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Stress shadow effect during multi-stage hydraulic fracturing with different wellbore arrangements

P L P Wasantha[1]**, H Konietzky**[2]**, T Xu**[3] **and B Xu**[3]

[1]College of Engineering and Science, Victoria University, Melbourne, Australia
[2]Geotechnical Institute, TU Bergakademie Freiberg, Freiberg, Germany
[3]School of Resource and Civil Engineering, Northeastern University, PR China

Wasantha.PallewelaLiyanage@vu.edu.au

Abstract. Multi-stage hydraulic fracturing was simulated using a two-dimensional universal distinct element code (UDEC). Five fracturing stages were considered along horizontally (i.e. parallel to the minor principal stress direction)- and diagonally (i.e. inclined to the minor principal stress direction)-positioned wellbores within the pay zone, where the spacing between wells was changed to 50 m and 100 m. Progressive fracture propagation and the evolution of stress shadow with sequential multi-stage fracturing were monitored. A marked stress shadow was observed for closer well spacings under both horizontal and diagonal well arrangements, leading to a significantly asymmetric fracture propagation about the wellbore. The diagonal well arrangement showed a nearly unidirectional fracture propagation after the first stage for the closer well spacing case. Fractures of sequential stages predominantly developed in alternating directions at greater well spacings irrespective of the wellbore arrangement. Progressive fracture development also showed that fractures created at earlier stages could further extend due to the stress shadow of later fracturing stages, and this effect is more pronounced for closer well spacings. After five stages, the overall fracture lengths indicate that a higher fractured area was created by horizontal well arrangement for any case of well spacing. Finally, the importance of optimizing the fractured area and fracture controllability to contain the fractures within the pay zone was highlighted.

1. Introduction

Multi-stage hydraulic fracturing, where multiple stimulations are performed along a horizontal well, can significantly improve the productivity of hydrocarbon-bearing tight shale formations. Multiple fracturing stages allow creating a large contact surface area in the reservoir, leading to a higher permeability and productivity [1-3,10]. The fracture initiation and propagation characteristics from a single wellbore are influenced by many factors, including the in-situ stress state, reservoir rock properties and pre-existing discontinuities. In sequential multi-stage fracturing, fractures created and the stress redistribution after one fracturing stages can have decisive impacts on the fracture development of the subsequent fracturing stages. Therefore, the stimulations have to be carefully positioned along the horizontal well to optimize the fracture propagation from each stimulation stage.

The complexity of the produced fracture network and the stimulated reservoir volume (SRV) during multi-stage fracturing are strongly influenced by the spacing between stimulations and the stress interference among different stimulation stages [4-7]. Conventional wisdom suggests that a higher number of stimulations with tighter spacing creates a greater SRV. But, the fracturing experiences have

shown that the production performance does not directly scale up with increasing closely-spaced stimulations [8]. This is primarily due to the stress shadowing effect, which accounts for the effect of stress redistribution in the vicinity of the horizontal well after one stimulation stage on the subsequent stimulation stages. Stress shadowing can affect fracture initiation and propagation characteristics of sequential fracturing stages, which is usually unfavourable on reservoir productivity. It can also cause fractures communicating with unwanted neighbouring formations leading to concerns over groundwater contamination and induced seismicity. For example, Wasantha et al. (2019) [9] observed a significant asymmetry of fracture propagation about the wellbore due to the stress shadow effect, which was more pronounced for closely-spaced stimulations. However, conventional stimulation design methods, which are mainly based on static models, do not effectively integrate the effect of stress shadow on fracture initiation and propagation during multi-stage fracturing [4,6].

A few different approaches are proposed in the literature to minimize the effect of stress shadow and optimize the stimulation spacing. Zeeb and Konietzky (2015) [11] showed diagonally aligned stimulations to the minimum principal stress direction, increased spacing and enabling the fluid to flow back after each stimulation stage can combinedly produce more uniform fracture patterns with significantly less fracture overlap after their 3-dimensional distinct element code (3DEC) numerical simulations. Walgast (2012) [12] also simulated multi-stage hydraulic fracturing using (UDEC) and showed backflow of fracturing fluid after each stimulation stage could effectively minimize the stress shadow effect and associated asymmetric fracture propagation about the wellbore in subsequent stimulations.

