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A PRACTICAL DESIGN TOOL FOR WELLBORE STRENGTHENING

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Abstract

Much progress has been made in recent years on "strengthening" a wellbore to reduce the incidence of lost circulation. The process involves creating and filling small fractures with loss-prevention materials (LPM) to alter the near-wellbore hoop stress, thus increasing the fracture resistance above the in-situ minimum horizontal stress. It has been well documented that this practice can increase the apparent breakdown limit by as much as 3 to 4 lb/gal. A number of properties influence the technology, including the wellbore diameter, well orientation, in-situ stress magnitude and orientation, rock properties, and the range of particle size, distribution and concentration of the loss-prevention materials. The ultimate success of this wellbore-strengthening practice, however, depends on how well a given application can be planned and engineered in the field.

This paper presents a new design tool to address the influence of key properties and the practical issues of wellbore strengthening. The software package can handle inclined wells with fully 3-D stress anisotropy. A probabilistic approach based on Monte Carlo simulation is implemented to address important data uncertainties, thereby allowing the proper risk assessment and evaluation of available options for specific applications. Built on a common spreadsheet, the design tool is fast and user-friendly so that drilling engineers feel comfortable using it. For flexibility, the program allows users to select from a list of standard or customized loss-prevention materials.

Introduction

The mud weight window serves as a critical design factor for the design of both the well and drilling fluid system. It defines the range between the minimum weight to avoid well collapse (compressive failure) and the maximum mud weight to avoid formation breakdown (tensile fracturing). The mud-weight window may be very narrow under certain conditions, thereby requiring expensive design changes or rendering drilling impractical. A common example is drilling through a depleted producing formation, where pore pressures have dropped since the start of production and the formation total stresses have decreased. At the same time, the neighboring shale layers may have maintained their pore pressure. As a result, the difference between the minimum mud weight required in the shales to prevent collapse and the maximum mud weight in the depleted interval to prevent formation breakdown and lost circulation may be insufficient. In such cases, the wellbore strengthening technique is one that has been employed to increase the breakdown limit of the depleted formation and allow the well to be drilled safely and economically.

Much progress has been made in recent years on the ability to "strengthen" wellbores by designer drilling fluids that alter the near-wellbore hoop stress. Today, several wellbore strengthening techniques are applied widely in the drilling industry. One such technique is plugging an existing or drilling-induced fracture at the tip (van Oort *et al.* 2007). This phenomenon frequently is demonstrated in frac-and-pack completions or in drill cuttings injection operations. This also has been illustrated in laboratory drilling simulations such as in the joint industry project DEA 13 (Morita *et al.* 2000). A second technique involves plugging the fracture at the mouth (wellbore wall). The drilling industry commonly refers to this as a "stress-cage" (Aston *et al.* 2005). Laboratory tests that simulate fractures of different width by two separated permeable disks appear to support plugging of the simulated fracture at the wellbore (Hettema *et al.* 2007, Tehrani *et al.* 2007).

This paper presents a practical software design tool for these two techniques, which are shown in **Fig. 1**. The two basic building blocks of the tool are (a) the accurate estimate of potential fracture size and (b) the appropriate blending of granular LPM. Challenges for the first one include the uncertainties of rock properties and downhole conditions, in addition to modeling difficulties. Challenges for the second building block include the variety of standard and locally-sourced LPM that necessitates the blending algorithms and the design software to be flexible and adaptive. The software is built on a spreadsheet framework for usability and simplicity. The closed-form solution for fracture aperture prediction allows the implementation of Monte Carlo simulations permitting more than 10,000 simulations in less than a minute. Users can customize choices for LPM loss by uploading particle-size distribution (PSD) and other properties into the program database.

