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TECHNICAL NOTE

Robustness to formation geological heterogeneities of the limited entry technique for multi-stage fracturing of horizontal wells

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Nomenclature

N	Number of hydraulic fractures in a stage
$\Delta p_{\mathrm{perf}_i}$	Local pressure drop through the perforations at the entrance of fracture # i
p^{w}	Pressure in the well
p_i^{f}	Pressure at the entrance of fracture # i
Q_i	Flow rate entering fracture # i
Q_o	Surface pump injection rate
f_{p}	Perforations cluster friction coefficient
D_{p}	Perforation diameter
n_{p}	Number of perforations in a cluster in front of a given fracture
ρ	Fracturing fluid density
C	Perforation discharge coefficient
σ_{h}	Minimum horizontal in-situ stress
z	True vertical depth
E	Young's modulus
v	Poisson's ratio
K_{Ic}	Fracture toughness
R	Fracture radius
σ_{I}	Interaction stress on a given fracture
t	time

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All horizontal wells in unconventional reservoirs are stimulated today by hydraulic fracturing in a sequential manner from the "toe" to the "heel" of the well ("multi-stage fracturing"). Typically, a fracturing stage consists in performing a hydraulic fracturing treatment over a section of the well isolated by a bridge plug from the previously created hydraulic fractures. One stage contains N perforation "clusters", typically between two and six, spaced from 10 to 30 m apart. A perforation cluster is the point of initiation of a hydraulic fracture. The technology therefore relies on the initiation and propagation of N hydraulic fractures simultaneously, balancing gain in rig time (large N) and robustness of the process (small N). In this note, using a recently developed numerical model (Lecampion and Desroches 2015), we investigate the effects of in-situ heterogeneities on the initiation and propagation of simultaneous hydraulic fractures and how well these effects can be mitigated.

The main engineering tool to promote simultaneous growth of multiple hydraulic fractures is the so-called limited entry technique, originally developed for vertical wells in the early 1960s (Lagrone and Rasmussen 1963). It aims at equilibrating the flow rate entering the different fractures even if the fracturing pressure is different. A local entry friction exists at the level of the perforations at the entrance of each fracture. It relates the pressure difference between the wellbore and the fracture $\Delta p_{\mathrm{perf}_i} = p^{\mathrm{w}} - p_i^{\mathrm{f}}$ to the flux Q_i entering the fracture $\#\ i$. For a cluster of n_{p} perforations of diameter

D_p linking the wellbore to the fracture, this pressure drop is typically approximated by (Crump et al. 1988):

$$\Delta p_{\mathrm{perf}_i} = p^{\mathrm{w}} - p_i^{\mathrm{f}} = f_{\mathrm{p}} Q_i^2 \qquad (\mathrm{SI\,units}) \tag{1}$$

$$f_{\mathrm{p}} = 0.807249 \frac{\rho}{n_{\mathrm{p}}^2 D_{\mathrm{p}}^4 C^2} \qquad (\mathrm{SI\,units}) \tag{2}$$

where C is a dimensionless discharge coefficient [typically between 0.55 (sharp perforations) and 0.9 (eroded ones)].

The knowledge of p_i^{f} for each hydraulic fracture allows to solve for the pressure in the wellbore and the flux entering each fracture, from the pressure drop Eq. (1) combined with the global volume balance $Q_o = \sum_i Q_i$—where Q_o is the surface pump rate. This calculation neglects any time variations of pressure and assumes a constant uniform pressure inside each fracture. It is a very strong approximation motivated by the fact that the fluid pressure in a propagating fracture is governed to the first order by the in-situ minimum stress.