The progressive stress redistribution and its impact on fracture propagation during multi-stage fracturing under different wellbore arrangements are not completely understood in the literature. This study simulates multi-stage fracturing using UDEC and investigates the evolution of stress shadow with sequential multi-stage fracturing and the resulting fracture propagation characteristics under two different wellbore arrangements – horizontal (i.e. parallel to the minor principal stress direction) and diagonal (i.e. inclined to the minor principal stress direction).

2. Numerical simulation

UDEC was used in the numerical simulation program to perform fully-coupled hydromechanical analyses of multi-stage fracturing. Several studies in the literature have successfully used UDEC for simulating hydraulic fracturing [e.g. 9,13,14]. The problem domain in UDEC comprises blocks and contacts, and fluid flow is only permitted within opened contacts. Therefore, in this study, fractures are pre-embedded in the models at pre-determined locations, which are initially closed, and the fracture contacts are broken and fluid flow is enabled upon receiving sufficient fluid pressure as a result of fluid injection to a selected domain in fractures. The embedded fractures for hydraulic fracture propagation were oriented perpendicular to the minor principal stress direction as previous studies report that hydraulic fractures primarily develop perpendicular to the minor principal stress direction at higher major-to-minor principal stress ratios [e.g. 9,15-16]. No fluid flow occurs into the blocks of the models, representing a low permeable reservoir rock.

Single-stage fracturing was first simulated, and the evolution of fracture geometries and wellbore pressure of the models were compared with those estimated using the KGD analytical fracture model [17-18] for validating the numerical models. Wasantha et al. (2019) [9] reports this validation procedure and the results, which show a good agreement between UDEC results and analytical predictions for the evolution of fracture length, width and wellbore pressure with fluid injection time.

Models of 1000 m x 2000 m were created to simulate multi-stage fracturing, and five sequential fracturing stages were simulated. Wellbores (i.e. the fluid injection domains) were positioned in the models to create two different arrangements – (1) horizontally, i.e., parallel to the minor principal stress direction, and (2) diagonally, i.e., inclined to the minor principal stress direction (fig. 1). Minor and major principal stresses of 80 MPa and 160 MPa, respectively, were applied to all models. Fracturing fluid was assumed to be water and was injected to pre-determined domains at a rate of 0.0833 m3/sec for 100 seconds for each stimulation stage. The spacing between stimulations was varied to 50 m and

100 m to better understand the role of stress shadow on overall hydraulic fracture propagation behaviour (fig. 1). Table 1 outlines the properties assigned for blocks, embedded fractures for hydraulic fracture propagation, and fracturing fluid.
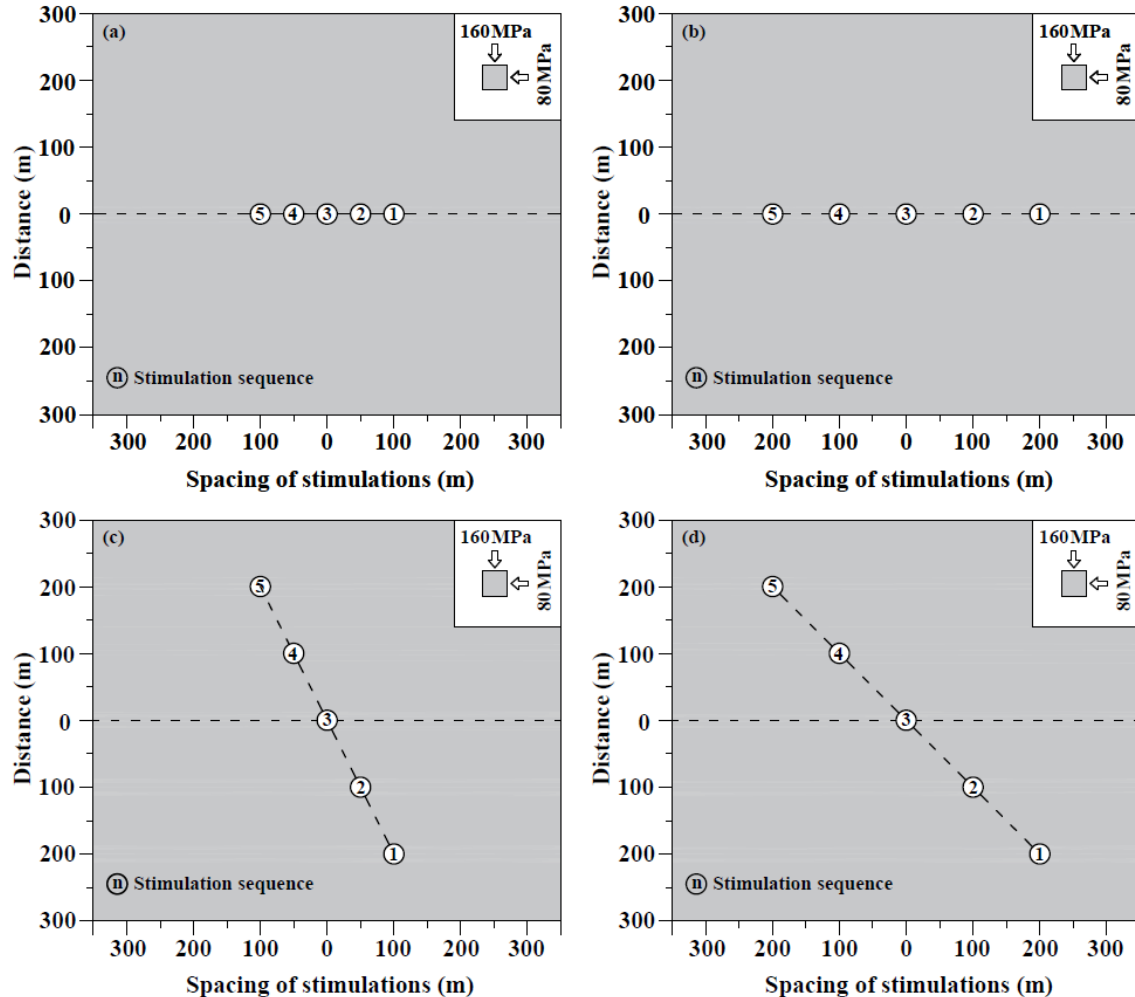