Fracture Width Prediction

This section addresses fracture size and aperture for a wellbore of any deviation and orientation under anisotropic stress conditions. The closed-form solution for the fracture aperture is based on linear fracture mechanics. The model depends on well deviation and orientation, fracture length, wellbore radius, in-situ stresses (S_V, S_H and S_h), bottomhole pressure and rock elastic properties (Young's modulus and Poisson's ratio). The closed-form solution was validated with published data and numerical results using finite elements over a wide range of parameters. The solution assumes that when the fracture length (L) is much larger than the radius (R) of the wellbore, the wellbore and the two fractures can be regarded as a single fracture with a length of 2(L + R). Similarly, when the fracture length is much smaller than the radius of the wellbore, each fracture can be regarded as an edge crack in a half-plane. There are numerical results for these two limiting cases, and the closed-form solutions compare well with the numerical results (Alberty and McLean 2004). Table 1 compares the closed-form solution and the finite element analysis for the fracture aperture at the wellbore. The following parameters were used for the comparison: P_W = 9200 psi, S_H = 9,000 psi, Young's modulus E = 1.09×10^6 psi, and Poisson's ratio ν = 0.225.

Table 1. Comparison of Finite Element Analysis and Closed-Form Solution (R=6 in.)			
	L = 6 in.	L = 9 in.	L = 12 in.
FEA solution (mm)	0.1702	0.2332	0.2921
Closed-form solution (mm)	0.1703	0.2343	0.2936
Relative error (%)	−0.071%	−0.472%	−0.541%

The required inputs for fracture aperture are uncertain, especially when these inputs are based on information from offset wells. The uncertainties can come from several sources, such as from logging and well testing analyses of offset wells, or from geology such as rock Young's modulus and Poisson's ratio. For example, it may be impossible to determine exactly the maximum horizontal stress in the well. It could very well range from say 5,400 to 5,600 psi, but an exact value within this range is unknown. The uncertainty in the input variables is shown in the top left corner (section labeled as I-1) in **Fig. 1**. One method to address this uncertainty is Monte Carlo simulation, a computational method that repeatedly and randomly samples possible input values and computes results based on these samplings. As opposed to a deterministic model, Monte Carlo provides a broader spectrum of possible outcomes and can rank which inputs most affect the output (sensitivity analysis). Each input with uncertainty is quantified by transforming it into a statistical distribution that relates to the possible range and distribution of values. Monte Carlo simulation statistically samples these defined input distributions, processes each collection of samples deterministically, and repeats the process until it produces an approximate solution. Each output in the solution is in the form of a distribution depicting the likeliness of a specific outcome. As with any convergent numerical method, a greater number of samplings will produce a better approximation. Generally, a typical simulation consists of several thousand iterations. Each input value can be modeled by a most likely, a minimum and a maximum value with an appropriate distribution, and can be based on logging analysis results, laboratory or well testing results or other databases. The Monte Carlo simulation samples each of these distributions, performs fracture-width calculations, and generates a fracture width distribution. The primary output from the simulation is the probability or risk of results such as the P10, P50 and P90 values of fracture aperture (the two plot labeled I-2 in **Fig. 1**), indicating the probability of having apertures less than the corresponding values.

One of the key advantages of Monte Carlo simulation is the ability to identify which input has the most impact, thereby enhancing efforts to reduce its uncertainty. Whereas the uncertainty analysis quantifies the variation in model outcome, the sensitivity analysis fills a complementary role by ordering the importance and relevance of the inputs in determining the variation in the output. The sensitivity graph in **Fig. 1** (Section I-3) in this example highlights the importance of minimizing the uncertainty in the minimum horizontal stress from leak-off or other tests. It also shows that for this example, uncertainty in the rock properties of Young's modulus and Poisson's ratio has little impact on final results.

Materials and Particle-Size Distribution
Various studies have indicated that better fracture seals are obtained when the PSD of the LPM is broad and contains a combination of both oversized and undersized particles with respect to the fracture width (Growcock *et al.* 2009, Alberty *et al.* 2004, Dick *et al.* 2000, Aston *et al.*

2004). The larger particles help plug the fracture mouth, while the smaller particles help seal the fracture. If the LPM blend only contains small particles, fracture sealing primarily is determined by bridging and filling the fracture through fluid loss or leak-off. If the LPM blend only contains large particles, the fracture can be plugged or bridged; however, voids between particles could allow fluid to leak into the fracture.

