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# Cuttings Transport With Oil- and Water-Based Drilling Fluids[1]

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*Deviated well sections are common in most modern offshore well construction designs. In the North Sea region, which is a good example of mature areas, practically all producer or injector wells have highly deviated well sections. These wells must be constructed in an optimal manner with respect to functionality, drill time, risk, and all affiliated costs. Throughout the years, most hole-cleaning and hydraulic models have been developed based on experimental results from relatively small-scale laboratory tests with model fluids. Hole-cleaning properties and hydraulic behavior of practical drilling fluids intended for field application differ from those of most model fluids. Furthermore, results from small diameter tests may not always be relevant for or scalable to field applications because of the presence of a huge number of dimensional quantities like velocity, fluid properties, time, length, and other scale differences. Hence, studies using sufficient large-scale experimental facilities in controlled laboratory environments with the application of various field-designed drilling fluids are necessary to improve engineering models and operational practices. The current paper presents results from such laboratory tests where field-applied drilling fluids have been used. In comparison tests, the different drilling fluids have similar density and viscosity functions within the relevant field-applied shear rate range. This shear rate range is also assessed in the tests. One of the drilling fluids is oil-based, and the other one is an inhibitive water-based drilling fluid of the KCl/polymer type.*
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*Keywords: petroleum engineering, petroleum wells-drilling/production/construction, drilling fluids, oil-based drilling fluids, water-based drilling fluids, well construction, cuttings transport efficiency*

## Introduction

Modern wells are normally designed with a significant deviated section. In the North Sea region, which is a good example of mature areas, practically all producer or injector wells have highly deviated well sections. These wells must be constructed in an optimal manner with respect to functionality, drill time, risk, and all affiliated costs. To drill these wells properly, it is, therefore, necessary to optimize the hydraulic performance. This performance includes optimizing hole cleaning with as low a contribution to the frictional pressure loss as possible.

Throughout the years, most hole-cleaning and hydraulic models have been developed based on experimental results from relatively small-scale laboratory tests with model fluids. Hole-cleaning properties and hydraulic behavior of practical drilling fluids intended for field application differ from those of most model fluids. Furthermore, results from small diameter tests may not always be relevant for or scalable to field applications because of the presence of a huge number of dimensional quantities like velocity, fluid properties, time, length, and other scale differences. Hence, studies using sufficient large-scale experimental facilities in controlled laboratory environments with the application of various field-designed drilling fluids are necessary to improve engineering models and operational practices. Li and Luft [1] conclude that "The empirical models for the sand concentration/sand bed height prediction during RIH or during the hole-cleaning period are limited to the conditions of the flow loop tests. Application of this type of correlation to different operational conditions should be done with caution." Due to this, the laboratory setup applied here is designed for field-applied drilling fluids of several types. It is designed to its current scale to facilitate verification of engineering models and field practice evaluation for both cuttings transport and pressure losses due to hydraulic friction [2–6]. Fluid properties are described through many different models designed to give a level of accuracy for relevant parts of the respective properties. An example of such model is the Quemada model [7–9]. This is a semi-physical model. It is still not clear if the use of this understanding will provide additional information for the cuttings transport properties. However, it is likely that the understanding of frictional pressure losses will be improved.

Several research groups focus on hole-cleaning experiments. A thorough summary of their work, including their experimental equipment, has been developed by Li and Luft [10]. In the following, results from large-scale laboratory tests using field-applied fluids are used to compare the hole-cleaning performance of oil and water-based drilling fluids. The drilling fluids have similar

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density and viscosity within the shear rate range that is relevant in the annular sections, where cuttings transport occurs, during drilling operations and in the conducted tests.

The reported experiments have been conducted in a flow loop that is constructed with a 10-m long test section. Inside the test section, a steel pipe with a 50.4 mm (2″) outer diameter rotates freely inside a 100 mm (about 4″) inner diameter wellbore where the outer wall is constructed of cement. While circulating the drilling fluids through the test section, sand/cuttings particles are injected. Three wellbore inclinations were applied in these experiments: 48, 60, and 90 deg from vertical. The dimensions of the flow loop are designed to ensure that the results can be scaled and compared to field applications [4], primarily for the 12.25″ and 8.5″ sections. The setup is designed to provide shear rate ranges and Reynolds numbers comparable to what the same fluid would have during field application.