Figure 1: Different wellbore arrangements used for UDEC models (the numbers indicate the sequential fracturing stages).

Table 1. Properties assigned to block material, fractures and fracturing fluid of UDEC models.

Block (intact material) properties	
Density (kg/m3)	2600
Elastic modulus (GPa)	50
Poisson's ratio	0.25
Cohesion (MPa)	25
Friction angle (°)	53
Fracture properties	
Cohesion (MPa)	25
Residual cohesion (MPa)	0

Friction angle (°)	53
Residual friction angle (°)	0
Dilation angle (°)	20
Fracture toughness (MPa.m$^{1/2}$)	1.5
Fracturing fluid properties (incompressible)	
Density (kg/m^3)	1000
Viscosity (Pa·sec)	0.001
Injection rate (m^3/sec)	0.0833

3. Results and discussion

Progressive fracture development and associated changes in the stress field were monitored during multi-stage stimulations. fig. 2 and 3 show the lengths of the developed fractures and the minor principal stress distributions after each fracturing stage for horizontal and diagonal well arrangements, respectively, under different well spacings. Marked changes to the in-situ stress field can be observed after each stimulation stage which is more pronounced for closely-spaced wells (i.e. 50 m). The stress shadow created after one stimulation stage significantly affects the fracture propagation of the subsequent stimulation. More importantly, the developed fractures show a directional preference where the major fracture component has developed in alternating directions about the wellbore axis for the case of horizontal well arrangement irrespective of the well spacing considered here (fig. 2a and 2b). This trend is more apparent for 100 m well spacing, where the stress shadow effect is less profound. Similar behaviour is displayed by the diagonal well arrangement when the well spacing is 100 m (fig. 3b). However, the fracture development is nearly unidirectional after the first stage in the case of 50 m well spacing of diagonal well arrangement (fig. 3a). This is a product of strong stress shadow development, favouring subsequent fracture propagation in one direction and restricting in the opposite direction.

