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Micro-Mechanical Modeling of Perforating Shock Damage

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Abstract

Shaped-charge jet-induced formation damage from perforation treatments hinders productivity. Manifestation of this damage is in the form of grain fragmentation resulting in fines that plug up pore throats along with the breakdown of inter-grain cementation. We use the Smooth Particle Hydrodynamic (SPH) computational method as a way to explicitly model, on a grain-pore scale, the dynamic interactions of grains and grain/pores to calculate the damage resulting from perforation-type stress wave loading. The SPH method is a continuum Lagrangian, meshless approach that features particles. Clusters of particles are used for each grain to provide representation of a grain-pore structure that is similar to x-ray synchrotron microtomography images. Numerous damage models are available to portray fracture and fragmentation. In this paper we present the results of well defined impact loading on a grain-pore structure that illustrate how the heterogeneity affects stress wave behavior and damage evolution. The SPH approach easily accommodates the coupling of multi-materials. Calculations for multi-material conditions with the pore space treated as a void, fluid-filled, and/or clay-filled show diverse effects on the stress wave propagation behavior and damage. SPH comparisons made with observed damage from recovered impacted sandstone samples in gas-gun experiments show qualitatively the influence of stress intensity. The modeling approach presented here offers a unique way in concert with experiments to define a better understanding of formation damage resulting from perforation completion treatments.

Introduction

Shaped-charge completions offer an economic way to perforate well casing and cement to establish connectivity to the reservoir rock. It has long been recognized that permeability damage, the crushed zone, resulting from shaped-charge perforation treatments is a major cause of inefficiency for well productivity^{1,4}. Experimental studies of shaped-charge perforation show this damage to be of three interrelated effects. One damage effect for consolidated rock is the breakdown of inter-grain cementation. A second damage effect for consolidated and unconsolidated rock is the creation of shock-induced fines. This is a result of grain fragmentation caused by the intense stress delivered by the penetrating jet, which can be on the order 2 to 4 million psi in the initial perforated rock region. Often fines occur most profusely near the perforation tunnel walls, but experiments show also that significant grain fragmentation can also exist beyond the tunnel walls⁵. Finally, there are transient flow effects of the shaped-charge explosive products combined with the overbalance or underbalance flow resulting from differences in pressure between the formation fluid and the wellbore fluid. These damage effects modify the near-wellbore stress field and the mechanical properties of the rock in this region. The fines are mobilized and intrude into or out of pore throats often causing localized suppression of flow. In addition to hindering production, these effects can also cause poor injectivity, uncertainty in fracture breakdown conditions, impairment to gravel packing and frac-packing treatments, and uncertainty in proppant distribution.

We apply the Smooth Particle Hydrodynamic (SPH) computational method to explicitly model, on a grain-pore scale, the dynamic interactions of grains and grain/pores undergoing fracture and fragmentation resulting from impact loading. The loading is similar in amplitude and duration to that induced into reservoir rock by shaped-charge perforation treatments. The SPH method, originally formulated for the treatment of astrophysical problems⁶, has been used over the past seven years to model solid mechanic problems, such as; bombcase fragmentation⁷, impact events⁸⁻¹⁰, and brittle fracture^{11,12}.

The main emphasis of this paper is to illustrate how heterogeneity on the grain-pore scale affects stress wave behavior and the damage imparted to reservoir material by shaped-charge type loading. We employ the SPH SPHINX code¹³ to model this heterogeneous behavior. Our calculations for two-dimensional representations of grain-pore structure examine the influence of pore space treated as a void, as fluid filled, and as clay filled. Work to obtain explicit three-dimensional reconstruction of the grain-pore structure from x-ray synchrotron microtomography images is ongoing. Although the simulations are two-dimensional, the results reflect, in a qualitative manner, the complex phenomenology associated with this loading. Simulations of well-defined plate impact loading capture the effect of stress intensity on the damage observed in samples of Berea sandstone recovered from gas-gun experiments. We feel that this SPH microscale modeling approach, in concert with experiments, offers an unique way to obtain a better understanding of formation damage resulting from perforation completion treatments and to provide calibration for macro-continuum damage modeling.

SPH Motivation

SPH is a Lagrangian, meshless method in which material elements are represented by mass points, known as particles, and are governed by the continuum equations of motion and constitutive models. Each particle has an interpolation function, W , associated with it, known as a kernel, which has a domain of interaction, $2h$, with neighboring particles (Fig. 1), where h is the smoothing length. Particles carry local values of position and velocity with values of, density, deformation rate, acceleration and energy obtained through interpolation with neighbor particles. Stress for each particle is then obtained from specific constitutive representations.

