Geomechanical behaviour of gassy soils and implications for submarine slope stability: a literature analysis

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Abstract: Submarine slope failures pose a direct threat to seafloor installations and coastal communities. Here, we evaluate the influence of free gas on the soil's shear strength and submarine slope failures in areas with gassy soils based on an extensive literature review. We identify two potential destabilization mechanisms: gas bubbles in the pore space lead to a reduced shear strength of the soil and/or gas induces excess pore pressures that consequently reduce the effective stress in the soil. Our evaluation of the reported mechanical and hydraulic behaviour of gassy sediments indicates that the unfavourable impact of entrapped gas on a soil's shearing resistance is not sufficient to trigger large-scale slope failures. Liquefaction failure due to high gas pressures is, however, a viable scenario in coarse-grained soils. Transferring the gas influence on the soil mechanical behaviour to constitutive models is identified as the most important prerequisite for a successful future analysis of slope stability.

Submarine slope failures are a common feature encountered at continental margins worldwide. The consequences of the slide events are potentially detrimental for coastal communities and offshore infrastructure (Locat and Lee 2002). It is hence of great interest to understand the processes that lead to and accompany submarine landsliding. The triggering mechanisms for large slide events on very low gradient slopes (1–2°) have been especially inscrutable, partly due to the lack of on-site studies (Urlaub *et al.* 2012). Based on the observation that several submarine landslides coincide with the occurrence and migration of free marine gas in the soil (Bünz *et al.* 2005; Lafuerza *et al.* 2012), gas is considered a conceivable trigger mechanism (Elger *et al.* 2018). A predominantly negative impact of free gas on the soil's mechanical behaviour is suspected. A precise assessment of the bearing capacity of gas-containing soils is, however, difficult from a geotechnical point of view, as the investigation of gassy soils is not yet very advanced due to the low relevance for engineering applications and the complexity in the required experimental testing procedures.

Thus, the influence of free gas on marine soils requires further investigation in order to assess the feasibility of gas acting as a trigger mechanism. We developed two working hypotheses for possible gas-induced failure mechanisms: either a reduction of the soil's shearing resistance due to enclosed gas bubbles in the soil, or the build-up of weakening excess pore pressures due to the acting gas pressure. Previous findings on the influence of gas have to a certain extent been contradictory (Wheeler 1988*b*; Hong *et al.* 2018), making a more detailed analysis necessary in order to evaluate the introduced hypotheses. Here, we gather the existing knowledge in the field of gassy soils from an extensive literature review. Particularly, we peruse the main characteristics of a gassy soil and the associated alteration of its geomechanical properties. The implications of entrapped gas bubbles for the overall soil structure can be severe. Hence, we review the processes of gas bubble growth, gas migration and gas-induced soil fracturing. Based on the current state of knowledge, we provide a further development of the existing approaches for gas-induced slope failure mechanisms. Consequently, on the basis of the scientific evidence previously published, we assess the feasibility of enclosed free gas in the soil as a potential trigger mechanism for submarine slope failures.

Continuously, the term 'soil' is used as a collective term for all loose rocks above the bedrock and thereby comprises all marine sediments (Press and Siever 1998).

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General characteristics of gassy soils

In the marine environment gases mainly exist in three different states: dissolved in the water phase, as gas hydrate, or as free gas in the pore space. While a gas in its dissolved form does not influence the mechanical behaviour of a soil, the formation or dissociation of hydrates and entrapped gas bubbles have a major impact on soil characteristics (Sills and Wheeler 1992; Jayasinghe 2013). Hydrates are only present within the gas hydrate stability zone, but marine gases from thermogenic or biogenic origin can occur in a wide variety of settings (Judd and Hovland 2009).

Conceptual delimitation of gassy soils

Gassy soil is a partially saturated soil whose void space is occupied by a continuous water phase and a discontinuous gas phase in the form of gas bubbles. The minimum degree of saturation required for the occurrence of a discontinuous gas phase is given with $S_r \geq 85$–90%; that is the gas content of the pore fluid is ≤ 10–15% (Nageswaran 1983; Fredlund and Rahardjo 1993; Grozic *et al.* 1999; Wang *et al.* 2018). Hence, capillary cohesion, which is often associated with unsaturated soils with low degrees of saturation, cannot develop (Fredlund and Rahardjo 1993). The characteristics of gassy soils, and thus also the mechanical behaviour, is influenced by several factors. For example, grain size, soil structure and load history, as well as the amount of gas, and the specific pressure regime play a role. In order to evaluate the role of soil texture, not enough research results have been published in this area so far. Above all, the grain size of a soil determines the structure of a gassy soil (Sills and Wheeler 1992). Consequently, this results in a fundamentally different soil behaviour depending on the grain size. A differentiated consideration of different soil types is therefore indispensable and hence well-sorted soils are presupposed in the following.

