FLUID-STRUCTURE INTERACTION RELATED ASPECTS DURING THE GROUTING OF CRACKS IN CONCRETE

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ABSTRACT

Fluid Structure Interaction (FSI) processes in cracked systems generally may be assigned to "Hydraulic Fracturing", which in the field of petroleum-engineering is well understood by mathematical and numerical descriptions and utilisation in situ. However there is a further important aspect related to this technique but opposite in the objective – grouting of cracked concrete structures under the aspect of full rehabilitation.
Unfortunately uncontrolled grouting may sometimes cause an opposite effect, e.g. creating of new cracks or further crack propagation. Based on the understanding of the closely coupled process between the injected fluid and the structural response especially the Stress Intensity Factor development at the crack front may serve as an efficient control parameter during the grouting procedure.

KEYWORDS

Concrete, cracks, grouting, repair, fluid structure interaction

INTRODUCTION

A certain category in the wide field of fluid structure interaction processes also has to be considered in civil engineering in all cases where an elastic structure in dynamic motion is in contact with a fluid at rest or vice versa. A wide class of problems stretching from flow induced vibrations in hydraulic engineering [1] to added mass concepts in dam engineering [2] may be assigned to this discipline. The injection procedure during the grouting of cracks in concrete structures also may be seen as an interaction between fluid penetration and structural response and basically is comprehended by the disciplines of fluid mechanics, structural mechanics and fracture mechanics. The closely coupled process is characterised by the time dependent fluid penetration as a function of the crack width and the herewith associated pressure development causing a further alteration of the cross section. In addition the stress intensity at the crack front, accountable for the stability (reliability) of the grouting procedure, is directly related with. The physical-mathematical formulation of these complex circumstances ever since has been a matter of special concern in the field of petroleum-engineering under the aspects of "hydro-fracturing ", to achieve optimal production conditions. Representative for the multitude of relevant treatises, Lit. [3,4,5,6] including recommendations for further readings, is specified. The grouting process of cracks mathematically may be exhibited similar to that one representative for hydraulic fracturing but with an essential difference concerning the crack (tip) behaviour. Opposite to the "hydraulic driven fracture" - a continuously moving fluid-fracture system – care has to be taken, strictly to avoid any instability of the system during grouting. Within this contribution a model both for a plane and a penny-shaped crack configuration is presented to comply with this demand.

MATHEMATICAL MODEL

Due to the intimately coupled process between the crack width-dependent fluid flow and the herewith pressure induced alteration of this flow-section as response of the structure (as shown in Figure 1), both fluid mechanics and structural mechanics principles have to be observed. Simultaneously, the stress development at the crack front has to be considered under the aspects of fracture mechanics methods.