The SPH approach, being continuum Lagrangian and meshless, combines the features of precise material tracking, traditionally obtained only with Lagrangian methods, and that of the freedom of flow, traditionally obtained only with Eulerian methods. Thus, advection problems inherent to Eulerian formulations do not occur and mesh tangling problems typical of Lagrangian formulations are alleviated. SPH particles exist only where actual material exists, precluding the need to zone up volumes of empty space that mesh-based methods usually require. Thus, the particulate nature of SPH easily accounts for large deformation, accomodates the mixing of multi-materials in a more natural way, and allows for explicit fracture features that occur in solid breakup.

Excellent overviews of the SPH approach^{14,15} discuss some of its strengths and limitations. One should realize that the standard SPH methodology is relatively immature compared with mesh based Lagrangian and Eulerian techniques, especially in the areas of boundary contacts, stability, conservation, and treating of fracture. For example, we currently eliminate a particle's influence to all its neighbors when it fails in tension. It would be more realistic to have communication cease between two particles when a failure condition is met, so as to reflect the correct tensor character of the stress state, to define the correct directionality for the fracture, and to give a better estimate of its effect to the surrounding material. There is considerable development ongoing¹⁶⁻¹⁸ that is striving to resolve these issues. These features and others are currently being researched for implementation into the SPHINX code. Thus, the calculated results given herein should be viewed only as qualitative. It is felt that with proper attention to these issues, SPH will become a fully viable and powerful computational continuum dynamics technique. Although quantitative values herein will be modified when the proper procedures and algorithms are implemented, the phenomenology on how damage is created by perforation-type loading in the form of granular fracture and fragmentation is basically correct and very insightful.

Grain-Pore Structure

Representation of a heterogeneous grain-pore structure for impact loading simulations is created to be similar in character to images of reservoir rock obtained from x-ray synchrotron microtomography data¹⁹. Fig. 2 shows a computer enhanced cross-section image of a sandstone with a porosity of 24.5%. Figs. 3a and 3b show a SPHINX code synthetic grain-pore structure with (a) dry pores and (b) fluid-filled pores. Each grain, shown by contrasting colors, consists of a cluster of SPH particles. This structure was obtained in a statistical manner, by first prescribing the total number of particles initially located in a specified x-y domain. Within this domain, a seed particle for each grain is randomly selected for the desired number of grains. Particles that complete the grain are made up of neighbors closest to the seed particle. After all available particles have been assigned to a grain, seed particles for porosity are randomly selected among the boundary particles of the grains. The pore space is created eliminating particles outward from the pore seed positions by trial and error until a representative structure is obtained. For material-filled pores, the vacated, once solid particles can be prescribed to be fluid, cement, clay, etc.. The above structure has a total of 16384 particles and 113 grains with nominal grain size of 100 microns over a square domain of (1.28 mm x 1.28 mm), having a total porosity of 14%.

While the above procedure produces fairly good two-dimensional grain-pore structures, extending it to realistic three-dimensional structures has been somewhat unsuccessful and tedious. An alternate approach for creating three-dimensional simulation models is to specify the surface of each grain independently and to ensure that grain-grain surface penetration does not occur. We are creating such structures with the aid of x-ray synchrotron microtomography data of sandstone samples²⁰. Stereo images are being prepared from this data to obtain x-y-z spatial definition of each grain and algorithms are being implemented to reconstruct three-dimensional structures from stacks of these images. This approach will allow resolution on the order of a few microns and provide a useful way to build realistic grain-pore models.

Plate Impact Simulations

The plate impact configuration for simulations of the two-dimensional heterogeneous grain-pore structure is shown in Fig. 4. This configuration is representative of gas-gun impact recovery experiments performed at Lawrence Livermore National Laboratory²¹. In these simulations, the impactor and the containment materials are treated as elastic materials with 6061-T6 aluminum properties of density = 2.7 gm/cc, Poisson's ratio = 0.33 and bulk modulus = 78 Gpa. The grains are modeled as pure sandstone quartz with density = 2.65 gm/cc, Poisson's ratio = 0.23 and bulk modulus = 75 Gpa. Clay-filled pore material has a density = 2.2 gm/cc, bulk modulus = 22 Gpa, and Poisson's ratio = 0.42 and fluid-filled pore material has a density = 1.0 gm/cc and a bulk modulus = 2.2 Gpa. The particle resolution for these calculations is $h=10$ microns with a total of 40642 particles. The boundary condition for the top and bottom surfaces are treated as roller boundaries that allow motion along but not across them. The rear boundaries of the target assembly and impactor plate are free surfaces.