Both field experience and laboratory investigations indicate that cuttings transport efficiency can be different when using oil-based drilling fluids compared to using water-based drilling fluids [11]. This also applies when the fluids have similar flow curves and characteristics, measured according to the American Petroleum Institute (API) specifications for the relevant shear rates. Current explanations base their arguments on different colloidal effects [12] and normal stress in the water-based drilling fluids [6] that are absent when using oil-based drilling fluids. Furthermore, recent results have shown differences in hole cleaning between cases with open gauge holes compared to inside casing [2].

## Experimental Equipment and Fluid Design

**Experimental Design.** The experiments are performed in the flow loop shown in Fig. 1. In Fig. 2, it is shown schematically. This facility is constructed as an annular section with a fully eccentric drill string with a free whirling motion during rotation, illustrated in Fig. 3. The test section can be tilted between angles from 90 deg (horizontal) to 48 deg. The flow loop has annular dimensions selected near the minimum of what can provide results that are scalable to field applications. The circulation system is constructed so that both oil-based and water-based field fluids can be used. The system also includes a particle handling system where dry cuttings particles can be injected at a constant, controlled rate into the circulating fluid. The speed of the particle feeder corresponding to the target particle mass flow rate was determined by a calibration prior to the experiments. The injected particles in the experiments are circulated once through the test section with the drilling fluid and then removed in a separation unit. Particles are not re-injected after being removed from the system, ensuring that initial size distribution is maintained through all experiments. The experiments are run both without particles and with synthetic cuttings represented by quartz sand particles with a size distribution from 0.9 to 1.6 mm.

Fig. 1 Photo of the flow loop test section in horizontal position

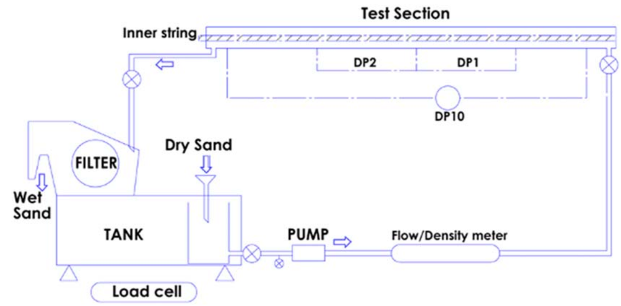


Fig. 2 Sketch of the flow loop [3]

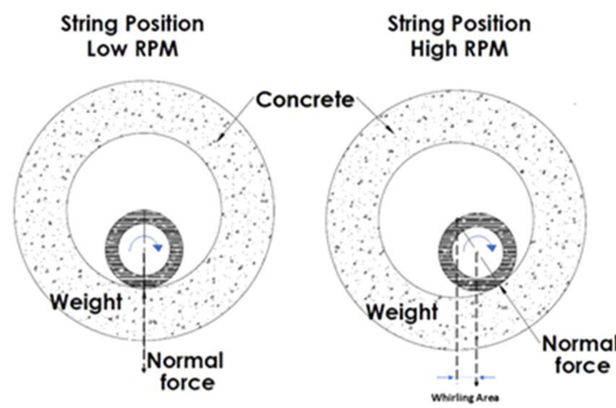


Fig. 3 Drill string position and rotation with whirl is sketched as expected during experiments with free whirling string

A sketch of the experimental system is presented in Fig. 2. The system consists of the following main components:

(1) Drilling fluid storage tank
(2) Sand injector unit
(3) Liquid slurry pump
(4) Density and flow meter
(5) Test section with pressure and differential pressure transducers
(6) Sand separator
(7) Sand reception system and fluid return to storage tank

The 10-m long test section is constructed inside an outer support pipe. Inside this support pipe, hollow cement inserts are placed in a continuous series to represent an open wellbore wall.

These cylindrical, hollow cement sections have a similar outer annular diameter of $D_o = 100$ mm.

