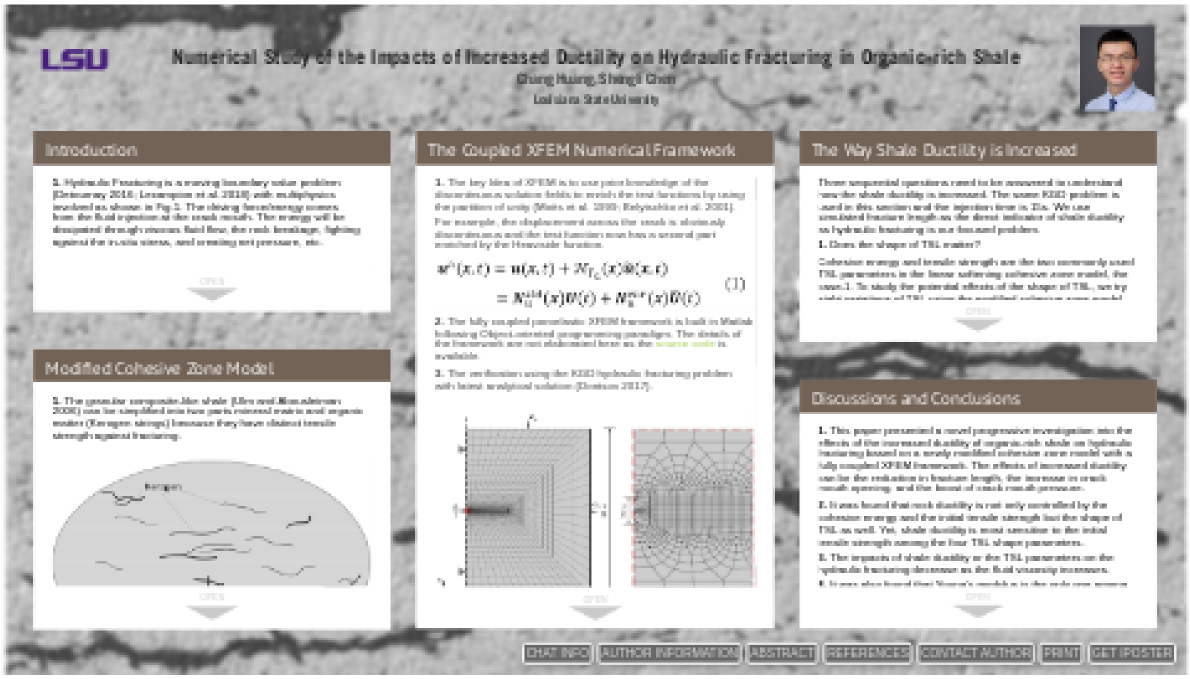
Numerical Study of the Impacts of Increased Ductility on Hydraulic Fracturing in Organic-rich Shale



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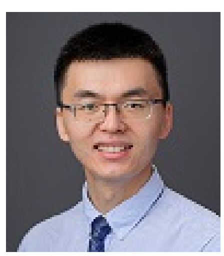

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1. INTRODUCTION

Please click below to start the opening talk.

1. Hydraulic Fracturing is a moving boundary value problem (Detournay 2016; Lecampion et al. 2018) with multiphysics involved as shown in Fig.1. The driving force/energy comes from the fluid injection at the crack mouth. The energy will be dissipated through viscous fluid flow, the rock breakage, fighting against the in-situ stress, and creating net pressure, etc.