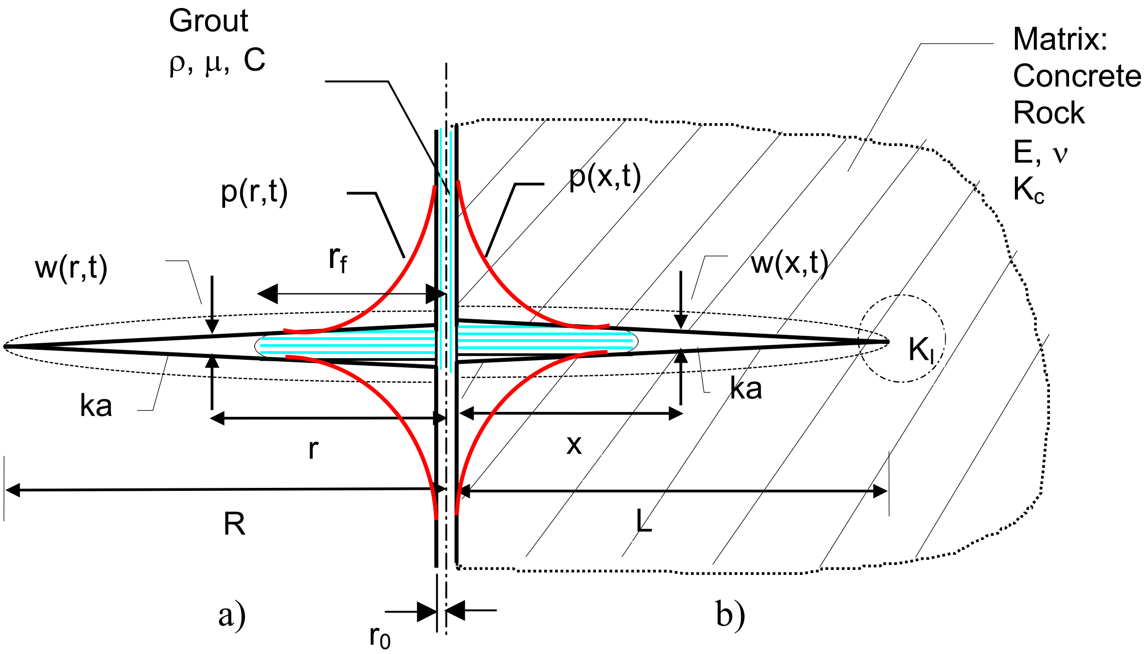


Figure 1: Scheme of the fluid-structure interaction process
a) penny shaped crack
b) wedge shaped crack

Fluid Mechanics Formulation
The physical description of fluid flow is based on the fundamental conservation principles – conservation of mass, momentum and energy, constitutive relationships and equations of state [7]. Disregarding the energy principle (which is not relevant for the present case), the characteristic equations for the conservation of mass and momentum are given by Eqn. 1 and Eqn. 2 (Cauchy equation of motion) respectively.

$$\frac{D\rho}{Dt} + \rho\nabla\cdot u = 0 \tag{1}$$

$$\frac{}{} = f - \nabla p + \nabla\cdot\tau \tag{2}$$

with ρ as the density of the fluid, u the velocity vector, ∇·u the divergence of the velocity, f the body force, ∇p the pressure gradient and ∇·τ the divergence of the surface forces (viscous stresses). D/Dt is the substantial derivative, representative for the Eulerian framework.
The constitutive relationship for a *Newtonian* fluid in the formulation of Stokes is shown in Eqn. 3,

$$= 2\left(\gamma - \frac{1}{}\nabla\cdot u\right) \tag{3}$$

where μ is the dynamic molecular viscosity and γ is the strain rate tensor. Postulating an incompressible fluid, the second term in the parenthesis of Eqn. 3 is equal to zero and the strain tensor τ then reads:

$$\tau = \mu\frac{1}{2}\left[\nabla u + (\nabla u)^t\right] \tag{4}$$

Combining the conservation equations Eqn. 1 and Eqn. 2 with the constitutive relationship Eqn. 4 results in the Navier-Stokes equation:

$$\frac{Du}{\quad} = f - \nabla p + \mu \nabla^2 u \tag{5}$$

Flow in a gap (crack)

For a flow in a narrow gap or crack some specific attributes are significant. Under the physically admissible assumption that the velocity component in z-direction is zero, the continuity equation (Eqn. 1) results in $\delta u/\delta x = 0$, which means that the flow is unidirectional and such the convective term in the substantial derivative vanishes. Under these aspects and by neglecting the body force, the Navier-Stokes equation for the *steady state* case reduces to:

$$0 = -\frac{\delta p}{\delta x} + \mu \frac{\delta^2 u}{\delta z^2} \tag{6}$$

Integration under consideration of the boundary condition $u(z) = 0$ at $z = \pm w/2$ and averaging the velocity over the cross-section leads to

$$(z)_{av} \qquad \frac{1}{\cdot \mu} \qquad (x)\frac{\delta p}{x} \tag{7}$$

For a slightly compressible injection fluid the following correlation between the density and the pressure is introduced

$$\rho(p) = \rho_0 e^{C(p-p_0)} \Rightarrow \rho_0[1 + C(p - p_0)]$$
$$\frac{\quad}{\delta t} = \rho_0 C \frac{p}{\delta t} \tag{8}$$

with C is the compressibility of the liquid.