Fine-grained soils

By geotechnical definition fine-grained, cohesive soils show grain sizes below a diameter of 0.063 mm and, accordingly, small natural pore spaces through which the gas bubbles cannot move. It cannot be ruled out that similar characteristics may occur in soils with slightly larger grain diameters and that a transition zone may occur. In order for the gas to invade the void space, the water phase has to be displaced by the gas phase. This process requires the gas pressure in the gas phase to exceed the capillary pressure acting in the capillary tubes between the grains. The necessary gas pressures usually exceed the soil's strength. Consequently, the gas causes local damage in the soil structure and forms large voids within the fully saturated soil matrix. These large gas voids are isolated, fixed with respect to the grain structure and randomly distributed within the saturated soil matrix (Wheeler 1986; Mabrouk and Rowe 2011). Hence, the two pore fluids do not mix but are spatially separated and thus the water phase can still be considered incompressible.

The size of the formed bubbles depends on a variety of boundary conditions, such as the material properties of soil, pore water and gas, the thermodynamic conditions, and the stress state. Scans from experiments conducted with fine-grained gassy soil show average bubble diameters of 0.1–1 mm (Wheeler 1988*a*). A schematic sketch of a fine-grained, gassy soil is shown in Figure 1a. In order to fully understand the mechanical impact of the gas bubbles on the overall soil behaviour it is essential to assess the interdependencies of the different influencing factors. A dominating parameter is the gas solubility, which is directly dependent on the acting gas pressure, the global pressure regime, temperature and salinity – which in turn will also adapt to a change in any other boundary condition.

Additionally, the gas pressure in neighbouring bubbles is not necessarily identical (Wheeler 1988*a*; Sills *et al.* 1991). In the ambition to create equilibrium, the gas pressures in adjoining bubbles adapt. Because the gas voids are fixed in the soil matrix, a gas exchange between two formed bubbles can only take place in the dissolved form by diffusive or advective transport in the pore water.

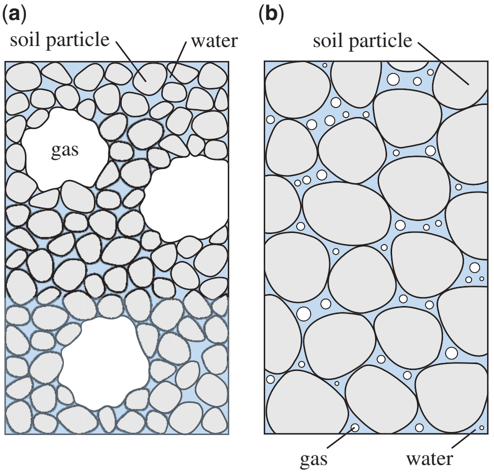

Fig. 1. Appearance of gassy soils according to Mabrouk and Rowe (2011): (**a**) fine-grained, gassy soil; (**b**) coarse-grained, gassy soil. Modified from Mabrouk and Rowe (2011, fig. 2), © 2011, with permission from Elsevier.

The existence of gas voids within the saturated soil matrix affects the stress state in the soil considerably. Knowledge about visual appearance of the gas voids is a requirement in order to evaluate the impact on the stress distribution. However, the description of the void's size and shape is not trivial, as it does not correlate directly with the internal gas pressure in the voids, the radii of the menisci, or the acting surface tension between the fluid phases (Wheeler 1988*a*; Sills *et al.* 1991). At the interface between the gas and the saturated soil matrix the pore water forms menisci bridging the spaces between the soil particles. The curvature radii of the menisci depend on the unique position of the solids, the surface tension, and the acting gas and water pressures (u_g and u_w; see Fig. 2). In the case of a high gas pressure compared to the pore water pressure, the menisci will have a concave shape to the gas phase and small radii. When the pressure difference $u_g - u_w$ reaches a critical upper boundary, gas encroachment to the saturated soil matrix occurs, that is the gas invades the pore space until reaching the limiting capillary pressure. In the opposite case of low gas pressures and comparably high pore water pressures in the surrounding saturated soil matrix, the radius of curvature will equal the radius of the gas void. A further decrease in the pressure difference $u_g - u_w$ leads to a flooding of the void with pore water.

The stress distribution in a gassy, fine-grained soil is comparable to a metal sheet containing a hole. The local stress state in the vicinity of the bubble is increased compared to the global stress state. There are localized effects of pore pressure build up and consolidation, as well as deformations and corresponding stress changes around the gas voids. Consequently, the pore pressure and stress distribution in the soil are potentially highly non-uniform on a small scale.

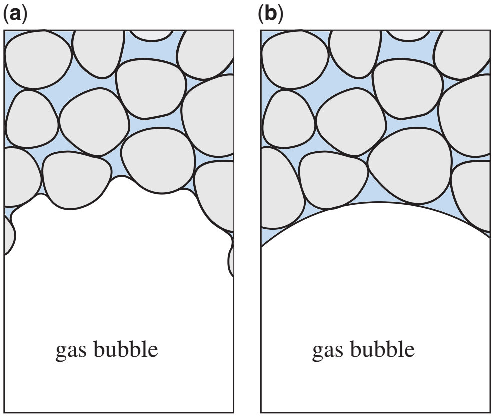

Fig. 2. Maximum and minimum expansion of a large gas bubble in a fine-grained saturated soil matrix (Wheeler 1988*a*): (**a**) maximum expansion ($u_g > u_w$); (**b**) minimum expansion ($u_g < u_w$).