In these simulations plasticity is only considered for the clay and it is assumed to obey a perfectly-plastic von Mises behavior having an unconfined compressive yield value = 50 Mpa. A simple brittle tensile failure description is assumed for the quartz grains. When the maximum principal stress for each grain particle exceeds a specified tensile failure stress the particle ceases communication with its neighbors. Another model considers a statistical fracture description^{12,22}, where grain particles are randomly seeded with a Poisson distribution of flaws, up to ten flaws per particle, and a Weibull distribution^{23,24} of tensile failure stress is assigned for each flaw. However, our simulations thus far indicate little difference in calculated damage for the two models. This may be due to the heterogeneous character of the grain-pore structure. Thus, we only discuss results below for the simple tensile model. In both tensile failure models, the particle resumes communication with its neighbors if the state of stress becomes compressive. Note, the discussion in the motivation section above infers the qualitative nature of this approach.

To illustrate how material heterogeneity influences stress wave propagation, it is informative to compare the response of a material having explicit heterogeneity to a material treated as being homogeneous and uniform. **Fig. 5a** shows the uniform distribution of the second deviatoric stress invariant at $0.15\ \mu\text{s}$ in a homogeneous target plate subjected to an impact velocity of $1.07\ \text{km/s}$. This produces a normal stress and deviatoric invariant amplitudes of $9.4\ \text{GPa}$ and $2.64\ \text{GPa}$, respectively. The second deviatoric stress invariant field for the same impact loading is shown for the 14 percent porosity grain-pore structure having clay-filled pores (**Fig. 5b**), water-filled pores (**Fig. 5c**), and void pore space (**Fig. 5d**). The disruption of the uniform stress state in the grain structures is caused by reflections along the grain surfaces where material impedance differences occur. These reflections cause components of the stress tensor to be transformed from a primary state of compression, that occurs for the uniform case, to mixed tensile and compressive components for the heterogeneous cases. Irregularity of the wave front increases and more disruption to the structure behind it occurs as the impedance of pore space material decreases. Although stress propagates through the mismatched impedance surfaces when material occupies the pore space, considerable wave energy is channeled in a "fingering" way at grain-grain contacts. This would be more apparent for higher porosity material where grains have fewer contacts. Another interesting observation is the increased collapse of pore space with a decrease of pore-fill material density.

Disruption to the normal axial stress response caused by heterogeneity is compared to the homogeneous stress response (**Figs. 6a, 6b and 6c**) for the location indicated in **Fig. 4**. The stress is zero for a particle after it fails in tension, unless it again becomes compressive. The response of a failed particle, small dash line, and a nearby unfailed particle, large dash line, are shown relative to the homogeneous response, solid line, for the clay-filled, fluid-filled and dry cases. Again, as above, the response exhibits more disruption as the impedance of pore space material decreases. **Fig. 6d** compares the maximum principal stress of the particles that have failed in tension for the dry pore case (small dash line), fluid-filled case (dash-dot line), and clay-filled case (large dash line), with the homogeneous material response (solid line) that remains in compression. Significant tensile stresses develop and tensile failure occurs very quickly for the dry and fluid-filled cases, but much later for the clay-filled case. In the uniform case, tensile stress will not occur until wave reflections from the impactor and containment vessel free surfaces interact at about $0.5\ \mu\text{s}$ in the region of the sample's right boundary for the properties and configuration considered here. These responses indicate how wave energy can be dispersed and/or reinforced by the heterogeneous structure and how stresses transformed early on from compression to tension cause tensile damage.

The calculated tensile damage distributions for the above fluid-filled and dry pore cases are shown in **Figs. 7a and 7b**. These snapshots are at a time after the complete wave imparted by the impacting plate has propagated through the grain-pore structure. The damage calculated, in regions highlighted by the dashed lines, is caused by localized pockets of tensile stress that arises from the impedance surface interactions causing debonding of grains, grain fracture and fragmentation. Considerably more damage in the form of grain fragmentation is observed over the first half of the dry pore sample and is localized in the region where large pore space was initially present, while only fracturing appears in the latter half of the sample. Isolated regions of fracturing are observed in the first half of the fluid-filled sample with little or no fragmentation. However, a small pocket fractured and fragmented material occurs in the central part of the latter half of this sample where a large pore initially existed. A large amount of compaction is evident for the dry case as opposed to a very slight amount for the fluid-filled case. It is this violent collapse, grains being driven and colliding with other grains in the dry case, that gives rise to the higher degree of damage. For the fluid-filled case, the fluid acts as a buffer mitigating strong grain-grain interactions but allows higher intensity of the stress wave to propagate further into the sample.

The above results show how stress wave propagation and damage is influenced by heterogeneity. The degree of damage imparted is directly associated with the loading intensity, its duration, the local tensile strength of the grains, and the type of pore-fill material. Fracture mechanic data for quartz grains²⁵ indicates a tensile strength on the order of 0.3 Gpa for 100 micron size grains under static indentation tests. It is unlikely however, that a grain would fracture at such a low tensile value when subjected to microsecond duration loading. Therefore, a tensile strength of 2.5 Gpa was used in the simple tensile failure model for the results shown in Figs. 5, 6 and 7.