Combining the continuity equation Eqn. 1 , the gap flow characteristic Eqn. 7 and the equation of state Eqn. 8, results in

$$\frac{p(\gamma,t)}{\delta t} = \frac{\quad}{12 \cdot \mu \cdot C \cdot f(k_a)} \cdot \frac{\quad}{\gamma^n} \frac{\quad}{\delta \gamma}\left[\gamma^n \quad {}^2(\gamma,t) \cdot \frac{\delta p(\gamma,\ )}{\delta \gamma}\right] \tag{9}$$

with $\gamma = x$, $n = 0$ and $\gamma = r$, $n = 1$ for the planar crack and the axially symmetric crack configuration respectively. The function $f(k_a)$ is a friction coefficient considering the roughness of the gap surfaces.

The Eqn. 9 is a representative of diffusivity equations where the fluid flow equation Eqn. 7 also may be interpreted as a rate equation based on Darcy's law. Under consideration of characteristic boundary conditions (Dirichlet, Neumann) and certain global mass criteria this equation may serve for the assessment of the time dependent pressure distribution in a gap during a grouting procedure. A similar strategy was used in a case of hydraulic fracturing stress determination [8].

Structural Mechanics Representation

The response of the 'unbounded impermeable' elastic medium, surrounding the crack configuration, due to the flow induced pressure development is given by the crack opening displacements and the associated stress intensity factor growth rate at the crack front. An expression for the crack opening displacements is given in [9] for both cases and is represented by Eqn. 10 in a formulation according to Lit. [3]:

$$w(\gamma,t) = w(\gamma,0) + \frac{8 \cdot \left(1-\nu^2\right)}{\pi \cdot E} \cdot \int_{\gamma}^{\Gamma} \frac{s^{(1-n)}}{\left(s^2 - \gamma^2\right)^{1/2}} \cdot ds \cdot \int_{\chi}^{s} \frac{p(u,t)}{\left(s^2 - u^2\right)^{1/2}} \cdot u \cdot du \tag{10}$$

with $\gamma = x$, $\Gamma = L$, $n = 0$, $\chi = 0$ and $\gamma = r$, $\Gamma = R$, $n = 1$, $\chi = r_0$ for the planar crack and the axially symmetric crack configuration respectively. The surrounding medium is defined through the modulus of elasticity E and the Poisson ratio ν, r_0 is the radius of the bore-hole . The mode 1 stress intensity factor (SIF) expression for both cases reads:

$$_I(t) = -^{1/} \int_0 \frac{(\gamma, t)}{\left(\Gamma^2 - \gamma^2\right)^{1/}} \left(-\right)^n \cdot d\gamma \qquad (11)$$

with the same labels as defined above.

NUMERICAL METHOD

The solution of the fluid flow equations Eqn. 9 under consideration of appropriate initial and boundary conditions and under direct compensation of Eqn. 10 at each time step (decoupling) was carried out by an implicit finite difference scheme. A detailed discussion weighing up the pros and cons compared to the explicit method may be found in Lit. [10] and is not discussed further here. An essential disadvantage lies in the fact that the 'propagation speed' is infinite and therefore the fluid front at each time step is adjusted due to a surface tension criterion and a global mass balance consideration. According to the particular boundary condition an associated tridiagonal algebraic system has to be solved. Additionally, at each time step the determination of the stress intensity factor is carried out via Eqn. 11.