As a consequence, Terzaghi (1943)'s approach of effective stresses ($\sigma' = \sigma - u$) is not applicable to cohesive, gassy soil in its entirety, but only for the water-saturated soil matrix excluding the gas voids. Providing a mathematical description for the stress state of the solid and the liquid phase, Wheeler (1986) introduced the parameter of operative stress σ'' ($\sigma'' = \sigma - u_w$). Local non-uniformities in the stress distribution around the gas voids are neglected in this approach as the current state of research does not allow a more sophisticated description. The quantification of the gas-induced stress changes is one of the major research objectives in the field of gassy soils.

To account for the significant changes in the soil's characteristics more accurately, the parameters of the void ratio of the saturated soil matrix, e_m, and the volume fraction of bubbles, f, are also introduced (see equations 1 and 2, respectively) as the conventional parameters of void space, e, and degree of saturation, S_r, do not provide an unobjectionable description for gassy soil anymore either (Wheeler 1986):

$$e_m = S_r \times e \tag{1}$$

$$f = \frac{(1 - S_r) \times e}{1 + e} \tag{2}$$

The void ratio of the saturated soil matrix describes solely the water-filled pore space, while the volume fraction of bubbles defines the gas-filled voids.

Coarse-grained soils

Sandy soils with grain fractions of diameters larger than 0.063 mm are considered coarse. In consequence of the comparably large grain size, the magnitude of the void space is correspondingly high. Therefore, in coarse-grained soils gas bubbles can be accommodated in the void space without structural changes in the grain matrix. Consequently, the existence of a gas phase in sands mostly changes the compressibility of the pore fluid (Sills and Wheeler 1992; Grozic *et al.* 1999). A characteristic coarse-grained, gassy soil is shown in Figure 1b. Because no structural changes in the grain matrix are required to host a gas phase in a sandy soil, the formation of gas bubbles requires less energy in coarse soil (Mabrouk and Rowe 2011).

When the pore fluids reach equilibrium, the pressure inside a gas bubble can be assumed equal to the pressure in the surrounding pore water ($u_g = u_w$). Hence, the effective stress approach ($\sigma' = \sigma - u$) is valid for gassy sands (Fredlund and Rahardjo 1993). This has also been experimentally verified by Finno *et al.* (2017).

Direct effect of gas on the geomechanical properties

The gas entrapped in a soil is a compressible medium. Consequently, considerable changes in the engineering properties of the gas–soil continuum can be expected. In fine-grained soils the gas alters the soil structure. Therefore, the soil supposedly does not behave like a saturated soil with a supplementary compressible pore fluid, but rather shows distinct properties. The precise expression of the alterations depends strongly on the type of gas, and on the influencing parameters solubility, temperature and stress state. Additionally, the drainage conditions are a relevant factor: drained conditions are characterized by the dissipation of excess pore pressures due to the drainage of the pore fluid from the pore space while under undrained conditions excess pore pressures build up as the pore fluid cannot escape the pore space. Whether drained or undrained conditions prevail depends on, amongst others, the load velocity and the soil permeability.

Compressibility and expansivity

The compressibility of fine-grained soils, irrespective of their degree of saturation, is characterized by their time-dependent consolidation behaviour. Under gravitational loading a low gas content prevents complete consolidation. When reaching critical gas pressures, higher gas contents can lead to fracturing of the saturated soil matrix. The fractures form a path for easy gas and pore water escape and consequently enhance the consolidation process. The impact of gas on self-weight consolidation can hence be estimated through the critical pressure for sediment fracturing. Before the onset of fracturing, a gassy soil under self-weight is prone to underconsolidation, while the formation of fractures decreases the time span until normal consolidation is reached (Sills and Gonzalez 2001). The consolidation behaviour under compressive loading is described by the double compressibility model, which was developed by Thomas (1987) based on a series of experiments. Under loading, gassy soil undergoes deformation due to the applied total stress and due to the consolidation stress. Both induced deformations happen independently.

Under undrained conditions the soil matrix will not change its volume, in contrast to the gas voids. In order to take on the volume change of the gas voids the soil matrix deforms at constant volume. The amount of stress, which is transferred to the gas void during the deformation process, is influenced by the shearing resistance of the saturated soil matrix (Thomas 1987).

Under drained conditions a saturated soil changes its volume. This change of void ratio depends on the effective stress. In a gassy soil, the void ratio of the saturated soil matrix depends on the operative stress. For isotropic loading (a soil cube under uniform loading from all coordinate directions) or earth pressure at rest (under the natural earth pressure from the surrounding soil) it can be assumed that the relationships for saturated soils and the saturated soil matrix of gassy soils are equal, that is the saturated soil matrix behaves identical to a saturated soil. The volume change behaviour of the gas voids, however, relates to the total stress state (Thomas 1987).

Consequently, the double compressibility of a gassy soil can be summarized by introducing two modes of deformation.

(1) Changes in total stress induces compression and dissolution of gas, and a deformation of the soil matrix around the voids due to local shearing. This is generally encountered during the initial undrained state after load application. Under unloading conditions, that is a decrease in total stress, the gas volume expands and a corresponding change in the stress state around the gas cavities takes place. Between the removal of load and changes in the gas regime a time difference in the range of minutes to hours occurs in fine-grained soils. The reasons for the temporal offset are not understood, yet (Thomas 1987).