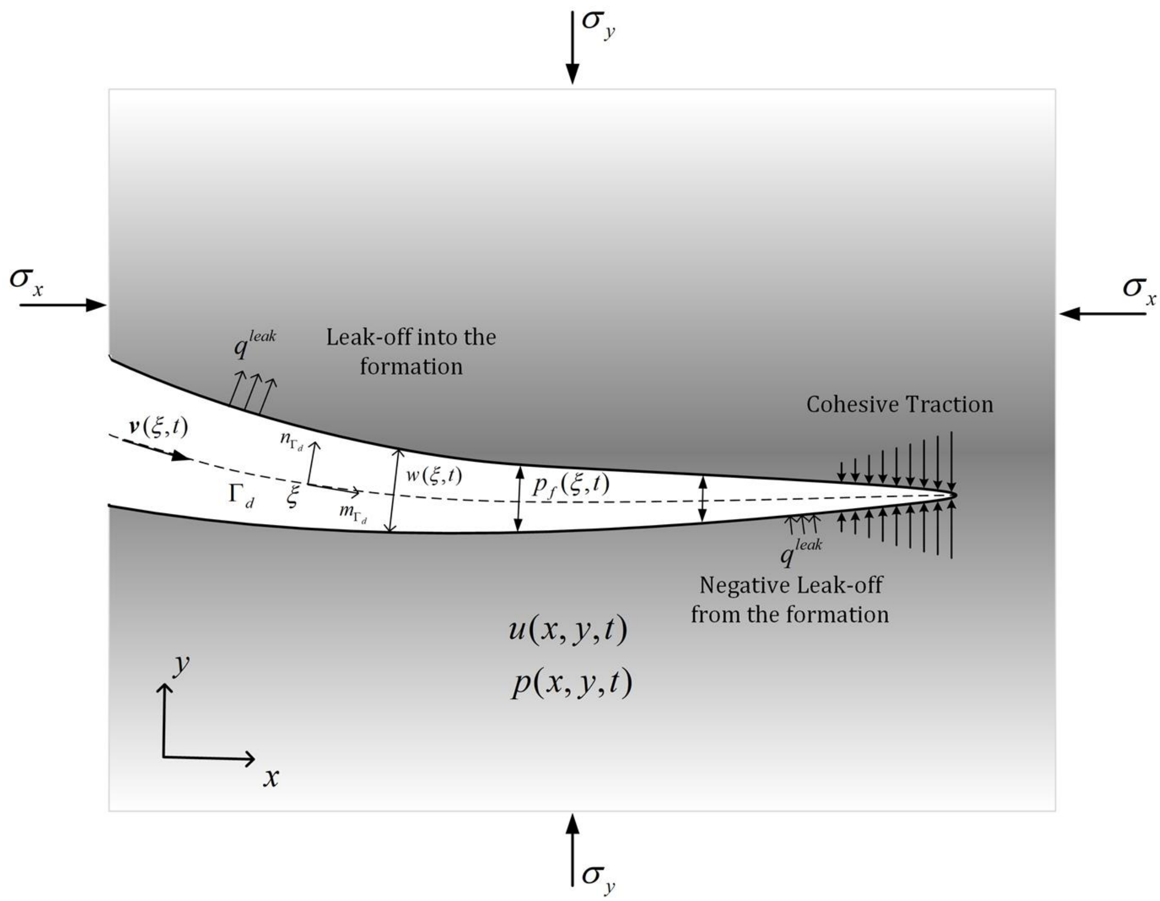

Fig. 1 Schematics of the multiphysics involved in hydraulic fracturing.

2. The cohesive traction between newly created crack faces could may not monotonously decrease with crack separation due to ample organic matter in shale (Abousleiman et al. 2016; Hull et al. 2017).

3. Modified cohesive crack model is developed to achieve various traction-separation laws (TSL).

4. The modified cohesive crack model is implemented in a newly developed and verified XFEM simulation framework.

5. The impacts of the increased rock ductility in terms of the cohesive TSLs and poroelastic moduli are studied.

2. MODIFIED COHESIVE ZONE MODEL

1. The granular composite-like shale (Ulm and Abousleiman 2006) can be simplified into two parts mineral matrix and organic matter (Kerogen strings) because they have distinct tensile strength against fracturing.

