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ORIGINAL PAPER

Effects of drilling fluids on the strength properties of clay-bearing rocks

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Abstract

Certain drilling problems are frequently observed during different types of drilling (e.g. geothermal, oil, geotechnical). In order to maintain the stability of boreholes, analysis of the essential parameters affecting their stability, including induced post-drilling stresses, the geomechanical properties of the rocks encountered during drilling and the type of drilling fluid used, should be considered. Well pressure, which is a function of the density of the drilling fluid, should be kept at a level that will not create shear- or tensile-type failure around the borehole walls; however, the mechanical properties of rocks are not constant and can be varied due to the interaction between drilling fluid and rock materials especially for clay-bearing rocks. Despite being aware of these factors, to date, no comprehensive study has been conducted on these issues. In order to overcome these shortcomings, the variations in mechanical properties of two clay-bearing sediments, which were saturated with different types of drilling fluids that are widely used in drilling practices, were investigated. By considering the obtained geomechanical properties, the effect of drilling fluids was compared and evaluated in terms of degradation of mechanical properties. As the occurrence of excess pore pressures that can develop under undrained conditions around a borehole is essential to borehole stability, the distribution of excess pore pressures and plastic deformations was also investigated by a finite element-based borehole simulation under drained and undrained conditions. By considering the results of experimental and numerical studies, some recommendations were presented for understanding wellbore stability.

Keywords Drilling fluid · Wellbore instability · Plastic deformation · Clay-bearing rocks

Introduction

Maintaining the stability of boreholes drilled for various purposes (geotechnical, geothermal, oil) has become an important rock engineering topic. The relief of stresses caused by drilling induces strain, which enables contraction of the borehole diameter. The characteristics of this strain mainly relate to the elastic limit of the host rock. The instability of boreholes is related to plastic strains developed by exceeding the elastic limit of rocks. The rocks in which drilling is performed are usually saturated with a drilling fluid that is selected by the drilling engineers to create appropriate well pressure by considering the density of the fluid and its ability to prevent shear- and tensile-type failure in the rock; however, this approach is based on the assumption that the rock has a constant strength, ignoring the interaction between the rock and the drilling fluid. But the geomechanical properties of rocks are highly vulnerable to the type of drilling fluids. Thus, it is important to evaluate the external effects on geomechanical parameters in problems related to borehole stability because of the impossibility of changing the stress conditions. Pasic et al. (2007) stated that borehole instability is related to some uncontrollable and controllable factors and the interaction between drilling fluid and rock is one of the controllable parameters that has a significant effect on borehole stability.

The stress components acting on the borehole wall can be defined as follows for a vertical well (Aadnoy 1996):

$$\sigma_{\mathrm{r}} = p_{\mathrm{w}} \tag{1}$$

$$\sigma_{\mathrm{t}} = 2\,\sigma_{\mathrm{a}} - p_{\mathrm{w}} \tag{2}$$

$$\sigma_{\mathrm{v}} = \gamma \mathrm{h} \tag{3}$$

where σ_r is the radial stress, p_w is the borehole pressure, σ_t is the tangential (hoop) stress, σ_a the is average horizontal stress and σ_v is vertical stress, γ is the unit weight of rock and h is the height of overburden.

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As it can be seen from the equations given above, the well pressure affects both radial and tangential stresses. However, it is not possible to change the stress conditions around the borehole through the well pressure. By considering this limitation, the primary concern should be directed at the strength properties of the rock, which is an input parameter in a great number of failure criteria (e.g. Mohr–Coulomb, Hoek-Brown, Drucker-Prager) that can be used for borehole stability evaluation and can be varied based on saturation with water and drilling fluids.

Up to now, the adverse effect of the saturation with water on the geomechanical properties of rock materials is generally known and studied by a great number of investigators (Goodman 1989; Dyke and Dobereiner 1991; Hawkins 1998; Lashkaripour 2002; Vasarhelyi 2005; Ergüler and Ulusay 2009; Yılmaz 2010; Torok and Vasarhelyi 2010; Karakul and Ulusay 2013; Wong et al. 2016); however, saturation around the borehole walls is generally created by drilling fluids with different compositions (e.g. bentonite, polymer/bentonite, KCl). Therefore, the stability of boreholes drilled for the geotechnical investigation, oil and gas, geothermal and mineral exploration is largely affected by the invasion of drilling fluid. As a result of the interaction between drilling fluids and rock formations located around the borehole wall, the mechanical properties of rock formations are varied and the level of this variation is mainly based on the type of drilling fluids. If the mechanical properties of rocks decrease dramatically due to saturation, then this leads to some borehole instabilities and related drilling problems. However, the variation level of mechanical properties due to saturation by drilling fluid is not constant and depends on the type of the drilling fluid. So it is very important to investigate and compare the effect levels of different drilling fluids on mechanical properties of rocks. However, there are limited numbers of previous studies which handle this issue in detail other than a limited number of studies of limited scope, as described below.

He et al. (2016) observed a decrease in the values of cohesion and internal friction angle of shales due to saturation. It was emphasised in this study that these variations are greater for bedding surfaces by considering the results of shear and triaxial test conducted to determine the variations on shear strength properties of intact rock and bedding surfaces of shales. The investigators did not use drilling fluids with different chemical compositions in their experiments; however, Yu et al. (2013) investigated the degree of reduction in the uniaxial compressive strength of shales, depending on saturation, for three different types of drilling fluid content (salt, gel-polymer and KCl-polymer), and determined the existence of a very high level of reduction in uniaxial compressive strength values under conditions in which drilling fluid containing organic salt was used. The measured decrease was determined as low for shales saturated with KCl and polymer-containing drilling fluids (Yu et al. 2013); however, variations in shear and tensile strength properties due to saturation with drilling fluid were not included in the study. Yan et al. (2013) stated that hydration makes clayey sediment types, such as shale, soft, causing it to produce swelling deformation after drilling, and emphasised that the development of collapse pressure in the rock material after the end of drilling is possible as a result of this pressure. Yan et al. (2013) stated that hydration makes clayey rocks (e.g. shale) soft and produces swelling deformations after drilling and emphasised that the development of a collapse pressure in the rock material after the end of drilling is possible as a result of this pressure. Yan et al. (2013) expressed that the interaction between KCl-based drilling fluids and argillaceous rocks creates swelling pressure and decreases geomechanical properties of these rocks. Yan et al. (2013) also determined that the uniaxial compressive strength of shale decreases around the saturation zone of the borehole.