SOLUTIONS (EXAMPLES)

Each method is as good as the correspondence to results of natural cases or experiments to be simulated with. Therefore a comprehensive investigation with the planar model has been carried out for in situ cases (grouting of cracks in the Koyna dam), block tests (repair of Zeuzier dam) and basic experiments with gaps formed by stiff steel plates. The results are documented in Lit. [11], which mainly is focussed on the engineering aspect of the procedure. A Fortran routine for the axial symmetric case is given in Lit. [12]. The pressure development for an open 'gap' , simulating an in situ procedure [13] is given in Figure 2, where also an extension up to a steady state behaviour is carried out, showing the typical logarithmic characteristic.

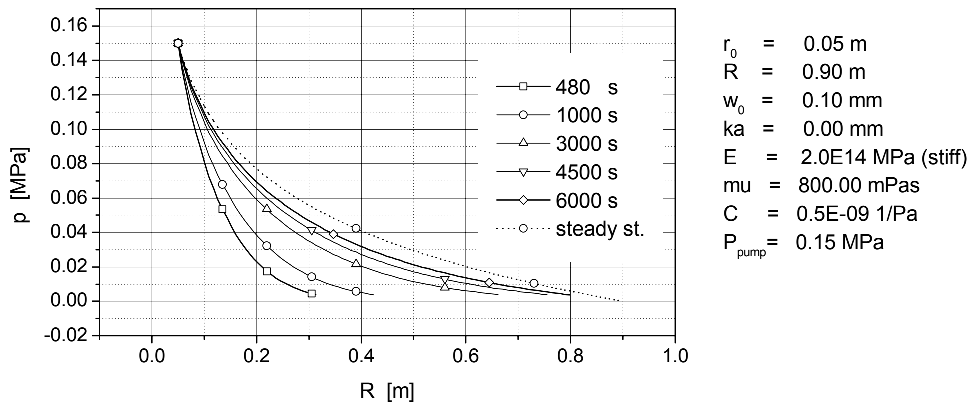
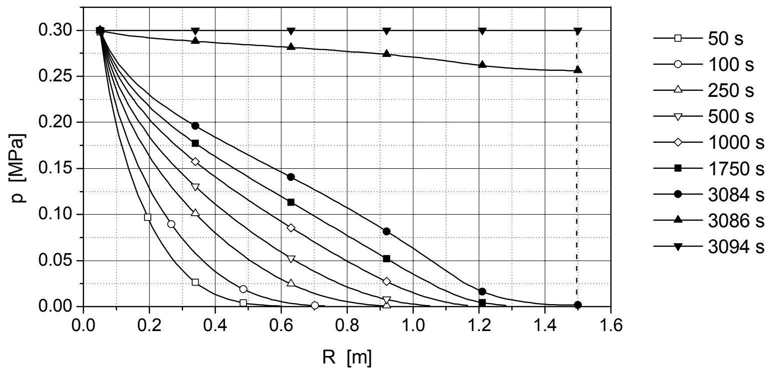
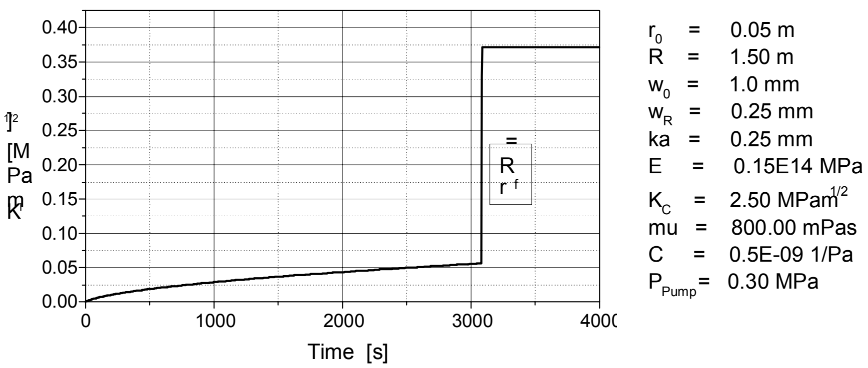


Figure 2: Pressure development in an open 'gap'

The pressure distribution and the associated time dependent Stress Intensity Factor (SIF) development in a radial crack configuration with wedge shaped geometry is documented in Figure 3a and in Figure 3b. The abrupt transition in the SIF-diagram up to the static pressure is typical for the fluid front approaching the crack tip. This analysis can be used for a save grouting procedure, to control the pressure according to a given limit of the fracture toughness K_{IC} of the concrete or rock [11].