As an illustrative example, let us consider the case of a horizontal section of a well at a true vertical depth of 7000 ft (2133 m), completed with a 5″ (12.7 cm) ID casing. We consider a stage comprising four clusters spaced 50 ft (15.2 m) apart, located in zones bearing a different far-field in-situ minimum horizontal stress. The first perforation cluster is located at a measured depth of about 2500 m. To avoid proppant settling in the wellbore, a minimum rate of about 18 BPM [for a 5″ (12.7 cm) casing] entering each fracture is desirable. Assuming a pump rate Q_o of $18 \times 4 = 72$ barrels per minute (BPM) (0.19 m^3/s), and the values of the in-situ stress listed in Table 1 (and taking $p_i^{\mathrm{f}} = \sigma_{\mathrm{h},i}$), a uniform perforation design with 10 perforations per cluster results in a large difference in the flux Q_i entering each fracture (see Table 1). Ultimately, very little proppant would be placed in the last cluster using such a "blind" design not accounting for the in-situ stress variation along the stimulated section. By adjusting the number of perforations in each cluster, however, one can balance the different fluxes by increasing the perforation pressure drop in front of zones with lower fracturing pressure. Results presented in Table 1 show that, within the aforementioned assumptions, the different fluxes can be equilibrated in such a way. We will refer to such practice as an engineered limited entry design (i.e. different n_{p} for each cluster) in comparison to a uniform perforation design (i.e. n_{p} equal for all clusters).

A number of well known issues linked to the perforating process itself can, however, detrimentally affect the robustness of limited entry (Economides and Nolte 2000): (1) not all perforations within a given cluster may take fluid (i.e. some perforation tunnels may not be linked to the fracture) (2) perforations erode as proppant slurry is pumped, reducing the pressure drop across the perforations, therefore modifying the balance of the fluxes entering the different fractures.

In order to fully investigate the robustness of the limited entry technique, one needs to simulate the complete process of initiation and propagation of multiple hydraulic fractures, also accounting for fluid flow in the wellbore together with perforation friction and stress interaction between fractures. We use a recently developed model

Table 2 Rock properties assumed for this study

E	ν	$E' = \frac{E}{1-\nu^2}$	K_{Ic}
kpsi (GPa)	–	kpsi (GPa)	psi.$\sqrt{\text{inch}}$ (MPa.$\sqrt{\text{m}}$)
3625 (25)	0.2	3777 (26.04)	1092 (1.2)

Table 1 Limited entry calculation: case of 4 clusters uniformly spaced by 50 ft (15.2 m) having different fracturing pressures (taken here as the minimum in-situ stress) and a total surface pump rate Q_o of 72 BPM (0.19 m^3/s)

Cluster #	1	2	3	4
σ_{h}/z psi/ft (MPa/m)	0.71 (0.016)	0.77 (0.017)	0.74 (0.0167)	0.8 (0.018)
σ_{h} in psi (MPa) @ 7000 ft (2133 m)	4970 (34.26)	5390 (37.16)	5180 (35.7)	5600 (38.6)
Uniform entry				
n_{p}	10	10	10	10
Q_i BPM (m^3/ s)	27.4 (0.072)	16.5 (0.043)	22.5 (0.059)	5.6 (0.014)
Engineered entry				
n_{p}	6	8	7	12
Q_i BPM (m^3/ s)	18.5 (0.049)	17.2 (0.0455)	18.5 (0.049)	17.8 (0.047)

Uniform versus engineered limited entry by adjusting the number of perforations per cluster, assuming a perforation discharge coefficient $C = 0.6$, a perforation of diameters 1/2″ and a slick-water fluid ($\rho = 1010$ kg/m ^{3}, viscosity of 5 cP, compressibility 4.5×10^{-10} Pa $^{-1}$)