By considering these results, it can be inferred that the geomechanical parameters across the invaded region are different from those of uninvaded regions. Therefore, different geomechanical parameters should be considered in stability analyses for different zones around a borehole. Liu et al. (2016) emphasised that the swelling pressure induced by hydration concentrates at crack tips within shales as a result of the water absorption process, and then microcracks are formed, which become connected to each other. This process leads to the formation of macrocracks, which are responsible for the failure of, and corresponding borehole instability in, a rock formation over time. Ewy et al. (2008) investigated the variation in undrained triaxial strength of shales due to saturation, using solutions with different chemical contents in their experimental studies, and determined significant and limited increments in triaxial strength for rock specimens saturated with 19% KCl solution and 23% NaCl solution; however, the authors also found a low level of strength reduction in rock samples saturated with 14% NaCl and 22% $CaCl_2$ solutions. Mkpoikana et al. (2015) studied the variation in uniaxial compressive strength for shale samples exposed to different drilling fluids for 24 h; it was determined in this study that the compressive strength of shale is greatly reduced under conditions in which polymer and KCl additives are used at the same time. Nmebgu and Ohazurulike (2014) stated that well instabilities are a result of a combination of mechanical and chemical factors, and can be summarised as hole closure or narrowing, hole enlargement or washout and fracturing and collapse. Liu et al. (2017) carried out unconfined compression and direct shear tests on polymer-fibre-reinforced sand samples with four different percentages of polymer, determining that the uniaxial compressive strength and cohesion values increased as a result of increased polymer concentration. On the contrary, a decrease in the internal friction angle was also observed in the study. Vipulanandan and Mohammed (2014) investigated the rheological properties of bentonite-based drilling fluid which is modified by polymer and expressed that the polymer modification decreases the yield point and apparent viscosity of drilling fluid at a large interval of strain rates. Vipulanandan and Mohammed (2014) also emphasised that maximum shear stress values of polymer-treated fluid were decreased in the interval of 5–33%. Shakib et al. (2013) and Aoki et al. (1993) stated that, because of the impermeable nature of clay-bearing rocks such as shales, the deformation of the rock around a newly drilled borehole develops under undrained conditions immediately after the borehole is drilled. Chen et al. (2003) found that "for a low-permeable formation, such as shale, an undrained condition exists for short exposure times." So, in addition to the drained behaviour, the undrained behaviour of rocks is also essential in evaluating borehole stability problems.

Shilko et al. (2018) investigated the effects on shear strength of shear bands of fluid-saturated rock, determining that "the pore pressure is controlled by dilation of the pore space in the solid skeleton of the shear band during plastic deformation and by squeezing of pores in surrounding blocks by the dilating shear band due to high stiffness of the host massif." They found the following parameter (A_{xy}) and emphasised that the variation in shear strength of the shear bands is corolled by this parameter:

$$A_{xy} = \dot{\varepsilon}_{xy}\eta\,(H+h)^2/k_0 \tag{4}$$

where h and H are half of the thickness of the shear band and the length of the block of rock that covers the shear band, respectively, ε_{xy} is the shear strain rate, k_o is the initial permeability of the rock block and shear band and η is the dynamic fluid viscosity.

Shilko et al. (2018) stated that, in the region in which A_{xy} approaches infinity, the combination of parameters given in Eq. 4 expresses a condition close to undrained (low fluid flow and high pore pressure). So, it is clear that high viscosity, which is a reason for high A_{xy}, means high pore pressure in porous rock under loading. Therefore, it can be said that the drilling fluid effect on the geomechanical properties is based on the viscosity of the fluid that saturates the rock. This is mainly due to difficulties related to drainage of such fluids because of their high viscosity. So, it can be inferred that the high viscosity of a fluid gives a high probability of the development of undrained conditions, in terms of fluid properties.

Skempton (1954) described the variation in pore water pressure as a function of the change in total stress using the following equations. It is clear from Eqs. 5 and 6 that the B coefficient will be greater if the bulk modulus (which is a function of compressibility) of pore fluid increases:

$$\Delta u = B\,\Delta\sigma \tag{5}$$

$$B = \frac{1}{1+n\,\dfrac{C_w - C_s}{C - C_s}} \tag{6}$$

where B is the pore water pressure coefficient, C is the compressibility of the solid skeleton, C_w and C_s are the compressibility of pore water and the solids forming the skeleton, respectively and n is the porosity.

The bulk modulus of water polymer solutions is around 3.5×10^9 N/m^2 (Javalagi and Singireddy 2012), while the bulk modulus of water is 2.15×10^9 N/m^2. This means that, if the pores are filled with polymer-based drilling fluid instead of water, then a higher excess pore water pressure development will be possible under undrained loading conditions, although the size of this variation still requires investigation.

By considering all of the studies mentioned above, it can be inferred that certain strength properties of shales and soils are vulnerable to saturation by specific fluids; however, limited studies investigated the effects of different chemical liquids on the different mechanical properties of rock. By taking into account the limited scope of these previous studies, this study aimed to comprehensively investigate the variation in geomechanical properties of clay-bearing rocks resulting from saturation with a variety of drilling fluids with different chemical compositions. In addition, this study focused on considering possible drained and undrained failures that can develop around a borehole, and the evaluation of borehole stability and the development of excess pore pressure under undrained conditions through the use of numerical modelling.

