Grain-scale analysis of proppant crushing and embedment using calibrated discrete element models

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Abstract
Proppant crushing and embedment in hydraulically-induced fractures is a major drawback to the recovery of unconventional oil/gas and geothermal energy production. This study provides a grain-scale analysis of the fracture evolution mechanisms of proppant crushing, rock fracture damage during proppant embedment, the influence of realistic reservoir/fracture fluid on proppant embedment, and the behaviour of proppant packs subjected to in-situ stresses using a discrete element modelling (DEM) approach. The results of this study reveal that the selection of an appropriate proppant type based on the nature of the reservoir formation plays a vital part in quantifying the degree of proppant crushing and embedment within fractures. The utilisation of frac-sand proppants instead of ceramic proppants in shallow soft sedimentary-based siltstone formations reduces proppant embedment up to 88%. However, whatever the depth of the fracture, the injection of ceramic proppants into granite-based geothermal formations is preferred to that of frac-sand proppants due to their lower proppant embedment and greater crush resistance. DEM analysis detected rock-spalling during the proppant embedment process, which ultimately led to the initiation of tensile-dominant secondary fractures in rocks. Fracture initiation, propagation, and coalescence during proppant crushing are analysed using calibrated DEM proppant-rock assemblies. Importantly, this study reveals that the saturation of formation rocks with fracturing/reservoir fluids may cause a significant increase in proppant embedment. Furthermore, proppant crushing, embedment, and re-arrangement mechanisms in proppant packs with different proppant distributions are analysed in this comprehensive numerical study.

Keywords Discrete element modelling · Fracture evolution · Proppant · Proppant crushing · Proppant embedment

1 Introduction

Proppants used during hydraulic fracturing play a pivotal role in determining the ultimate fracture permeability within fractures [60]. Generally, proppants are used to keep fracture walls open by resisting high closure stresses. In 1947, silica granules were first utilised as a proppant agent, and to date, numerous types of proppants with concentrations up to 20lbm/gal have been used for fracturing treatment (Montgomery and Smith, [42]). With the advancement of fracking in unconventional oil/gas reservoirs, proppants also evolved from traditional silica granules to novel proppant types such as ceramic, resin-coated proppants, frac-sand and many more with various innovative mechanical improvements [7, 22, 32, 35, 50, 57]. Due to their cost and availability for unconventional oil/gas recovery, ceramic, resin-coated, and frac-sand proppants have become popular types of proppants (Gallagher [19]). However, unforeseen oil/gas recovery reductions experienced from highly-impermeable unconventional deposits have regularly led to questions about proppant performance in fractures [15]. It is now understood that proppant degradation mechanisms may occur in fracture deposits under extreme reservoir conditions, and of these mechanisms, crushing and embedment of proppants require close attention [2, 21, 44]. The simultaneous processes of...
mechanical instability of proppants which occur upon resisting high fracture closure stress and proppant grain indentation into the fracture surface can lead to a drastic increase in fracture tortuosity and fracture aperture reductions, lowering the fracture permeability [14]. Although many macro-scale experimental and numerical studies have been conducted to understand the ultimate impact of crushing and embedment, the realistic proppant and rock response upon undergoing crushing and embedment is yet to be fully studied. Therefore, the numerical approach conducted using grain-scale discrete element modelling (DEM) provides comprehensive insights into proppant-rock interactions in realistic fracture reservoir environments.

The phenomena of crushing and embedment of proppants in fractures have been investigated using experimental approaches with the assistance of high-stress uniaxial and triaxial test conditions. The studies by Vincent [51] revealed that the crushing of proppants might reduce the fracture conductivity by up to 99%. Laboratory-scale experimental analysis conducted by Bandara et al. [5] on the response of proppant subjected to high stresses revealed that the generation of fines as a result of crushing of ceramic proppant (6% fines), resin-coated sand (35% fines), and frac-sand (51% fines) can reduce proppant pack porosities by 75%, 88% and 98%, respectively. In addition, Alramahi and Sundberg [2] showed that the embedment of high-strength ceramic proppants into shale surfaces may reduce the conductivity by nearly six orders of magnitude at higher stresses. Moreover, experimental analyses by Kumar et al. [31], Akrad et al. [1], Corapcioglu [11], and Rybacki et al. [48] showed that parameters such as rock mineralogical content, type of formation rock, saturation conditions, saturated exposure time, and rock creeping effects may further contribute to proppant embedment. These studies provided an understanding of the mechanical, microstructural, mineralogical, morphological and chemical responses of individual proppants, proppant packs and formation rocks exposed to high-stress reservoir environments. Although these studies have provided insights into the macro-scale analysis of proppant crushing and embedment mechanisms, they were unable to provide non-destructive fracture analysis at a granular level [10]. Therefore, the need to study the proppant fracture mechanisms and embedment into the formation rock has motivated the present study.

Brittle, granular materials like proppants and rocks tend to crush, fracture, and fragment instead of plastically deforming when subjected to high stresses [47]. Therefore, understanding proppant-rock fracture initiation, fracture propagation, and fracture coalescence mechanisms during proppant crushing, and capturing proppant-rock deformation upon experiencing proppant embedment are of crucial importance [39, 61]. To date, many finite element models and continuum models have been developed to study grain crushing and embedment mechanisms [26, 36, 40, 58]. However, the inability to accurately observe the evolution processes of grain crushing and deformation during proppant crushing and embedment is a serious drawback [65]. Therefore, discrete element modelling (DEM) provides a better alternative for the quantitative study of this complex behaviour in brittle materials at a granular scale [17, 18, 37, 59]. In the current study, the DEM approach was used to study the complex behaviour of proppant-rock interactions during crushing and embedment. In addition, the crushing and embedment behaviour of different types of proppants and the response of formation rocks are comprehensively analysed. Moreover, the effect of proppant packing and re-arrangement of particles caused by high closure stresses is analysed at a granular-scale.