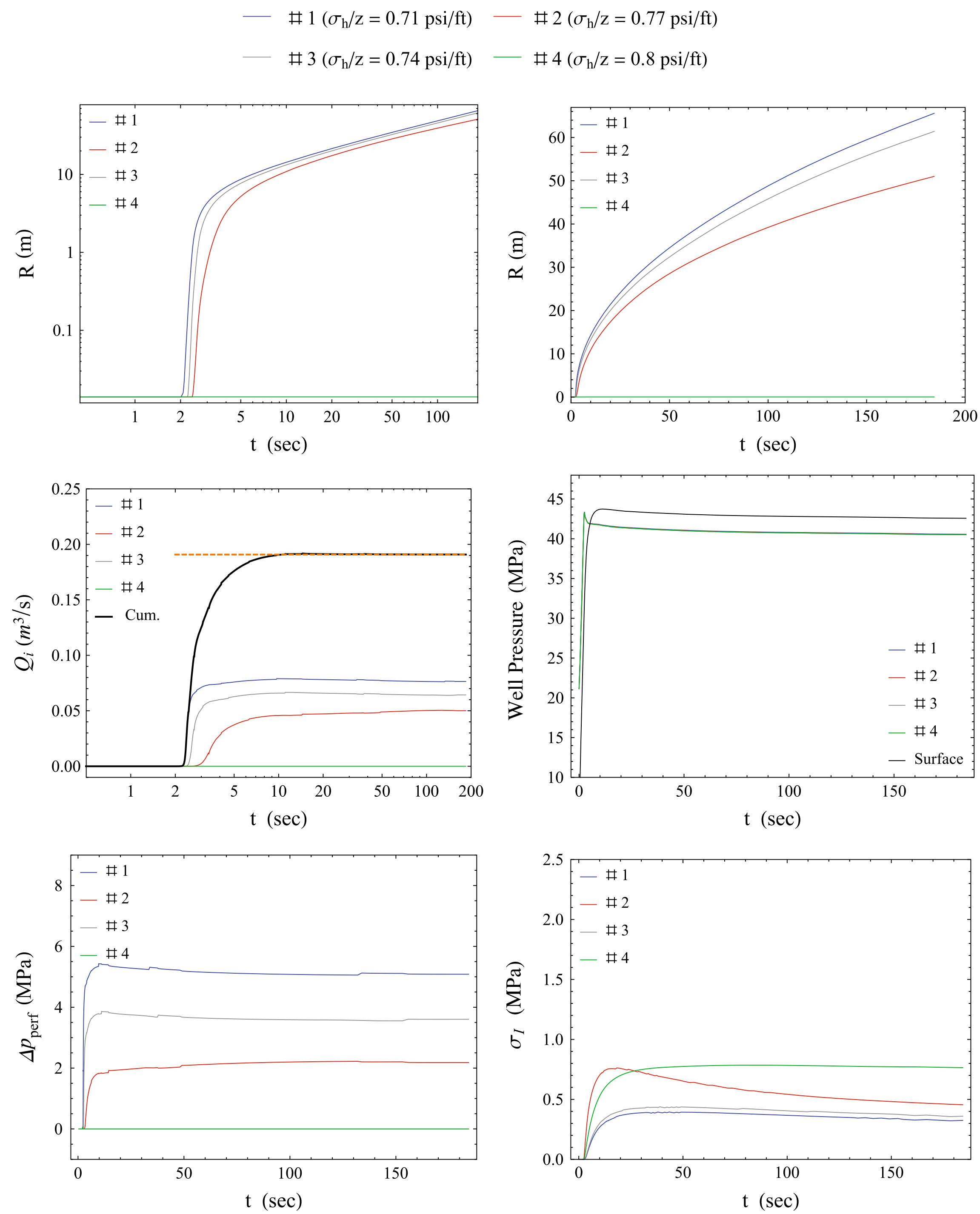

Fig. 1 Heterogeneities of the minimum in-situ stress—uniform limited entry design: case of 10 perforations per cluster ($n_p = 10$), i.e. large perforation pressure drop. Fractures radius, inlet fluxes, downhole and surface pressures, perforation clusters pressure drop and mean interaction stresses (i.e. average of σ_I over each fracture). Note that fracture #4 does not initiate

accounting for all these features, assuming that all fractures remain radial, transverse to the wellbore [see Lecampion and Desroches (2015) for more details, model validation and simulations for a perfectly homogeneous case]. Results using this model for the case where the in-situ stress is uniform along a stage have shown that a perforation friction larger than the interaction stress σ_I promotes simultaneous growth; i.e. large perforation friction counteracts stress shadow [see also Lecampion et al. (2015) for more simulations]. However, the effects

