A transient Cuttings Transport Model for vertical wellbores
Development, implementation and validation

L.S. Peene
A transient Cuttings Transport Model including mud gelling

L.S. Peene¹, R. El Boubsi², R.L.J. Helmons³, S.A. Miedema⁴, T. Bakker⁵

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Abstract

This paper addresses the development and validation of a transient computational model describing the transport of drilled cuttings in vertical wellbores. The model can be used for evaluation of hole cleaning performance. The model accounts for the time-dependent effect of mud gelling (thixotropy). The model is validated with measurements from a drilling operation. Combined with field measurements, application of the model could aid in early detection of downhole effects and events, which will help to prevent costly drilling problems like borehole collapse and stuck pipe.

Keywords: Drilling, cuttings transport, hole cleaning, gelling, thixotropy, Drift-flux

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1. Introduction

To survive and prosper in today’s low-price oil and gas market, operating companies are continuously challenged to lower their finding and producing costs. This requires that improvements are made in the field of drilling engineering. New technologies such as Managed Pressure Drilling (MPD) and drilling automation hold the key to efficiently performing intricate and high-speed tasks and make complex wells technically and economically feasible (Florence, 2010) (Macpherson, 2013). In this context, models are being developed which describe the state of the drilling fluid (mud) system at different parts of the drilling process.

Cuttings are generated by the bit and transported to the surface by circulating mud down the drill string, through the bit, and up through the annular space between the hole and the drill string. Cuttings transport process is quite complex since it is influenced by many different parameters. A review of experimental observations is presented by (Kelin, 2013).

Cuttings transport models are used to evaluate hole cleaning, which is the challenge of transporting cuttings out of the hole. Additionally, concentration of cuttings is used to determine mixture properties, in order to perform calculations on wellbore hydraulics. This paper addresses the development and validation of a transient computational model concerning cuttings transport in vertical wellbores.

1.1. Previous developments in cuttings transport modeling

An overview of previous developments made in cuttings transport modeling is presented by (Pilehvari, 1999). One could divide the modeling approach into two main classes; the empirical approach based on experimental data (Larsen, Pilehvari, & Azar, 1993) or use of more fundamental mechanistic approaches (Govignet, 1989). The considered models are usually based on steady state considerations. It is emphasized that there are many transient phenomena that affect cuttings transport in a drilling operation. Examples of such phenomena are variations in rate of penetration (ROP) and mud flow rate. A transient model covering such phenomena is presented by (Cayeux, 2013). A similar approach is considered in this study, including mud gelling as a new element. For the sake of simplicity only vertical wellbores are considered.

1.2. New elements introduced in this study

An effect that remains underexposed until now is mud gelling (thixotropy). It is a time-dependent effect usually observed in drilling fluids. Gelling means that the internal fluid structure strengthens with time in absence of agitation. A step towards computational modeling was taken by (Garrison, 1939); however his method is not suitable for implementation into this model. A new method is therefore developed and discussed in this document.

1.3. The mud system

The mud system typically consists of drilling fluid (a solution like a brine or an emulsion of water in oil, containing low gravity solids, e.g. bentonite, and high gravity solids, e.g. barytes) and cuttings (drilled solids).

2. The Cuttings Transport Model

This section elaborates on the physics and mathematical framework behind the Cuttings Transport Model.

2.1. Solid-liquid mixture flow

A vertical annular flow geometry is considered in the model. Through this geometry, a solid-liquid mixture composed of drilling fluid and cuttings flows with a mean upward velocity \( v_{\text{mean}} \) [m/s]. The cross-sectional velocity variations are ignored. The annular geometry is assumed to be constant along the wellbore depth. In the following, symbols corresponding to the mixture, drilling fluid and cuttings are respectively indicated by the indices \( \text{mix} \), \( \text{fluid} \) and \( \text{cut} \). The Drift-flux model is used to implement slip velocities, i.e. the mixture inside a control volume is considered to be homogeneous even though its phases have relative velocities to each other (Shi, et al., 2005). The average velocity in the axial direction (approximation to a one dimensional flow) is expressed as a function of the various phase velocities:

\[
v_{\text{mean}} = \alpha_{\text{fluid}} u_{\text{fluid}} + \sum_{k=1}^{N} \alpha_k u_k
\]

where \( u \) is the phase velocity [m/s] and the indice \( k = 1,2,...,N \) is a dimensionless number indicating every fraction of cuttings, where \( N \) represents the total number of fractions \( \alpha \) is the dimensionless mass concentration, which for cuttings is defined as:

\[
\alpha_k = \frac{\rho_k c_k}{\rho_{\text{fluid}} c_{\text{fluid}} + \sum_{k=1}^{N} \rho_k c_k}
\]

where \( \rho \) is the phase density [kg/m\(^3\)] and \( c \) the dimensionless phase concentration. By definition \( \sum_{k=1}^{N} c_k = c_{\text{cut}} \) and \( c_{\text{fluid}} + c_{\text{cut}} = 1 \). The cuttings fractions are defined according to a characteristic particle size and density \( \rho_k \) (or specific gravity \( SG_k \)). In order to transport the concentration of every fraction along the wellbore depth, a transport equation is used to account for the mechanisms of advection and diffusion:
\[
\frac{\partial c_k}{\partial t} + \frac{\partial}{\partial z} (c_k \cdot u_k(c_{cut})) = \frac{\partial}{\partial z} (\varepsilon_z \frac{\partial c_k}{\partial z})
\]  

(3)

with \( t \) time [s], \( z \) the path along the vertical wellbore in upward direction [m] and \( \varepsilon_z \), the diffusion coefficient in \( z \) direction [m²/s].

2.2. Drilling fluid

Drilling fluids are commonly described by non-Newtonian flow models. They typically have a finite non-zero yield stress \( \tau_0 \) [Pa], which must be overcome to set the fluid in motion. Also the effective viscosity \( \mu \) [Pa·s] decreases with increasing shear rate, a phenomenon commonly referred to as shear thinning. This study considers the presence of a yield point \( \tau_0^\prime \) [Pa] and a constant (plastic) viscosity \( \mu_B \) [Pa·s] as defined in the Bingham plastic flow model. \( \tau_0^\prime \) and \( \mu_B \) are commonly derived from measurements in the field and referred to as \( \tau_0^\prime \text{true} \) and \( \mu_B \text{true} \) respectively.

2.3. The time-dependent effect of mud gelling

The following method is developed in order to take the effect of mud gelling (thixotropy) into account. The effective gel strength \( \tau_0^\prime \) [Pa] is defined, representing the strength of the drilling fluid internal structure as a function of time, see Figure 1. From the moment that agitation (mud circulation and/or drillpipe rotation) stops, indicated by \( t_{\text{stop}} \), the effective gel strength increases asymptotically until the maximum value of \( \tau_0^\prime \text{true} \). Lacking detailed information, a constant rate of gelling \( \dot{\tau}_0 \) is applied, which is based on a linearization between the 10 second gel strength \( \tau_0^{10\text{sec}} \) and 10 minute gel strength \( \tau_0^{10\text{min}} \). The time until maximum gel strength is reached is referred to as the gelling time \( t_{\text{gel}} \). This yields a conveniently applicable method, as these quantities are commonly measured during drilling operations, and the resulting equation is simple:

\[
\frac{d\tau_0}{dt} = \frac{\tau_0^{10\text{min}} - \tau_0^{10\text{sec}}}{590 \text{ s}}
\]  

(4)

Figure 1 Computational method applied for integration of the mud gelling effect

2.4. Yield criterion

By virtue of its yield stress, represented by the effective gel strength, the drilling fluid will support immersed particles up to a critical diameter for an indefinite period of time. The intuitive consideration that the buoyant weight of a particle is supported by the vertical component of the force due to the yield stress, implicates that the particle will remain suspended as long as the support force (due to the effective gel strength) is larger than the buoyancy force (due to gravity). Regarding calculation of the yield criterion, sphericity is assumed; however for future studies the introduction of a shape factor is advised. A dimensionless parameter \( Y \) is introduced which denotes the ratio of the forces due to the effective gel strength \( \tau_0^\prime \) and due to gravity (Chhabra, 2008) (Song & Chiew, 1997). Neglecting numerical constants, its simplest definition is:

\[
Y = \frac{\tau_0^\prime(t)}{g \cdot d_p \cdot (\rho_{\text{cut}} - \rho_{\text{fluid}})}
\]  

(5)

where \( d_p \) is the characteristic particle dimension [m] and \( g \) the gravitational constant [m/s²]. Thus, small values of \( Y \) will favor motion of a sphere. A critical \( Y \) value of 0.06 is considered in the model which is based on numerical predictions for spherical particles by (Blackery & Mitsoulis, 1997).