2 Methodology

2.1 Discrete element modelling (DEM)

DEM is a numerical modelling technique with the ability to portray the mechanical behaviour of granular assemblies in terms of particle-like discrete elements such as discs and spheres where the interaction of the particles occurs at particle-to-particle contacts and particle motion is governed by Newton’s second Law [12]. In addition, an assembly can be simulated as a bonded particle model (BPM), where bonds between particles can be simulated in order to mimic the brittle behaviour of materials such as rock [45]. Generally, a contact between two particles possesses finite normal and shear stiffnesses, and the mechanical behaviour of the assembly is interpreted by the movement of each particle and the force and moment acting at each contact [46]. Hence, the utilisation of BPM combined with DEM to simulate proppant crushing and embedment behaviour has gained the attention of many researchers [13], Zheng and Tannant [66, 67]. However, the accuracy of a DEM simulation relies on selecting an appropriate contact model to represent the mechanical behaviour of the assembly and assigning individual micro-parameters. In the present study, an existing linear-parallel contact model was selected in Particle Flow Code 3D (PFC3D) to accurately model the mechanical behaviour of granular proppant and rock assemblies. In the linear parallel-bonded contact model, two bond types are available: (1) contact bond (presented in terms of an elastic spring of contact normal $k_n$ and shear stiffness $k_s$ acting at the point of the contact which permits only force to be transferred) and (2) parallel bond (presented in terms of a set of elastic springs dispersed over a finite section of the contact plane
and centred at the contact point which can resist the moment generated as a result of particle rotation (Lisjak and Grasselli, [38]). Cho et al. [8] show that the contact normal stiffnesses ($k_n$ and $k_s$) remain active upon the breakage of the bond as long as particles stay in contact. However, parallel bond stiffness ($k_{n,p}$-parallel bond normal stiffness and $k_{s,p}$-parallel bond shear stiffness) is permanently lost when the parallel bond breaks (see Fig. 1).

### 2.2 Calibration of micro parameters of proppants

For the present study, two different proppant types: sintered bauxite ceramic and frac-sand, were subjected to analysis. The micro-parameters used in the DEM simulations were iteratively varied until the DEM model reproduced the strength parameters of ceramic and frac-sand proppants obtained from laboratory-scale single pellet compression tests conducted on each proppant type. The laboratory-scale compression tests were performed on 16/30 mesh size (average diameter of 1 mm) proppants of each type. The laboratory compression tests were performed using a 4 kN InstronDX apparatus in the Deep Earth Energy Research Laboratory (DEERL) of the Civil Engineering Department at Monash University, Australia. Additional tests were conducted to obtain general proppants properties. The sintered bauxite ceramic proppant had a specific gravity of 3.52, bulk density of 1.92 kg/m$^3$, single-particle crush strength of 197 MPa (obtained by conducting laboratory-scale single pellet crushing tests), Poisson’s ratio of 0.25, and sphericity of 0.9. The frac-sand proppant had a specific gravity of 2.6, bulk density of 1.61 kg/m$^3$, single-particle crush strength of 31 MPa (obtained by conducting laboratory-scale single pellet crushing tests), Poisson’s ratio of 0.25, and sphericity of 0.7.

Despite the proppants not being perfect spheres, both proppant types were modelled assuming they were spherical with a diameter of 1 mm (see Fig. 2). In addition, both proppants were modelled using a cluster of homogenous particles. For both proppant types, a uniform particle size of 0.03 mm was selected by iteratively changing the size until no significant variation in the corresponding mechanical strengths was obtained between the laboratory and the calibrated model. Single-grain diametrical compression tests were simulated at an axial loading rate of 0.08 ms$^{-1}$ to ensure a quasi-static loading environment. All the other required micro-parameters for the calibrated proppants were assigned by iteratively varying them using a trial-and-error method until the stress–strain curve from the numerical model followed a similar pattern to that of the laboratory test specimens. The micro-parameters of the calibrated ceramic and frac-sand proppants are listed in Table 1. A similar proppant calibration technique was adopted in our previous study; Bandara et al. [3].

Figure 3 shows the stress–strain response obtained from the experimentally-tested single grain crushing tests and
the numerically-calibrated ceramic and frac-sand proppant models. Table 2 provides a summary of the strength parameters from the experiments and the calibrated models. According to Fig. 3, for both proppant types, the stress–strain curves from experiments and the DEM model follow a similar trend. Table 2 shows that the differences in the maximum stress (crush strength) and Young’s modulus for ceramic (3.48% and 3.73%, respectively), and frac-sand (0.34% and 1.81%, respectively) are minor. These results indicate that calibrated proppant models accurately mimic real proppant behaviour when subjected to increasing stress under diametrical compression conditions. According to Fig. 3a, the stress–strain behaviour of experimentally-tested single proppants inclines downwards during the initial loading stage, which cannot be monitored during the stress–strain response of the numerically-calibrated ceramic proppant. This is a common phenomenon often experienced during experimental testing due to the initial contact between the specimen and the loading plate (De Silva et al. [49]). In Fig. 3a, the accuracy of the calibrated model is represented by shifting and redrawing the projection of the stress–strain response of the numerically calibrated proppant on the elastic region of the experimental results. In Fig. 3b, the stress–strain behaviour of experimentally-tested frac-sand proppant inclines downwards from the stress–strain response of the numerically calibrated proppant during the latter part of the loading stage. This deviation in experimental result can be explained as a result of the coupled effect of grain rotation and asperity damage undergoing in frac sand proppant at higher loading levels.

2.3 Calibration of micro-parameters of rocks

Five different formation rock types were modelled in PFC3D to understand proppant interactions with different formation rocks. The rock types were dry-intact siltstone, 30-day water-saturated siltstone, 30-day NaCl (25%)-saturated siltstone, 30-day oil-saturated siltstone, and dry-intact granite. The densities and porosities for each rock type were measured, and unconfined compression tests were conducted using cylindrical cores of 4 mm in diameter and 8 mm high (similar dimensions were used to calibrate the rocks in PFC3D). All the laboratory compression tests were performed using a 50 kN InstronDX in the Deep Earth Energy Research Laboratory (DEERL) of the Civil Engineering Department at Monash University, Australia.

Similar to the calibration process for proppants, the micro-parameters for the rock DEM models were iteratively varied until the simulations reproduced the laboratory unconfined compression test results. The rocks were modelled as a homogenous agglomerate of particles in a cylindrical shape with dimensions equivalent to the laboratory-tested rock samples (Fig. 4). A uniform particle size of 0.08 mm was selected, using the same technique as was used to identify proppant particle size. A unconfined compression test on the rock models was conducted at a slow axial loading rate of 0.08 ms\(^{-1}\) to ensure a quasi-static loading environment. The appropriate micro-parameters for the individual calibrated rock models were found in a trial-and-error process until the stress–strain curve from the numerical model matched the laboratory-tested UCS results. The micro-parameters of the rock specimens are illustrated in Table 3. Figure 5 illustrates the laboratory and DEM stress–strain responses for each rock type, and Table 4 provides a summary of the results in Fig. 5a–e. Table 4 portray excellent agreement between the
Similar to the experimental testing of single pellet propellant, upon conducting UCS testing for each rock specimen, a downward inclination in the stress–strain response during the initial loading stage can be observed.