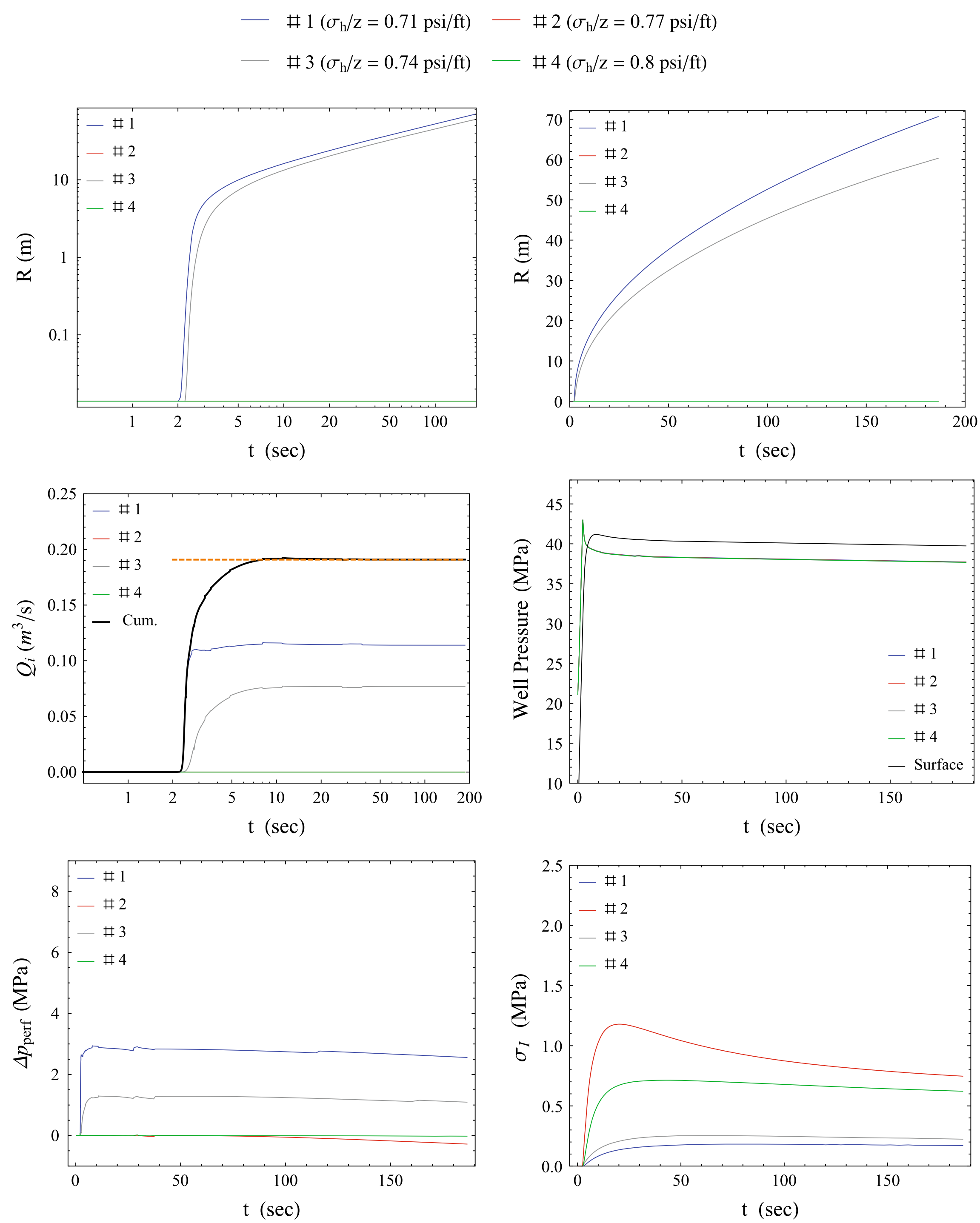

Fig. 2 Heterogeneities of the minimum in-situ stress—uniform limited entry design: case of 20 perforations per cluster ($n_p = 20$), i.e. small perforation pressure drop. Fractures radius, inlet fluxes, downhole and surface pressures, perforation clusters pressure drop and mean interaction stresses (i.e. average of σ_I over each fracture). Note that fractures #2 and 4 do not initiate

of stress heterogeneities or rock strength variations have not yet been investigated.