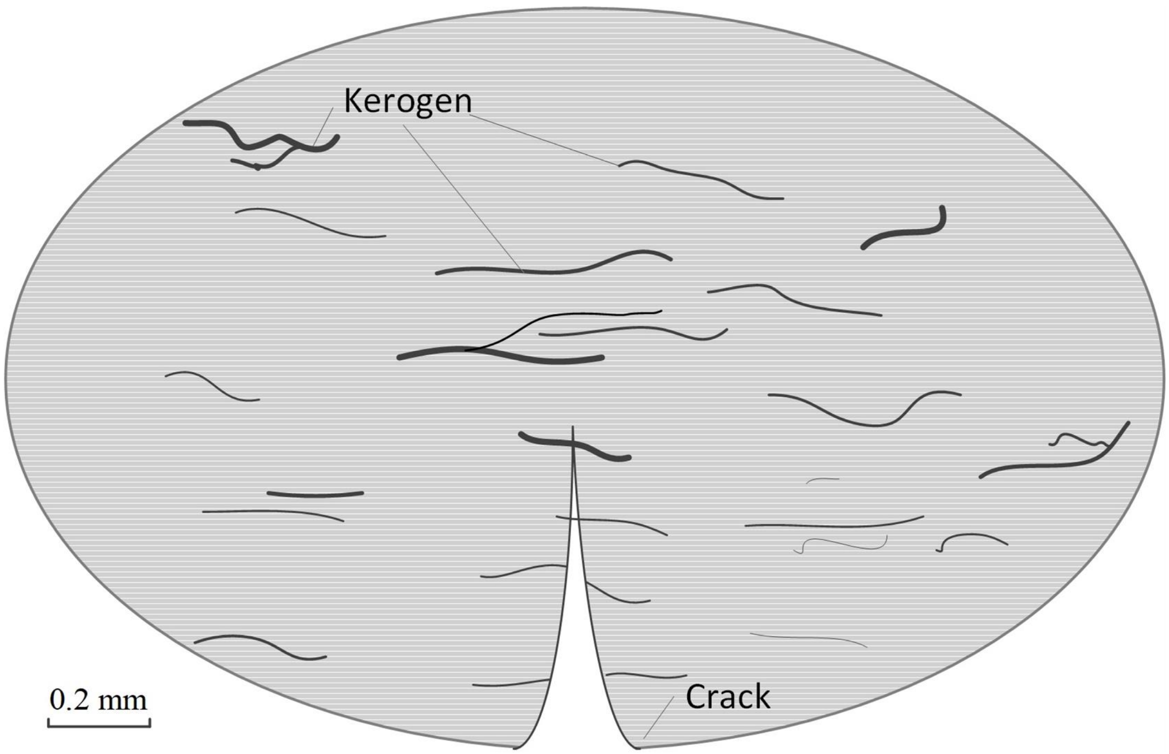

Fig. 2 Schematic of a hydraulic fracture propagating in composite shale with mineral matrix and scattered kerogen.

2. The tensile traction can keep increasing after the breaking of the mineral matrix as shown from the experimental study (Abousleiman et al. 2016; Hull et al. 2017).

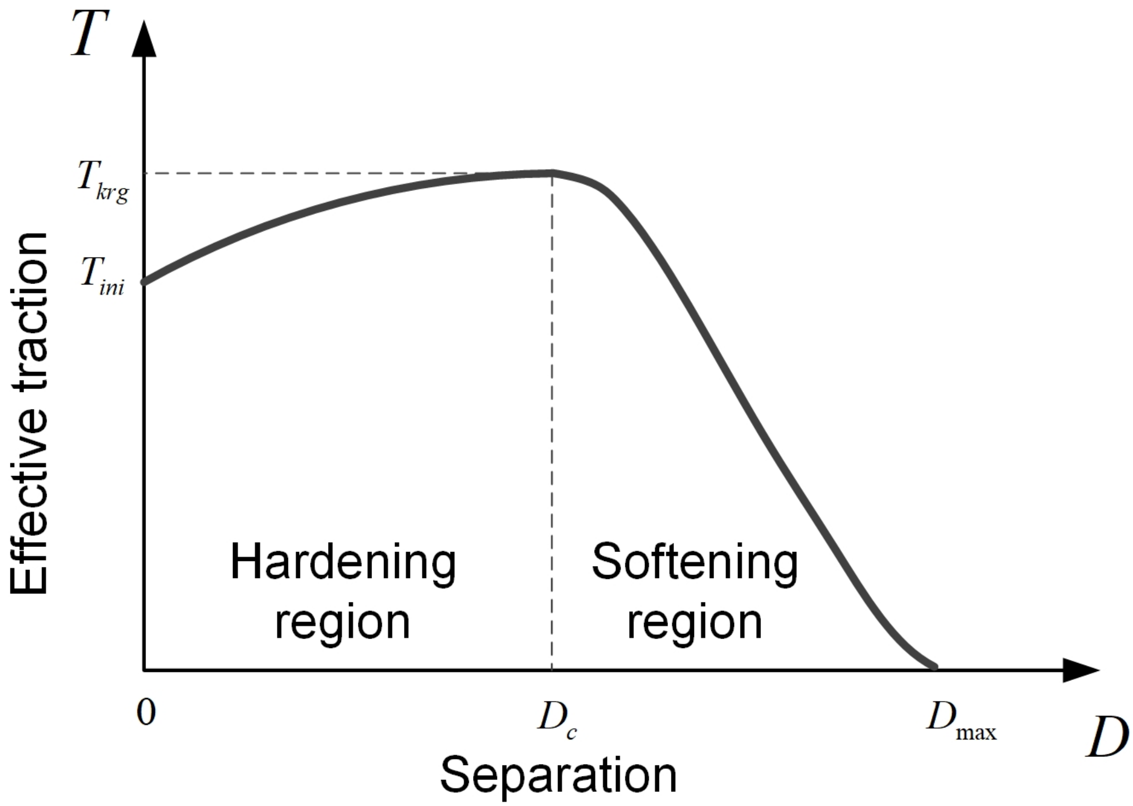

Fig. 3 The relationship between cohesive traction and the crack separation (TSL)

The initial tensile strength T_{ini} is related to the tensile strengths of mineral matrix and kerogen strings, which further depends on local kerogen content and stretch degree of kerogen strings at the wake of crack opening, etc. The cohesive traction between crack faces within the process zone should be mainly attributed to kerogen strings as the matrix is already damaged. We define the ultimate tensile strength, T_{krg}, the maximum value that the kerogen strings can reach at the critical separation D_c. The tensile strength eventually diminishes to zero at separation D_{max}.