### Table 2: Summary of strength parameters from experiments and calibrated models [3]

| Single proppant test | Calibrated ceramic proppant | Calibrated frac-sand proppant |
|----------------------|-----------------------------|------------------------------|
| Maximum stress (crush strength) (MPa) | | |
| Experimental | 197 | 35.8 |
| Numerical | 204 | 35.7 |
| Deviation (%) | 3.48 | 0.34 |
| Young’s modulus of proppant (GPa) | | |
| Experimental | 3.83 | 0.798 |
| Numerical | 3.98 | 0.783 |
| Deviation (%) | 3.73 | 1.81 |

3 Mechnical response of single proppant to increasing stress levels

When injecting proppants into fractures, the processes of proppant migration, distribution and settlement are highly dependent on the fracture surface roughness and the complexity of the fracture. As a result, there are three different types of proppant distributions that can be expected within fractures: (1) partial monolayer proppant arrangement, (2) uniform monolayer proppant arrangement, and (3) multi-layer proppant arrangement. In a partially proppant-distributed fracture, an individual proppant is subjected to significantly high single-point loading at the proppant-proppant or proppant-rock contact. The probability of the occurrence of either proppant crushing or embedment is high. Hence, in this section, we analyse the behaviour of a single proppant upon subjection to in-situ stress conditions.
by considering the impact of the type of proppant, the type of formation rock, and effect of realistic reservoir environments. A series of DEM simulations using calibrated proppant-rock models was performed to analyse the response of a single proppant placed on the rock surface and subjected to increased stress environments. The set-up of the numerical model in the DEM simulations is shown in Fig. 6. To reduce the computational cost, the thickness of the simulated rock was limited to 2 mm.

3.1 Single proppant interaction with sedimentary-based siltstone formation

3.1.1 Crushing and embedment response of proppants with increasing stress levels

Proppant embedment = Total deformation
- Proppant deformation - Rock deformation

(1)

In this section, the effect of proppant type on interactions with dry-intact siltstone sedimentary-based formations is analysed. Figures 7a and b represents the variation of compressive stress with numerical time-steps for ceramic and frac-sand proppants, respectively. In this analysis, numerical time-steps were used as the variable for the x-axis, instead of axial displacement/strain, to provide better comparative visualisation of the variation of compressive stress. In addition, to accurately study the mechanical response of individual ceramic and frac-sand proppants, the embedment induced as a result of increasing stresses was calculated using Eq. 1, and the results are presented in Fig. 7c. In Eq. 1, the proppant deformation and rock deformation refer to distinct deformation undergoing within proppant and rock, respectively, as a result of the increasing stresses. Thus, to calculate these two parameters, numerical simulation tests were performed on the individual proppant and rock, separately and their respective deformations were recorded with increasing stresses. Then, proppant embedment was calculated by deducting respective proppant deformation and rock deformation from the total deformation at each loading level (total deformation is the deformation we record when conducting DEM simulation of a single proppant-rock test). Similar embedment analysis was adopted by [67] to accurately detect the embedment with load increments.

According to Fig. 7a and b, the ceramic proppant shows a slow stress growth with numerical time steps. However, the frac-sand proppant reaches the failure stress rather rapidly. This behaviour of ceramic proppants is mainly due to the significant plastic deformation which occurs as a result of the dominant proppant embedment mechanism. However, in frac-sand proppant, the stress response is more linearly variable with numerical time-steps due to the dominant crushing process of frac-sand proppant when interacting with siltstone formations at increasing stress levels. According to the results depicted in Fig. 7c, both proppants tend to show an increase in proppant embedment with stress increment. In addition, the results reveal that the ceramic proppant shows a significantly high proppant embedment at each stress level in comparison with frac-sand proppant. According to Fig. 7c, at stress levels of 10, 20, 30, 40, and 50 MPa, ceramic proppant shows a

| Table 3 | Micro-parameters of calibrated rock types |
|---------|------------------------------------------|
| Parameter | Dry-intact siltstone | Water-saturated siltstone | 25% NaCl-saturated siltstone | Oil-saturated siltstone | Dry-intact granite |
| Particle size (mm) | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |
| Number of particles | 38,246 | 38,246 | 38,246 | 38,246 | 38,246 |
| Particle density (kg/m³) | 2650 | 2650 | 2650 | 2650 | 2650 |
| Damping ratio | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Linear contact parameters | | | | | |
| Young’s modulus/stiffness (GPa) | 1.5 | 1.5 | 1.5 | 1.5 | 81 |
| k-ratio (k₀/kₛ) | 3 | 3 | 3 | 3 | 3.5 |
| Parallel bond parameters | | | | | |
| Young’s modulus/stiffness (GPa) | 2 | 2 | 1.5 | 1 | 2.9 |
| k-ratio (k₀/kₛ) | 1 | 1 | 1 | 1 | 1 |
| Tensile strength (MPa) | 6 | 5.9 | 3 | 2.1 | 85 |
| Cohesion (MPa) | 21 | 20 | 12 | 10 | 21 |
| Tensile failure (°) | 30°C | 29°C | 12°C | 10°C | 30°C |
| Friction coefficient | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
proppant embedment of 224, 244, 257, 277, and 323 μm, respectively. However, at 10, 20, and 30 MPa stress levels, only a minor embedment is shown by the frac-sand proppant; 27 (88% lower than the ceramic proppant at a similar stress level), 38 (84.3% lower), and 56 μm (78.1% lower), respectively. Moreover, for ceramic proppants, a
higher embedment-stress gradient can be observed at lower stress levels; however, the rate of proppant embedment declines at higher stresses. Although frac-sand shows significantly lower proppant embedment than ceramic proppants, frac-sand proppants have no potential to withstand any compressive stress beyond 35 MPa, as the frac-sand proppants undergo a significant amount of crushing. Nevertheless, no crushing of ceramic proppant is experienced at increasing stress levels upon interaction with the dry-intact siltstone rock formation. However, the following section provides a detailed analysis of proppant-rock fracture initiation, fracture propagation, and fracture coalescence mechanisms when undergoing sand proppant crushing and ceramic proppant embedment while capturing proppant-rock deformation. These findings are consistent with the numerical findings presented by Zheng and Tannant [67] and Zheng et al. [67].

