15.11 Global determination of the soil type

The global soil type in which the pipeline is installed is used for the determination of safety factors. The classification of global soil types given in Table 15-2 is applied in MDrill.

Table 15-2 – Classification of the soil type

Global soil type	φ [°]	c [kN/m^2]
Sand	$\varphi > 32.5$	$c \leq 0.5$
Sand	$30 < \varphi \leq 32.5$	$c \leq 0.5$
Clay	$\varphi > 30$	$c > 0.5$
Sand	$25 < \varphi \leq 30$	$c < 1$
Clay	$25 \leq \varphi \leq 30$	$c \geq 1$
Sand	$22.5 < \varphi < 25$	$c < 5$
Clay	$\varphi \geq 22.5$	$c \geq 5$
Clay	$\varphi > 17$	$c \geq 10$
Clay	$20 < \varphi \leq 22.5$	
Clay	$17 \leq \varphi \leq 20$	$c \geq 5$
Clay	$17 \leq \varphi \leq 20$	$c < 5$
Peat	$\varphi < 17$	

Drilling fluid pressures calculation

This section includes background information on the calculation of the following drilling fluid pressures:

- Minimum required drilling fluid pressure [§ 16.1]
- Maximum allowable drilling fluid pressure [§ 16.2]

16.1 Minimum required drilling fluid pressure

Drilling fluid consists of a mixture of water and bentonite or may have another composition (polymers) . This mixture has some special properties. The flow behavior of the fluid is an important characteristic for the development of drilling fluid pressure during the different drilling stages. Various types of drilling fluids exist. Generally, the flow behavior of drilling fluid can be described with the Bingham model. The Bingham model describes the fluid by means of a viscosity term and a threshold term from which flow is initialized. The threshold is called the yield point.

MDrill calculates the required minimum fluid pressure at predefined locations. In these calculations, the flow properties of the drilling fluid (density, viscosity and yield point) play an important role.

During all stages of the drilling process, a pipe is present in the borehole, drill pipe or product pipe. The return flow of drilling fluid with cuttings occurs in the annulus between the borehole wall and the pipe. The required fluid pressure to initiate flow depends on the width of the annulus (radius borehole minus radius drill pipe), the properties of the drilling fluid and the required annular fluid flow rate.

To obtain the minimum required pressure, the following pressure values must be calculated and added up:

(49) $$P_{mud,\,min} = P_1 + P_2$$

where:

P_1 Static pressure of the drilling fluid column [kN/m²].

P_2 Excess pressure necessary to maintain the annular flow of drilling fluid with cuttings in the borehole [kN/m²].

16.1.1 Static pressure of the drilling fluid column P_1

As the drilling head is at a lower level than the exit point of the drilling fluid, a pressure difference has to be overcome which is equal to the difference in height times the unit weight of the drilling fluid:

(50) $$P_1 = \gamma_b \cdot h$$

where:

P_1 Static pressure of the drilling fluid column [kN/m²].

γ_b Unit weight of the drilling fluid [kN/m³].

h Height between boring front and exit point of the drilling fluid [m].

16.1.2 Excess pressure to maintain flow of drilling fluid P_2

To initiate the flow of drilling fluid, a specific shear resistance in the fluid must be overcome. The drilling fluid flows through an annulus. The required excess fluid pressure depends on the width of the annulus (difference between borehole and drill pipe or product pipe radius), the flow properties of the drilling fluid, and the required flow rate.

The required excess pressure for flow is obtained by multiplying the pressure per unit length with the length of the borehole in which the drilling fluid is flowing:

(51) $$P_2 = \frac{dp}{dz} \cdot L$$

where:

P_2 Excess pressure necessary to maintain the annular flow of drilling fluid with cuttings in the borehole [kN/m²].

dp/dz Flow resistance per unit length of borehole [kN/m³].

L Distance in the borehole between the boring front and the exit point of the drilling fluid [m].