Selected rock types and laboratory experiments

The vulnerability of clay-bearing rocks to saturation was tested using sedimentary rock types containing various proportions of clay and differing porosities. Special attention was given to selecting rocks with different geological ages so as to include a wide variation in terms of their strength and elastic properties. The locations for sampling such rock types were chosen using 1:25000 and 1:100000 geological maps. A certain number samples of three different rock types were collected from the chosen locations. Note that it was not possible to prepare cylindrical cores of adequate length and diameter to perform rock mechanics tests on the Claystone-2 samples. Therefore, two different clay-bearing rock types (Claystone-1 and Mudstone) were used in the rock mechanics tests.

In order to identify the mineralogical content of the samples, X-ray diffraction analyses were carried out. XRD analyses were performed at the Central Research Laboratories of İzmir Katip Çelebi University. The X-ray diffraction (XRD) analyses were carried out on studied rocks to determine rock sample mineralogy and the diffractograms were determined by a Panalytical Empyrean diffractometer with a goniometer step size of 0.0001°. The percentage of the minerals was determined by considering method suggested by Gündoğdu (1982). X-ray diffractograms of claystone and mudstone and mineralogical content of tested rocks were given in Fig. 1 and Table 1, respectively. As can be seen from Table 1, the clay contents of claystone and mudstone are higher than 50% and so the sensitivity of clay minerals to saturation can be evaluated by using these rock types.

All geomechanical tests (uniaxial compressive, triaxial compression, Brazilian indirect tensile) were performed on rock cores with a NX dimension of 54.7 mm, as suggested by (ISRM 2007). The adverse effects of saturation on the clay-bearing rock samples, and low core recovery faced during the extraction of cores from the samples, were major problems. In order to overcome these problems, the number of rock samples collected from the field was increased, so the requisite number of cores was obtained.

The experiments were carried out under both dry and completely saturated conditions. A total of 191 rock mechanics tests (triaxial, uniaxial compressive, Brazilian tensile strength, porosity and unit weight) were performed. Confining stresses (σ_3) of 0, 1, 2 and 4 MPa were used in triaxial tests. The core samples were saturated in a water tank under a vacuum, as suggested by the ISRM (2007); three different types of drilling fluids (bentonite-, polymer/bentonite- and KCl-based) were used. The tests were also performed under dry and water-saturated conditions to determine the level of decrease in strength properties due to saturation with drilling fluids and to compare this level with the values obtained due to saturation with water. All rock samples were only tested under one saturation condition (dry or fully saturated condition) and the saturation was created by considering the method suggested by ISRM (2007).

However, the strength properties of claystone saturated with water could not be determined due to difficulties related with preparation of test samples and dramatic decreasing of strength of test samples due to saturation with water. The drilling fluids were prepared according to API Specification 13A (2010). The compositions of three different drilling fluids are given in Table 2. The viscosity values of drilling fluids were also measured by using a Couette rotational viscometer. The viscometer operates at six different speeds between 3 and 600 rpm. The apparent viscosity values calculated for drilling fluids are given in Table 3. The results of physical and geomechanical parameters determined by laboratory experiments are presented in Table 4.

Effect of drilling fluid saturation on geomechanical properties of rocks

The negative effects of saturation on the geomechanical parameters of rock have previously been studied. In this study, rock mechanics tests were conducted under dry and saturated conditions, in which the saturation was created by using drilling fluids with different compositions (bentonite-, polymer/bentonite- and KCl-based), as well as water. The geomechanical properties of the rocks saturated with different drilling fluids are given in Table 4 and Fig. 2. The shear strength properties of the rocks were determined by triaxial tests and from Mohr's circles based on uniaxial compressive and Brazilian tensile strength values. Typical Mohr–Coulomb failure envelopes, obtained for mudstone saturated with different drilling fluids, are provided in Fig. 3, from which it is clear that the highest and lowest shear strength values were determined under conditions of saturation by polymer- and bentonite-based drilling fluids, respectively.

According to the results of the experiments carried out on the saturated claystone cores, the highest and lowest cohesion values were obtained using polymer- and KCl-based drilling