### 3.1.2 Formation rock damage and fracture evolution during ceramic proppant embedment

The DEM simulation of a single proppant-rock response to increasing stress levels provides a novel approach to understanding the granular level fracture evolution mechanism during proppant embedment. The evolution of the proppant embedment of ceramic proppants with increasing stress conditions is presented in Fig. 8. In the DEM simulation, a crack or fracture visualised as a disc is generated when the bonding between two individual particles breaks. Here, tensile cracks occurring in the proppant are shown by a red disc, while tensile and shear cracks occurring within...
rock are shown by blue and pink discs, respectively. At minor stress levels (0.6 MPa), ceramic proppants show the initiation of a small number of tensile cracks at the contact location with the top loading platen. In addition, the generation of tensile dominant fractures can be observed in the siltstone formation, which initiates from its contact interface with the proppant. With the increment of the stress level to 10 MPa, the embedment of ceramic proppant in the siltstone rock causes rock particle spalling, which is typical when the rock surface is indented with high-strength proppants. In addition to fracture aperture reduction due to proppant embedment, the phenomenon of fines generation as a result of rock particle spalling might further reduce fracture conductivity by blocking the path of oil/gas flow [25]. With the increase in ceramic proppant embedment with the increment of stress-levels, the tensile dominant fractures initiated at the proppant-rock contact interface tend to propagate gradually. As illustrated at the fracture evolution figure at 50 MPa, a number of fractures have propagated from the proppant-Indented location. Importantly, beyond 50 MPa stress levels, several major fractures coalesce, causing significant damage to the proppant-embedded rock formation. Although ceramic proppant shows an embedment of 323 μm at only 50 MPa, beyond this
stress level, the rock surface cannot take any further increase in loading due to the significant damage caused to the rock formation as a result of secondary fracture initiation, propagation and coalescence. Upon reaching this damage stress level (beyond 50 MPa in this instance), ceramic proppant undergoes further embedment at a higher rate until it fully indents into the rock surface. This can be clearly observed in Fig. 7c, as upon reaching the 50 MPa stress level, the embedment-stress gradient of ceramic proppant suddenly increases. Importantly, the initiation and propagation of ceramic proppant embedment-induced secondary fractures in siltstone formations have been revealed in our previous studies [5], 5. Some of the experimental findings obtained from Bandara et al. [5] are presented in Fig. 9. Figure 9a shows a computed-tomography scanned reconstructed image of secondary fracture initiated and propagated at a proppant-embedded location. Furthermore, Fig. 9b illustrates a 3D-profilometer scanned image at a ceramic proppant-embedded location, where a fracture has initiated upon partial embedment of ceramic proppant in a siltstone formation. The process of secondary fracture initiation and propagation as a result of proppant embedment is mainly due to the layered crystal structural orientation of the kaolinite minerals of siltstone. It has been identified that during the process of proppant embedment, existing hydrogen and van der Waals bonds of layered kaolinite minerals of siltstone specimens collapse and generate fractures [56, 41]. These findings further validate the results obtained in the current DEM simulation of the single ceramic proppant-siltstone rock response to increasing stress levels. Moreover, the findings in Fig. 8 reveal that during the ceramic proppant-siltstone rock response to increasing stresses, ceramic proppant does not show a tendency to undergo any crushing. However, small numbers of tensile fractures can be observed near the contact interface between the top-loading platen and the proppant.

3.1.3 Fracture evolution during frac-sand proppant crushing and embedment

In addition, Fig. 8 illustrates the detailed fracture evolution during sand proppant crushing with increasing stress levels. According to the results, tensile dominant fractures within the sand proppant can be observed near its contact location with the top platen at a very early stress level of 0.5 MPa. However, with the gradual increment of stress levels, more tensile dominant fractures initiate within the sand proppant at both its contact interfaces with the top platen and the rock. With the initiation of cracks, at around 57% of the peak load (21 MPa), tensile fractures tend to propagate within the frac-sand proppant. At 90% of the peak failure stress (33 MPa), a major meridional crack (diametrical crack) in the sand proppant initiates from the upper loading platen and propagates towards the rock. As the sand proppant reaches this stage, further increment in loading causes a major diametrical crack to coalesce with minor fractures causing significant damage to the proppant microstructure. According to Fig. 8, at the 37 MPa stress level, a number of cracks have propagated from the major diametrical fracture, ultimately leading to catastrophic proppant crushing failure.
3.2 Single ceramic and frac-sand proppant interaction with granite formation

3.2.1 Crushing and embedment response of proppants with increasing stress levels

Granite is the most abundant rock type in geothermal formations [25], which can be enhanced with hydraulic fracturing with proppants. Therefore, in this section, the behaviour of ceramic and sand proppants interacting with granite formations under the influence of increasing stress conditions is analysed in detail. Figure 10a and b provides the single proppant compressive stress response with increasing numerical time-steps for ceramic and frac-sand proppants, respectively. Similar to the findings observed when interacting with siltstone formations, slower stress growth in ceramic proppants is observed compared with frac-sand proppants when proppants are subjected to compression in granite formations. Importantly, according to Fig. 10a, with the increase in loading, ceramic proppant shows a number of additional peak stress points upon reaching its preliminary failure at 123 MPa. According to the results, the ceramic proppant shows initial peak stress at 123 MPa and suddenly drops to 3 MPa, followed by another stress increment curve. In addition, the second load increment curve of the ceramic proppant follows a saw-tooth behaviour in the proppant stress-numerical steps response. This is mainly due to the breaking of asperities or the disintegration of the ceramic proppant during the loading process. Interestingly, even after preliminary failure at 123 MPa, ceramic proppant is subjected to further

![Secondary-induced fractures](image)

![Proppant-embedded locations](image)

Fig. 9 a Computed-tomography scanned reconstructed image of secondary fracture initiation and propagation at proppant embedment location, and b 3D-profilometer scanned image at ceramic proppant embedded location [4]
strength increment up to 143 MPa, later followed by full crushing of the proppant. However, for the frac-sand proppant, the loading curve follows a rapid and linear stress response followed by a rapid and catastrophic crushing process at a very low compressive stress of 40 MPa (Fig. 10b). Although both ceramic and frac-sand proppants show a dominant proppant crushing mechanism upon interaction with granite formations, proppant embedment also occurs simultaneously with increasing stress levels. Figure 10c illustrates the proppant embedment variation of ceramic and frac-sand proppants with stress levels calculated with the aid of Eq. 1. According to Fig. 10c, the embedment observed during the first loading curve of ceramic proppant and frac-sand proppant follows a similar embedment increment with each stress level. According to the results, frac-sand proppant shows an embedment of only 60.4 μm at its maximum load capacity of 40 MPa, and frac-sand proppant undergo severe crushing beyond this stress level. In addition, ceramic proppant shows an embedment of only 121.5 μm at a very high-stress level of 120 MPa during its first loading curve. However, upon reaching 120 MPa stress levels, both ceramic proppant and the proppant contacting granite interface may be expected to undergo severe damage. This can be predicted due to the higher embedment-stress gradient depicted by the ceramic proppant during its second loading curve. According to the results, during the second loading curve exhibited by ceramic proppant, embedment values of 293.5 (368% increment compared to the embedment observed in the first loading cycle), 404.3 (407%), 459.1 (388%), 536.8
(388.8%), 558.6 (359.4%), and 587.6 μm are obtained at stress levels of 40, 60, 80, 100, 120, and 140 MPa, respectively. In the following section, a detailed analysis of the evolution of ceramic and frac-sand proppant crushing and embedment in granite formations with increasing stress levels is provided with the assistance of numerically-modelled DEM simulations.