3. THE COUPLED XFEM FRAMEWORK

1. The key Idea of XFEM is to use prior knowledge of the discontinuous solution fields to enrich the test functions by using the partition of unity (Moës et al. 1999; Belytschko et al. 2001).

For example, the displacement across the crack is obviously discontinuous and the test function now has a second part enriched by the Heaviside function.

$$\begin{aligned}\boldsymbol{u}^h(\boldsymbol{x},t) &= \boldsymbol{u}(\boldsymbol{x},t) + \mathcal{H}_{\Gamma_d}(\boldsymbol{x})\widetilde{\boldsymbol{u}}(\boldsymbol{x},t) \\ &= \boldsymbol{N}_u^{std}(\boldsymbol{x})\boldsymbol{U}(t) + \boldsymbol{N}_u^{enr}(\boldsymbol{x})\widetilde{\boldsymbol{U}}(t)\end{aligned} \qquad (1)$$

2. The fully coupled poroelastic XFEM framework is built in Matlab following the object-oriented programming paradigm. The details of the framework are not elaborated here as the source code (http://github.com/neclipse/HFXFEM-Single-Crack-Verified) is available.

3. The verification using the KGD hydraulic fracturing problem with the latest analytical solution (Dontsov 2017).

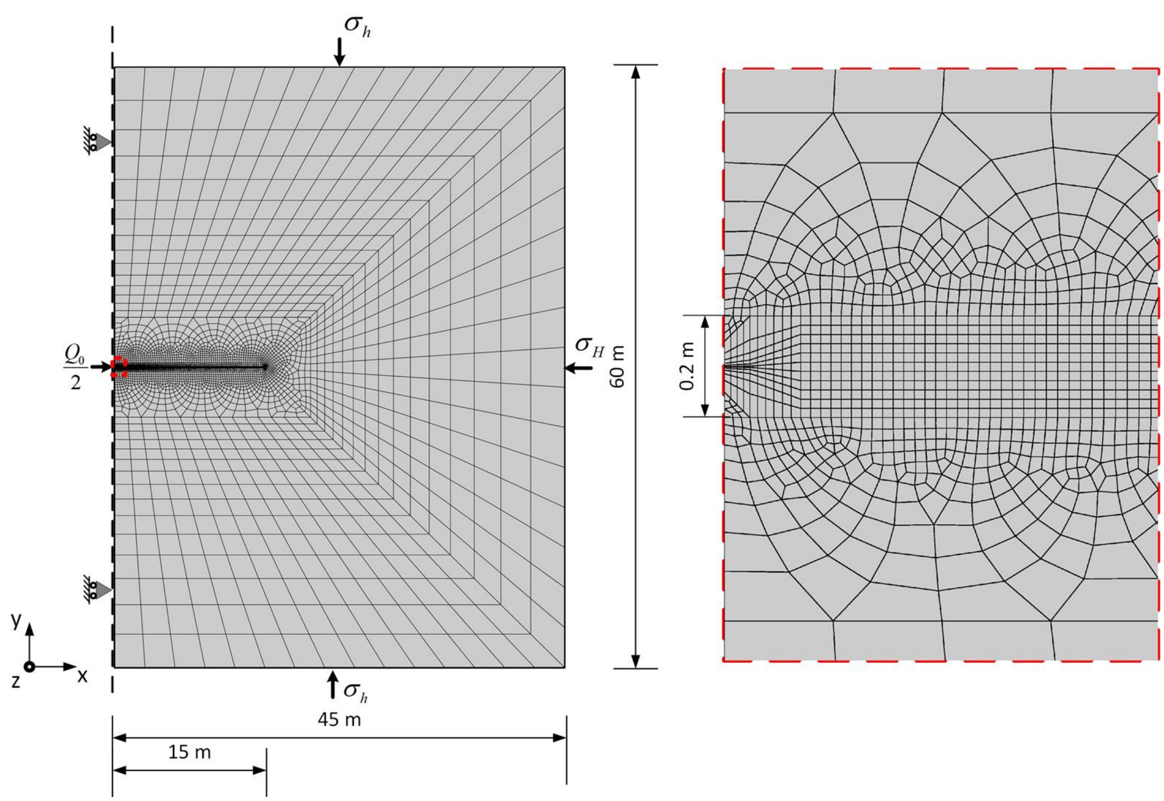

Fig. 4 Mesh and boundary conditions for the simulation of the KGD hydraulic fracturing problem with a zoomed-in view of the near injection zone to the right.