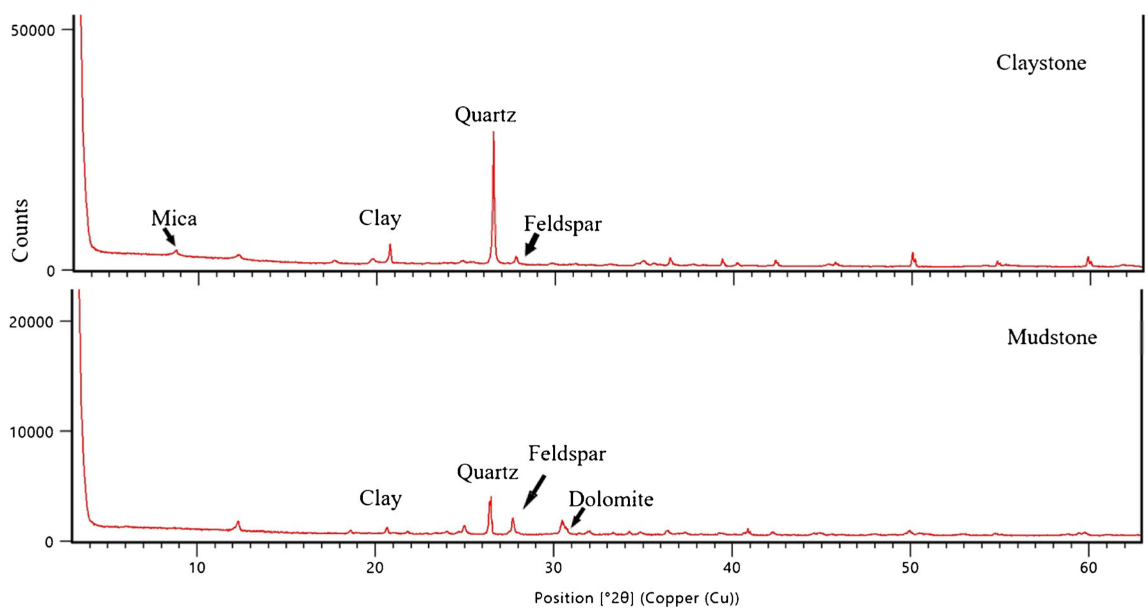

Fig. 1 X-ray diffractograms of claystone and mudstone

Table 1 The mineral content and geological ages of studied rock types

Rock types and geological ages[1]		Mineral content (%)				
		Mica	Clay	Feldspar	Quartz	Dolomite
Claystone	Lower Miocene	12.2	72.5	4	11.3	
Mudstone	Campanian-Paleocene		54.4	24.1	10.4	11.1

[1] Dönmez et al. (2014)

fluids, respectively; however, the highest and lowest internal friction angle values were determined for samples saturated with KCl- and bentonite-based drilling fluids, respectively. For the mudstones, while the best drilling fluid was polymer-based, in terms of cohesion and internal friction angle, the samples that gave the lowest cohesion values were saturated with bentonite-based drilling fluid.

So, it can be inferred that polymer-based drilling fluid is most favourable option in terms of shear strength of clay-bearing rocks. The strength values determined under dry and saturated conditions for claystone and mudstone are in Fig. 2. These results are compatible with the results of the experiments conducted by Liu et al. (2017), which were performed on sand samples. Yu et al. (2013) also carried out some uniaxial compressive strength tests on another clay-bearing rock (shale) by using different kind of drilling fluids and determined lower decrement in uniaxial compressive strength values (higher compressive strength values) for the condition of saturation by polymer- and KCl-based drilling fluid as determined in this study. Ewy et al. (2008) investigated the variation of undrained triaxial strength of shale due to saturation and found an increment in undrained strength values of rock samples by using KCl-based drilling fluid. On the other hand, the decrement in uniaxial compressive strength, cohesion and tensile strength values were determined to be close to 40% for mudstone saturated with water in this study. The decrement ratios close to 40% were also found by Karakul and Ulusay (2013) for other clay-bearing rocks such as marl and argillaceous limestone. The highest strength values were generally obtained for rock samples saturated with polymer-based drilling fluids and these values are so close to those obtained under dry condition. As it can be seen from Fig. 4, the variation trends observed in cohesion, tensile strength and uniaxial compressive strength values due to saturation are generally harmonious, but this is not the case for the internal friction angle. The highest variation levels (minimum values) due to saturation with drilling fluids, as a percentage of the value determined under dry conditions, were found to be 67% for claystone and 85% for mudstone for uniaxial compressive values, and 62% for claystone and 83% for mudstone for Brazilian tensile strength values, under saturation with bentonite-based drilling fluids. The highest reduction in cohesion values was found to be 16% for claystone under saturation with KCl-based drilling fluid, and 10.5% for mudstone under saturation with bentonite-based drilling fluid. As a result, it can be said that, while higher decrements in strength properties (up to 35–40%) were generally observed under saturation with bentonite-based drilling fluids, the decrease observed in the strength values of the samples saturated with polymer-based liquids was rather limited and is very close to the strength values under dry conditions. On the other hand, the variation observed in the angle of friction due to saturation showed variable tendencies (increasing and decreasing) in the interval between 87 and 108% of the value determined under dry conditions, which is too limited. This is most likely related to the different lubrication properties of the drilling fluids used, the evaluation of which was beyond the scope of this study.

Grillet et al. (2012) stated that polymer gels have high adhesive properties and do not flow under low stresses. The authors expressed that, because a limited part of the applied energy is stored as recoverable elastic energy in the gel network, there is a requirement for more work which is needed to remove the gel from a surface. Zosel (1985) emphasised that, when a polymer encounters a surface, an adhesive bond is developed that has considerable strength. This adhesive contribution would explain why higher strength properties are generally obtained

Table 2 Composition of drilling fluids used in this study

Additive	Drilling fluid type/additive concentration		
	Bentonite (g/l)	Polymer/bentonite (g/l)	KCl (g/l)
Bentonite	22.8	22.8	–
Polymer	–	8	–
KCl	–	–	28.5
NaOH	0.17	0.17	0.17

Table 3 Apparent viscosity values of drilling fluids

RPM	Apparent viscosity (cP)		
	Bentonite	KCl	Polymer/ bentonite
600	3	12,5	33
300	4	2	39
200	3	1.5	46.5
100	6	3	66
6	50	50	300
3	100	100	500

Table 4 Results of the physical and geomechanical experiments

Rock type	Drilling fluid	Triaxial compressive test (*)		Uniaxial compressive strength (MPa)	Brazilian tensile strength (MPa)	Unit weight (kN/m^3)	Porosity (%)
		c (MPa)	ϕ(°)				
Claystone	Bentonite	2.47 (1.94)	31.7 (36.73)	6.93	0.86	21.68	20
	Polymer/bentonite	1.99 (1.95)	39.2 (41.37)	9.1	1.03		
	KCl	1.46 (1.66)	43.7 (42.85)	8.25	0.99		
	Dry	1.54 (1.97)	44.2 (42.20)	10.31	1.37		
Mudstone	Bentonite	17.135 (17,82)	57.25 (53.03)	100.88	10.61	26.67	8
	Polymer/bentonite	20.29 (21.10)	57.35 (53.87)	112.92	11.64		
	KCl	18.765 (19.79)	53.4 (50.71)	105.57	10.69		
	Water	8.8175 (12.26)	56.575 (52.62)	76.54	8.32		
	Dry	13.89 (19.90)	51.55 (49.70)	117.64	12.65		