### 3.2.2 Fracture evolution during ceramic proppant crushing and embedment

In this section, the mechanisms of ceramic proppant embedment and crushing, fracture generation, propagation, and coalescence during proppant embedment and crushing under increasing stress conditions are discussed. Figure 11 shows the DEM-simulated fracture evolution results for ceramic proppant interaction with the granite formation. According to Fig. 11, during the initial loading stage, tensile fractures appear near the proppant-top loading plate contact interface. In addition, the gradual and slow indentation of ceramic proppant into the granite formation during the initial loading phase induces shear fractures near the proppant-rock contact area. The generation of shear fractures on the granite formation rock upon the interaction of ceramic proppant may be due to ceramic proppant rotation and sliding on the stiff granite surface. This ceramic proppant behaviour of sliding on stiff granite formations can be clearly seen in the first row of Fig. 11. As described in Sect. 3.1.1, a higher ceramic proppant embedment of 323 μm was observed in soft siltstone formations even at very low stress of 50 MPa. However, due to the stiff, brittle nature of granite formations, even at very high stress of 100 MPa, ceramic proppant embedment of only 110 μm was detected. Nevertheless, at higher stress levels up to 100 MPa, constant interaction between high-strength ceramic proppant and very stiff granite rock leads
to significant asperity changes within the proppant as well as within the rock surface. To accurately visualise the asperity damage in the proppant assembly, the DEM results of the fracture propagation pattern of the proppant are presented in the third and fourth rows of Fig. 11. According to the results, upon reaching 100 MPa, the cluster of particles starts to fragment. Further increment of loading up to 120 MPa causes additional tensile fractures to initiate from the top and bottom contact regions of the ceramic proppant. Importantly, upon reaching 123 MPa, rock particle spalling from the granite surface can be detected. Similar to the findings described in Sect. 3.1.2, with the initiation of particle spalling from the rock surface, ceramic proppants tend to embed into the formation at a higher rate, eventually causing significant damage to the granite near the contact with the ceramic proppant. The sudden unloading phase identified after reaching 123 MPa in Fig. 10a is due to the initiation of particle spalling from the granite surface. However, with the further increase in loading, the phenomenon of particle spalling increases substantially, leading to a rapid increment in the rate of proppant embedment, as detected in the second loading curve. In addition, simultaneously to the proppant embedment process, a significant increase in proppant fragmentation can be observed during the second loading curve, as illustrated in the fourth row of Fig. 11. Upon reaching 100 MPa during the second loading curve, a substantial number of tensile-dominant fractures can be seen near the top and bottom contact points of the ceramic proppant. However, further increase in loading up to 140 MPa permits the sudden propagation of distinct vertical split fractures converging from the top and bottom of the ceramic proppant contact points, making the ceramic proppants mechanically unstable to withstand any additional load.

3.2.3 Fracture evolution during frac-sand proppant crushing

As described in Sect. 3.2.1, frac-sand proppants undergo a dominant crushing mechanism in granite formations when exposed to elevated stress conditions, which is shown in Fig. 12. According to the results, upon initial compression of sand proppant, stress concentrates at the proppant contact points with top loading platen and rock that act as flaw initiation zones [11]. As a result, a significant number of tensile-dominant fractures initiate within the sand proppant assembly, even at low stress of 20 MPa. Further increase in stress to 30 MPa results in major diametrical cracks propagating and converging from the top to the bottom of the sand proppant assembly. Moreover, as the sand approaches its failure strength, sand granules start to form fractures with the rapid propagation of multiple cracks. On the verge of sand proppant failure, two major fractures can be observed almost perpendicular to each other, with additional micro-cracks coalesced from the two tensile fracture planes. A similar fracturing mechanism was identified by Zhao et al. [64] by analysing the single sand fracture mechanism using X-ray micro-tomography (see Fig. 13). Note that the current DEM simulations were performed based on the assumption that sand proppants are perfectly spherical. The realistic fracturing mechanism of non-spherical sand particles may slightly differ in terms of the number of fragments created.

3.3 Single ceramic proppant interaction with saturated siltstone formations

3.3.1 Impact of rock-saturation condition on mechanism of proppant embedment

According to the results reported in Sects. 3.1.1 and 3.2.1, the occurrence of proppant embedment is noteworthy even in dry siltstone and granite formations. In realistic hydraulic fracturing reservoir conditions, formation rocks are often exposed to various types of reservoir and fracture fluids over a long period. Therefore, in such circumstances, the impact of proppant embedment may be even critical and have a noteworthy impact on oil/gas recovery from sedimentary-based unconventional reservoir formations. Therefore, this section quantifies the effect of ceramic proppant embedment in siltstone formations exposed to different saturation conditions (30 days water-saturated siltstone, 30 days NaCl (25%) saturated siltstone, 30 days oil-saturated siltstone). DEM simulations of compressing a single proppant on a rock face were conducted to understand the influence of reservoir/fracture fluid saturation on proppant embedment. The simulation results under different saturation conditions are compared with the simulation results of dry-intact siltstone specimens with ceramic proppant. In this section, the type of proppants is limited to ceramic, as the effect of proppant embedment becomes critical when using ceramic proppant compared with less-stiff sand proppant. The embedment into formation rock by a single proppant was calculated using Eq. 1.

Figure 14a represents the embedment obtained from DEM simulations for different saturated siltstone formations with increasing stress levels. It is evident that regardless of the saturation condition, fracture/reservoir fluid saturation of siltstone formation rock has a significant impact on the increment of proppant embedment compared with dry-intact siltstone formation. A maximum ceramic proppant embedment of 613 μm was detected for water-saturated siltstone formation rock at 50 MPa stress level, while, under similar stress conditions, dry-intact proppant showed an embedment of only 323 μm. In addition, for both dry-intact and water-saturated siltstone formations,
maximum stress-level to withstand embedment was 50 MPa. For 25% NaCl saturated and oil-saturated siltstone specimens, the maximum stress level that could withstand embedment further reduced to 25 and 20 MPa, respectively. Beyond the maximum stress levels, significant damage was experienced by the formation rock due to ceramic proppant embedment, and the formation rock is no longer able to withstand any further increase in stress. Proppant embedment in dry-intact siltstone formation shows a reduction in its increment rate upon reaching 10 MPa stress. In contrast, for the water-saturated, 25% NaCl-saturated and oil-saturated siltstone specimens, a higher incremental rate in proppant embedment can be detected with increasing stress levels. For instance, even at a very low confining stress of 20 MPa, high proppant embedment amounts of 323.9 (33% increment compared to embedment in dry-intact siltstone at 20 MPa), 426.1 (74% increment), and 625.7 μm (155.6% increment) are shown by water-saturated, 25% NaCl saturated, and oil-saturated siltstone specimens, respectively.

