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RESEARCH ARTICLE

DETERMINATION OF RESIDUAL DEFORMATION IN SEALING ELEMENTS IN TWO: AXIAL LOADING

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ABSTRACT

Solution of the sparital task on tension-deformation condition of biaxial loaded well packer is considered in the article. Koshi method for variations of the components of tensor deformations in complex loading in the well has been used. The theory of plastic flow has also been applied, borders of plastic zone at the period of packing deformation have been determined and some variants in the particular case for satisfying stabilly conditions of the sealing have been solved. The obtained results are compared with the results of the works carried out by other authors.

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INTRODUCTION

Many cases of plane deformation state of plat are devoted to the study of this problem [Babanly et al., 2016]. The paper concerns the solution of spatial task. Let's consider sealing element subjected to two-axial compression on the edges by equally distributed forces placed in its plane. We chose beginning of Cartesian system of coordinates in central plane. AxisOX_1 andOX_2aredirectedtowards the operating efforts, but OX_3 – normally to packing elements plane [Mammadov, 2017].

Let's suppose that

$$\sigma_{11} = m\sigma_{22} \tag{1.1}$$

where σ_{11} and σ_{22} – are stresses, applied on the edges; and m – is real positive number. Let surface of sealing element in the considered moment of time be disturbed as following**:**

$$x_3 = \pm\left(x_{30} + \delta\cos\omega_1 x_1 \cos\omega_2 x_2\right) \tag{1.2}$$

Here 2 x_3 – is the thickness of undisturbed condition, and δ – is a small quantity. It is supposed that, there are no displacements and tangent stresses be for disturbing moment, that is

$$e_{ij} = 0 \text{ and } \sigma_{ij} = 0 \text{ at } i \neq j,\ i,j = 1,2,3. \tag{1.3}$$

Due to Koshi formulae for variations of deformation tensor components we have [Mammadov, 2017]:

$$\delta e_{ij} = \frac{1}{2}\left(\frac{\partial u_{ji}}{\partial x_i} - \frac{\partial u_{ji}}{\partial x_j}\right) \tag{1.4}$$

where u_{ji} –is variation of displacement component. As the material is considered uncompressed, then

$$\frac{\partial u_i}{\partial x_j} = 0 \tag{1.5}$$

If to disregard sluggish members and volume forces because of their infinitesimal, then equations of Koshi movement in variations have the form

$$\frac{\partial\left(\delta\sigma_{ij}\right)}{\partial x_j} = 0 \; . \tag{1.6}$$

On that ground, surface of the plate doesn't test any loading, boundary conditions at $x_3 = \pm x_{30}$ have the form

$$\left(\sigma_{ij} + \delta\sigma_{ij}\right)\nu_j = 0 \text{, where } \sigma_{33} = 0 \tag{1.7}$$

ν_j – are guiding normal of cosine to the surface disturbances determined from equation (2). Dependence between stresses and deformations will be removed due to the theory of small elastic-plastic deformations, that is [Mammadov et al., 2015]

$$\sigma_{ij} = \sigma\delta_{ij} + \frac{2\delta_{ij}}{3e_i}e_{ij} \; , \tag{1.8}$$

where σ_{ij} – is kroneker symbol, σ – is hydrostatic pressure tension and

$$\bar{\sigma}_{i_0} = \sqrt{1 - m + m^2}\,\sigma_{11} \; , \qquad e_{i_0} = \frac{2\sqrt{1 - m + m^2}}{2 - m}e_{11} \tag{1.9}$$

From the experiment on pure tension we have

$$\sigma_{i_0} = \varnothing\left(e_1\right) \; . \tag{1.10}$$

Varying(8) on the basis (10), (4), (5) and (6) we get the system of differential equations in quotient devivatives with four unknowns u_i and $\delta\sigma$:

$$\frac{\partial}{\partial x}\left[\delta_{11}\delta\sigma + \left(\delta k e_{ij} + k\right)\delta e_{ij}\right] = 0 \; , \tag{1.11}$$