2.5. Slip velocity

The terminal settling velocity \( v_{TSV} \) [m/s] of a cutting particle with respect to the mean mixture velocity is calculated by the semi-empirical equation of (Zanke, 1977) (Miedema, 2015). Using the constant plastic viscosity, for the sake of simplicity, the equation is given by:
The settling velocity decreases when the volume concentration of a dispersed phase increases, due to the increased drag acting on a particle. This increased drag is a consequence of particles hindering each other, as well as the reduced area of free flow. The semi-empirical equation of (Richardson & Zaki, 1954) is used to describe this phenomenon by means of the dimensionless hindered settling function \( V(c_{cut}) \). The equations used are:

\[
v_{\text{slip}} = v_{TSV} \cdot V(c_{cut}) = v_{\text{mean}} - u_k
\]

\[
V(c_{cut}) = \begin{cases} 
(1 - c_{cut})^{n_{RZ} - 1} & \text{if } c_{cut} < c_{cut,\text{max}} \\
0 & \text{if } c_{cut} = c_{cut,\text{max}}
\end{cases}
\]

with \( c_{cut,\text{max}} \) the dimensionless random close packing limit above which flow is no longer possible and \( n_{RZ} \) the dimensionless Richardson and Zaki index (Rowe, 1987):

\[
n_{RZ} = 2.35 \cdot \frac{2 + 0.175 \cdot (Re_p)^{3/4}}{1 + 0.175 \cdot (Re_p)^{3/4}}
\]

which is a function of the dimensionless particle Reynolds number \( Re_p \)

\[
Re_p = \frac{v_{TSV} \cdot d_p \cdot \rho_{\text{fluid}}}{\mu_B}
\]

### 2.6. Mixture properties

The model can be used to calculate mixture density and viscosity. This is useful for wellbore hydraulics calculations as they influence the Equivalent Circulating Density (ECD). Mixture density \( \rho_{\text{mix}} \) [kg/m³] is calculated according to the following equation:

\[
\rho_{\text{mix}} = \rho_{\text{fluid}} \cdot c_{\text{fluid}} + \sum_{k=1}^{N} \rho_k c_k
\]

The effective mixture viscosity \( \mu_{\text{mix,eff}} \) [Pa·s] is calculated according to a commonly used power law function (Eilers, 1941) (Maron & Pierce, 1956) (Krieger & Dougherty, 1959) (Quemada, 1977) according to plastic viscosity and cuttings concentration:

\[
H(c_{cut}) = \left(1 - \frac{c_{cut}}{c_{\text{crit}}}ight)^{-C_1 \cdot c_{\text{crit}}}
\]

\[
\mu_{\text{mix,eff}} = \mu_B \cdot H(c_{cut})
\]

This equation is governed by the single-sized packing of the particle shape considered \( c_{\text{crit}} \), for single-sized spheres, \( c_{\text{crit}} \approx 0.64 \) and \( C_1 = 2.5 \). The equation increases asymptotically for \( c_{\text{cut}} \to c_{\text{crit}} \), representing the critical volume fraction that lies near \( c_{\text{cut,\text{max}}} \).

### 3. Model operation and outputs

The model is implemented in MATLAB. Model operation and results are presented in this paper by means of three examples. These respectively consider the cuttings concentration, the mud gelling phenomenon and the capability to evaluate hole cleaning performance with the model.

#### 3.1. Cuttings concentration

The model is explained with reference to Figure 2. Essential model parameter are presented as follows:

1. The top left diagram displays the volumetric concentration of drilled solids along the wellbore. As was earlier explained, cuttings are subdivided into a number \( N \) of discrete fractions characterized by particle size \( d_{p,k} \) [m] and specific gravity \( SG_k [-] \).
2. The top center diagram displays the mean velocity of the mixture and phase velocity of every phase. The difference between mean and phase velocity is the slip velocity, which is different for each fraction.
3. The rightmost diagram presents the mixture density and viscosity, depending on the concentration of cuttings. Note that viscosity increases slightly more than proportional.
4. The two diagrams at the bottom display the cuttings proportions at depths of 950 and 400 meters.
3.2. The mud gelling phenomenon

The impact of mud gelling on cuttings transport is presented by means of comparative analysis. A fluid circulation stop is simulated using three different gelling intensities: little, moderate and strong. Corresponding properties are listed in Table 2. The same initial state is used for all three simulations, see Table 2. The constant cuttings concentration (5%) and equally distributed fractions represent an idealized stationary drilling and circulation. The geometry, resolution, SG and PV are kept constant for all situations, see Table 1. Simulation results are presented in Figure 4. The influence of different gelling rates on cuttings concentration is observable. A fluid with little gelling intensity restrains only smaller cuttings from settling. Moderate gelling prevents more cuttings from settling, although the largest cuttings are not captured and thus settle. In case of strong gelling, after some time, all cuttings are restrained by the fluid structure and are prevented from settling.