During hydraulic fracturing, various forms of fracturing fluids can be injected to rock formations. These fluids
include slickwater, cross-linked, visco-elastic surfactant, oil-based, acid-based, alcohol-based, emulsion-based, and form-based fluids [20, 54]. The interaction of formation rocks with injected fracture fluids can result in the softening of fracture surfaces and weakening of formation rock due to the reduction in the rock’s Young’s modulus [33]. Importantly, the effect of rock’s Young’s modulus on proppant embedment has been subjected to extensive study by a number of authors [2, 11, 67]. According to these authors, the decrease in Young’s modulus of a formation leads to a substantial increase in proppant embedment. Therefore, in order to accurately quantify proppant embedment with fracture fluid interaction in the current DEM analysis, Young’s modulus variations in calibrated siltstone assemblies are presented in Fig. 14b. In addition, the mechanical strength variation (unconfined compressive strength) of each calibrated saturated-siltstone formation is illustrated in the same figure. According to the results, the reduction in the Young’s modulus and the UCS of the calibrated saturated-siltstone show an inverse correlation to ceramic proppant embedment, consistent with the findings of Alramahi and Sundberg [2] and Zheng et al. [67]. In reality, siltstone saturation with different fracture/reservoir fluids can lead to several microstructural and mineralogical alterations in rock specimens. The experimentally-tested siltstone specimens used for the DEM calibration process in the present study have mainly kaolinite and quartz-rich mineralogical compositions. In addition, the experimentally-tested siltstone specimens have higher volume pore structures with porosities ranging up to 20%. Therefore, the saturation of siltstone specimens causes significant strength degradation to its microstructure, as clay minerals and cement materials interact with surrounding water bodies by means of absorption, ion exchange, and swelling mechanisms [63]. In addition, the existence of a large volume pore structure within siltstone specimens further accelerates fracture surface softening. Furthermore, the interaction of NaCl with the kaolinite and quartz minerals of siltstone leads to mineral corrosion, causing formation softening and strength weakening [16, 53]. Similarly, with the interaction of oil and siltstone, the organic compounds present in oil reduce siltstone’s mechanical stability due to chemical weathering [6].

3.3.2 Proppant embedment-induced formation rock damage

In this section, we evaluate proppant embedment-induced formation rock damage in saturated siltstone specimens. Figure 15 shows the DEM results of fracture damage in calibrated siltstone assemblies at their respective maximum failure stress. In addition, the tensile and shear fractures generated during proppant embedment-induced formation damage are separately recorded. Figure 16 represents the variation of tensile and shear fracture counts produced by DEM-calibrated rock assemblies under different saturation conditions. Similar to the findings reported in the previous sections, significant formation damage occurs in the process of proppant embedment, and the extent of formation damage is greater in saturated siltstone specimens than dry siltstone specimens. According to Fig. 15, in the DEM simulation with dry siltstone, proppant embedment at the
maximum stress (50 MPa) shows a single major fracture generated from the proppant indented location, propagating to the rock model boundary. With the effect of saturation of siltstone specimens, fractures tend to propagate in multiple
directions at the onset of the respective failure stress. In addition, the fractures propagated in multiple directions coalesce from the proppant-indented location, forming a fracture network within all the saturated siltstone specimens. Therefore, it is evident that asperity damage in saturated siltstone specimens is substantially greater, which can negatively affect oil/gas recovery. Moreover, according to Fig. 16, the total induced fracture count increases to 7280, 6738, 9129 in water-saturated, 25% NaCl saturated, and oil-saturated specimens, respectively, compared with dry siltstone specimens (4503 fracture counts). The higher fracture counts portrayed by oil-saturated siltstone specimens correlate to the higher embedment shown by the ceramic proppant even at a very low-stress level. In addition, the fracture mechanism illustrated by all the simulated siltstone specimens shows a tensile-dominant fracturing mode. The small number of shear fractures shown by all the specimens may result from frictional slip between fracture surfaces during fracture propagation and coalescence.

4 Mechanical response of proppant pack to increasing stress levels

The arrangement of proppants within fractures after proppant injection with fracture fluid is a complex process heavily dependent on many dynamics, including particle type, morphology, geometry, existing inter-particle forces and particle-environmental forces (e.g. particle-fluid interactions, buoyancy, drag and Magnus lift forces) [27]. However, it is also crucial to study the behaviour of proppants within a proppant assembly or a pack and its response to stress conditions as it plays a significant role in ultimate oil/gas recovery. Therefore, this section provides a comprehensive analysis of proppant pack behaviour and its response to increasing stress.

To enable the accurate analysis of the effect of proppant concentration on the mechanisms of proppant pack embedment, crushing, and proppant re-arrangement, DEM models of four different proppant arrangements: partial-monolayer proppant arrangement (the results from Sect. 3 were obtained for purposes of comparison), uniform-monolayer proppant arrangement, uniform-multilayer proppant arrangement with two proppant layers, uniform-multilayer proppant arrangement with three proppant layers were simulated in PFC3D (see Fig. 17). Each proppant layer consists of three by three proppant distributions (a total of nine proppants). Moreover, in order to prepare two and three layers of proppants, each proppant layer is placed one above the other in a cubic particle arrangement. Importantly, to minimise computational time, the particle size in bonded particle agglomerates representing proppant (ceramic and frac-sand) was increased to 0.09 mm.

4.1 Effect of proppant concentration on proppant pack embedment

Proppant embedment = Total deformation

- Proppant deformation - Rock deformation

Proppant pack deformation

The effect of proppant concentration on proppant embedment is subjected to analysis in this section. According to Sect. 3, proppant embedment is the dominant proppant degradation mechanism for three situations, including ceramic proppants embedding to siltstone, ceramic proppants embedding to granite, and sand proppant embedding to siltstone formation. Hence, these three combinations of proppant-rock models were used to further study the proppant embedment mechanisms under different proppant mass concentrations. The proppant embedment variations with compressive stress for ceramic proppant-siltstone, ceramic proppant-granite, and sand proppant-siltstone formations are illustrated in Fig. 18a, b, and c, respectively. Here, the proppant embedment of the DEM simulations was calculated using Eq. 2. A similar method adopted in Eq. 1 was utilised to calculate proppant deformation and rock deformation in Eq. 2 as well. However, an additional parameter, proppant pack deformation (re-arrangement/deformation occurring within proppant packs when subjected to increasing stresses) was calculated for.
uniform mono-layer and multilayer arrangements types by conducting separate numerical simulation tests by replacing the modelled rock with a loading platen.