(2) Changes in the operative stress cause an overall drainage and a subsequent compression of the saturated soil matrix (Thomas 1987). The independent development of the volume fraction of gas bubbles f (deformation mode 1) and of the matrix void ratio e_m (deformation mode 2) under compressive loading over time is shown in Figure 3. Under fully saturated

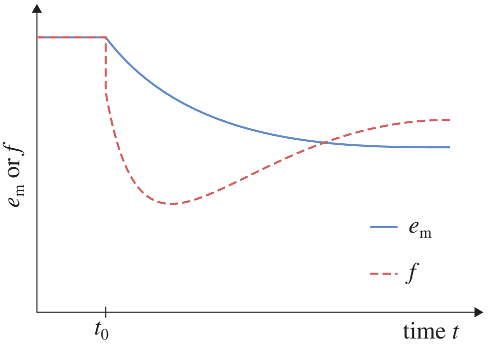

Fig. 3. The development of the volume fraction of bubbles f and the void ratio of the saturated soil matrix e_m over time following load application (Wheeler 1986; Thomas 1987).

conditions the development of the stress state during the consolidation process can be calculated based on the approach by Terzaghi (1943). The quantification of the gas impact is, however, difficult based on existing knowledge. Concerning the compressive behaviour of coarse-grained soils, no definite proposition on the geomechanical properties can be made due to a lack of research efforts on the topic.

Liquefaction potential

The unloading of coarse-grained soils with a gas-saturated pore fluid leads to gas exsolution which starts as soon as the total stress reaches the solubility limit. The exsolution process keeps the pore pressures of both fluids on a constant level while the total stress is further reduced. This leads to a significant reduction in effective stress. The pore pressure only starts to decrease when the effective stress becomes very small, that is when the compressibility of the grain skeleton equals that of the pore fluid mixture (Sobkowicz and Morgenstern 1984; Amaratunga and Grozic 2009). This process is depicted in Figure 4.

Once the effective stress, and thus the grain-to-grain contact forces approach zero the soil matrix liquefies. Because of the decreasing permeability and the accompanying drainage restriction, the pore pressure build-up and liquefaction potential rise in loose fine sands (Amaratunga and Grozic 2009).

Shear strength

For fine-grained, gassy soils a variety of triaxial test series with different boundary conditions have been conducted and published in the past. The most detailed works on the undrained shear strength of gassy, fine-grained soils were published by Nageswaran (1983), Wheeler (1986, 1988*a*, *b*) and Sultan *et al.* (2012), and can be summarized in a detailed conceptual model.

Shear loading induces a deformation of the soil. According to Wheeler (1988*a*) the deformation of the saturated soil matrix is directly coupled to changes in the gas void pressure. This has a major impact on the general shearing behaviour of a soil, as the soil experiences shrinkage or growth of the cavities, bubble flooding and plastic yielding of the surrounding saturated soil matrix caused by stress concentrations around the voids. These processes have a major impact on the shearing behaviour of the soil (Wheeler 1988*a*, *b*). It is important, therefore, to consider these processes when assessing the detrimental or beneficial effect of gas on the shear strength.

Shrinkage of the gas cavities leads to an overall decrease of the volume fraction of bubbles, f. Consequently, the required stress to cause further deformation increases, resulting in a strain-hardening behaviour of the soil. According to Boyle's gas law the gas pressure rises proportionally to a decrease in volume. Hence, a potential movement of gas into solution due to an increase in gas pressure by a decrease in gas volume during the process of cavity shrinkage reduces the bubble stiffness and thereby leads to a reduction in the strain-hardening effect. Vice versa, cavity growth increases f, decreases the required stress for further deformation, and results in a strain-softening response, which could be reduced by an increase in bubble stiffness by gas exsolution processes (Wheeler 1988*a*, *b*).

The pore water pressure in the saturated soil matrix increases significantly during undrained shearing, while the gas pressure within the cavities is expected to stay constant, being solely dependent on the total stress. The pressure difference ($u_g - u_w$) is hence likely to decrease to negative values and might thereby reach a range of values critical for bubble flooding. The widespread flooding of gas

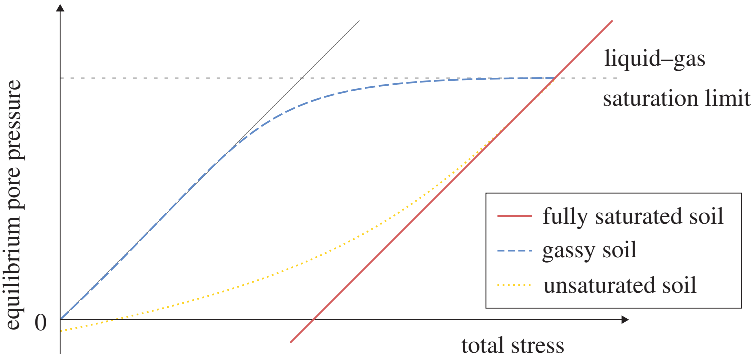

Fig. 4. Equilibrium pore pressure of the pore fluids during undrained isotropic unloading in dependence of the total stress state based on Sobkowicz and Morgenstern (1984).

bubbles strengthens the surrounding soil matrix by decreasing e_m, thereby, altering the shear strength beneficially. When the stage of complete bubble flooding is reached, the examined soil is fully saturated but contains water-filled cavities. As long as gas fills the voids, the cavity roofs are supported by the tension forces of the menisci. In a fully saturated state, the support is lost. Hence, cavity collapse and a resulting detrimental impact on the shear strength is likely (Wheeler 1988*a*, *b*). This process can, for example, be observed in the test results of Sultan *et al.* (2012) where the gas-caused damage in the soil structure results in a detrimental development of the sample's shearing resistance. Mostly, an increase in the amount of gas within the sample intensifies the detrimental impact of the gas (Grozic *et al.* 2005; Sultan *et al.* 2012). The influence of the bubble size on the shear strength has not been investigated, yet.