*Parenthesised values are average values from the results of the triaxial test and those obtained from Mohr's circles based on Brazilian tensile strength and uniaxial compressive strength values

for rock samples saturated with polymer-based drilling fluids. On the other hand, the interaction between water (or another fluid) and clay minerals has previously been investigated in a number of studies. Karakul and Ulusay (2013) stressed that the combined effect of porosity and clay content is mainly responsible for decreased geomechanical properties in rocks due to saturation. Such an adverse effect is more pronounced in claystone due to its higher porosity and clay content, which means also a higher effective clay content than in mudstone. As shown in Table 4, while the average cohesion value of claystone obtained under dry conditions is higher than the value obtained under saturated conditions with polymer-based drilling fluid, the opposite trend is valid for mudstone, which has too low porosity; however, there are some studies that have stressed that saturation by KCl-based drilling fluid prevents abnormal strength reduction (Ewy et al. 2008; Yu et al. 2013), although this is not at the level of values obtained due to saturation by polymer-based fluid.

While there are no effects of excess pore pressure on the evaluation of borehole stability under drained conditions, this is very important in the evaluation of undrained borehole stability. So, in addition to variations in the geomechanical properties of clay-bearing rocks due to saturation by drilling fluids, the behaviour related to excess pore pressure development, which has an effect on the fluid properties, should also be considered in borehole stability evaluation. In order to examine to this issue, numerical analyses were performed.

Numerical analyses

The geomechanical parameters of rocks control their deformation behaviour under various stresses. The level of stress (yield point) at which plastic deformation begins in a rock is of great importance in terms of expressing the point at which deformation that cannot be recovered develops. This level is closely related to the effective stresses the rock material is exposed to. Therefore, the occurrence and amount of pore water pressure is very important in terms of effective stresses and plastic point distributions. As found in previous studies,

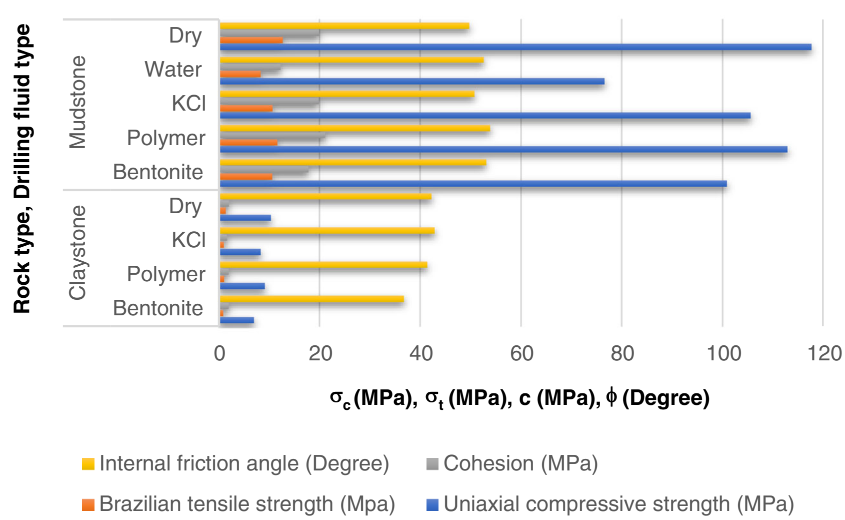

Fig. 2 Strength properties of different rocks saturated with different drilling fluids

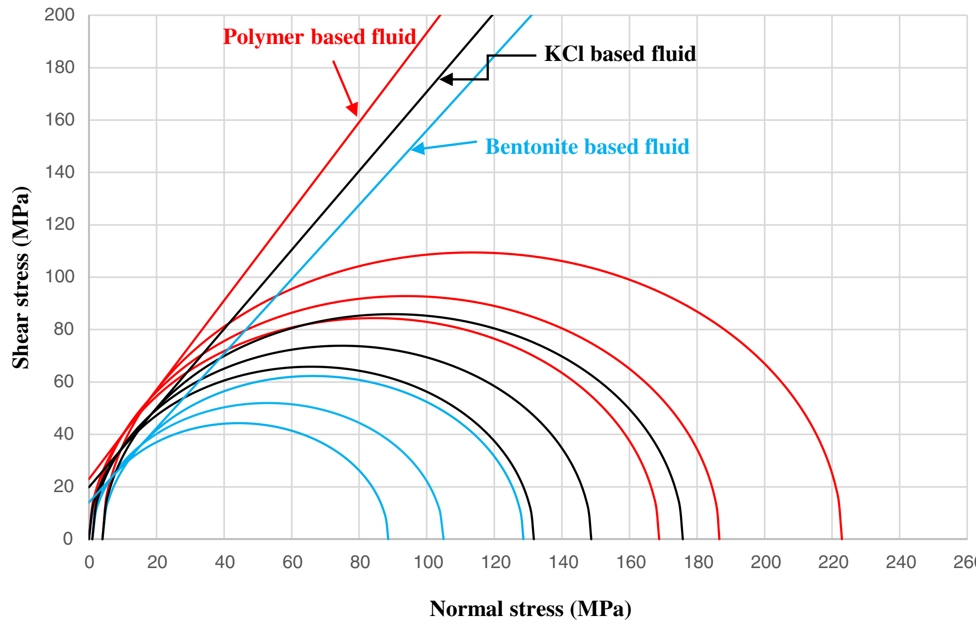

Fig. 3 Comparison of typical Mohr–Coulomb failure envelopes obtained for mudstone saturated with different drilling fluids

plastic deformation can develop around a borehole under both drained and undrained conditions, especially in clay-bearing rocks. So, the distribution and level of excess pore water pressures that can develop under undrained conditions around a borehole are essential to borehole stability, and directly related to the rock and fluid properties. Consequently, drilling fluids do not only affect the geomechanical parameters of the rocks, but also the quantitative values of the pore water pressures, and thus the effective stresses around the borehole. In order to examine these effects in detail, and to decide which drilling fluid is more favourable in this respect, the distribution of excess pore water pressures and plastic points around a borehole were investigated using numerical simulations under conditions of different drilling fluids.