Based on the DEM simulation results, an increase in proppant concentration within a fracture appears to reduce proppant embedment. For instance, at a compressive stress of 30 MPa, changing the proppant concentration from a partial monolayer to uniform monolayer (1 layer), two uniform layers, and three uniform layers of proppants in ceramic-siltstone assemblies cause an embedment change from 256.2 to 22.1 (91.4% reduction), to 16.4 (93.6% reduction), and to 10.8 µm (95.8% reduction), respectively. In addition, a substantial drop in embedment is found for the simulation of ceramic proppant embedding to granite at 40 MPa. Embedment changes from 62.7 to 8.8 (85.9% reduction) and to 4.7 µm (92.4% reduction) when the proppant concentration varies from partial monolayer to uniform monolayer (1 layer) and to two uniform layers, respectively. Similarly, in the simulation with sand proppant and siltstone at 25 MPa, embedment varies from 51.7 to 15.8 (69.4%), and to 2.9 µm (94.3%) when partial monolayer of proppants shifts to uniform monolayer (one layer) and two uniform layers, respectively. For both ceramic-granite and sand-siltstone simulations, no proppant embedment is shown at any stress level when the fracture consists of a uniform multilayer with three layers of proppants. Therefore, the results confirm that a higher proppant concentration within fractures greatly contributes to the minimisation of the effect of proppant embedment. Importantly, the DEM results of the current analysis agree well with the experimental studies conducted by Bandara et al. [6], Wen et al. [55], and Volk et al. [52], who experimentally confirmed that proppant embedment is drastically curtailed with the increase in proppant concentration. This is primarily due to the higher single-point loading acting on the proppant-rock contact interface in partial and uniform monolayer proppant arrangements compared with multilayer proppant packing arrangements. To accurately visualise this, the force chain between the proppant and rock interface of the DEM simulation of the uniform monolayer (1 layer) and uniform multilayer arrangements at 150 N are analysed. Here, the centre

\[
\text{Proppant pack porosity at a particular stress level} = \frac{\text{Total volume at the particular stress level} - \text{Total volume of the proppants}}{\text{Total volume at the particular stress level}}
\]

Fig. 17 DEM simulation assemblies of different proppant pack arrangements a Partial-monolayer proppant arrangement, b uniform-monolayer proppant arrangement, c uniform-multilayer proppant arrangement with two proppant layers, d uniform-multilayer proppant arrangement with three proppant layers
compared with proppants in the uniform-multilayer proppant arrangement (a thicker line in the force chain signifies a larger magnitude of force).

4.2 Effect of proppant concentration on proppant pack crushing

In this section, an analysis of the influence of proppant concentration on the proppant pack crushing effect is presented. As Sect. 3 indicated, the crushing phenomenon is the most dominant proppant degradation mechanism in the sand proppant-granite assembly. Hence, a sand proppant—granite DEM assembly is utilised to analyse the influence of proppant concentration on proppant crushing. Figure 20 represents the variation of proppant pack porosity with numerical loading time for a sand proppant—granite DEM simulation with different proppant arrangements. The proppant pack porosity was calculated using Eq. 3. With increased loading time, the porosity in the proppant pack gradually reduces. This is mainly due to proppant crushing and fragment re-arrangement within the proppant pack as a result of proppant pack compaction. At the numerical step level of $25 \times 10^3$, the uniform monolayer (1 layer) proppant pack reaches an approximate maximum stress value of 30 MPa. According to Fig. 20, at that instant, reductions in the pack porosity are 8.4%, 3.9%, and 2.5% for uniform monolayer (one layer), two uniform proppant layers, and three uniform proppants layers, respectively. To accurately visualise the sand proppant pack behaviour at this stress level, the DEM results for proppant packs with uniform monolayer and two uniform layers at 30 MPa stress levels are presented in Figs. 21 and 22, respectively. In addition,
Fig. 23 provides a quantitative analysis of the number of fractures within proppant in the uniform monolayer and uniform multilayer (2 layers) proppant arrangements at the stress of 30 MPa. According to Fig. 21, it is evident that all the proppants within the single uniform layer undergo a significant amount of crushing upon subjection to a stress of 30 MPa. This is further confirmed by Fig. 23a, as almost all the proppants under the single monolayer proppant distribution show a fracture count of up to 500. In addition, according to Fig. 21b, all the proppants undergo substantial asperity damage upon subjection to crushing, which may later contribute to the production of large amounts of fines. The greater reduction in proppant pack porosity represented by the uniform single monolayer proppant distribution in Fig. 20 is primarily as a result of the clogging of the generated proppant fines within the existing free volumes of the proppant pack. The minor reduction in the proppant pack porosity shown in Fig. 20 with increasing number of proppant layers is due to the less degree of proppant crushing in multiple layer proppant packs. According to Fig. 22, at a stress of 30 MPa, only a limited number of proppants within the two-layer proppant pack undergo full crushing, although some minor fractures can be observed in the rest of the proppants in the multilayer arrangement. In a multilayer proppant pack, in-situ stresses tend to redistribute and reduce the single-point loading on a proppant, eventually reducing the proppant crushing effect. As shown in Fig. 22b and 23b, only four out of nine proppants in the top layer undergo full crushing, while the rest of the proppants assist in maintaining a consistent fracture aperture at high stress levels. The findings of the current DEM analysis are in accordance with the results obtained via experimental techniques by Bandara et al. [6] and Herskovits et al. [24], and these researchers further confirmed the resistance of proppant crushing in multilayer proppant packs compared to monolayer proppant arrangements.