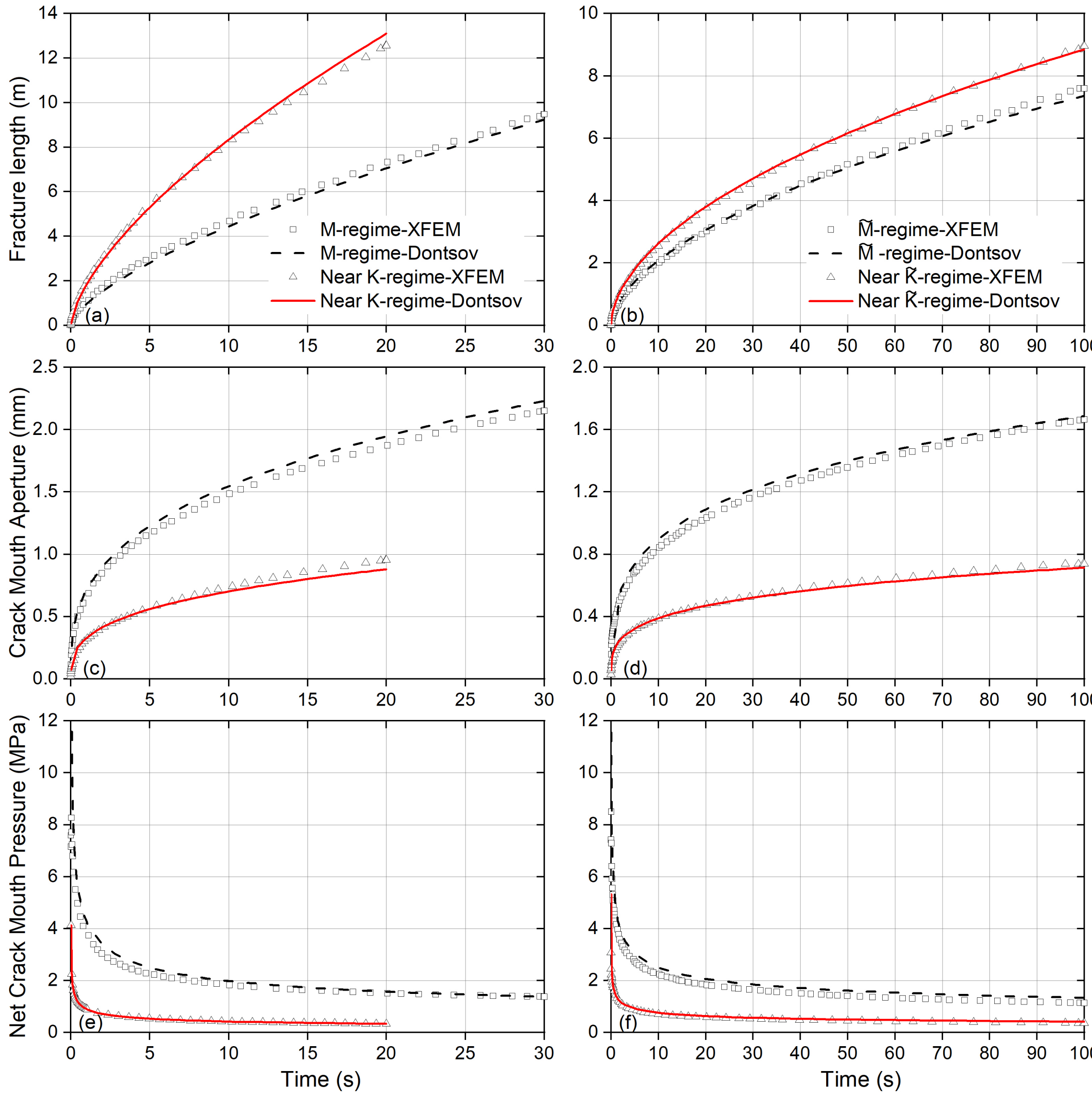

Fig. 5 The comparison of (a) (b) crack length, (c) (d) crack mouth opening; and (d) (e) net crack mouth pressure between current XFEM scheme and Dontsov's analytical solution. The left column listed the results for storage-viscosity regime and near storage-toughness regime and the right column plots the results for leak-off-viscosity and near leak-off-toughness regime.

4. THE WAY SHALE DUCTILITY IS INCREASED

Three sequential questions need to be answered to understand how the shale ductility is increased. The same KGD problem is used in this section and the injection time is 15s. We use simulated fracture length as the direct indicator of shale ductility as hydraulic fracturing is our focused problem.

1. Does the shape of TSL matter?

In the linear softening cohesive zone model, the case-1, the cohesive energy and tensile strength are the two commonly used TSL parameters. To study the potential effects of the shape of TSL, we tried eight variations of TSL using the modified cohesive zone model while controlling the same cohesive energy and tensile strength as cases 2-9. The simulation results are compared in Fig.5 and it is clear that the shape of TSL does matter.