During triaxial testing of a coarse-grained gassy soil the gas leads to a soil response between the drained and the undrained response of the same soil in a fully saturated state. With regard to the shear strength this is either beneficial or detrimental, depending on the mechanical behaviour of the sand in question (e.g. dilative or contractive response, respectively). When all the gas is resoluted during the shearing process, a fully saturated soil behaviour can be expected (Rad *et al.* 1994; Grozic *et al.* 1999; Fourie *et al.* 2001; Vega-Posada *et al.* 2014).

Concluding, it can be said that from the current state of knowledge an unambiguous statement regarding the influence on the shear strength cannot be made – especially for fine-grained soils. Several processes with a significant influence on the shearing behaviour could be identified. However, the relevant small-scale processes are difficult to observe and hence challenging to describe mathematically. Also, the actual soil response depends strongly on the prevailing boundary conditions of the test series and the amount of studies is not sufficient in order to establish reliable empirical correlations. It has thus not been possible to quantify the impact of gas on a soil's shearing behaviour, yet. Hence, a conclusive and reliable relation between gas content and bearing capacity cannot be formulated based on the current state of knowledge. An overview on the qualitative shearing response of gassy soil is given in Figure 5.

Indirect effect of gas on the soil structure

Especially in fine-grained soil the expansion and potential migration of gas bubbles leads to damage in the soil structure, which changes the mechanical behaviour of the soil. Both mechanisms change the stress state in the immediate environment of the gas bubble (Wheeler 1986; Sultan *et al.* 2012). Because of the size of the pore space, coarse-grained soils are not affected by these processes (Grozic *et al.* 1999).

Bubble growth

The magnitude of bubble growth is strongly dependent on the availability and the production rate of the gas, and therefore relates to the individual boundary conditions. The growth of a gas bubble will affect the surrounding soil, because the increasing bubble displaces pore water and/or applies forces to the grain matrix. As explained above, the characteristics of the formed gas cavities in a fine-grained soil strongly depend on the applied total stress. The approach developed by Wheeler (1990) assumes a homogeneous soil matrix and spherical gas bubbles. Thereby, a symmetrical stress distribution around the gas cavity may be anticipated. When the gas pressure increases compared to the total stress – for example due to ongoing bacterial degradation of organic material – the cavity expands. Until the hypothetical yield criterion of twice the undrained shear strength ($2c_\mathrm{u}$) is reached, linear elastic soil behaviour is assumed. The resultant bubble growth is expected to induce plastic yielding in the saturated soil matrix adjoining the gas void. When yielded, Wheeler (1990) suggests a perfectly plastic soil matrix behaviour, that is all deformations are irreversible and an increase or decrease in soil stiffness during yielding is neglected. The yielded zones spread out from the bubble in a spherical manner. A potential plastic collapse mechanism is formed once the yielded zones around several cavities connect.

The onset of yielding is defined by the constitutive description of the saturated soil and the applied yield criterion. Moreover, a certain difference in gas pressure and mean total stress in the soil matrix limits the process of cavity expansion and contraction, because the processes of bubble flooding and gas encroachment to the soil matrix have to be considered as well (see Fig. 2). While higher shear strengths and lower volume fractions of bubbles favour gas encroachment and bubble flooding, in soils with lower shear strength the gas cavities are more prone to expansion and contraction.

Bubble migration

The movement of gas in a soil matrix can occur as discrete bubbles through the soil matrix or along, for example, gas-induced fractures. Apart from these gas-induced fracture structures, existing geological features, such as faults or erosional surfaces, can represent a possible low-resistance migration path for free gas (Judd and Hovland 2009; Lafuerza *et al.* 2012).