We shall use the same example as that presented above ($N = 4$ clusters with variations of in-situ stress as per Table 1). We restrict our study to slick water treatments. The rock parameters are listed in Table 2. The simulations carried out here are focused on fracture initiation and radial propagation (until the fracture reaches the reservoir height) to provide insight into the initial and crucial stage of fracture growth before proppant is injected into the

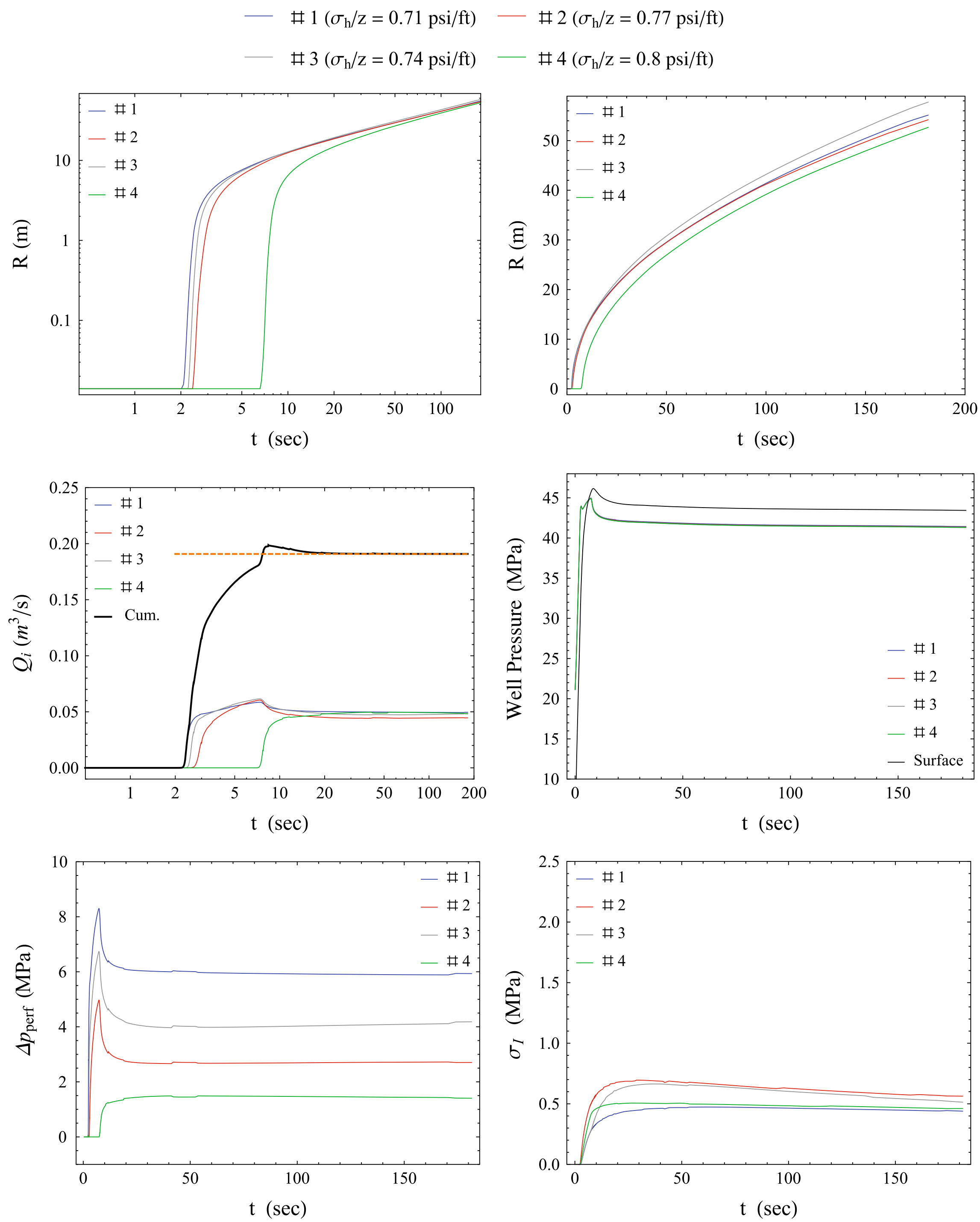

Fig. 3 Heterogeneities of the minimum in-situ stress—engineered limited entry design. Fractures radius, inlet fluxes, downhole and surface pressures, perforation clusters pressure drop and mean interaction stresses (i.e. average of σ_I over each fracture)

fractures. Indeed, the amount of proppant that could be placed in each fracture is, to the first order, proportional to the fluid partitioning at the end time of the simulation.