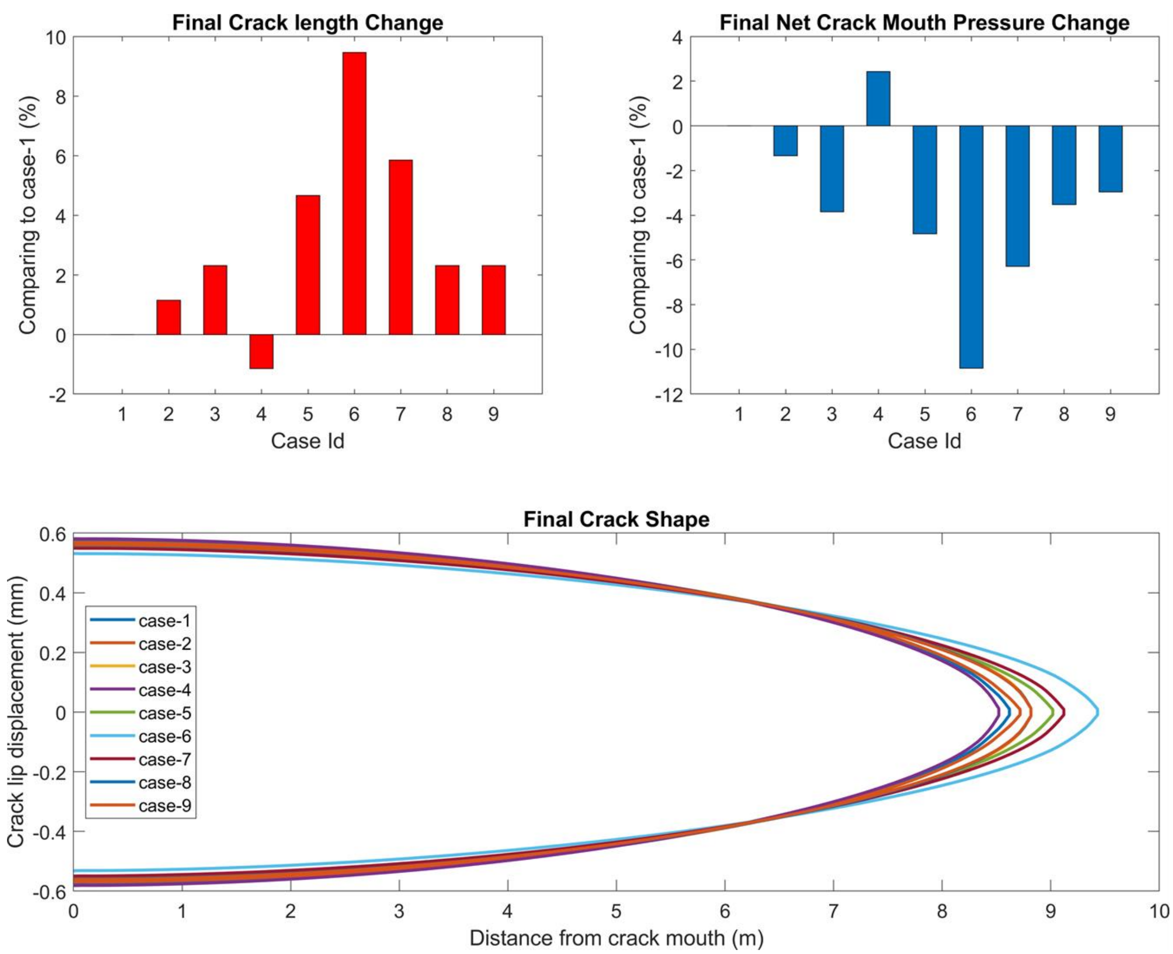

Fig. 5 Comparison of hydraulic fracturing results for nine variations of TSL shapes with the same cohesive energy and the same tensile strength.

2. How does each TSL shape parameter play a role?

The question can be answered by setting each TSL shape parameter as the controlling parameter and keeping the other three as constants. Furthermore, we repeat the parametric study by increasing the injection fluid viscosity from 0.5 mPa.s to 5 and 50 mPa.s.