Where

$$k = \frac{2\sigma_i}{3e_i}$$

More ever

$$k + \delta k \cdot e_{ij} = \begin{cases} 2A = \dfrac{2}{3} \cdot \dfrac{d\varnothing}{de_{i_0}} & npu\; i = j \\ B = \dfrac{1}{3} \cdot \dfrac{\varnothing}{e_{i_0}} & npu\; i \neq j \end{cases} \tag{1.12}$$

If to take the beginning of the coordinates system in the neck centre (residual deformation), then on the basis of process symmetry relatively to coordinate planes we will have.

$$u_i\left(\overline{x}_i\right)=\begin{cases}u_i\left(-\overline{x}_i\right) & npu\, i\neq j\\ -u_i\left(\overline{x}_i\right) & npu\, i=j\end{cases} \tag{1.13}$$

Under $\overline{x}_i$ collection of arguments is implied, more were, signs change every time only before one argument. According to boundary conditions (2) and condition (13) we find particular solution of the system (11) in the form [Nguyen Gang Li, 1978]:

$$\begin{aligned}
&u_1\left(\overline{x}_j\right)=\alpha\left(m\right)\sin\omega_i x_i\cos\alpha\omega_i x_2\varphi_1\left[\left(1+\lambda\right)\omega_1 x_3\right]\\
&u_2\left(\overline{x}_i\right)=\beta\left(m\right)\cos\omega_i x_i\sin\lambda\omega_1 x_2\varphi_2\left[\left(1+\lambda\right)\omega_1 x_3\right]\\
&u_3\left(\overline{x}_j\right)=\cos\omega_1 x_1\cos\lambda\omega_1 x_2\varphi_3\left[\left(1+\lambda\right)\omega_1 x_3\right]\\
&\delta\sigma=\left(1+\lambda\right)\omega_1\cos x_1\cos\lambda\omega_1 x_2\varphi_4\left[\left(1+\lambda\right)\omega_1 x_3\right]\\
&u_1\left(\overline{x}_j\right)=\alpha\left(m\right)\sin\omega_i x_i\cos\alpha\omega_i x_2\varphi_1\left[\left(1+\lambda\right)\omega_1 x_3\right],
\end{aligned} \tag{1.14}$$

where

$$\alpha\left(m\right)=\frac{2\sigma_{11}-\sigma_{22}}{\sigma_{11}+\sigma_{22}}=\frac{2-m}{m+1},\qquad \beta\left(m\right)=\frac{2\sigma_{22}-\sigma_{11}}{\sigma_{11}+\sigma_{22}}=\frac{2m-1}{m+1} \tag{1.15}$$

Putting (1.14) into (1.11), integrating the third equation once and considering detail of functions φ_3 and φ_4, we get

$$\begin{aligned}
&B\alpha\left(m\right)\left(1+\lambda\right)^2\varphi_1''-\alpha\left(m\right)\left[2A-B\left(1+\lambda\right)^2\right]\varphi_1'-\left(1+\lambda\right)\varphi_4=0,\\
&B\beta\left(m\right)\left(1+\lambda\right)^2\varphi_2''-\beta\left(m\right)\left[2\lambda^2A+B\left(1-\lambda^2\right)\right]\varphi_2-\lambda\left(1+\lambda\right)\varphi_4=0,\\
&\left(1+\lambda\right)^2\left(2A-B\right)\varphi_3''-B\left(1+\lambda^2\right)\varphi_3+\left(1+\lambda\right)^2\varphi_4=0
\end{aligned} \tag{16}$$

in $x_3=\pm x_{30}$

$$\alpha\left(m\right)\varphi_1+\lambda\beta\left(m\right)\varphi_2+\left(1+\lambda\right)\varphi_3''=0 \tag{1.16}$$

In (1.17) v_1 can be changed to– $\frac{\partial u_3}{\partial x_1}$, v_2 to– $\frac{\partial u_3}{\partial x_2}$, and v_3 to one, as tangential to disturbed surface forms small angle on the surface $0x_1x_2$. Disregarding infinite small members of the second order and considering them, and also correlation (14), boundary conditions will have the form [Maltsev, 1978]:

$$\begin{aligned}
&\left(1+\lambda\right)B\alpha\left(m\right)\varphi_1'-\left(B-\sigma_{11}\right)\varphi_3'=0\\
&B\beta\left(m\right)\left(1+\lambda\right)\varphi_2'-\lambda\left(\beta-m\sigma_{11}\right)\varphi_3'=0
\end{aligned} \tag{1.17}$$

$$B\beta(m)(1+\lambda)\varphi_2'-\lambda(B-m\sigma_{11})\varphi_3'=0$$

in $x_3=x_{30}$.