In the large uniform perforation friction drop case, only three fractures initiate and propagate (Fig. 1): cluster #4, which bears the highest in-situ stress, does not even initiate. Due to the in-situ stress difference, the other three fractures exhibit different inlet flux, pressure drop across the perforations and propagate at different velocities. For the lower uniform perforation friction case, only two fractures initiate and propagate (clusters #1 and 3)—see Fig. 2. Moreover, fracture #1 takes about a third more fluid

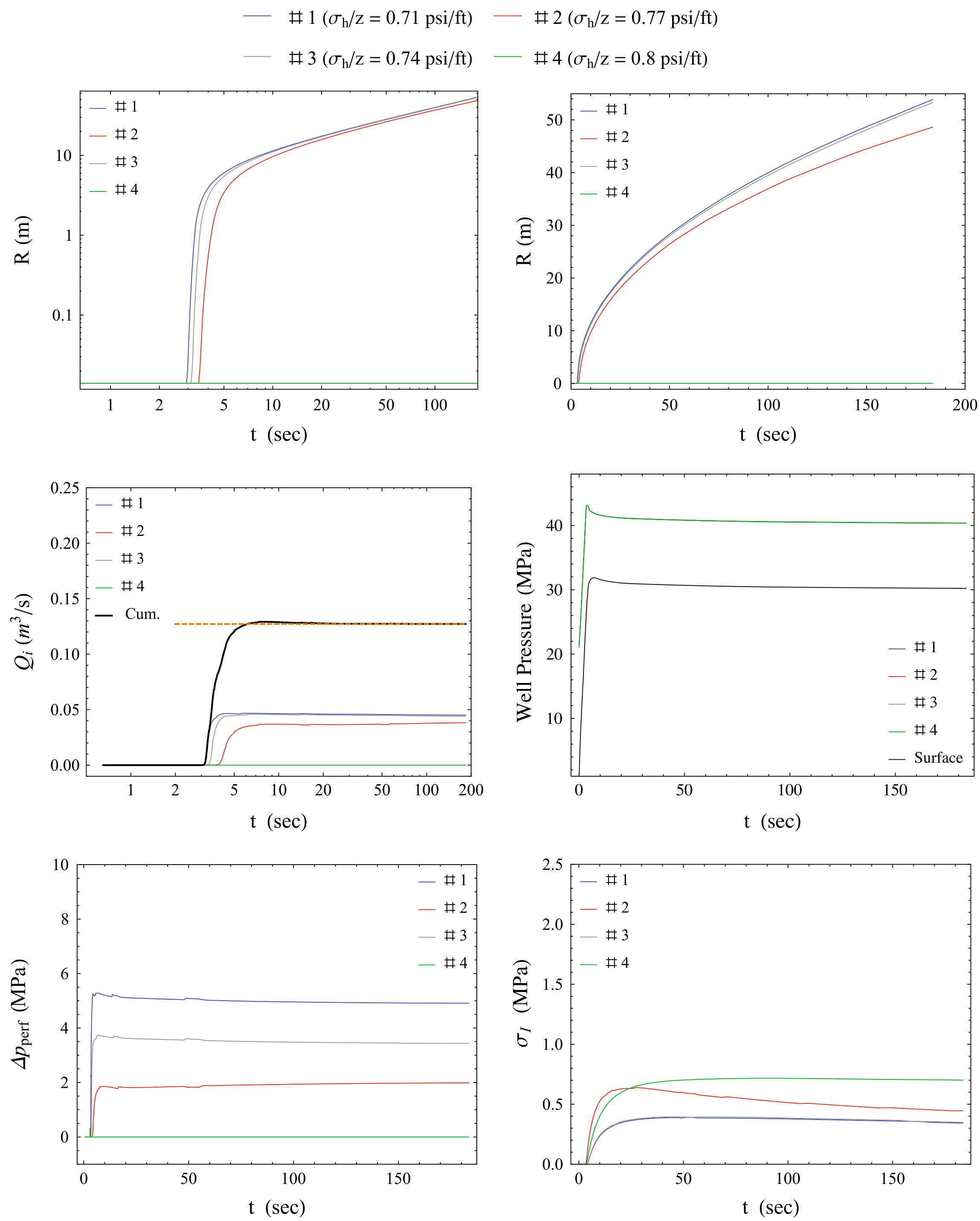

Fig. 4 Heterogeneities of the minimum in-situ stress—engineered limited entry design but with injection performed with 2/3 of the designed pump rate. Fractures radius, inlet fluxes, downhole and surface pressures, perforation clusters pressure drop and mean interaction stresses (i.e. average of σ_I over the fracture). Note that fracture #4 does not initiate

than #3. The downhole pressures for both cases are very similar, the surface pressure being slightly lower for the small perforation friction case. It is, however, impossible to tell from the surface pressure response alone if two, three or more fractures are actually propagating.

Figure 3 displays the results for the engineered limited entry case, where the number of perforations in each cluster has been adjusted to compensate the heterogeneity in in-situ stress (recall Table 1 for the numbers of perforations for each cluster). With such an adjustment, the four