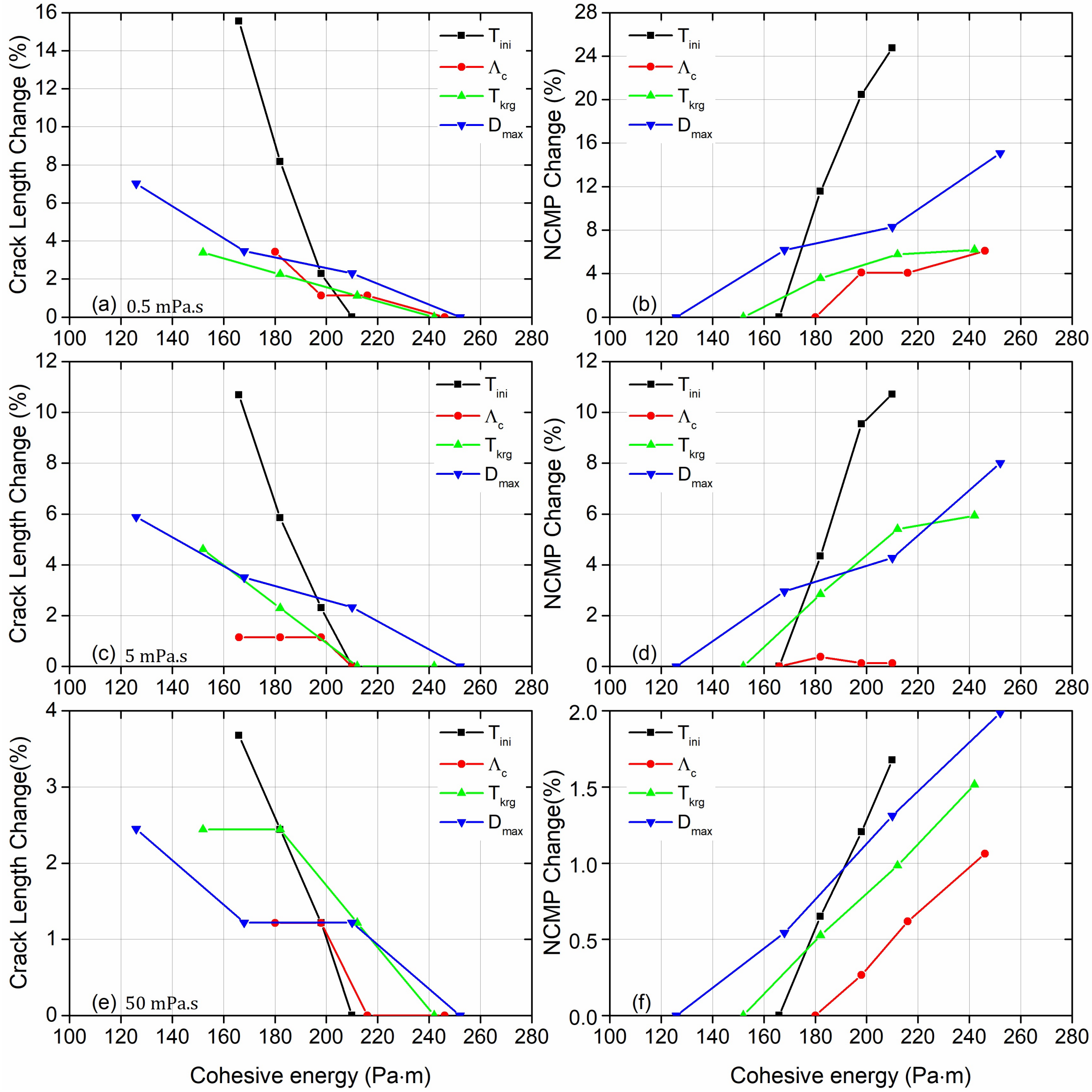

Fig. 7 Influences of each TSL parameter on the fracturing results under three fracturing fluid viscosities. The left column shows the change of crack length and the right column shows the change of net crack mouth pressure (NCMP). Relative change is based on the minimum value within each group.

The increase of any of the four TSL parameters leads to decreases in fracture length and increases in net crack mouth pressure. It is obvious that the results are most sensitive to the initial tensile strength $T_{ini.}$

3. How about the poroelastic parameters?

In addition to the cohesive TSL parameters, the poroelastic parameters may also affect the brittleness or ductility. Among the four independent constitutive parameters, Young's modulus, Poisson's ratio, Biot effective stress coefficient, Biot Modulus, only Young's modulus show significant impacts on the shale ductility. The smaller Young's modulus, the more ductile the shale becomes.