The variations of the length of fractures developed at different stimulation stages are shown in fig. 4. fig. 4a and 4c show that the hydraulic fractures continue to propagate even after their original stimulation period when the wells are closely spaced, which can be attributed to the stress shadow created during subsequent stimulation stages. The overall lengths of fractures were observed to be 1692 m and 1570 m for 50 m and 100 m well spacings, respectively, under the horizontal well arrangement, and 1582 m and 1515 m for 50 m and 100 m well spacings, respectively, for the case of diagonal well arrangement. This shows that horizontal well arrangement has produced more fractured area than the diagonal well arrangement for any case of well spacing. In addition, closer well spacing has produced more fractured area under both cases of well arrangements. However, the stress shadow-driven fracture extension can be viewed as uncontrollable and could lead to fractures communicating with unwanted neighbouring formations. A more systematic fracture development can improve the confidence of the fracturing operations and help to contain the fractures to the pay-zone. Therefore, selecting the operational parameters of fracturing to optimize the fractured area and controllability of fracture propagations is vital for hydraulic stimulation projects. It should be noted that the practical pay zones are of finite thickness, and the adjacent zones can have different in-situ stress and material properties compared to those of the pay zone. These differences between pay-zone and adjacent zones can have implications on hydraulic fracture propagation but were not considered in this study.
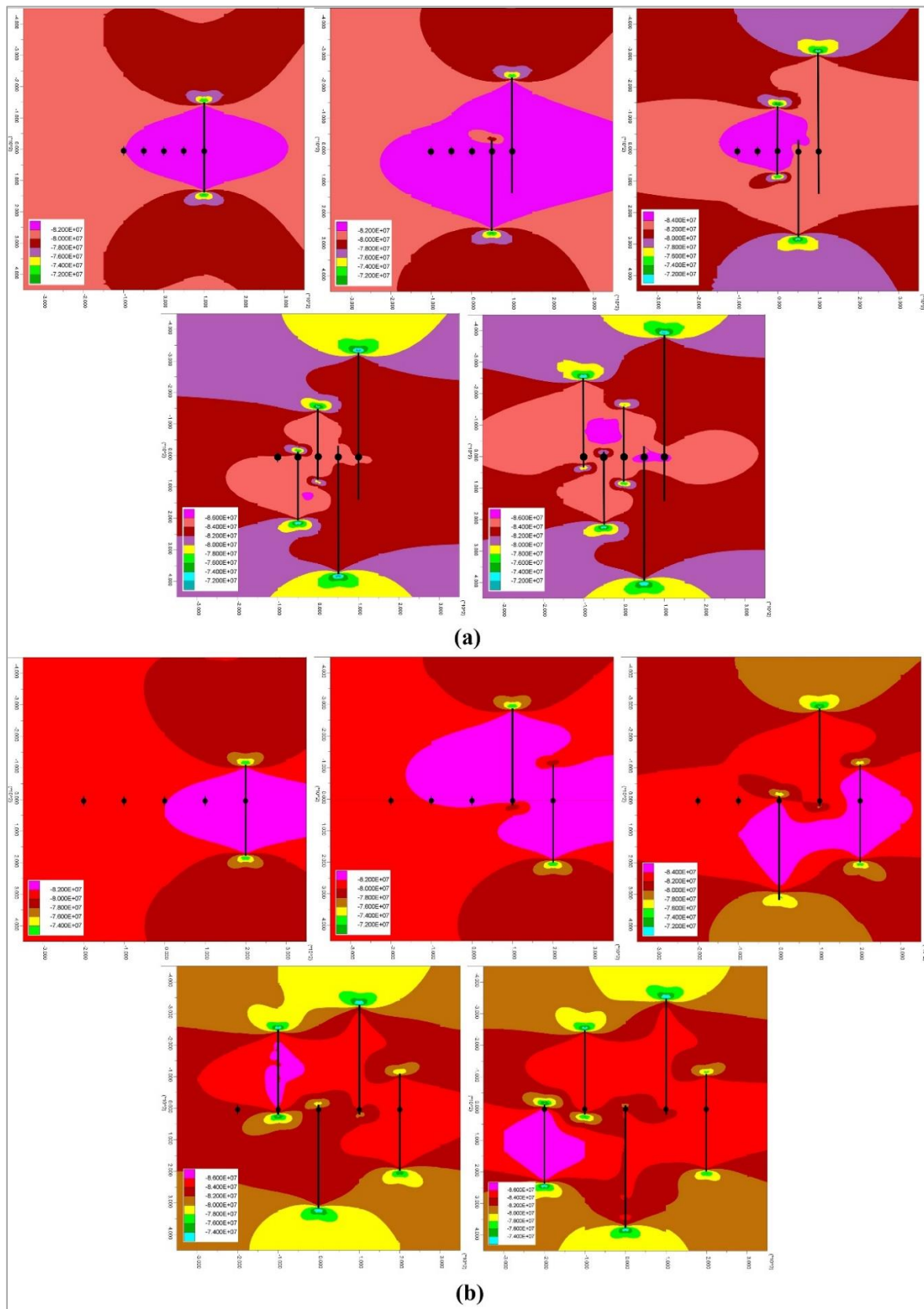
Figure 2: Minor principal stress distribution patterns and fracture lengths with sequential fracturing for horizontal well arrangement (1) 50 m well spacing, and (2) 100 m well spacing.
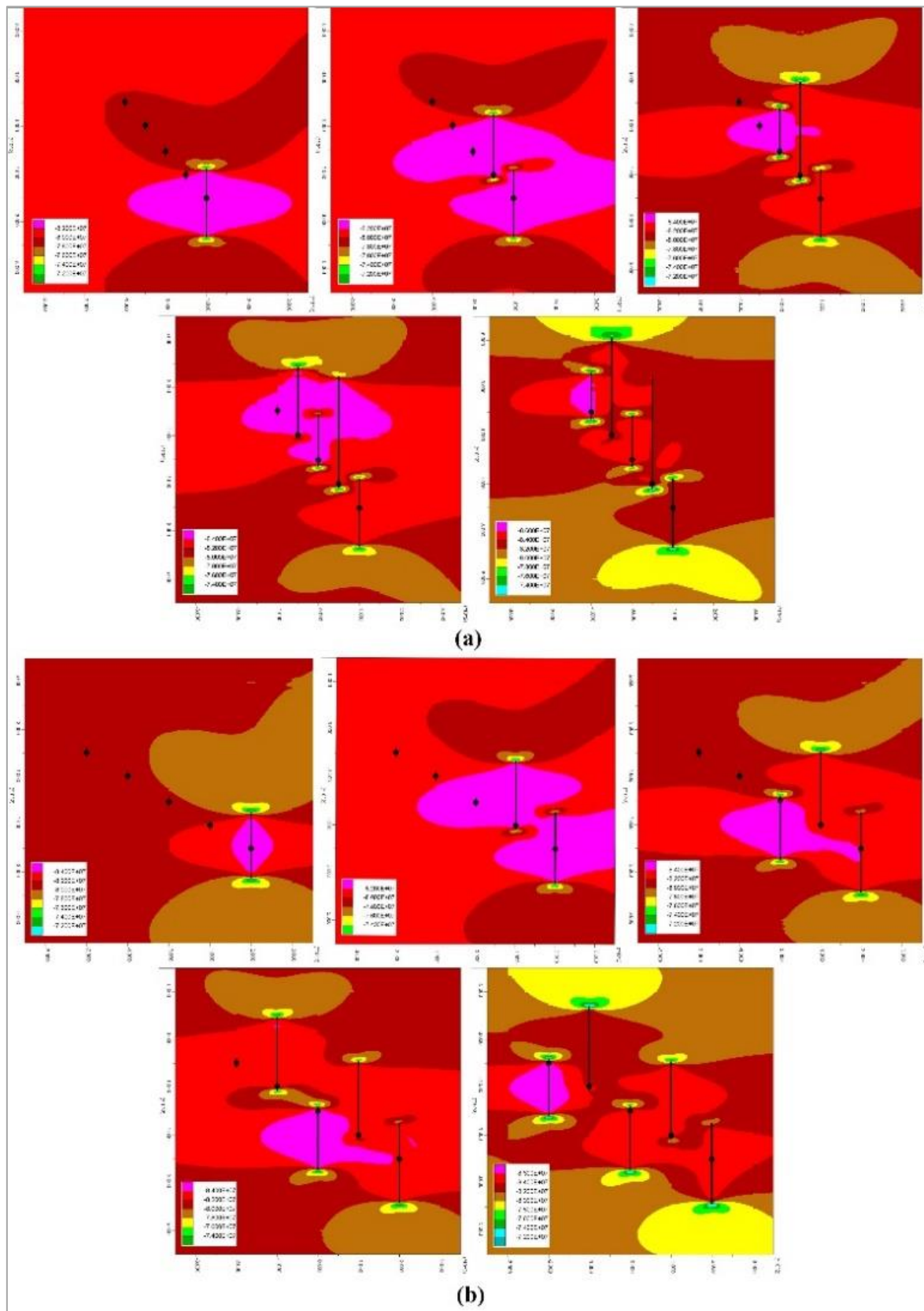
Figure 3: Minor principal stress distribution patterns and fracture lengths with sequential fracturing for diagonal well arrangement (1) 50 m well spacing, and (2) 100 m well spacing.
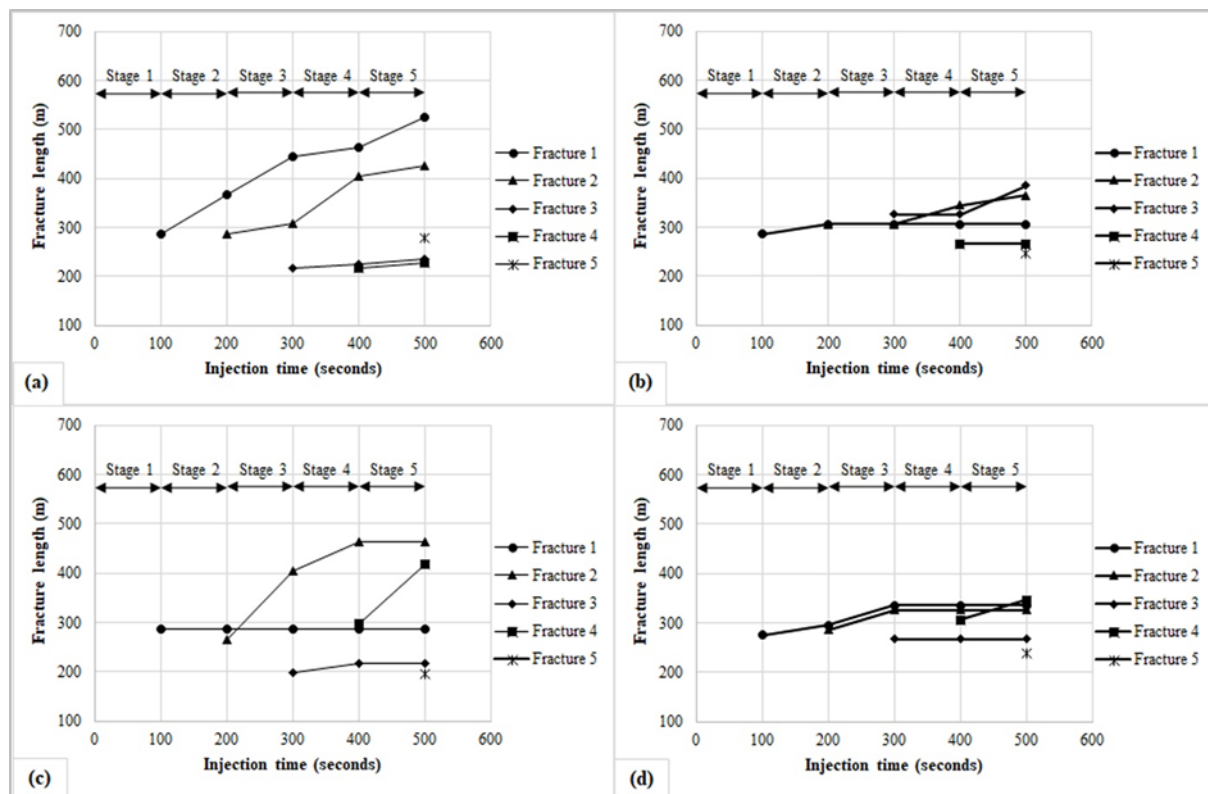
Figure 4: Fracture lengths at different injection times (a) horizontal well arrangement – 50 m spacing, (b) horizontal well arrangement – 100 m spacing, (c) diagonal well arrangement – 50 m spacing, (d) diagonal well arrangement – 100 m spacing.

4. Conclusions

Five sequential stages of hydraulic fracturing were simulated using UDEC. Two different wellbore arrangements within the pay zone were considered – horizontal and diagonal – and wellbores were spaced with 50 m and 100 m spacings for each case. The evolution of the minor principal stress field with progressive fracturing showed a significant stress shadow development, particularly for closer well spacings. The developed fractures showed a considerable asymmetry about the wellbore as a result. The diagonal well arrangement under 50 m spacing was an exception which showed a near unidirectional fracture propagation after the first stimulations stage. Under 100 m well spacing, both well arrangements showed fractures propagating in alternating directions about the wellbore axis. For any case of well spacing, horizontal well arrangement produced a larger overall fractured area than that of diagonal well arrangement. It was highlighted that controllability of fracture development to contain the fractures within the pay zone is also important while attempting to maximize the fractured area.

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