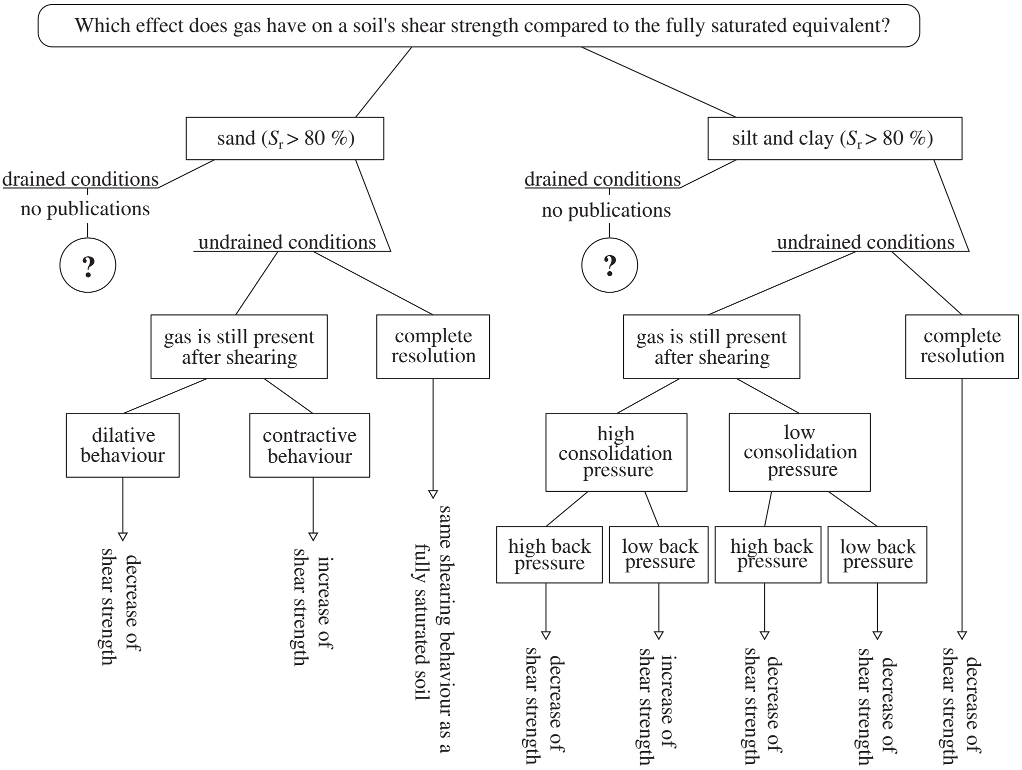

Fig. 5. The impact of gas on a soil's shear strength based on investigations concerning coarse-grained soils (Sobkowicz and Morgenstern 1984; Sills and Wheeler 1992; Rad *et al.* 1994; Grozic *et al.* 1999, 2000; Fourie *et al.* 2001; Grozic 2013; Amaratunga and Grozic 2009; Rebata-Landa and Santamarina 2012; Vega-Posada *et al.* 2014; Wang *et al.* 2018) and fine-grained soils (Nageswaran 1983; Wheeler 1986, 1988*a*, *b*; Sills *et al.* 1991; Sills and Wheeler 1992; Sills and Gonzalez 2001; Sultan *et al.* 2012; Hong *et al.* 2018).

In coarse-grained soil layers the migration of discrete bubbles through the comparably large pore space happens either by advective transport with the groundwater flow or is buoyancy driven (Judd and Hovland 2009). The description of the ascent of a discrete bubble in a fine-grained soil matrix is not so trivial due to several processes which influence the controlling boundary conditions. These include the change of the thermodynamic conditions along the path of ascent, the change of the bubble velocity in a vertical direction according to the change in bubble radius, processes of gas expansion and gas dissolution, and possibly the formation of hydrate when the conditions are suitable (Li and Huang 2016). However, these processes become irrelevant when the nature of the soil matrix inhibits the bubble migration. Movement of bubbles that are larger than the particles making up the soil matrix is only possible if the driving buoyancy force is higher than the soil's shearing resistance. For the calculation of the counteracting resisting force no analytical solution exists. Wheeler (1990) suggests two estimating approaches to analyse this scenario. Firstly, an equilibrium of forces consisting of the buoyancy of the bubble and the resistance of the soil is proposed. Secondly, based on the assumption of continuous cavity expansion in the upper part of the bubble and a corresponding continuous cavity contraction in the lower part of the bubble, another approach to define the resistance of the soil to gas migration was developed (Wheeler *et al.* 1990). A similar approach was published by van Kesteren and van Kessel (2002).

From the three introduced approaches the critical bubble radius for bubble ascent $r_{\mathrm{b,crit}}$ through a saturated, fine-grained soil matrix can be derived. For a generic soil with a unit weight of saturated soil matrix of $\gamma_{\mathrm{m}} = 20\ \mathrm{kN\ m^{-3}}$, the critical bubble radius depends on the undrained shear strength of the saturated soil matrix $c_{\mathrm{u,m}}$ (see Fig. 6). Hereby, the unit weight of the gas is assumed $\gamma_{\mathrm{g}} = 0\ \mathrm{kN\ m^{-3}}$. The depth scale is based on a typical development of $c_{\mathrm{u,m}}$ with depth for a normally or slightly overconsolidated soil of $1\ \mathrm{kN\ m^{-1}}$ below the seafloor