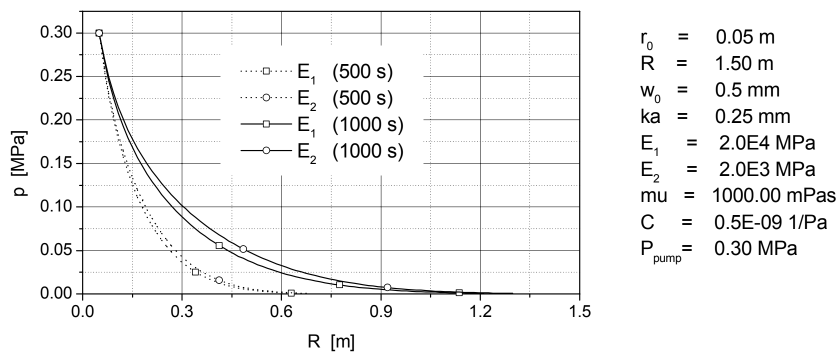
a)



b)

Figure 3: Radial crack system - wedge shaped geometry
a) pressure development
b) associated Stress Intensity Factor

The influence of the crack environment on the fluid structure interaction process characterised by a variation of the Modulus of Elasticity, both on the pressure distribution, the crack profile and the SIF-development is shown in Figure 4a, Figure 4b and Figure 4c respectively.



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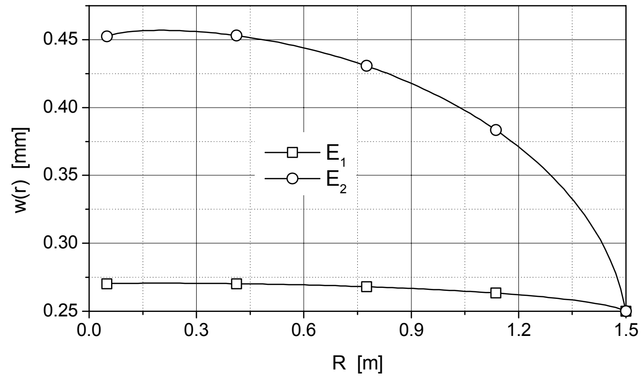

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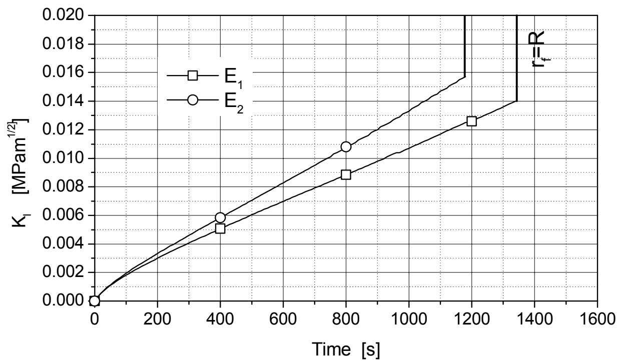

c)

Figure 4: Radial crack system with different moduli of elasticity (E_1/E_2=10)

a) pressure distributions
b) crack opening profiles
c) SIF-characteristics

Whereas for this special case the pressure distributions (Figure 4a) due to different moduli of elasticity with a ratio of E_1/E_2 =10 correspond quite well, naturally the crack opening profiles (Figure 4b) show significant discrepancies. The SIF-gradients (Figure 4c) are different, with a steeper inclination for the softer material.
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CONCLUSION

The present investigation may be seen as an illustration of the physical process which is characteristic for the grouting of cracks. Especially parameter studies can serve the purpose of understanding the influence of fluid, matrix and geometrical attributes on a stable procedure.

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