### Table 1 Constant simulation parameters

<table>
<thead>
<tr>
<th>Geometry, discretization and fluid properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of simulated wellbore section ( T_D ) [m]</td>
</tr>
<tr>
<td>Casing or hole diameter ( D_{\text{hole}} ) [cm]</td>
</tr>
<tr>
<td>Drillpipe outer diameter ( D_{\text{pipe}} ) [cm]</td>
</tr>
<tr>
<td>Spatial resolution ( \Delta z ) [m]</td>
</tr>
<tr>
<td>Temporal resolution ( \Delta t ) [s]</td>
</tr>
<tr>
<td>Mud specific gravity ( S_{\text{fluid}} ) [-]</td>
</tr>
<tr>
<td>Mud plastic viscosity ( \mu_B ) (or ( PV )) [Pa·s]</td>
</tr>
</tbody>
</table>

### Table 2 Drilling fluid properties for gelling simulations

<table>
<thead>
<tr>
<th>Gelling intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little</td>
</tr>
<tr>
<td>( \tau_0^{\text{10sec}} ) [Pa]</td>
</tr>
<tr>
<td>( \tau_0^{\text{10min}} ) [Pa]</td>
</tr>
<tr>
<td>( \tau_0^B ) (or ( Y^P )) [Pa]</td>
</tr>
<tr>
<td>( d\tau_0/dt ) [Pa/min]</td>
</tr>
<tr>
<td>( \tau_{\text{gel}} ) [min]</td>
</tr>
</tbody>
</table>
3.3. Hole cleaning evaluation

The capability of the model to evaluate hole cleaning performance is now presented. Simulations use the parameters indicated in Table 1. The wellbore initially contains no cuttings \( c_{\text{cut}} = 0 \) and a sheared mud with an effective gel strength equal to \( \eta_{\text{gel}} \). A stationary ROP is maintained for a given period of time, so that cuttings are flowing into wellbore control volume from the bottom. Cuttings are removed from the hole, applying a stationary mud flow rate \( Q_{\text{fluid}} \). Cuttings concentration along the wellbore is presented in Figure 5 and Figure 6. The impact on hole cleaning performance can thus be evaluated. It is observed that the bottoms-up time (the time required to travel from total depth to the surface) shows large variation among different cuttings.

4. Validation

The modeled settling behaviour is simulated with the Cuttings Transport Model and compared with measurements from a real drilling operation. This is done by analyzing cuttings that arrive at the surface before and after a mud circulation stop. They are measured by sieve analysis. An adapted procedure is used, to keep the cuttings intact and exclude drilling fluid components (colloidal particles).

4.1. Transient field measurements of cuttings

A total number of twenty samples are taken before and after four circulation stops. Such circulation stops are necessary to connect new drill pipes to the drill string. Figure 7 presents a transient series of relative cuttings concentration. The measurements show the following trend:
The first sample is considered to provide a reference. The corresponding curve can be seen as the stationary output of the well in ‘normal’ drilling operation. After mud circulation is restarted, a second sample is taken, which shows a significant size decrease in the emerging particles. Taking the time intervals into consideration, over the course of the following minutes, of the emerging cuttings go steadily back towards the reference state, of the sample taken before the circulation stop.

![Figure 7](image_url)

Figure 7 Measured cuttings time series for a circulation stop. Samples are taken at the shale shakers, where coarse particles are separated from drilling mud.

The interpretation of the trend is as follows:

- As the mud flow circulation is stopped, drilling fluid remains (near to) stationary in the well, allowing solid particles to settle down along the wellbore. The longer that the interruption takes; the further the distances that particles will settle. As explained, the velocity of the particles - and thus their associated settling distance during this time - depends on the particle and fluid properties. Particles with larger dimensions and/or higher densities have greater settling velocities than particles with smaller dimensions and lower densities. Consequently, when the connection is finished and circulation recommences, particles with larger settling velocities should have settled over longer distances compared to particles with smaller settling velocities.

The same trend is observed for cuttings measured at three additional mud circulation stops. The expected settling behaviour is validated.