In order to explain the relationship between excess pore pressure and drilling fluids, and to evaluate the stability under drained and undrained conditions, a borehole drilled in claystone was simulated by PLAXIS 2D, which is a two-dimensional finite-element software. A 2-m-thick zone around a borehole was modelled as an invasion region, as suggested by Zhang (2017). This zone was defined using the geomechanical properties of the rock saturated with drilling fluid. Beyond this zone, dry conditions were considered. A total of 2231 triangle elements were used in the model. The geometry of borehole was simulated using an axisymmetric model.

In order to explain the different loading conditions (drained and undrained), two different simulations were performed. While the drained analyses were performed using effective geomechanics parameters, the undrained analyses, which gave total stresses, excess pore pressures and effective stresses, were based on assuming an implicit undrained bulk

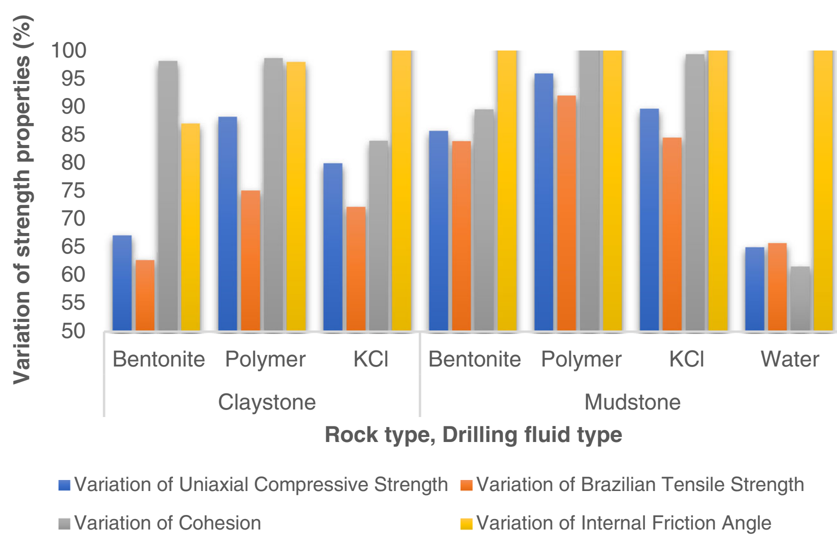

Fig. 4 Variation in strength properties due to saturation with different drilling fluids as a percentage of strength properties determined under dry conditions

modulus (rock material and pore fluid), linked to the effective elastic properties (E' and ν') used in the analyses. Young's modulus and Poisson's ratio under undrained conditions were calculated using the following equations in the numerical simulations (Plaxis 2016):

$$E_{\mathrm{u}} = 2G\,(1+\nu_{\mathrm{u}}) \tag{7}$$

$$\nu_u = \frac{3\,\nu' + \alpha\,B\,(1-2\nu')}{3-\alpha B\,(1-2\nu')} \tag{8}$$

$$B = \frac{\alpha}{\alpha + n\left(\frac{K'}{K_{\mathrm{w}}} + \alpha - 1\right)} \tag{9}$$

$$\alpha = \frac{K'}{K_{\mathrm{s}}} \tag{10}$$

where v' is Poisson's ratio under drained conditions, B is Skempton's B parameter, n is the porosity, K' is the effective bulk modulus of the material, K_{w} is the bulk modulus of water, α is Biot's pore pressure coefficient and K_{s} is the bulk modulus of the solid material.

The bulk modulus of the solid rock material used here was calculated by considering the Voigt–Reuss–Hill average modulus formulation, given below (Mavko et al. 2009):

$$M_{\mathrm{VRH}} = \frac{M_{\mathrm{v}} + M_{\mathrm{R}}}{2} \tag{11}$$

The effective and solid material bulk modulus, and Biot's pore pressure coefficient values of the rocks studied, are given in Table 5.

By considering the equations given above, total stress rate, effective stress rate and rate of pore pressure can be calculated, respectively (Plaxis 2016):

$$\dot{\sigma} = K_{\mathrm{u}}\,\dot{\varepsilon_{\mathrm{v}}} \tag{12}$$

$$\dot{\sigma'} = (1-\alpha\,B)\;\dot{\sigma} = K'\,\dot{\varepsilon_{\mathrm{v}}} \tag{13}$$

$$\dot{u}_{\mathrm{e}} = B\;\dot{\sigma} = \frac{\alpha\;\dot{\varepsilon_{\mathrm{v}}}}{n\,C_{\mathrm{w}} + (\alpha-n)\,C_{\mathrm{s}}} \tag{14}$$

The rock behaviour was described using a linear elastic perfectly plastic material (Mohr–Coulomb) model. The numerical simulations were performed using the geomechanical properties of claystone that are given in Tables 4 and 5. After evaluating the stability of the borehole at different depths, the results of the 180 m depth, which clearly expressed the distribution of plastic points and excess pore pressure development, were investigated. The plastic points, excess pore pressures and cartesian total stress distributions around the borehole, determined under drained, undrained/saturated with bentonite-based fluid and undrained/saturated with polymer-based fluid conditions, are given in Figs. 5 and 6. As can be understood from the figures, the drained condition was the most unfavourable. The failure zone observed under drained conditions was larger than those of the undrained conditions, and tensile-type failure was dominant around the borehole. This is mainly due to the absence of negative pore pressure development around the borehole wall, which helps to enhance their durability. The failures were generally identified as of the tension type; however, a considerable amount of shear-type failure was also observed close to the opening under drained conditions.