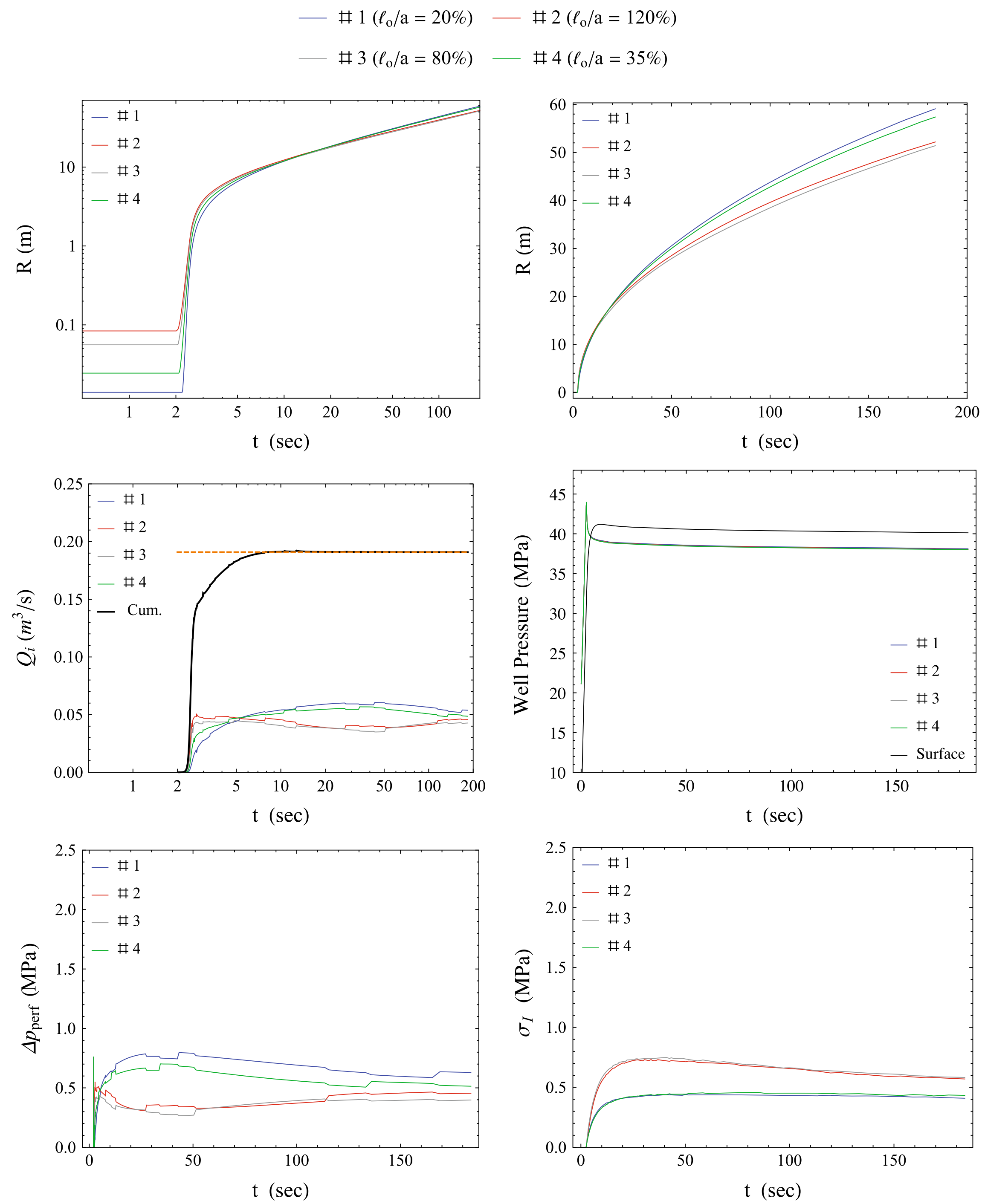

Fig. 5 Heterogeneities in the initial defect lengths—uniform limited entry design, uniform in-situ stress: case of 20 perforations per cluster ($n_p = 20$), i.e. small perforation pressure drop. Fractures radius, inlet fluxes, downhole and surface pressures, perforation clusters pressure drop and mean interaction stresses (i.e. average of σ_I over the fracture)

clusters initiate and the four fractures propagate. The surface pressure is higher than for the uniform perforation friction cases. It is interesting to note that cluster #4 initiates later: two breakdowns (defined here as a local maximum in pressure) can be distinguished over a period of three seconds (such a signal may not be properly recorded in practice due to noise and low sampling rate). The cumulative injected flux also temporarily exceeds the surface injection rate, an effect associated with the release of fluid stored through wellbore compressibility, which is responsible for further wellbore pressurization and allows the breakdown of cluster #4. The flux entering each fracture reaches a similar value for all fractures after less than a minute. The fracture extension after three minutes of treatment is similar for all clusters. The engineered limited entry design is thus able to compensate extremely well the heterogeneities in minimum stress.

As a test for the robustness of the limited entry technique to operational constraints, e.g. a slow ramp up of the pumps at the beginning of pumping, we investigate the case where the total injection rate on surface would be 2/3 of the designed rate. Such a change results in the initiation of only three fractures (Fig. 4). The fluxes entering the three propagating fractures are, however, closer to one another compared to the cases of uniform perforation friction. The evolution of the three propagating fracture extension is also more similar as a result.