Flow resistance dp/dz

The minimum required pressure dp/dz is the optimal value for which the calculated flow rate Q is equal to the requested flow rate Q_{req} (necessary to initiate flow of drilling fluid).

Calculated flow rate Q

The calculated flow rate Q is the contribution of five components:

(52) $$Q = Q_{1,1} + Q_{1,2} + Q_2 + Q_{3,1} + Q_{3,2}$$

where:

$$Q_{1,1} = -2\pi\left[-\frac{\tau_0 R_0^{\,3}}{3\mu_0} - \frac{dp}{dz}\frac{R_1^{\,2}}{4\mu_0}\left(\left(\frac{R_0^{\,4}}{4R_1^{\,2}}\right) - \lambda^2\left(R_0^{\,2}\ln\left(\frac{R_0}{R_1}\right) - \frac{1}{2}R_0^{\,2}\right) + \frac{1}{2}C_2 R_0^{\,2}\right)\right]$$

$$Q_{1,2} = 2\pi\left[-\frac{\tau_0 r_0^{\,3}}{3\mu_0} - \frac{dp}{dz}\frac{R_1^{\,2}}{4\mu_0}\left(\left(\frac{r_0^{\,4}}{4R_1^{\,2}}\right) - \lambda^2\left(r_0^{\,2}\ln\left(\frac{r_0}{R_1}\right) - \frac{1}{2}r_0^{\,2}\right) + \frac{1}{2}C_2 r_0^{\,2}\right)\right]$$

$$Q_2 = \pi\cdot\left(r_1^{\,2} - r_0^{\,2}\right)\cdot\left[-\frac{\tau_0}{\mu_0}r_0 - \frac{dp}{dz}\cdot\frac{R_1^{\,2}}{4\mu_0}\cdot\left(\left(\frac{r_0}{R_1}\right)^2 - 2\lambda^2\cdot\ln\left(\frac{r_0}{R_1}\right) + C_2\right)\right]$$

$$Q_{3,1} = -2\pi\cdot\left[\frac{\tau_0}{3\mu_0}r_1^{\,3} - \frac{dp}{dz}\cdot\frac{R_1^{\,2}}{4\mu_0}\cdot\left(\left(\frac{r_1^{\,4}}{4R_1^{\,2}}\right) - \lambda^2\cdot\left(r_1^{\,2}\cdot\ln\left(\frac{r_1}{R_1}\right) - \frac{1}{2}r_1^{\,2}\right) + \frac{1}{2}C_4\cdot r_1^{\,2}\right)\right]$$

$$Q_{3,2} = 2\pi\cdot\left[\frac{\tau_0}{3\mu_0}R_1^{\,3} - \frac{dp}{dz}\cdot\frac{R_1^{\,4}}{8\mu_0}\cdot\left(\frac{1}{2} + \lambda^2 + C_4\right)\right]$$

The constants are:

$$\lambda^2 = \frac{2\tau_0\cdot r_0}{R_1^{\,2}\cdot\frac{dp}{dz}} + \left(\frac{r_0}{R_1}\right)^2$$

$$C_2 = \frac{4\tau_0}{R_1^{\,2}\cdot\frac{dp}{dz}}\cdot\left[r_0\cdot\ln\left(\frac{R_0}{R_1}\right) - R_0\right] - \left(\frac{R_0}{R_1}\right)^2 + 2\left(\frac{r_0}{R_1}\right)^2\cdot\ln\left(\frac{R_0}{R_1}\right)$$

$$C_4 = \frac{4\tau_0}{R_1\cdot\frac{dp}{dz}} - 1$$

$$r_1 = \frac{2\tau_0}{\frac{dp}{dz}} + r_0$$

r_0 is the solution to the following equation:

$$\frac{\tau_0^2}{\frac{dp}{dz}} + \tau_0 r_0 \left[1 + \ln\left(\left(\frac{2\tau_0}{\frac{dp}{dz}} + r_0 \right) \frac{R_0}{r_0 R_1} \right) \right] - \tau_0 (R_0 + R_1) + \frac{1}{4}\frac{dp}{dz}\left(R_1^2 - R_0^2\right)$$

$$+ \frac{1}{2}\frac{dp}{dz} r_0^2 \ln\left[\left(\frac{2\tau_0}{\frac{dp}{dz}} + r_0 \right) \frac{R_0}{r_0 \cdot R_1} \right] = 0$$

