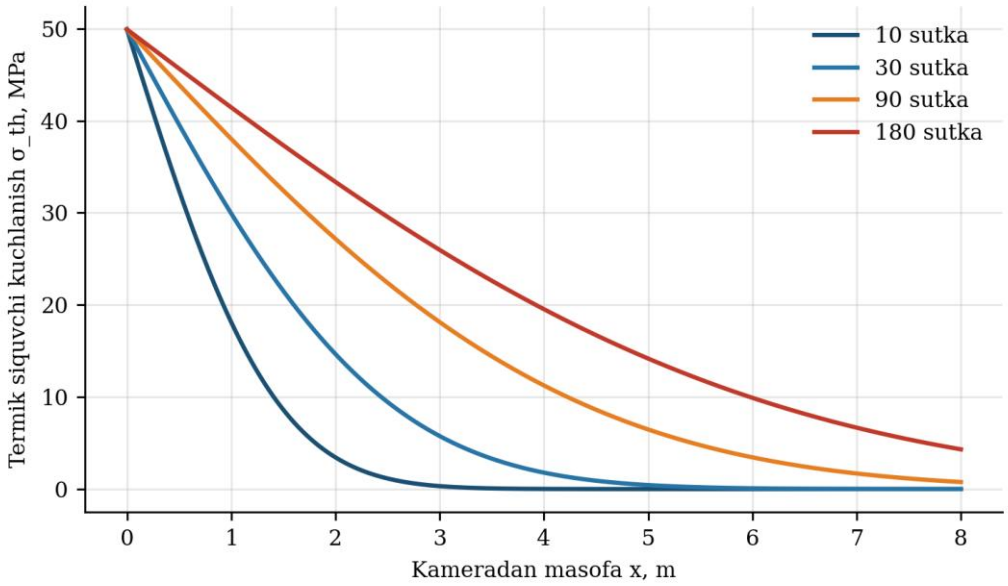
2-jadval. Issiqlik va termik kuchlanishning vaqt bo'yicha o'zgarishi

Vaqt, sutka	Isish zonasi chuqurligi ($\Delta T = 5\,\%$), m	T (x = 1 m), °C	σ_{th} (x = 1 m), MPa
10	2,2	379	18,1

Vaqt, sutka	Isish zonasi chuqurligi (ΔT = 5 %), m	T (x = 1 m), °C	σ_{th} (x = 1 m), MPa
30	3,7	610	29,9
90	6,5	768	38,0
180	9,1	835	41,4

4.2. Termik kuchlanishlar

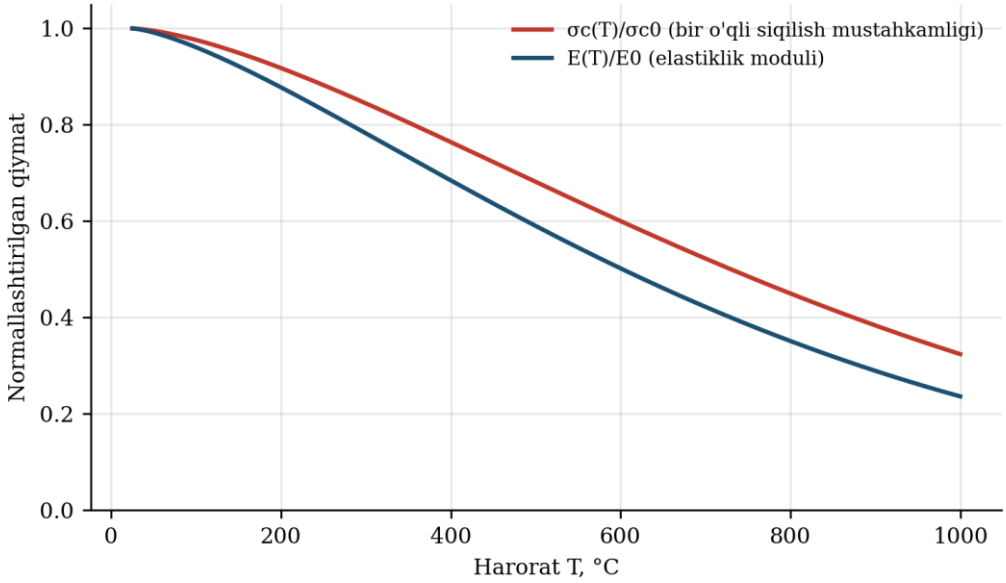
3-rasmda termik siquvchi kuchlanishning taqsimoti keltirilgan. Devor yaqinida kuchlanish maksimal qiymatga (taxminan 50 MPa, ξ = 0,4 bo'lganda) yaqinlashadi va u parametrlarga ko'ra jinsning dastlabki siqilish mustahkamligidan (45 MPa) katta bo'lishi mumkin. Bu devor yaqinidagi yupqa qatlamda termik parchalanish, qatlamlanish (spalling) va mikroyoriqlar hosil bo'lishini tushuntiradi. Shuningdek, kuchlanish gradienti katta bo'lgan zonada (isish frontida) siljish va cho'zilish kuchlanishlari yuzaga keladi; Najafi va boshq. (2014) YOKG panellari atrofida termomexanik sonli tahlilda kuchlanish maydoni haroratga bog'liq ravishda qayta taqsimlanishini ko'rsatgan.