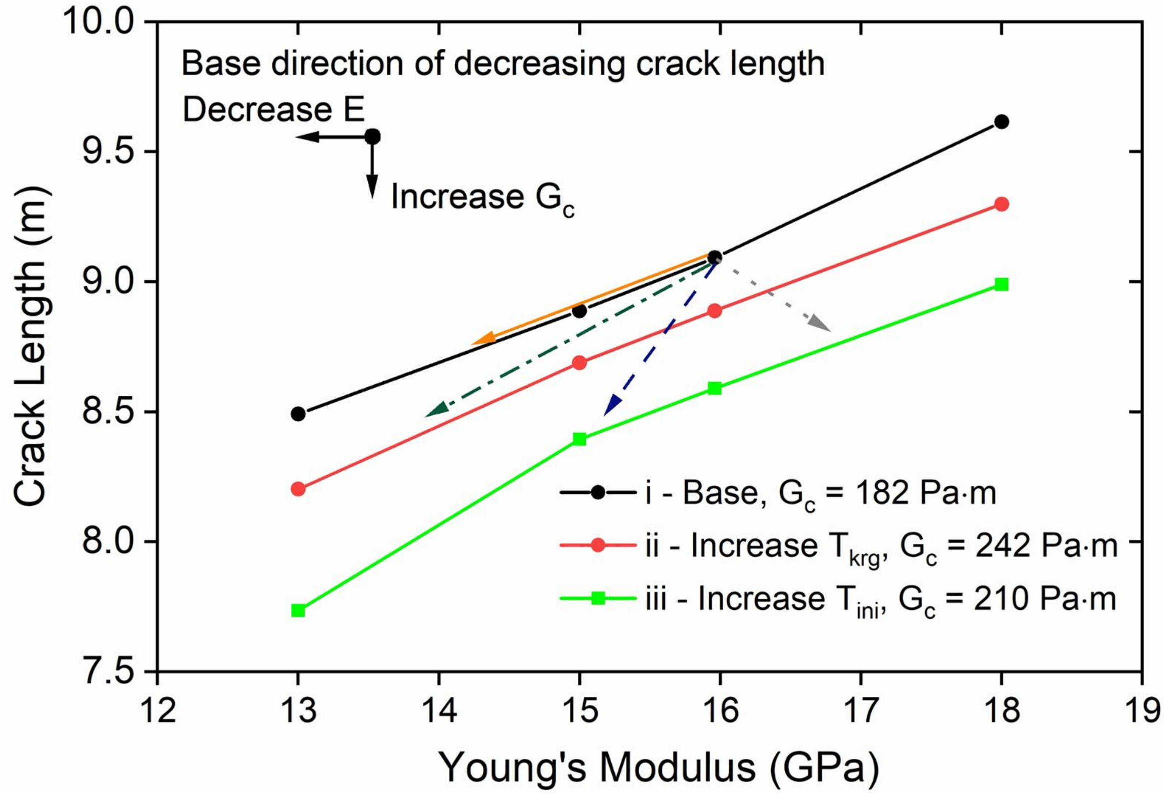

Fig. 8 Influences of Young's modulus and two TSL parameters on hydraulic fracture length.

It clearly shows that crack length goes down with the decrease in Young's modulus and the increase of cohesive energy $G_{c.}$

5. DISCUSSIONS AND CONCLUSIONS

1. This paper presented a novel progressive investigation into the effects of the increased ductility of organic-rich shale on hydraulic fracturing based on a newly modified cohesive zone model with a fully coupled XFEM framework. The effects of increased ductility can be the reduction in fracture length, the increase in crack mouth opening, and crack mouth pressure.

2. It was found that rock ductility is not only controlled by the cohesive energy and the initial tensile strength but the shape of TSL as well. Yet, shale ductility is most sensitive to the initial tensile strength among the four TSL shape parameters.

3. The impacts of shale ductility or the TSL parameters on the hydraulic fracturing decrease as the fluid viscosity increases.

4. It was also found that Young’s modulus is the only one among four common poroelastic parameters to considerably influence the ductility/brittleness of rock formation and hydraulic fracture lengths. The increase in cohesive energy accompanied by the decrease of Young’s modulus, in general, will significantly reduce the fracture length or stimulated reservoir volume.

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The source code in GitHub (https://github.com/neclipse/HFXFEM-Single-Crack-Verified)

ABSTRACT

The popular cohesive zone model that only features decreasing traction along with crack separation may not adequately represent the crack behavior in shale due to ample organic matter. This paper starts by proposing a modified cohesive zone model that can represent various traction-separation laws (TSL) within a unified formulation. Then a fully coupled poroelastic XFEM framework to simulate hydraulic fracturing in organic-rich shales was developed in Matlab and comprehensively verified against the latest analytical solutions. The influences of increased ductility in different forms were studied using the modified cohesive zone model in the context of field-scale hydraulic fracturing simulations. Three important conclusions were drawn. First, the shape of TSL does affect the hydraulic fracturing given the same cohesive crack energy and tensile strength. It infers that ductility is not only controlled by cohesive crack energy and tensile strength, which further indicates the necessity of the newly proposed TSL. Second, the tensile strength, controlling when the cohesive crack starts propagating, has the greatest impacts on the hydraulic fracturing, among all TSL shape parameters. The impacts of TSL parameters become less significant as the fracturing fluid viscosity increases. Lastly, Young's modulus is the only one among four common poroelastic parameters that significantly changes the ductility/brittleness of rock formation and hydraulic fracture lengths. The increase in cohesive energy accompanied by the decrease of Young's modulus will greatly reduce the induced fracture length.

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