Requested flow rate

The requested flow rate Q_{req} is equal to:

(53) $$Q_{req} = Q_{ann} \cdot (1 - f_{loss})$$

where:

- f_{loss} Circulation loss factor [-].
- Q_{ann} Annular backflow rate [kN/m³] .

16.1.3 Minimum drilling fluid pressure for Stage 1 (pilot pipe in pilot hole)

For the first drilling stage of the horizontal directional drilling process, the minimum drilling fluid pressure is calculated for the drilling direction from the left and the right, using the following formulas:

(54) $$p_{\text{min, left}}^{\text{pilot}} = \gamma_b \cdot h + L_{left} \cdot \left(\frac{dp}{dz} \right)_{\text{pilot}}$$

(55) $$p_{\text{min, right}}^{\text{pilot}} = \gamma_b \cdot h + (L - L_{left}) \cdot \left(\frac{dp}{dz} \right)_{\text{pilot}}$$

where:

- L_{left} Distance in the borehole between the drilling head and the left exit point of the drilling fluid [m].
- L Total length of the borehole [m].

16.1.4 Minimum drilling fluid pressure for Stage 2 (drill pipe in pre-ream hole)

(56) $$p_{\text{min, left}}^{\text{pre-ream}} = \min\left[p_{\text{min, right}}^{\text{pilot}} ; \gamma_b \cdot h + L_{left} \cdot \left(\frac{dp}{dz} \right)_{\text{pre-ream}} \right]$$

(57) $$p_{\text{min, right}}^{\text{pre-ream}} = \min\left[p_{\text{min, left}}^{\text{pilot}} ; \gamma_b \cdot h + (L - L_{left}) \cdot \left(\frac{dp}{dz} \right)_{\text{pre-ream}} \right]$$

16.1.5 Minimum drilling fluid pressure for Stage 3 (product pipe in borehole)

(58) $$p_{\text{min, left}}^{\text{pull}} = \min\left[p_{\text{min, right}}^{\text{pre-ream}} ; \gamma_b \cdot h + L_{left} \cdot \left(\frac{dp}{dz} \right)_{\text{pull}} \right]$$

(59) $$p_{\text{min, right}}^{\text{pull}} = \min\left[p_{\text{min, left}}^{\text{pre-ream}} ; \gamma_b \cdot h + (L - L_{left}) \cdot \left(\frac{dp}{dz} \right)_{\text{pull}} \right]$$

16.2 Maximum allowed drilling fluid pressure

In the borehole, an excess drilling fluid pressure is maintained to enable sufficient outflow of drilling fluid and cuttings. At high pressures, the borehole will fail through uncontrolled expansion. The cavity expansion theory describes the definition of the maximum allowable drilling fluid pressure at which the wall of the borehole becomes unstable. Such limit pressure is the highest pressure that can be sustained by a cavity in the soil. Logically, this forms an upper boundary for the drilling fluid pressure in the borehole [Lit 11].

When the borehole is created, the drilling fluid will exert pressure on the soil. When the pressure rises above a certain value, plastic deformation of the soil will occur, initially adjacent to the borehole. When the pressure is increased further beyond this value, the zone with plastic deformation will increase. If the zone with plastic deformation reaches the surface a blow-out will occur.

In order to prevent blow-outs or damage to structures close to the borehole, care should be taken that the plastic zone remains within a safe radius around the hole. Therefore the pressure that creates a plastic zone that does not extend beyond the established safe radius must be determined.

To determine the maximum allowable drilling fluid pressure, different formulas are used, depending on the soil material sequence above the pipeline.