Conventional LPM blends based on the Ideal Packing Theory (IPT) often ignore the presence of barite in the drilling fluid itself. While this approach may be sufficient for lighter fluids (Aston *et al.* 2004), the presence of barite in heavier fluids reduces or eliminates the need to add fractions of finer LPM. Barite particles can fill the voids between larger LPM and form a good seal behind the plug close to the wellbore wall. Experimental data suggest the PSD of the finer fractions of the LPM affect fluid-loss characteristics and seal pressure integrity (Kaageson-Loe *et al.* 2008). This highlights the importance of optimizing the LPM blend design by utilizing the barite already present in the mud. Typically, barite loading in weighted muds is much higher than the LPM concentration used in wellbore-strengthening applications.

Typical wellbore-strengthening applications use some combination of (a) sized synthetic graphite, (b) crushed, sized marble (CaCO₃), and (c) crushed nutshells (Growcock *et al.* 2009). The choice of LPM blend for a given fracture width strongly depends on the PSD of the LPMs. Consequently, as long as the PSDs for given LPMs are available, the software tool is flexible enough to use locally-sourced products. **Fig. 1** (Section II) shows the available LPM used for this example simulation, and the required inputs to specify the presence and type of barite in the drilling fluid. The user can select from a collection of PSD files that can be customized to suit their needs and LPM availability.

Blending and Concentrations
The classical approach to size the LPM based on the fracture width is to use the IPT approach (Dick *et al.* 2000). This rule implies that ideal packing is obtained when the cumulative volume percentage of the bridging material varies linearly with the square root of the particle diameter. Commonly used models typically match the D90 of the particle-size distribution to the maximum size of the opening, which is the fracture width at the wellbore. The remainder of the smaller particles is designed to minimize voids between the larger particles and provide a seal to prevent fluid leak-off.

Monte Carlo simulation generates P10, P50, and P90 fracture widths that indicate the probabilities of fracture widths less than those calculated values. The blending algorithm generates optimum LPM blend required to plug and seal fracture width for each probabilistic value, and is shown in **Fig. 1** (Section II). The choice of LPM for P10 and P50 fracture widths are a sub-set of the optimum P90 blend. Extensive series of experiments with an innovative testing apparatus (Kaageson-Loe *et al.* 2008) clearly show the mechanism of fracture plugging. A seal formed at the entrance of the aperture, along with fracture filling and sealing with the finer fractions, have resulted in the best fracture sealing. The bridging quality of the final blend and product coverage also are shown in **Fig. 1** Section III.

The three plots marked as Section III of **Fig. 1** illustrate the cumulative PSD of an LPM blend that provides an effective sealing pressure for a sample fracture width distribution P10, P50, and P90 values of 361, 583,

and 731 microns, respectively. By switching PSD files and LPM choices, the tool can be used to objectively compare concentration requirements for various types of LPM, such as calcium carbonate, sized synthetic graphite, or crushed nutshells.

Finally, an inversion technique is used to generate the gain in net fracture pressure as a result of a successful wellbore- strengthening application. Assuming that a fracture can be perfectly bridged and sealed, the tool generates the net fracture pressure for the P10, P50, and P90 fracture widths as shown in **Fig. 1** Section III.

Summary

This paper presents a practical, fast and user-friendly design tool for wellbore-strengthening application. Monte Carlo simulation allows estimating the probability of a fracture of a certain size given the uncertainties of the various parameters that affect fracture growth. It also helps to comparatively evaluate the effect of each input parameter on the final result.

Uncertainties in the fracture width imply a corresponding variation in the LPM blend and concentration and the tool generates results that allow a conservative P10 or more aggressive P90 values. The design tool allows variety and local sources of LPMs and is flexible and adaptive. The design tool incorporates barite and drilling solids into the blending algorithm, allowing accurate estimation in both weighted and non-weighted fluids. Finally, the tool generates a probabilistic estimation of the net fracture pressure gained by successful application of this wellbore strengthening technique.