The drill string is represented by a rod of $D_i = 50.4$ mm diameter inside the hollow cement sections. This steel rod defines the inner diameter of the annulus applied in the test section. Additional details about the experimental equipment can be found in Ytrehus et al. [3]. In agreement with Li and Luft [1], Saasen [4] stated that "even though laboratory experiments are necessary to improve the understanding of well flow phenomena, is not straightforward to use experimental results directly to create correlations. The complexity of the geometry and fluid properties includes far too many dimensionless quantities that need to be within the same range to be valid." With the used dimensions, it is possible to provide results for some well dimensions, such as 8½″ section and 12¼″ section, in drilling operations.

**Fluid Properties.** The drilling fluid volumes are field fluids collected from onshore mud plants supplying offshore installations on

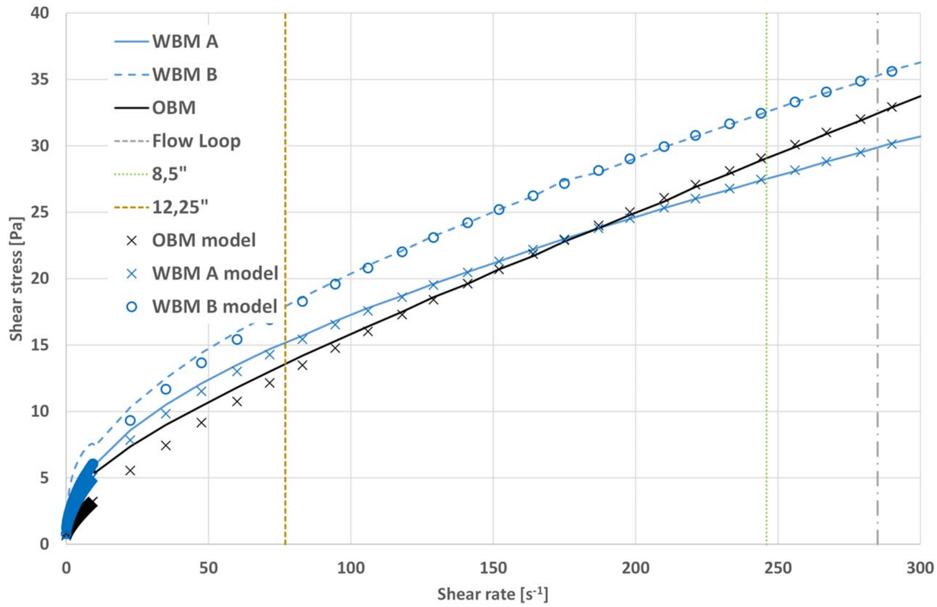


**Fig. 4 Viscosity curves for the different fluids are plotted (vertical lines indicate maximum shear rate for annular flow in the flow loop configuration and in relevant wellbore sizes with a 5.5″ drill string)**

the Norwegian continental shelf (NCS). Detailed information about fluid compositions is not available. However, the oil-based drilling fluid (OBM) is built using a non-aromatic base oil. No low-end modifiers have been used. The water-based drilling fluid (WBM) was a KCl/polymer-based fluid. The polymers consisted of a blend of polyanionic cellulose (PAC) and Xanthan gum. No partially hydrolyzed polyacrylamide (PHPA) was used, as an offshore application of these polymers is limited on the NCS.

The properties are measured using an Anton Paar rheometer with a concentric cylinder option (rotating bob inside a stationary cup). Although the situation is better than when measured in accordance with API procedures [13], some inaccuracy is still expected during the very low shear rate measurements due to the relatively large annular gap between the cup and the bob. This gap has to be sufficiently large to handle the barite particles. Within this accuracy, it is reasonable to approximate the drilling fluids' yield stresses by a linear extrapolation using the two lowest shear rate measurements as described by Power and Zamora [14,15] if using measurements in accordance with API. The fluids are modeled as Herschel–Bulkley fluids using dimensionless shear rates to produce a set of mutually independent Herschel–Bulkley parameters [16–18], as shown in Eq. 1. The flow curves are shown in Fig. 4, and the Herschel–Bulkley parameters are tabulated in Table 1.

The Herschel–Bulkley model is here expressed as

$$\tau = \tau_y + \tau_s \left( \frac{\dot{\gamma}}{\dot{\gamma}_s} \right)^n \tag{1}$$

where the surplus stress, $\tau_s = \tau - \tau_y$ is calculated from the yield stress $\tau_y$, and the shear stress $\tau$ is measured at a representative shear rate of $\dot{\gamma}_s$. In this work, we used $\dot{\gamma}_s = 302\ \mathrm{s}^{-1}$. The flow behavior index, $n$, must be determined at a different relevant shear rate. This shear rate to match the shear stress was selected to be 152 $\mathrm{s}^{-1}$.