16.2.1 Maximum allowable drilling fluid pressure in undrained layers

In undrained layers, the maximum allowable drilling fluid pressure is:

(60) $$p_{max;und} = \min(0.9 p_{lim;und} ; p_{max;und}) + u$$

where the maximum and limit drilling fluid pressures are defined as:

(61) $$p_{\lim;und} = \sigma'_0 + C_{u;f} \cdot \left[1 - \ln\left(\frac{C_{u;f}}{G_f}\right)\right]$$

(62) $$p_{\max;und} = \sigma'_0 + C_{u;f} \cdot \left[1 - \ln\left(\frac{C_{u;f}}{G_f} + \left(\frac{R_b}{R_{p;\max}}\right)^2\right)\right]$$

where:

$C_{u,f}$	Average factorized undrained cohesion [kN/m²]: $C_{u;f} = C_u / f_c$
f_c	Partial safety factor on the cohesion [-].The default value is set to 1.4 [-].
C_u	Average undrained cohesion [kN/m²].
σ_0'	Initial effective stress [kN/m²]: $\sigma'_0 = \frac{3}{4}\frac{\sigma'_v}{f_\gamma}$
σ_v'	Vertical effective stress at the pipe centre [kN/m²].
f_γ	Partial safety factor on the unit weight. The default value is set to 1.1 [-].
G_f	Average factorized shear modulus [kN/m²]: $G_f = \frac{E}{f_E \cdot 2(1+\nu)}$
f_E	Partial safety factor on Young modulus [-]. The default value is set to 1.25 [-].
R_b	Radius of the hole [m].
$R_{p,max}$	Maximum allowable radius of the plastic zone [m]:$R_{p;max} = h_h / 2$
u	Pore pressure at pipe centre [kN/m²].

Parameters $C_{u;f}$ and G_f are determined from two methods:

- Linear weighted average between the ground level and the pipe centre;
- Distance depth average between the ground level and the pipe centre.

For example, the weight average undrained cohesion in the configuration in Figure 16-1 is:

$$C_u = \frac{C_{u,2} \cdot \left(\frac{1}{h_1} - \frac{1}{h_1 + h_2}\right) + C_{u,1} \cdot \left(\frac{1}{0.5D_0} - \frac{1}{h_1}\right)}{\frac{1}{0.5D_0} - \frac{1}{h_1 + h_2}}$$

The calculation of the maximum drilling fluid pressure is performed using both methods, after which the minimum value is taken.

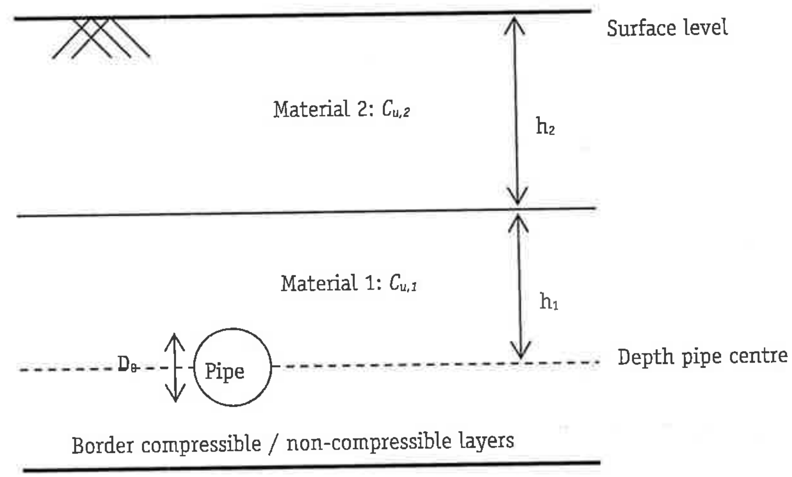

Figure 16-1 – Schematization of h_1 and h_2

In case no data about the undrained strength of the soil is available, an estimated C_u value can be obtained using the subsequent formula:

(63) $$C_u = c \cdot \cos\varphi + p \cdot \sin\varphi$$

with:

$$p = \frac{\sigma'_v + \sigma'_h}{2}$$

σ_v'	Vertical effective stress [kPa].
σ_h'	Horizontal effective stress [kPa].
φ	Angle of internal friction [°].
c	Cohesion [kPa].