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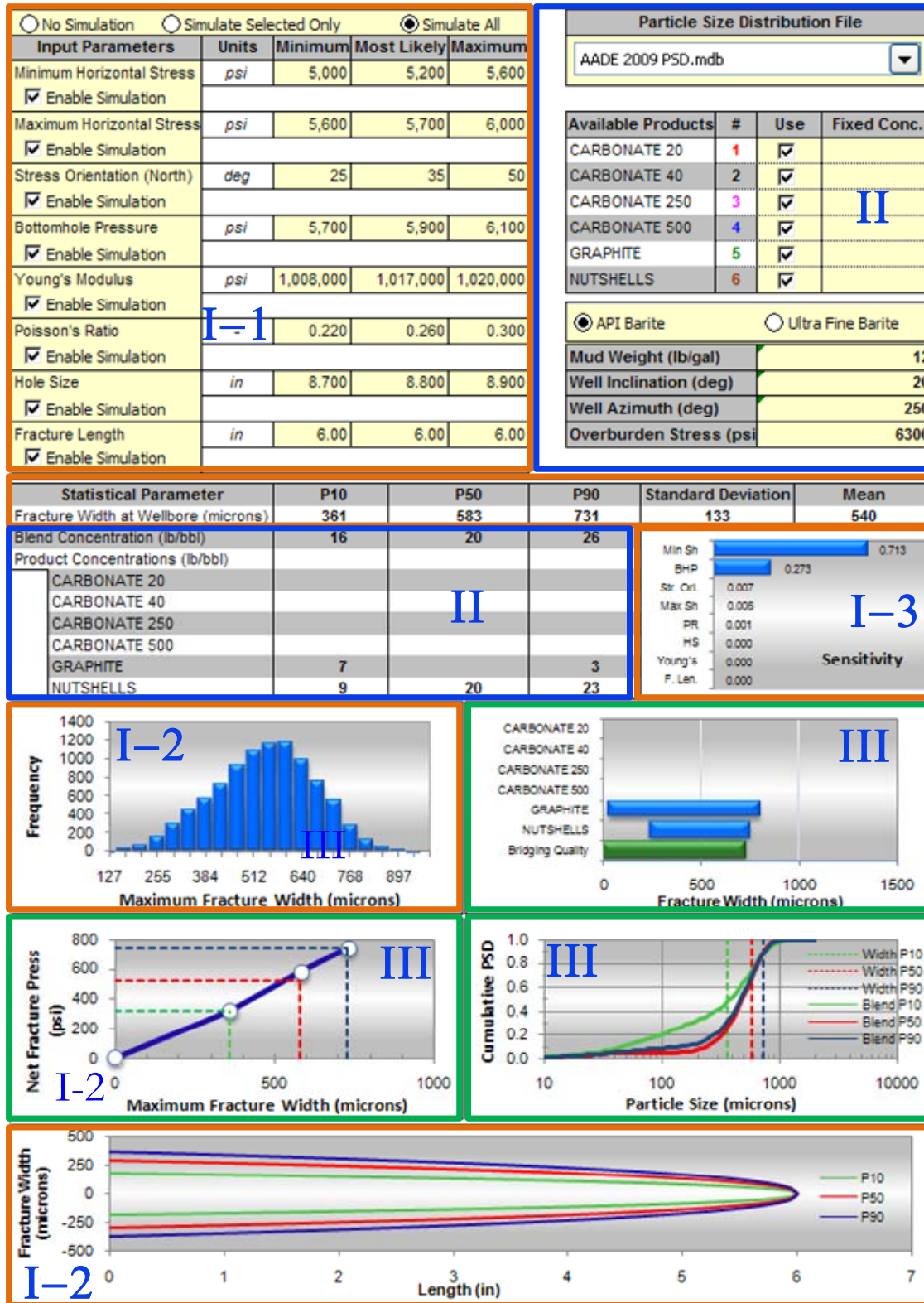
Fig 1. Screen capture of the wellbore strengthening design software. (Colored rectangles are superimposed for demonstration purposes only and distinguish software sections based on discussions in text: orange for Section I, blue for Section II, and green for Section III).