4.2. Simulation result for the circulation stop

A simulation is now performed with the Cuttings Transport Model, using parameters that correspond to the measured drilling operation and circulation stop. Figure 8 presents cuttings arriving at the surface before and after the mud circulation stop.

![Figure 8](image_url)

Figure 8 Simulation result: cuttings arriving at the surface, before and after a circulation stop.
5. Discussion

When comparing the simulation result in Figure 8 with the measured cuttings series (Figure 7), the observed trend is quite similar. Some differences are observed including:

- The simulation result shows a rather cascaded progression, compared to the measurements. Every fraction builds up to the reference concentration in a separate manner. In reality, the relative proportions of the particle fractions show a more transitional development. Fractions build up to the reference concentration not separately, but alongside one another in a gradual fashion.

This difference can be explained by the following deviations of the model with respect to reality:

- A non-uniform cross-sectional flow profile will be present in reality, including a possible plugged flow profile which can occur due to viscoplastic fluid behaviour. Cross-sectional variations of velocity cause mechanical dispersion of solids and fluid along the wellbore trajectory.
- The effect of mud gelling is implemented by a simple linear function, based on quantities which are commonly measured in the field. This allows for convenient calculations, however in reality the effective gel strength is suspected to vary in a more complex manner and depends on more variables.
- The yield criterion currently implemented considers spherical particles. More study is needed into this topic to develop a relation and/or critical values for non-spherical particles.
- In reality the cuttings composition is highly dependent on the generation at the drill bit and other effects in the wellbore. These are complex phenomena which depend on many parameters and are not addressed in the model. Modeling these effects is preferred; it however requires more research.

6. Concluding remarks

A transient Cuttings Transport Model is developed that can be used to calculate cuttings concentration and mixture properties along a vertical wellbore. Its key developments with respect to previous studies are:

- The cuttings are considered by creating particle groups.
- Mud gelling is considered using a linear function, based on quantities being commonly measured in the field.
- The cuttings settling behaviour is validated according to measurements on an operational drilling rig.
- Simulation results show a similar trend compared to field measurements, considering the transient development of cuttings arriving at the surface (shale shakers) before and after a mud circulation stop.
- The model has the ability of monitoring and evaluating hole cleaning performance into account.

The following is recommended for future work:

- The development of a more detailed function to describe mud gelling behaviour. This requires more measurements of gel strength with time.
- Concerning the increasing complexity of wellbores nowadays and the increased challenge of hole cleaning, the model should be expanded towards non-vertical wellbores. Additional physical mechanisms require the introduction of other parameters such as cuttings bed formation and the impact of drillpipe rotation and eccentricity.

The measurements performed in this study provide valuable knowledge concerning the settling behaviour of cuttings. Dealing with these results however, one should keep in mind that properties of cuttings and drilling fluids vary widely, depending on operation and environment.