4.3 Effect of proppant concentration on proppant pack re-arrangement

In addition to proppant crushing, with an increase in the number of proppant layers, proppant packs tend to undergo a significant amount of proppant re-arrangement and elastic and plastic proppant pack deformation with increasing stress conditions [62]. The DEM results of sand proppant re-arrangement with increasing stress levels are illustrated in Fig. 24. Generally, with increased stress, proppant packs undergo a higher strain hardening process due to proppant re-arrangement into voids, resulting in a denser pack arrangement, ultimately increasing proppant-proppant contacts and limiting proppant motion [43]. According to
In general, shale and siltstone formations are the most abundant sedimentary-based rock formations which contain trapped unconventional oil and gas resources. In addition, granite formations often exist as the formation rock for geothermal resources. Therefore, for the recovery of unconventional oil/gas and geothermal energy, attention must be given to the behaviour of proppants in tight rock formations if production recovery targets are to be met. The series of DEM proppant-rock numerical simulations in the present study gives detailed insights into the mechanisms of proppant crushing, embedment, and re-arrangement in fractured reservoir environments. According to the results of this study, the selection of an appropriate proppant type based on the type of reservoir formation plays an important role in determining the extent of proppant crushing and embedment in the fractures. The results reveal
that sand proppants are the preferred proppant type for shallow depth (less than 35 MPa in-situ stresses) sedimentary-based oil/gas recovery due to their lower proppant embedment. However, as sand proppants tend to crush beyond 35 MPa in-situ stress, high-strength ceramic proppants are essential for oil/gas recovery in deep sedimentary-based formations with high in-situ stresses at the expense of proppant embedment. For the extraction of geothermal energy from granite-based formations, high-strength ceramic proppants are preferred over low-strength frac-sand proppants even under very low in-situ stress conditions, as both proppant types show minimal proppant embedment. Importantly, the DEM analysis reported here shows that ceramic proppants have the potential to withstand high in-situ stresses up to 140 MPa without undergoing full crushing. Furthermore, the current study reveals that ceramic proppants often undergo very high embedment in formation rocks on exposure to reservoir and fracture fluid saturation. However, in realistic reservoir conditions, the mechanism of proppant crushing and embedment may be severely intensified due to consistent proppant-rock interaction and saturation with various fracture/reservoir fluids, high temperatures followed by cool conditions, and high closure stresses. Therefore, it is crucial to take these factors into consideration in the synthesis of proppants and the selection of appropriate proppant types prior to proppant injection. Importantly, the DEM analysis indicates the importance of higher proppant concentrations in fractures owing to their ability to minimise proppant crushing and embedment. The achievement of higher proppant concentrations in fractures with better proppant distribution patterns (preferably proppant packs with multilayer packing arrangements) can be managed by the process of graded proppant injection. The injection of finer proppants into fractures followed by larger proppants allows finer particles to initially penetrate into deep

Fig. 22  Sand proppant crushing within uniform-multilayer proppant distributed fracture with two layers at 30 MPa. a General side view, b Top view (2nd layer), and c Top view (1st layer)
fractures, while larger proppants assist in forming a multilayer proppant packing arrangement with better proppant coverage. The mechanism of graded proppant injection has gained the attention of many researchers [30–30] and this was comprehensively analysed in our previous study with the aid of experimental approaches [4].

6 Conclusions

The mechanisms of proppant crushing and embedment in formation rocks have been subjected to comprehensive analysis with the aid of a numerically-simulated DEM approach. The influence of proppant type, type of formation rock, and reservoir/fracture fluid saturation condition on crushing, embedment, and proppant rock damage were extensively studied using a single proppant-rock model in PFC3D. In addition, the proppant crushing, embedment, and re-arrangement undergone in multilayer proppant packs with increasing stress levels were evaluated and discussed. The following conclusions can be drawn:

- The utilisation of frac-sand proppants instead of ceramic proppants in sedimentary-based siltstone formations under low in-situ stress conditions shows improved results in terms of reduced proppant embedment. At 10, 20, and 30 MPa stress levels, only minor embedment is shown by frac-sand proppant: 27 (88% lower than ceramic proppant at a similar stress level), 38 (84.3% lower), and 56 µm (78.1% lower), respectively. However, even in a relatively soft siltstone formation, frac-sand proppants often undergo crushing at compressive stress over 35 MPa.
- DEM analysis revealed that during the process of ceramic proppant embedment in soft sedimentary-based siltstone formations, rock spalling generally occurs as a result of constant fragmentation of the rock surface upon interaction with high-strength proppants. In addition, the occurrence of ceramic proppant embedment in siltstone formations with increasing stress-levels leads to the initiation of tensile-dominant secondary fractures. Importantly, beyond 50 MPa stress levels, these secondary proppant embedment-induced fractures tend to propagate and coalesce, causing significant damage to the siltstone formation. Upon reaching this damage stress-level, ceramic proppant undergoes further embedment at a higher rate until it is fully indented into the rock surface.
- For granite-based formation rock types, injection of high-strength ceramic proppants is preferred over low-strength frac-sand proppants, even under very low in-situ stress conditions, as both proppant types show limited proppant embedment. Moreover, ceramic proppants have the potential to withstand high in-situ stresses up to 140 MPa in stiff granite formations without undergoing full crushing. However, ceramic proppants show significant embedment under these conditions.
- DEM analysis reveals the fragmentation characteristics of ceramic proppant grains due to disintegration of the proppant microstructure when subjected to high stresses in granite formations. Around the 120 MPa stress level,
Fig. 24 Re-arrangement of proppant packs subjected to loading.
additional tensile fractures initiate from the top and bottom contact regions of the ceramic proppant, and at the point of failure (140 MPa), sudden propagation of distinct vertical split fractures is detected. However, sand proppants show a major diametrical crack propagating and converging from the top and bottom of the proppant at a very low-stress level (30 MPa). However, approaching frac-sand proppant failure (40 MPa), proppants showed brittle fracture with rapid propagation of multiple cracks.

- The saturation of siltstone formations with fracturing/reservoir fluids leads to a significant increment in proppant embedment. The results reveal that even at a very low confining stress of 20 MPa, substantially high ceramic proppant embedment amounts of 323.9 (33% increment compared to embedment in dry-intact siltstone at 20 MPa), 462.1 (74% increment), and 625.7 µm (155.6% increment) are found in water-saturated, 25% NaCl saturated, and oil-saturated siltstone specimens, respectively.

- Proppant embedment reduces to a great extent in the presence of proppant packs with better proppant distributions. The results reveal that at a compressive stress of 30 MPa, changing the proppant concentration from partial monolayer to one, two, and three uniform layers of proppants in ceramic-siltstone assembly causes an embedment change from 256.2 to 22.1 (91.4% reduction), 16.4 (93.6% reduction), and 10.8 µm (95.8% reduction), respectively. Similar reduced embedment findings were found in other proppant-rock assemblies.

- The presence of a multilayer proppant pack leads to lower proppant crushing effects as in-situ stresses tend to redistribute and reduce the single-point loading on a single proppant. In addition, with the increment of stress, proppant packs tend to undergo a greater strain hardening process due to proppant re-arrangement into voids.

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