The water-based fluid did not maintain a fully constant viscosity profile throughout the period of experiments. It is very difficult to keep the properties of a large volume of field-applied water-based drilling fluid completely constant through many circulations in a flow loop. This is well known in field operations, and continuous adjustments are made to the fluid batch to maintain the properties. Facilities for such adjustments were not available at our test site. This fluid is therefore represented by a WBM A and a WBM B where the first corresponds to measurements at the beginning of the experimental campaign and the second corresponds to the latest parts. The observed increase in viscosity must be kept in mind when evaluating the results. Possible causes of the viscosity increase are the evaporation of water and the inclusion of fines from the sand used as cuttings. In the plots, the water-based fluid is normally denoted by WBM, and this fluid will have properties between WBM A and WBM B. For the oil-based fluid, these effects were not significant, and this fluid is represented by the same fluid parameters throughout the entire test series.

**Table 1 Herschel–Bulkley parameters for the fluids**

| | OBM | WBM A | WBM B |
|---|---|---|---|
| $\tau_y$ (Pa) | 0.63838 | 0.61442 | 0.77715 |
| $\tau_s$ (302 1/s) (Pa) | 33.2616 | 30.1856 | 35.6229 |
| $n$ (152 1/s) (−) | 0.73643 | 0.55048 | 0.54981 |
| $k$ (Pa $\cdot$ s$^n$) | 0.49612 | 1.302 | 1.5424 |

Note: WBM A indicates the WBM properties when starting the campaigns, and WBM B is the properties toward the end of the experimental campaigns.

## Results and Discussion

The applied fluids are circulated through the experimental system without any cuttings prior to any tests with injected sand particles. This is to investigate pressure drop profiles for the fluids without any disturbances. Such tests will indicate if there are problems with the instrumentation system or if the fluid behavior diverts from the expected. The results can be observed in Fig. 5.

One of the most challenging parameters to scale properly between laboratory and field applications is the drill string rotation. In field applications, this is often run at 100–150 rpm. For the flow loop setup, the corresponding rotation rates are likely much lower, but it is difficult to estimate the exact values. The plotted results in Fig. 6 indicate a significant effect from string rotation already at 10 rpm in the flow loop at a typical flow rate during drilling operations, here represented by 0.7 m/s superficial annular velocity. It can be observed that cuttings are almost fully removed from the test section at 50 rpm and higher rotations when the test section is in a horizontal position.

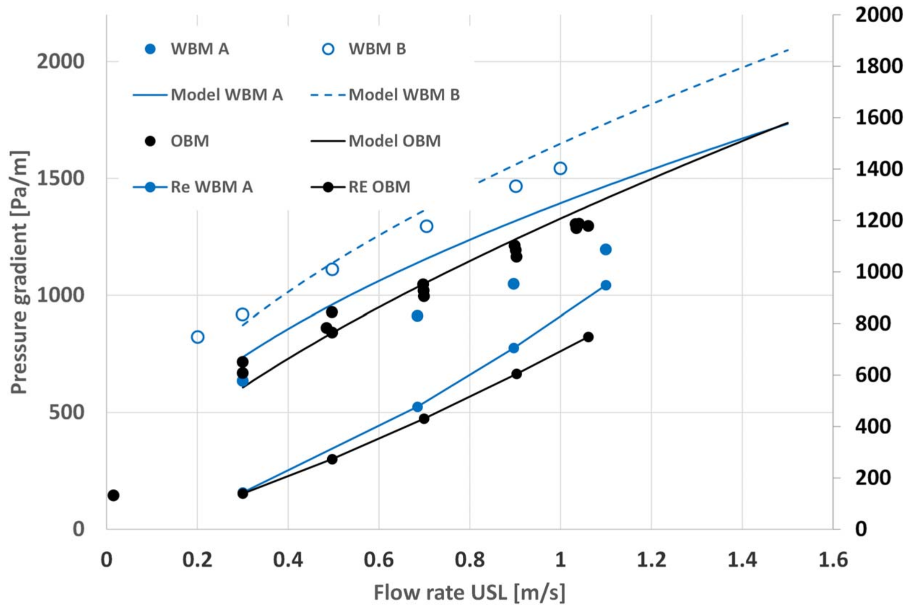


**Fig. 5 Pressure drop plotted at flow rates for OBM and WBM in horizontal position (model data and experimental data are included, and corresponding Reynolds numbers are plotted using secondary axis)**