3-rasm. Termik siquvchi kuchlanishning masofa va vaqt bo'yicha taqsimoti

4.3. Mexanik xossalarning pasayishi

4-rasmda (8)-tenglama asosida hisoblangan mustahkamlik va elastiklik modulining haroratga bog'liq pasayishi ko'rsatilgan. Model bo'yicha 300 °C da mustahkamlik dastlabki qiymatning taxminan 85 % ini, 600 °C da 60 % ini va 900 °C da 38 % ini tashkil etadi. Elastiklik moduli esa tezroq pasayadi: mos ravishda 78 %, 50 % va 29 %. Bu tendensiya qumtosh va granitlarning yuqori harorat ta'sirida sinov natijalari bilan sifat jihatdan mos keladi (Heuze, 1983; Zhang va boshq., 2009; Sirdesai va boshq., 2017). Moduli pasaygan jins tarkibida deformatsiya ortadi, ya'ni massiv «yumshaydi».

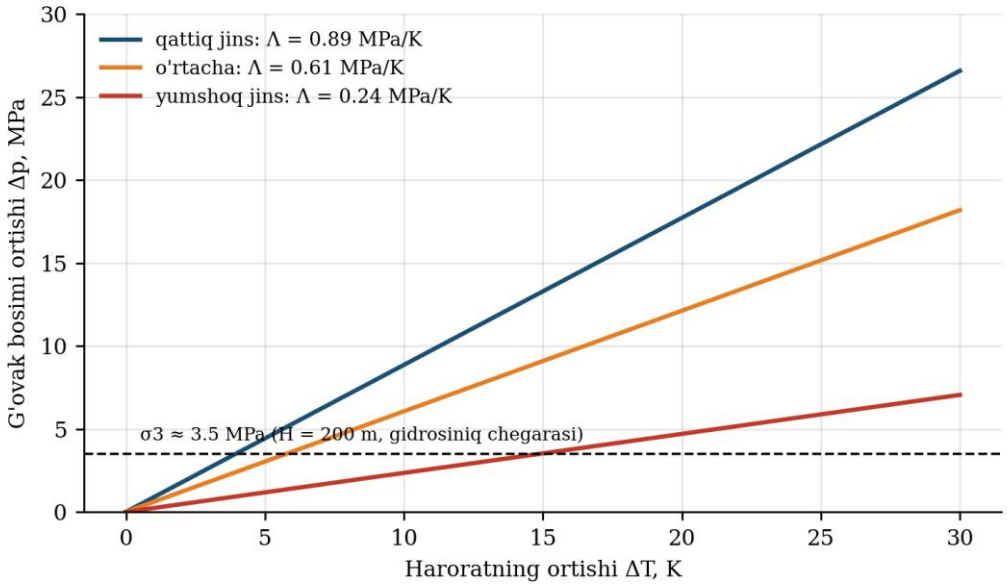


4-rasm. Harorat ortishi bilan mexanik xossalarning pasayishi (model)

4.4. G'ovak bosimining termik ortishi

(7)-tenglama bo'yicha suv uchun $\lambda_f = 5{,}76 \cdot 10^{-4}$ 1/K va $\beta_f = 4{,}5 \cdot 10^{-10}$ 1/Pa deb olinganda, g'ovak fazosi siqiluvchanligiga qarab Λ taxminan 0,24 dan 0,89 MPa/K gacha o'zgaradi (5-rasm). Bu — drenajsiz (yuqori chegara) holat, ya'ni juda past o'tkazuvchanlikda har bir Kelvin isish bir necha yuz kPa bosim hosil qiladi. Taxminan 200 m chuqurlikdagi minimal bosh kuchlanish $\sigma_3 \approx 3{,}5$ MPa deb qabul qilinsa (gorizontal kuchlanishlar nisbati 0,7), gidravlik sinish chegarasiga faqat 4–15 K ga isish bilan yetilishi mumkin. Amalda jinsning o'tkazuvchanligi, yoriqlar va