Shear-type failures were more dominant under undrained conditions than drained conditions; this is most likely related to positive (tension) excess pore water pressure development observed around the borehole walls, which prevents tensile-type failure around the borehole. The tensional pore pressures induce a bridge inside the rock material that prevents tensile-type failure. The radial stress, tangential stress and excess pore pressure distributions around borehole were given in Figs. 5 and 6. While excess pore pressure varied between 26 and − 14 MPa under undrained conditions with a bentonite-based drilling fluid, these values reached to the interval between 32 and − 28 MPa under undrained conditions with a polymer-based drilling fluid. These values are considered high and effective for borehole stability; however, in a narrow zone close to the bottom of the borehole, tension-type pore pressure was dominant close to the borehole wall. This enhances the durability of the borehole, when compared to drained conditions. So, it is clear that drilling fluids with a high bulk modulus (such as polymer-based fluid) are favourable for the stability of borehole walls and unfavourable for the

Table 5 Elastic properties of the rocks used in the numerical analyses

Rock type	Bulk modulus (GPa)					E (GPa)	ν	K_{vr} (GPa)	K' (GPa)	α
	Mica	Clay	Feldspar	Quartz	Dolomite					
Claystone	41.1	1.5	37.5	37		1.6	0.3[1]	6.91	1.33	0.19
Mudstone		1.5	37.5	37	94.9	17.59	0.25	13.46	11.73	0.87

[1] Gerçek (2007)

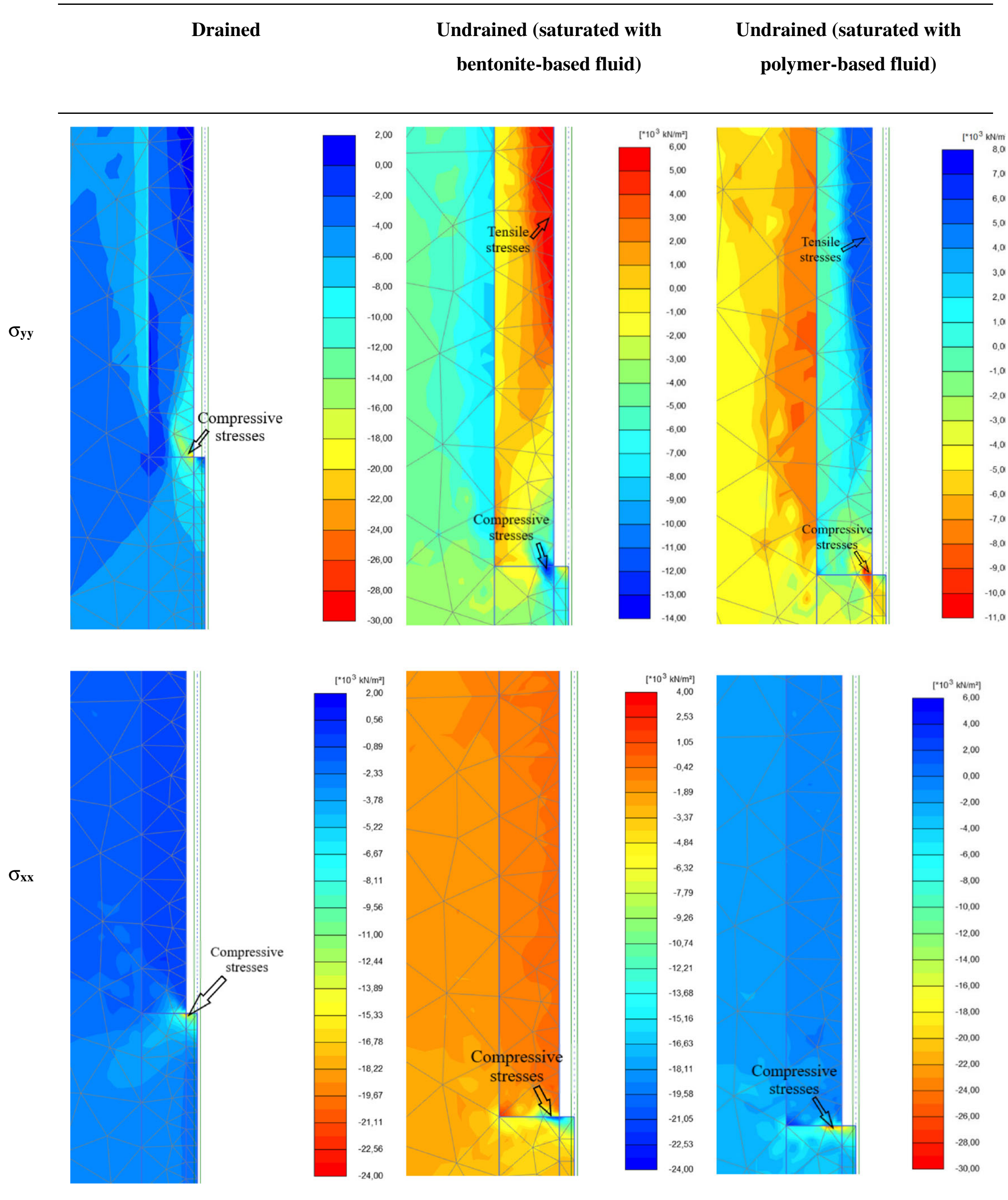

Fig. 5 Cartesian total stress distributions around a borehole

stability of the region close to the bottom of the hole under undrained conditions, in terms of excess pore pressure development. As higher positive pore pressures develop under undrained conditions saturated with polymer-based drilling fluid than under undrained conditions saturated with bentonite-based drilling fluid, the region of shear failure is larger under the latter. Consequently, the results of numerical simulations show good agreement with rock mechanics experiments in terms of variation of strength of clay-bearing rocks. Both numerical and experimental studies express that clay-bearing rocks saturated with polymer-based fluid have higher strength than the rocks saturated with bentonite-based drilling fluid around the borehole walls. However, numerical simulations also show that higher positive pore pressure development due to saturation with polymer-based drilling fluid has an adverse effect on variation of strength of clay-bearing rocks close to bottom of borehole under undrained conditions.