Finally, we investigate the effect of rock strength variation between clusters. In the context of linear elastic fracture mechanics, variations of the length of the initial radial flaw at the wellbore wall can be viewed as a proxy for strength variation. We vary the size of each initial defect between clusters: respectively 20, 120, 80 and 35 % (from heel to toe) of the casing radius, and assume here that the in-situ stress is uniform (a stress gradient of 0.75 psi/ft (0.0169 MPa/m) translating to a value of 5250 psi (36.2 MPa) at the considered depth). Figure 5 displays the results for the case of small perforation friction, which is the most sensitive to any heterogeneity. Even though the different clusters initiate at different times, with the largest defect initiating earlier as expected, all fractures initiate. The amount of energy put in the system is such that the difference in the initial defect length appears irrelevant. More simulations covering a wider range of variation (with very small—say 1% of wellbore radius—and large defects) should, however, be performed to confirm that rock strength variations have only a second order effect.

In conclusion, it appears that a proper use of the limited entry technique can, in principle, counteract stress interaction between growing fractures as well as the effect of geological formation heterogeneities, provided stress variations are properly characterized. However, the effect of additional entry friction due to the presence of near-wellbore fracture tortuosity—which we have not accounted for in this note—can ruin the balance obtained via engineered limited entry as it typically differs from fracture to fracture within a stage [see Lecampion et al. (2015) for more discussion].

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