16.2.2 Maximum allowable drilling fluid pressure in drained layers

In non-compressible drained layers, the maximum allowable drilling fluid pressure is:

(64) $$P_{\max;d} = \min(0.9\, p_{\lim;d} ; p_{\max;d}) + u$$

The maximum and limit drilling fluid pressures p_{max} and p_{lim} are defined as:

(65) $$p_{\lim;d} = (p'_f + c_f \cdot \cot\varphi_f) \cdot Q^{\frac{-\sin\varphi_f}{1+\sin\varphi_f}} - c_f \cdot \cot\varphi_f$$

(66) $$p_{\max;d} = \left(p'_f + c_f \cdot \cot\varphi_f\right) \cdot \left[\left(\frac{R_b}{R_{p;\max}}\right)^2 + Q\right]^{\frac{-\sin\varphi_f}{1+\sin\varphi_f}} - c_f \cdot \cot\varphi_f$$

(deformation)

(67) $$p_{\max;d} = \left(p'_f + c_f \cdot \cot\varphi_f\right) \cdot \left[\left(\frac{R_b}{\frac{2}{3}h}\right)^2 + Q\right]^{\frac{-\sin\varphi_f}{1+\sin\varphi_f}} - c_f \cdot \cot\varphi_f \quad \text{(soil cover)}$$

where:

$$Q = \frac{\sigma'_0 \cdot \sin\varphi_f + c_f \cdot \cos\varphi_f}{G}$$

$$p'_f = \sigma'_0 \cdot \left(1 + \sin\varphi_f\right) + c_f \cdot \cos\varphi_f$$

c_f Average factorized cohesion [kN/m²]: $c_f = c / f_c$

f_c Safety factor on the cohesion. The default value is set to 1.4 [-].

c Average cohesion between the border of compressible / non-compressible layers and the pipe centre [kN/m²]

φ_f Factorized friction angle [°]:

$$\varphi_f = \arctan\left(\tan\varphi / f_\varphi\right)$$

f_φ Partial safety factor on the angle of internal friction. The default value is set to 1.1 [-].

φ Average friction angle between the border of compressible / non-compressible layers and the pipe centre [°]

σ_0' Initial effective stress [kN/m²]:

$$\sigma'_0 = \frac{3}{4}\frac{\sigma'_v}{f_\gamma}$$

σ_v' Vertical effective stress at the pipe centre [kN/m²].

f_γ Partial safety factor on the unit weight. The default value is set to 1.1 [-].

R_b Radius of the hole [m]

$R_{p;max}$ Maximum allowable radius of the plastic zone [m]:

$$R_{p;\max} = \sqrt{2\varepsilon_{g;\max}\frac{R_b^{\,2}}{Q}}$$

h Height between the border of compressible / non-compressible layers and the pipe centre [m].

G_f Average factorized shear modulus between the border of compressible / non-compressible layers and the pipe centre [kN/m²]:

$$G_f = \frac{E}{f_E \cdot 2(1+\nu)}$$

f_E Partial safety factor on Young modulus [-]. The default value is set to 1.25 [-].

$\varepsilon_{g;max}$ Maximum deformation of the borehole [-]: $\varepsilon_{g;max} = 0.05$

u Pore pressure at pipe centre [kN/m²]

Parameters c, φ and G are determined using two methods:

- Linear weighted average between the ground level and the pipe centre;
- Distance depth average between the ground level and the pipe centre.

The calculation of the maximum drilling fluid pressure is performed using values determined by both methods for the calculation of the maximum allowable radius of the plastic deformation zone $R_{p;max}$, after which the minimum value for the maximum allowable drilling fluid pressure is taken.