$$\varphi_4+2A\varphi_3''=0$$

It is supposed that in normal to coordinate axis x_1 and $\overline{x}_2$ crosses the following conditions are satisfied:

$$\int_{-x_{30}}^{+x_{30}}\delta\sigma_{12}dx_3=\int_{-x_{30}}^{+x_{30}}\delta\sigma_{13}dx_3=\int_{-x_{30}}^{+x_{30}}\delta\sigma_{23}dx_2=0 \tag{1.18}$$

From (15)-(17) in corresponding values of m and λ, all particular cases are obtained.

From the fourth equation of system (16) we determine φ_1 and put into the first equation of the system, where φ_4 is determined and put into the second and third equations, we get:

$$B\beta(m)(1+\lambda^2)(1+\lambda)^2\varphi_2''-\beta(m)(1+\lambda)[4\lambda^2A-B](1-\lambda^2)\varphi_2+$$
$$+B\lambda^2(1+\lambda)^4\varphi_3^{(IV)}-\lambda^2(1+\lambda)^2[2A-B(1-\lambda_2^2)]\varphi_3''=0$$
$$-B\beta(m)(1+\lambda)^3\lambda\varphi_2''+\beta(m)\lambda(1+\lambda)[2A-B](2-\lambda^2)\varphi_2-$$
$$-B(1+\lambda)^4\lambda\varphi_3^{(IV)}+(1+\lambda)^2[4A-B(2-\lambda^2)]\varphi_3''-B(1+\lambda^2)\varphi_3=0. \quad (1.19)$$

The first equation of system (19) is multiplied to $\lambda(1+\lambda)$, and the second –to $1+\lambda^2$, adding it we get [Kokoshvili, 1978]:

$$2\beta(m)\lambda(1+\lambda)(1-\lambda^2)[A-B(1+\lambda^2)\varphi_2]=B(1+\lambda)^4\varphi_3^{(IV)}-$$
$$-[2A(2+\lambda^2)-B(2-\lambda)^4](1+\lambda)^2\varphi_3''+B(1+\lambda^2)^2\varphi_3 \quad (1.20)$$

In all cases when m and λ are so, the expression $\beta(m)\lambda(1+\lambda)(1-\lambda^2)[A-B(1+\lambda)^2]$ turns to zero, we get equation in the form

$$\varphi_3^{(IV)}-\frac{2A(2+\lambda^2)-B(2-\lambda^4)}{B(1-\lambda)^2}\varphi_3''+\frac{(1+\lambda^2)^2}{(1+\lambda)^4}\varphi_3=0 \quad (1.21)$$

But in other cases, determining φ_2 from (20) and, putting it into the first equation of the system (19), we get equation in the form

$$\varphi_3-a_0\varphi_3^{(IV)}+a_1\varphi_3''-a_2\varphi_3=0, \quad (1.22)$$

$$a_0=\frac{4A(1+2\lambda+3\lambda^2)-B(1+4\lambda+4\lambda^2-2\lambda^5-3\lambda^6)}{B(1+\lambda^2)(1+\lambda)^2} \quad 1.23)$$

$$a_1=\frac{12A^2\lambda^2(1+\lambda^2)+4AB(1-2\lambda^4)+B^2[(1-\lambda^2)(3\lambda^6-1)+8\lambda^4]}{B^2(1+\lambda^2)(1+\lambda)^4} \quad (1.24)$$

$$a_2=\frac{(1+\lambda^2)[4A\lambda^2+B(1-\lambda)^4]}{B(1-\lambda)^6} \quad (1.25)$$

In the same way boundary conditions can have the form Inscription

$$\left.\begin{aligned}\varphi_3'''-\frac{\sigma_н(1+m\lambda^2)-B(1+\lambda)}{B(1+\lambda)^2}\psi_3'=0\\ \varphi_3''+\frac{1+\lambda^2}{(1+\lambda)^2}\varphi_3=0,\end{aligned}\right\} \quad (1.26)$$

Condition (13), boundary conditions (26), (27), (18) and $u_3(0,0,x_{30})=-\delta$ give make it possible to determine arbitrary constants of inteqration but the condition of stability loss is determined from (1.26)

$$\sigma_1>f(m,\lambda,A,B). \quad (1.27)$$

Setting m, it is possible to find λ, which gives minimum value of function $f(m,\lambda,A,B)$.