Acknowledgements

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_1 )</td>
<td>[-]</td>
<td>Dilute limit viscosity-concentration gradient</td>
</tr>
<tr>
<td>( c_{\text{crit}} )</td>
<td>[-]</td>
<td>Maximum packing of particles</td>
</tr>
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<td>( c_{\text{cut}} )</td>
<td>[-]</td>
<td>Combined volumetric concentration of cuttings fractions</td>
</tr>
<tr>
<td>( c_{\text{cut,max}} )</td>
<td>[-]</td>
<td>Random close packing limit above which flow is no longer possible</td>
</tr>
<tr>
<td>( c_{\text{fluid}} )</td>
<td>[-]</td>
<td>Volumetric concentration of drilling fluid</td>
</tr>
<tr>
<td>( c_k )</td>
<td>[-]</td>
<td>Volumetric concentration of cuttings fraction ( k )</td>
</tr>
<tr>
<td>( D_{\text{hole}} )</td>
<td>[m]</td>
<td>Casing or hole diameter</td>
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<td>( D_{\text{pipe}} )</td>
<td>[m]</td>
<td>Drillpipe outer diameter</td>
</tr>
<tr>
<td>( d_p )</td>
<td>[m]</td>
<td>Characteristic particle dimension / size</td>
</tr>
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<td>[m/s²]</td>
<td>Gravitational constant</td>
</tr>
<tr>
<td>( H )</td>
<td>[-]</td>
<td>Relative mixture viscosity function</td>
</tr>
<tr>
<td>( k )</td>
<td>[-]</td>
<td>= 1.2 ... ( N ). Indice used to indicate cuttings fraction</td>
</tr>
<tr>
<td>( N )</td>
<td>[-]</td>
<td>Total number of cuttings fractions</td>
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<td>( n_{\text{RZ}} )</td>
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<tr>
<td>Symbol</td>
<td>Unit</td>
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<td>[Pa·s]</td>
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<td>$ROP$</td>
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<tr>
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<td>Time</td>
</tr>
<tr>
<td>$t_{\text{gel}}$</td>
<td>[s]</td>
<td>Gelling time, time between agitation stop and reaching maximum gel strength</td>
</tr>
<tr>
<td>$t_{\text{stop}}$</td>
<td>[s]</td>
<td>The moment in time at which agitation (mud circulation or drillpipe rotation) stops</td>
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<td>Specific gravity of cuttings fraction $k$ (relative density compared to fresh water)</td>
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<td>Specific gravity of drilling fluid (relative density compared to fresh water)</td>
</tr>
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<td>[m/s]</td>
<td>Phase velocity of drilling fluid</td>
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<td>[m/s]</td>
<td>Phase velocity of cuttings fraction $k$</td>
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<td>$V$</td>
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<td>Hindered settling function</td>
</tr>
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<td>[m/s]</td>
<td>Mean mixture velocity</td>
</tr>
<tr>
<td>$v_{\text{slip}}$</td>
<td>[m/s]</td>
<td>Particle slip velocity</td>
</tr>
<tr>
<td>$v_{TSV}$</td>
<td>[m/s]</td>
<td>Terminal settling velocity of a particle</td>
</tr>
<tr>
<td>$Y$</td>
<td>[-]</td>
<td>Ratio of support force (due to fluid yield stress) w.r.t. buoyancy force (due to gravity), acting on a particle</td>
</tr>
<tr>
<td>$YP$</td>
<td>[Pa]</td>
<td>Abbreviation / field term or symbol commonly used for fluid yield point (according to Bingham plastic flow model)</td>
</tr>
<tr>
<td>$z$</td>
<td>[m]</td>
<td>Path along wellbore in vertical upward direction</td>
</tr>
<tr>
<td>$\sigma_{\text{fluid}}$</td>
<td>[-]</td>
<td>Mass concentration of drilling fluid in mixture</td>
</tr>
<tr>
<td>$\sigma_k$</td>
<td>[-]</td>
<td>Mass concentration of cuttings fraction $k$</td>
</tr>
<tr>
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<td>[s]</td>
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<td>$\Delta z$</td>
<td>[m]</td>
<td>Spatial step size (discretization)</td>
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<tr>
<td>$\varepsilon_z$</td>
<td>[m/s]</td>
<td>Diffusion coefficient in vertical ($z$) direction</td>
</tr>
<tr>
<td>$\mu$</td>
<td>[Pa·s]</td>
<td>Fluid viscosity</td>
</tr>
<tr>
<td>$\mu_B$</td>
<td>[Pa·s]</td>
<td>Fluid plastic viscosity (according to Bingham plastic flow model)</td>
</tr>
<tr>
<td>$\rho_{\text{cut}}$</td>
<td>[kg/m$^3$]</td>
<td>Density of cuttings, or of a cutting</td>
</tr>
<tr>
<td>$\rho_{\text{fluid}}$</td>
<td>[kg/m$^3$]</td>
<td>Density of drilling fluid</td>
</tr>
<tr>
<td>$\rho_k$</td>
<td>[kg/m$^3$]</td>
<td>Density of cuttings fraction $k$</td>
</tr>
<tr>
<td>$\rho_{\text{mix}}$</td>
<td>[kg/m$^3$]</td>
<td>Density of mixture</td>
</tr>
<tr>
<td>$\tau_0$</td>
<td>[Pa]</td>
<td>Fluid yield stress or gel strength</td>
</tr>
<tr>
<td>$\tau_{0,10\text{sec}}$</td>
<td>[Pa]</td>
<td>10 second gel strength (measured after 10 seconds of zero agitation)</td>
</tr>
<tr>
<td>$\tau_{0,10\text{min}}$</td>
<td>[Pa]</td>
<td>10 minute gel strength (measured after 10 minutes of zero agitation)</td>
</tr>
<tr>
<td>$\tau_0^{B}$</td>
<td>[Pa]</td>
<td>Fluid yield point (according to Bingham plastic flow model)</td>
</tr>
<tr>
<td>$\tau_0^{\text{eff}}$</td>
<td>[Pa]</td>
<td>Effective gel strength</td>
</tr>
</tbody>
</table>

References