To quantify the cuttings transport efficiency, the term relative bed height is introduced. In the following analysis, the term bed height refers to the height of a bed with a given porosity in the annulus between the wellbore and the drill string. The relative bed height is normalized with respect to the wellbore diameter. The bed height is calculated based on the average volume concentration of particles in the test section, assuming that all particles are sedimented on the low side with a representative bed porosity. The average cuttings volume concentration is calculated from the known mass densities of fluid and cuttings and from the measured change in test section weight due to the cuttings [2,3]. Ideally, this calculation should be adjusted for the fraction of cuttings which is suspended. However, this fraction can be shown to be negligible with the applied cuttings injection rate and on the order of the accuracy of the weight measurements. The contribution of the suspended particles can, therefore, be neglected in the present experiments.

It can also be observed in Fig. 6 that the water-based fluid gives a slightly higher cuttings bed than the corresponding oil-based fluid at a flow rate of 0.7 m/s in the horizontal section. This observation is in line with the reported results in Sayindla et al. [11], except that the difference in cuttings transport efficiency between the fluids without drill string rotation is significantly less in the present results.

The cuttings bed height at 60 deg inclination is shown in Fig 7. A significant difference in cuttings transport efficiency is observed for the flow rate of 0.7 m/s superficial velocity. For this flow rate, the oil-based fluid provides a distinctly lower cuttings bed height than the water-based fluid. When the flow rate is increased to 0.9 m/s superficial velocity, the cuttings bed height for the water-based fluid is significantly reduced, and the differences between the fluid's hole-cleaning performances are almost not observable when string rotation is present. This observation indicates that the water-based fluid has a critical condition for cuttings transport efficiency with flow rates between 0.7 and 0.9 m/s. For no string rotation, the oil-based fluid appears more efficient than the water-based fluid also at the highest flow rate.

The cuttings bed heights at 48 deg inclination, plotted in Fig. 8, show that for a flow rate of 0.7 m/s, the water-based fluid gives a lower cuttings bed height than the oil-based fluid. This is in contradiction to the observations at the other well inclinations. At a flow rate of 0.9 m/s without string rotation, a similar trend is observed.

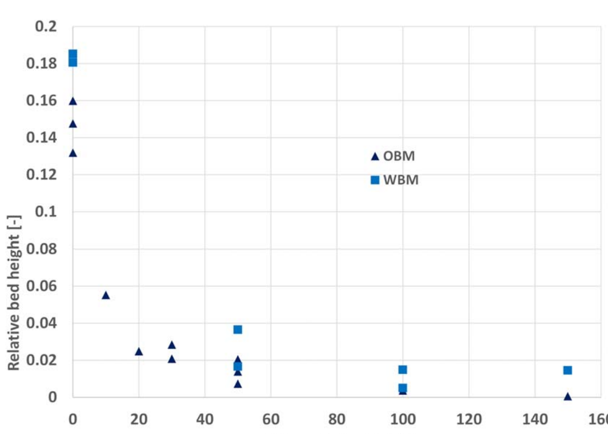


**Fig. 6 Plot of cuttings bed for OBM and WBM in horizontal position at increasing string rotation at constant flow rate corresponding to 0.7 m/s annular velocity**

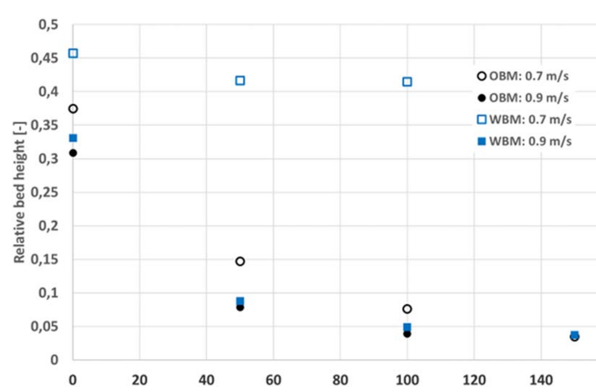


**Fig. 7 Cuttings bed is plotted for OBM and WBM at 60 deg inclination at flow rates corresponding to 0.7 and 0.9 m/s at various string rotation speeds**