2. Special cases.

a) in $m=0,5$ and $\lambda=0$ from (1.21) we get equation

$$\sigma_3^{(IV)}-2\left(2\frac{A}{B}-1\right)\varphi_3''+\varphi_3=0 \quad , \tag{2.1}$$

Corresponding boundary conditions received by the equation have:

$$\left.\begin{array}{c}\varphi_3''+\frac{B-\sigma_{11}}{B}\cdot\varphi_3'=0\\ \varphi_3''+\varphi^3=0\end{array}\right\} \text{ in } x_3=\mp x_{30} \tag{2.2}$$

In this case stability loss condition was found in the form:

$$\sigma_1>4A \text{ or } \sigma_{i0}>2\sqrt{3}A \tag{2.3}$$

b) in $m=1$ we get biaxial tension of the packer with equal forces between themselves. For simplicity let's take $\lambda=0$. In this case $\alpha(m)=\beta(m)=0,5$ and $\varphi_1=\varphi_{21}$. Then, from equation (1.21) we get

$$\varphi_3^{(IV)}-2Pn2\varphi_3''+n^4\varphi_3=0 \quad , \tag{2.4}$$

where

$$n-\frac{1}{\sqrt{2}}, \quad P=\frac{1}{2}\left(3\frac{A}{B}-1\right) \tag{2.5}$$

Boundary conditions for (2.4) will be:

$$\left.\begin{array}{c}\varphi_3'''-\frac{(\sigma_{11}-B)}{2B}\cdot\varphi_3'=3\\ \varphi_3'+0,5\varphi_3=0\end{array}\right\} \tag{2.6}$$

in $x_3=\pm x_{30}$ (2.7)

Characteristic equation for (2.4) has roots where

$$\pm i\gamma n=\pm i(p+iq)n \, .$$
$$\pm\bar{i}\,\gamma n=\pm i(p-iq)n$$

Where

$$p=\sqrt{\frac{1-P}{2}}, \quad q=\sqrt{\frac{1+P}{2}} \, . \tag{2.7}$$

General solution (2.4) we find in the form $\varphi_3(t)=c_1\sin\gamma nt+c_2\sin\bar{\gamma}nt+c_3\gamma nt+c_4\cos\bar{\gamma}nt$ (2.8)
Where

$$t=(1+\lambda)\varpi_1 x_3 \, . \tag{2.8}$$

By for ceofa detail of the function $\varphi_3(t)$ $c_1=c_2=0$ and $c_3=\bar{c}_4$, should be taken, as $\varphi_3(t)$ must be the true function. This,

$$\varphi_3(t)=c\cos\gamma nt+\bar{c}\cos\gamma nt \, . \tag{2.9}$$

$$cN\cos\gamma nh+c\bar{N}\cos\bar{\gamma}nh=0 \tag{2.10}$$

where,

$N = 0,5\left(1-\gamma^2\right)$, $\overline{N} = 0,5\left(1-\overline{\gamma}^2\right)$.

$h = \left(1+\gamma\right)\omega_1 x_{30}$.

Equation (2.10) will be satisfied always, if we accept:

$$c = D\left(1-\overline{\gamma}^2\right)\cos\overline{\gamma}nh,$$
$$\overline{c} = -D\left(1-\gamma^2\right)\cos\gamma nh, \quad (2.11)$$

here, D – is unknown arbitrary constant. Consequently,

$$\varphi_3\left(t\right) = D\left[\left(1-\overline{\gamma}^2\right)\cos\overline{\gamma}nh\cdot\cos\gamma nt - \left(1-\overline{\gamma}^2\right)\cos\gamma nh\cos\overline{\gamma}nt\right]. \quad (2.12)$$

In $t = h$ $x_1 = x_2 = 0$, $u_3 = -\delta$.