Comparison with Impact Experiments

Qualitative comparisons of calculated damage are made with thin-section images²⁶ of damage observed in Berea sandstone samples recovered from gas-gun impact experiments²¹. The tests were performed in a configuration similar to Fig. 4. An image of an unshocked-undamaged sample is shown in (Fig. 8). Front surface images of recovered samples impacted to 9.4 Gpa and 6.4 Gpa in Figs. 9a and 9c are compared with SPHINX damage calculations in Figs. 9b and 9d. Although the amount of damage observed in the experiment is greater than the calculated damage, the nature of the calculated damage is similar. For the 9.4 Gpa impact loading, the calculation shows more fragmentation in agreement with the experiment as compared to more distinct grain fracturing and less fragmentation for the 6.4 Gpa loading. In general, more damage would be expected on the front impacted-surface and tend to decrease in the interior of the sample. New experiments will provide interior damage data by thin sectioning normal to the front surface. The limitation of two-dimensional simulations allowing only portrayal from the front surface into the interior emphasizes the need for three-dimensional simulations.

Conclusions

We have demonstrated the use of the Smooth Particle Hydrodynamic (SPH) computational method as a way to model, on a grain-pore scale, the dynamic interactions of grains and grain/pores to simulate the damage resulting from stress wave loading. Simulations of a plate impact configuration show the influence of explicit heterogeneity for void pore space, fluid-filled pores and clay-filled pores. Qualitative agreement is obtained for calculated damage with the damage observed on recovered samples of Berea sandstone from gas-gun impact experiments. The significant increase in fragmentation damage at the 9.4 Gpa loading as opposed to the 6.4 Gpa loading is achieved. Although these grain-pore scale simulations are two-dimensional, they capture the essence of how damage to the rock fabric can occur from perforation-type stress wave loading. They illustrate the complexity of how heterogeneity affects stress wave behavior which in turns affects damage evolution. These results along with perforation experiments suggest that a number of aspects such as grain size, porosity, grain angularity, smoothness, cementation, clay content, fluid content, unconsolidation, etc., may all play a role in perforation-induced damage. We beleive that authentic representation of three-dimensional grain-pore structures are needed to properly evaluate these effects. Therefore, effort is ongoing to develop realistic grain-pore strucutress with the aid of x-ray micrtomography data. They will allow direct correlation to well-defined impact experiments. Exercising grain-pore scale simulations over a wide range of geophysical parameters will help calibrate and provide more reliable macro-continuum damage descriptions. These employed in concert with perforation phenomenology experiments²⁷ will hopefully lead to improved perforation treatment designs.

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Fig. 1 Cubic B-Spline Kernel approximation and domain of interpolation dependence, $2h$, for SPH particle i on particles j .

Fig. 2 Computer enhanced image of 24.5% porosity sandstone from x-ray microtomography data¹⁹.

Fig. 3 SPHINX setup model for grain-pore structures having size 1.28mm x 1.28mm with 113 grains, nominal grain size of 100 microns, and total porosity of 14 percent. (a) dry pores and (b) fluid-filled pores.

Fig. 4 SPHINX configuration for plate impact simulations representative of gas-gun recovery experiments. The white circle denotes a region where time histories are monitored.

(a) homogeneous plate

(b) clay-filled pores

(c) fluid-filled pores

(d) dry pores

Fig. 5 Comparisons of calculated second deviatoric stress invariant distributions for plate impact loading of 9.4Gpa of (a) homogeneous plate, (b) grains with clay-filled pores, (c) grains with fluid-filled pores, and (d) dry pores. Material in pore-space is shown as black for clarity.

Fig. 6 Comparisons of axial stress and maximum principal stress responses for heterogeneous structures with homogeneous target at location shown in Fig. 4. Axial stress - (a) clay-filled pores, (b) fluid-filled pores, and (c) dry pores with homogeneous response as solid line, failed particle as small dash line, and unfailed particle as large dash line. (d) maximum principal stress of failed particle with homogeneous response as solid line, dry pores as small dash line, fluid-filled as dash-dot line, and clay-filled as large dash line.

(a) fluid-filled pores

(b) dry pores

Fig. 7 Calculated damage for plate impact loading of 9.4Gpa of (a) grains with fluid-filled pores and (b) grains with dry pores. Regions of intense fracture or fragmentation are within dashed outlines. Material in pore-space is shown as black for clarity

Fig. 8 Thin-section image of undamaged Berea sandstone.

(a) experiment - 9.4Gpa

(b) calculation - 9.4Gpa

(c) experiment - 6.4Gpa

(d) calculation - 6.4Gpa

Fig. 9 Comparisons of calculated damage for plate impact loading with Berea sandstone samples recovered from gas-gun experiments. (a) experiment for 9.4Gpa impact, (b) calculation for 9.4Gpa impact, (c) experiment for 6.4Gpa impact, and (d) calculation for 6.4Gpa impact.

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