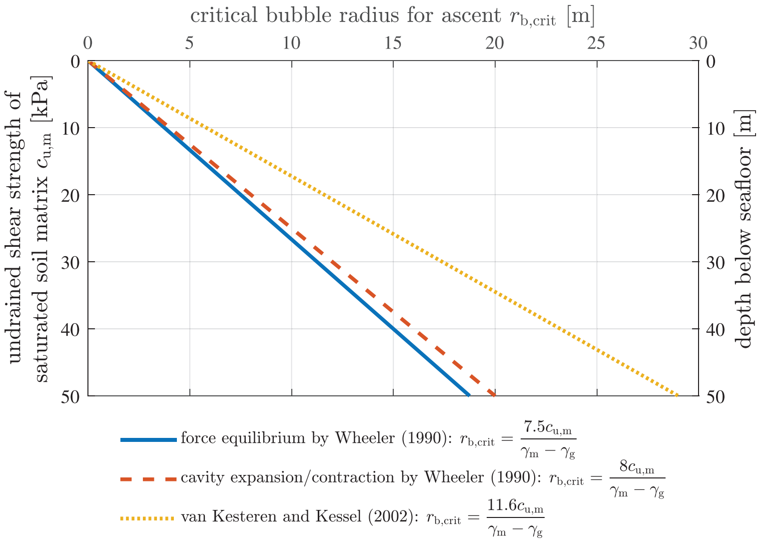

Fig. 6. Critical bubble radius for ascension $r_{\mathrm{b,crit}}$ in a saturated soil depending on the undrained shear strength $c_{\mathrm{u,m}}$ of the saturated soil matrix.

(Randolph and Gourvenec 2011), and merely serves as a reference.

It is obvious that bubble migration through the saturated soil matrix is only a realistic scenario for very low shear strengths. In some marine sediments these might occur in very shallow sediment layers close to the seafloor due to high water content (Baudet and Ho 2004; Madhusudhan *et al.* 2017). However, especially in sediments with high organic carbon content the formation of crusts with increased shear strengths due to interparticle bonding and cementing effects in the upper layers was observed (Busch and Keller 1982; Dean 2010). Shallow gas bubble migration in corresponding regions hence becomes less likely. Furthermore, due to the depth dependency of $c_{\mathrm{u,m}}$ the resistance to bubble ascent increases with increasing depth below the seafloor. In the depth ranges where slide planes of submarine landslides are located (50–250 m below seafloor) bubble migration can therefore be ruled out. As buoyancy – the main driving force for bubble migration – is directed upwards, horizontal gas migration is even less likely. Because fine-grained soils are poor hosts for gas migration processes they often act as a natural barrier. Movement of the gas phase is thus restricted to layers with coarser grain sizes or to faults and fractures.

As the migration of discrete bubbles through the saturated sediment matrix was ruled out as a potential transport mechanism for free gas in marine soils, sediment fracturing induced by high gas pressure and a subsequent movement of gas through the fracture become more likely. As fractures provide low-resistance drainage paths for both pore fluids, gas and water, fracturing potentially describes a mechanism which strengthens rather than weakens the soil, as a dissipation of excess pore pressure becomes possible (Sills and Gonzalez 2001). Under these circumstances fracturing is a spatially restricted, beneficial feature in a gassy soil (see Fig. 7). Unfortunately, preferential conditions for the onset of fracturing could not be quantified so far. Many authors have hypothesized about the possibility of gas-induced fracturing of the soil matrix: the approaches include the application of a yield criterion and soil failure in the vicinity of the gas cavities, linear elastic fracture mechanics, or local liquefaction due to excess pore pressure build up. Additionally, techniques such as computed tomography scanning, X-ray density measurements and mercury intrusion porosimetry were applied in several test series on different soils and conditions (Wheeler 1990; Sills and Gonzalez 2001; van Kesteren and van Kessel 2002; Elger *et al.* 2018; Johnson *et al.* 2018). However, the development of a satisfying mathematical approach, which can be verified by experimental testing, is still pending. In the offshore oil industry approaches for hydraulic fracturing have been proven satisfying for engineering applications, which involve the fracturing of rock formations under high fluid pressures. Here, the mathematical approach for the description of the fracture behaviour presupposes a linear elastic material behaviour. The onset of fracturing is defined by the Mohr–Coulomb failure criterion (Valkó and Economides 1995). Whether this approach is a reliable

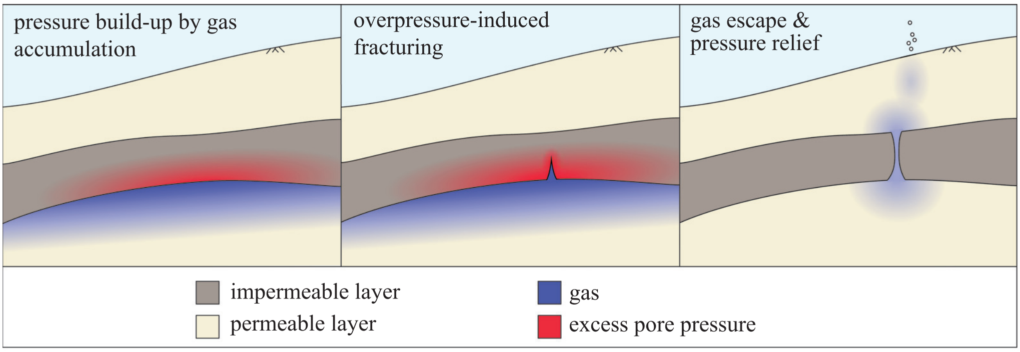

Fig. 7. Schematic process of a large-scale gas-induced fracture in a fine-grained soil layer initiating the dissipation of excess pore pressures by creating a low-resistance drainage path.

description of fracturing induced by a gaseous instead of a liquid fluid has not yet been proven. The development of a reliable mathematical description of gas-induced fracture behaviour of granular materials would contribute significantly to a better understanding of the mechanical behaviour of gassy soils and geological processes such as piping, which describes a vertically directed erosion process. It is therefore highly relevant for further research efforts in this field.