Considering it and (2.14), we find:

$$D = -\frac{\delta}{2lmN\cos\gamma nh\cdot\sin\gamma nh}. \quad (2.13)$$

After putting (2.12) into (2.6)the latter can be written in the form of:

$$k_0 \sin 2pnh = pqsh2qnh, \quad (2.14)$$

Where

$$k_0 = \frac{(\sigma_{11}-B)}{2B} - \frac{p}{2}$$

Equation (2.14) has 2 valid roots $h \neq 0$, different from zero, equal between themselves on the value and opposite on sign, while carrying condition $k > q^2$, which is brought to equality

$$\sigma_{12} > 2B + 3A \quad (2.15)$$

Comparison (2.15) and (2.3) testifies that critical intensity of tensions for formation of neck in the packers considerably depends on parameters m and λ. c) In $m = 0$ we get monobasic compression of packer. For simplicity let's take $\lambda = 0$. Then, we get plane deformation condition relatively to deformation increments. In this case $\alpha\left(m\right) = 2$, $u_2 = 0$ and from (1.21) we get equation (2.1) and boundary conditions (2.2). That's why, the same condition of stability loss is obtained:

$$\sigma_{11} > 4A \text{ or } \sigma_{i0} > 4A \quad (2.16)$$

Which his more, than in case $m = 0,5$, $\lambda = 0$. In all these cases conditions (1.18) are satisfied automatically. By the same way, the cases are solved, when

$$\lambda = \sqrt{\frac{A-B}{B}} \text{ or } \lambda = \sqrt{\frac{2A+B}{B} \mp \frac{\sqrt{A\left(A+B\right)}}{B}}$$

in any m, however in these cases new integral constants appear which are easyly determined from the first equation (1.18), among all possible m it is possible to choose such value, that in the given λ critic force will have minimum value. 3. It is known that experiment in a complex loading confirm better only plastic flow, than the theory of small elastic plastic deformations [9].

That's why it is very interesting to solve the task about the neck with the help of plastic flow theory. Let's accept theory of plastic flow in a simple form:

$$d\text{Э}_{ij} = \frac{dS_{ij}}{2G} + f(J_2)S_{ij}dJ_2 \; (ij = 1,2,3) \tag{3.1}$$

where G – is elastic module of displacement; Э_{ij} – are components of deformation deviator; S_{ij} – are components of tension deviator; but J_2 – is second variant of tension deviator. In this task it has the form

$$J_2 = \frac{1}{2}\left(S_{11}^2 + S_{22}^2 + S_{33}^2\right) \tag{3.2}$$

as it is supposed,

$S_{ij} = 0$ in $i \neq j$.

In the excited condition of the packer in (3.1) value differentials can be changed to their variations. Solving them relatively to the variations of tension deviator components we get

$$\delta S_{ij} = 2G\delta\text{Э}_{ij} - P(J_2)S_{ij}S_{pq}\delta\text{Э}_{pq} \; (i,j,P,q = 1,2,3) \tag{3.3}$$

$$P_1(J_2) = \frac{4G^2 f(J_2)}{1 + 4Gf(J_2)J_2}. \tag{3.3'}$$

In consequence of incompressibility of the material deformation deviator components are equal to the variations of tensor deformation components, that is

$$\delta\text{Э}_{ij} = \delta e_{ij}, \text{ a } \delta S_{ij} = \delta\sigma_{ij} - \delta_{ij}\sigma \tag{3.4}$$

For simplicity here the case $m = 0,5$, $\lambda = 0$ is considered. Putting function $\psi(x_1, x_3)$ on the basis of the incompressibility condition

$$u_1 = -\frac{d\psi}{dx_3}, \quad u_3 = -\frac{d\psi}{dx_1} \tag{3.5}$$

and excluding the equilibrium equation in variations $\delta\sigma$, we get

$$\frac{d^4\psi}{dx^4} + 2\mu\frac{d^4\psi}{dx_1^2 dx_3} + \frac{d^4\psi}{dx^4} = 0 \tag{3.6}$$