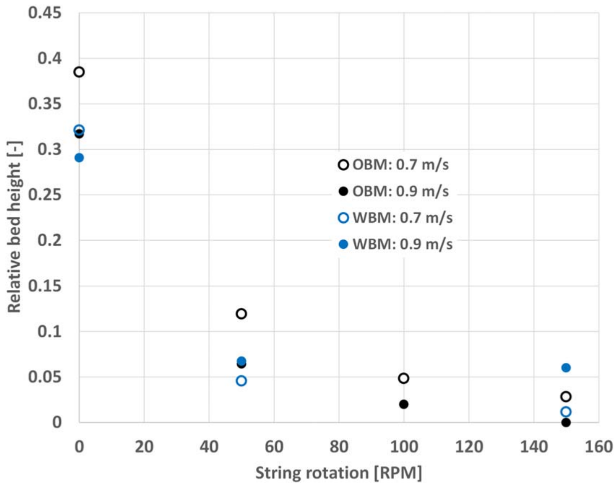


**Fig. 8 Cuttings bed height plotted for OBM and WBM at 48 deg inclination at flow rates corresponding to 0.7 and 0.9 m/s at various string rotation speeds**

When string rotation is introduced, the oil-based fluid is equally or more efficient in removing cuttings. Since this is a more vertical-like well section, this effect is likely to be caused by a slightly higher viscosity in the water-based fluid. Initially, the water-based fluid had a slightly higher viscosity at the lower shear rates (Fig. 4). This low shear rate viscosity increased further with time due to changes in the water-based fluid. The experiments at 48 deg were performed as one of the later series, so there is likely a higher viscosity difference between the fluids than in most other plots. In near vertical wells, cuttings beds do not exist, and increased viscosity is anticipated to improve cuttings removal. For inclinations where cuttings beds are likely to appear during the drilling process, the cuttings bed properties may impact the cuttings transport efficiency since different drilling fluids may give different properties in the respective cuttings bed. A possible explanation why oil-based fluids are more efficient for cuttings transport than KCl/polymer water-based fluids at highly deviated sections could likely be effects within the cuttings bed due to polymer chains or other bindings consolidating the bed more efficiently. These aspects are addressed both generally [19] and specifically with the presently used fluids [20], together with a thorough viscoelastic analysis by Pedrosa et al.

## Conclusion

The presented results show that abilities for cuttings transport efficiency of the tested fluids do vary significantly with parameters like well angle, drill string rotation, and flow rate. Field experience is supported by these results, showing that the typical oil-based fluid in most conditions is more efficient for hole cleaning than the similar viscosity water-based KCl/polymer fluid. It is also demonstrated that cuttings transport efficiency effects can be seen as function of flow rate, demonstrating methods to achieve more optimal hydraulic design in the tested conditions.

The findings support the main conclusions presented for horizontal conditions by Sayindla et al. [11] that oil-based and water-based drilling fluid show differences in cuttings transport capabilities even if their viscosities are similar.

For other inclination angles, comparable results are not known. At such tested inclinations, the relative behavior differed a little. In well inclination angle of 60 deg, the oil-based fluid was significantly more efficient at flow rate of 0.7 m/s, while at 48 deg, the water-based fluid was more efficient at the same flow rate, especially in combination with low or no string rotation. For higher flow rates (0.9 m/s), the differences were small or moderate.

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## Conflict of Interest

There are no conflicts of interest.

## Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

## Nomenclature

$k$ = consistency index
$n$ = flow behavior index
ID, $D_i$ = the inner diameter of an annular space
OD, $D_o$ = the outer diameter of an annular space
$\tau$ = shear stress
$\dot{\gamma}$ = shear rate
$\dot{\gamma}_s$ = shear rate of surplus stress
$\tau_s$ = surplus stress at selected point s
$\tau_y$ = yield stress

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