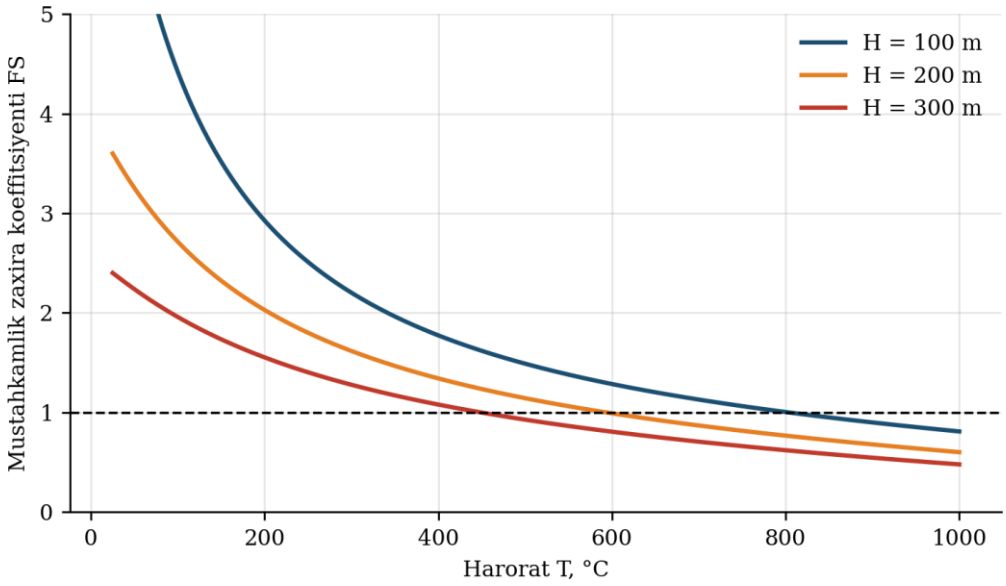
bug'lanish tufayli bosim sezilarli pasayadi; shunga qaramay, bu natija past o'tkazuvchan qoplovchi jinslarda isish tezligini nazorat qilish zarurligini ko'rsatadi (Palciauskas & Domenico, 1982; McTigue, 1986).



5-rasm. Drenajsiz sharoitda termik bosim ortishi $\Delta p = \Lambda \Delta T$ va gidrosinish chegarasi

4.5. Kamera shifi turg'unligi

6-rasmda (10)-tenglama bo'yicha FS koeffitsiyentining harorat va chuqurlikka bog'liqligi ko'rsatilgan. Oddiy haroratda 100, 200 va 300 m chuqurliklarda FS mos ravishda taxminan 7,2; 3,6 va 2,4 ga teng. Isish natijasida mustahkamlik pasayishi va termik kuchlanish qo'shilishi tufayli FS kamayadi: FS = 1 chegarasiga 100 m da ~804 °C, 200 m da ~596 °C va 300 m da ~449 °C da yetiladi (3-jadval). Chuqurlik ortishi bilan tog' bosimi ortadi, shu sababli chuqur kameralarda yuqori haroratga chidamlilik zaxirasi kichik bo'ladi.



6-rasm. Kamera shifi jinslarining mustahkamlik zaxira koeffitsiyenti FS

3-jadval. Turg'unlik zaxirasi koeffitsiyenti

Chuqurlik H, m	FS (25 °C)	FS (600 °C)	FS = 1 bo'lgan T, °C
100	7,2	1,29	~804
200	3,6	0,99	~596
300	2,4	0,81	~449

Natijalarni umumlashtirib aytish mumkin: (1) isish zonasining chuqurligi sekin o'sadi, lekin devor yaqinidagi qatlam tez shikastlanadi; (2) termik kuchlanishlar jinsning dastlabki mustahkamligi bilan bir tartibda; (3) g'ovak bosimi ortishi va mexanik yumshash o'zaro kuchaytiruvchi omillardir; (4) chuqurlik ortishi turg'unlikka salbiy ta'sir qiladi. Bu xulosalar TGM bog'lanish YOKG da muhim ekanini ko'rsatgan adabiyotlar bilan mos keladi (Rutqvist & Stephansson, 2003; Yang va boshq., 2016).