Corresponding boundary conditions have a form

$$(G - \sigma_{11})\frac{d^2\psi}{dx_1^2} - G\frac{d^2\psi}{dx_3^2} = 0, \tag{3.7}$$

$$G(1+\mu)\frac{d^2\psi}{dx_1 dx_3} + \delta\sigma = 0 \text{ in } x_3 = x_{30} \tag{3.8}$$

Particular solving (3.6) we find in the form

$$\psi(x_1, x_3) = \sin\omega_1 x \cdot \xi(\omega_1, x_3) \tag{3.9}$$

Further process of solution (3.6) with boundary conditions (3.7) and (3.8) is the former one. Consequently, we get the stability loss condition in the form

$$\sigma_{11} > 2G(1+\mu) \text{ oder } \sigma_{20} > \sqrt{3}G(1+\mu) \tag{3.10}$$

4. For comparison the obtained results in the case $m = 0,5$, $\lambda = 0$ due to the various theories let's suppose that graph $\sigma_{i0} \square e_{i0}$ is a cubic parabola and function $\varnothing(e_{i0})\ \xi(\sigma_{i0})$

$$e_{i0} = \xi(\sigma_{i0}) \tag{4.1}$$

Then

$$\frac{d\varnothing}{de_{i0}} = \frac{1}{\dfrac{d\xi e\sigma_{i0}}{d\sigma_{i0}}} \tag{4.2}$$

In a pure tension due to the theory of plastic flow we have

$$de_{i0} = \frac{d\sigma_{i0}}{E} + \frac{4}{9} f(J_2)\sigma_{i0}^2 d\sigma_{i0} \tag{4.3}$$

as

$$3S_{11}^2 = 4J_2 = \frac{4}{3}\sigma_{i0}^2, \quad E = 3G \tag{4.4}$$

In order (4.3) to present cubic parabola, the function $f(J_2)$ must be constant, that is

$$f(J_2) = c = const$$

Integrating (4.3), we get

$$e_1 = \frac{\sigma_{i0}}{E} + \frac{4}{27} c\sigma_{i0}^3 \tag{4.5}$$

Comparing (4.5) with (4.1), we have

$$\xi(\sigma_1) = \frac{\sigma_{i0}}{E} + \frac{4}{27} c\sigma_{i0}^2 \tag{4.6}$$

Then from (2.3), considering (4.2) and (4.6), we find

$$\sigma_{i0} > \frac{6\sqrt{3}E}{9 + 4cE\sigma_{i0}^2}. \tag{4.7}$$

From (3.8) and (3.3) we get

$$\sigma_{i0} > \frac{6\sqrt{3}E}{9 + 4c\sigma_i^2}$$

Consequently, in the case $m = 0,5$ and $\lambda = 0$ the results obtained by various theories coincide.

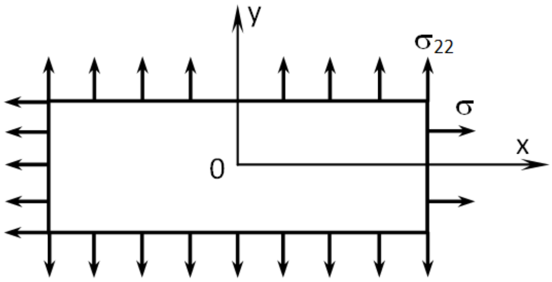

Fig.1.The scheme of the initial

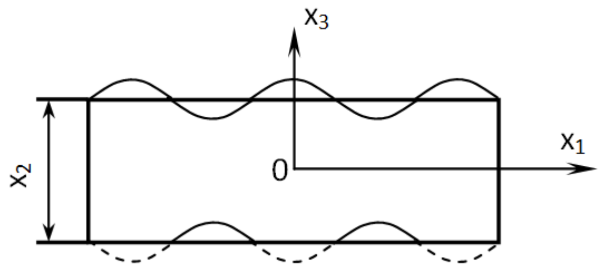

Fig. 2. Seal scheme after loading of the sealant

Conclusion

Koshi method for variations of tensor deformation components is well described in the complex biaxial loading of well sealing elements.

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