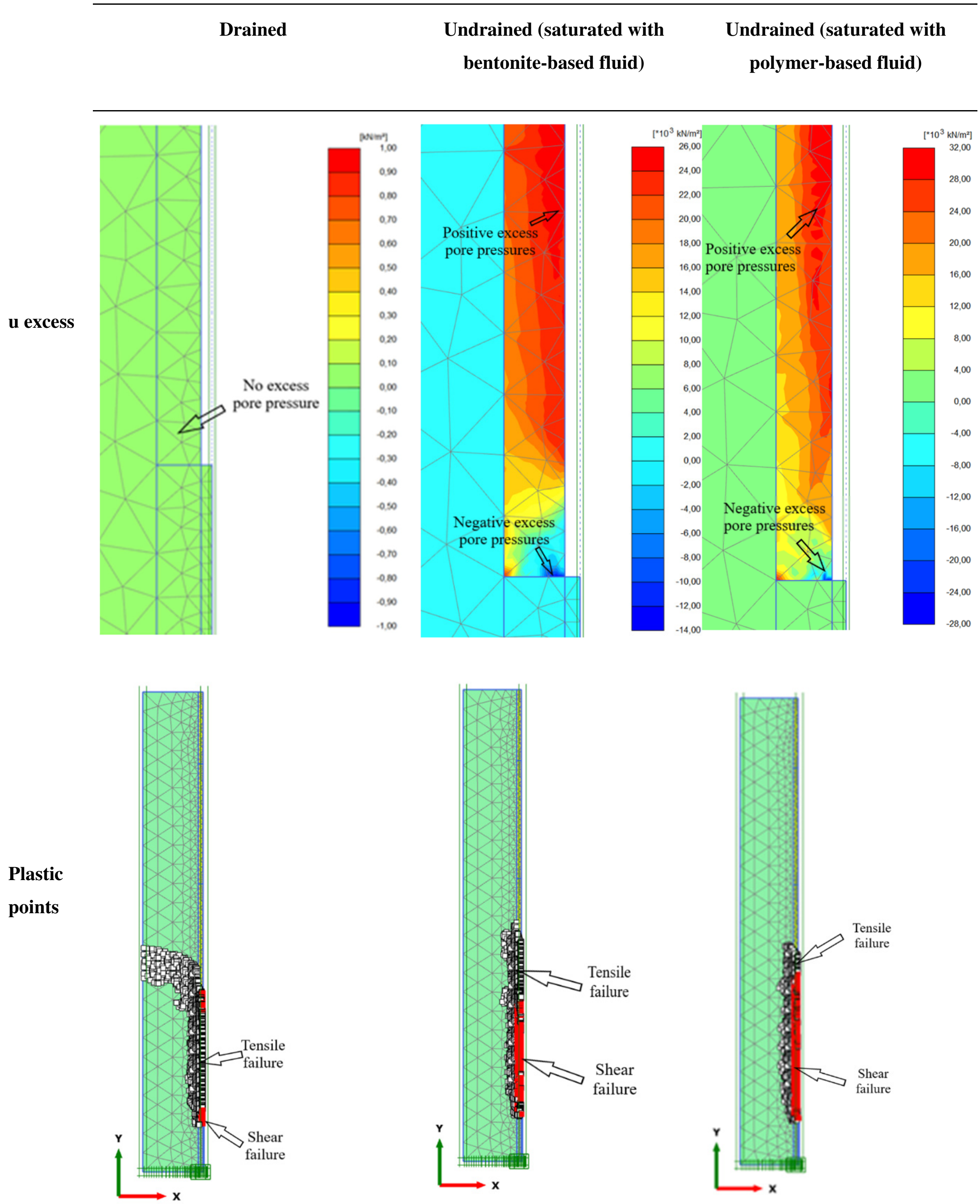

Fig. 6 Excess pore pressure and plastic point distributions around a borehole

Conclusions

Experimental studies showed that, while the effects were limited in Paleocene mudstones with low porosity, the adverse effects of saturation were considerable in Miocene claystones with high porosity. By considering the results of the geomechanical tests, it was found that rocks saturated with polymer-based drilling fluids generally had higher shear, uniaxial compressive and tensile strength values, compared to those saturated with bentonite- or KCl-based drilling fluids. On the other hand, the percentage variation in internal friction angle determined as a result of saturation showed opposing trends (both increasing and decreasing), which were too limited.

The results indicated that the interval of induced excess pore pressures was larger for borehole walls saturated with polymer-based drilling fluids. So, the positive pore pressures were found to be dominant in wide regions located close to the borehole walls, and negative pore pressures were dominant in the region close to the bottom of the borehole. This means that, while the effects of polymer-based drilling fluid are favourable in the region close to the borehole walls, these effects are unfavourable in the regions located close to the bottom of the hole. Consequently, it is clear that polymer-based drilling fluid is more useful than other types of drilling fluids (e.g. bentonite- and KCl-based) in clay-bearing rocks, in terms of borehole stability.

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