5. AMALIY JIHATLAR VA XAVFLARNI BOSHQARISH

Chuqurlik va qatlam geometriyasini tanlash. Model bo'yicha chuqurlik ortishi bilan turg'unlik zaxirasi kamayadi, shu sababli kamera chuqurligi, qatlam qalinligi va qoplovchi jinslar xossalari loyihalash bosqichida baholanishi kerak. Qoplovchi

jinslar tarkibida suvli qatlam mavjud bo'lsa, ular o'rtasidagi himoya qatlami qalinligi isish zonasining kutilgan chegarasidan sezilarli katta bo'lishi lozim (Burton va boshq., 2007).

Bosimni boshqarish. Kamera ichidagi gaz bosimini atrofdagi gidrostatik bosimdan past ushlab turish ifloslantiruvchi moddalarning yer osti suvlariga o'tishini kamaytiradi. Kapusta va Stańczyk (2011) gazlashtirishdan keyin suvda fenollar, aromatik uglevodorodlar kabi organik birikmalar paydo bo'lishi mumkinligini qayd etgan, Younger (2011) esa gidrogeologik nazorat zarurligini ta'kidlagan.

Monitoring. Haroratni, siljishlarni va mikroseysmik hodisalarni kuzatish geomexanik holatni nazorat qilishning asosiy usuli hisoblanadi. Mellors va boshq. (2016) YOKG da seysmik va elektr qarshilik usullarini o'z ichiga olgan geofizik monitoring imkoniyatlarini ko'rsatgan. Shuningdek, yer yuzasining cho'kishini geodezik kuzatish bilan modellar kalibrlanishi lozim.

Karbonat angidridni saqlash bilan uyg'unlik. Gazlashtirishdan keyin hosil bo'lgan bo'shliqlarni CO_2 saqlash uchun qo'llash g'oyasi ham muhokama qilinadi; bu holda jinslarning termik shikastlanishi va yoriqlar tarmog'i germetiklikka ta'sir qiladi (Yang va boshq., 2016). Shu sababli issiqlik ta'siridagi geomexanik tahlil faqat gazlashtirish bosqichi uchun emas, balki keyingi foydalanish uchun ham zarur.

Cheklovlar. Maqolada keltirilgan natijalar analitik, bir o'lchamli va shartli parametrli bo'lgani uchun aniq konning loyihaviy ma'lumoti sifatida ishlatilmasligi kerak. Keyingi tadqiqotlarda mahalliy jinslarning laboratoriya sinovlari (haroratga bog'liq σ_c, E, α_T, k), uch o'lchamli TGM sonli modellash va dala monitoringi ma'lumotlari bilan tekshirish talab etiladi.

6. XULOSA

1. YOKG da issiqlik uzatilishi, g'ovak suyuqlik oqimi va jins deformatsiyasi o'zaro bog'liq jarayonlar bo'lib, ularni faqat TGM bog'lanish nazariyasi doirasida to'g'ri baholash mumkin.

2. Isish zonasining chuqurligi vaqt kvadrat ildiziga mutanosib o'sadi: modelda 10 sutkada ≈ 2,2 m, 180 sutkada ≈ 9,1 m.

3. Devor yaqinidagi termik siquvchi kuchlanish (≈ 50 MPa gacha, $\xi = 0{,}4$ da) jinsning oddiy sharoitdagi mustahkamligi bilan bir tartibda bo'lib, termik shikastlanish va qatlam ajralishiga olib kelishi mumkin.

4. Harorat 600 °C ga yetganda mustahkamlik ≈ 60 %, elastiklik moduli ≈ 50 % gacha pasayadi; bu massivning yumshashi va deformatsiyalarning ortishiga sabab bo'ladi.

5. Drenajsiz sharoitda termik bosimlanish $\Lambda \approx 0{,}24–0{,}89$ MPa/K ni tashkil etib, past o'tkazuvchan jinslarda gidrosinish xavfini keltirib chiqarishi mumkin.

6. Kamera shifi turg'unlik zaxirasi chuqurlik ortishi bilan kamayadi; modelda FS = 1 chegarasiga 100, 200 va 300 m chuqurliklarda mos ravishda ≈ 804, 596 va 449 °C da yetiladi.

7. Amaliyotda chuqurlikni asosli tanlash, kamera bosimini boshqarish, harorat va siljishlar monitoringi hamda aniq obyekt uchun laboratoriya va sonli tadqiqotlar o'tkazish tavsiya etiladi.

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