Discussion

Through an extensive literature study we analysed the mechanical behaviour of gas-bearing soil with regard to potential causes of slope instabilities at continental margins. Even though the characteristics of the *in-situ* shear stress during a slope failure event are most similar to shear in a direct simple shear test, the effect of gas on the shear strength has so far mostly been investigated in triaxial tests. Hence, the conclusions drawn from the published triaxial tests are applied in the evaluation of slope stability. A gassy soil's mechanical behaviour is influenced by many factors, and small changes in the boundary conditions may possibly lead to a fundamentally different soil response: detrimental to the shearing resistance, no change compared to the fully saturated equivalent, or beneficial to the shearing resistance. The establishment of a coherent relationship represents the current objective of research in the field of gassy soils. Based on the current state of knowledge, Figure 5 summarizes the effects of different influencing factors on the shear strength of a soil. The impact of gas on the shear strength is unfavourable for most boundary conditions. Because the favourable boundary conditions are not identical to those that are expected at the seafloor, we conclude that occluded gas in the soil matrix has a predominantly negative impact on the shearing resistance of marine soils. Because of the small slope angles, at which most failures occur, the driving forces of the slope are far lower than the frictional forces in the potential glide plane. Consequently, to overcome the resisting forces a vast shear strength decrease is required to induce slope failure. As a shear strength decrease in a realistic range cannot overcome the resisting forces a much more far-reaching change in the soil structure must take place to produce slope failure. Hence, a reduction of the shear strength is not a realistic trigger mechanism. A shear strength reduction due to occluded gas bubbles can therefore rather be classified as a preconditioning factor than as a trigger mechanism.

A significant decrease in effective stresses can lead to liquefaction failure of the soil. Coarse-grained soils show an unambiguous reduction of effective stresses when gas exsolutes and expands in the pore fluid, as shown in Figure 4. The exsolution process is controlled by the total stress. Potential geological processes that lead to a reduction in total stress are, for instance, changes in sea-level, slope failures, or other erosive processes. Gas-induced liquefaction failure of a slope in an area of shallow water depths under tidal influence, and hence under total stress variation, has been identified as a viable trigger mechanism by Clare *et al.* (2016). The destructive potential of liquefaction failure is therefore not to be overlooked. Under naturally occurring conditions, it is also likely that an ongoing gas production, due to biological activity, upward migration of thermogenically formed gases, or hydrate dissociation, triggers gas exsolution and expansion. This scenario, however, has not been investigated yet. Nevertheless, increasing pore pressures induced by gas under constant total stress conditions resulting in an effective stress decrease represents a logical assumption. Restricting the validity to coarse-grained soil, we can thus confirm the hypothesis of gas-induced excess pore pressures and subsequent liquefaction.

The processes in fine-grained soils are more complex and are not only influenced by the stress state but also by other factors, such as shear strength of the saturated soil and the degree of saturation. It seems that increasing gas pressures do not lead to decreasing effective stresses in fine-grained soil. The extent to which increasing gas pressures have a negative impact on the soil structure cannot be conclusively clarified based on the current state of research.

It is difficult to determine if an increase in gas pressures and its consequences can trigger submarine slope failures. Extensive liquefaction of soil surely provides a viable trigger mechanism. It is, however, questionable whether the occurring gas pressures reach sufficiently high magnitudes on a larger scale in order to trigger a liquefaction failure event. Rapid unloading due to slides triggered in a different way and a subsequent liquefaction proposes a realistic scenario for the retrogressive advance of a slide complex, but not for the trigger itself.

Based on the equivocal results of the evaluation, it must be questioned whether processes on a small-scale soil mechanical level are generally capable of triggering submarine slope failures. Therefore, we propose that large-scale processes, for example uplift of large sediment packages or piping mechanisms, are more likely trigger mechanisms. Nevertheless, a further investigation of the problem would be useful in order to reliably exclude gassy soil as a triggering mechanism. To conclusively clarify the question at hand for complex stratigraphic sequences and the involved feedback processes, an evaluation with the help of numerical models is indispensable. In this regard, the development of appropriate constitutive models is a prerequisite.

Conclusion

Based on the literature research carried out, the following findings concerning the general mechanical behaviour of gassy soils can be derived:

- Terzaghi (1943)'s principle of effective stresses is applicable for coarse-grained gassy soils but not for fine-grained gassy soils in their entirety;
- increasing gas pressures lead to a decrease in effective stresses and thus potentially to liquefaction failure in coarse-grained soils. In fine-grained soils increasing gas pressures do not result in an effective stress reduction.

With respect to the generation of slope failures the following findings are of importance:

- small changes in the boundary conditions potentially lead to a fundamentally different response of gassy soil ranging from detrimental, to no effect, to beneficial to the shearing resistance;
- for the common stress conditions at continental margins the impact of gas on the shear strength is mostly unfavourable but not strong enough to present a viable trigger mechanism for slope failures. Processes on a small-scale soil mechanical level do not show a lot of potential to work as a large-scale trigger mechanism;
- the migration of discrete gas bubbles through an intact fine-grained saturated soil matrix is not possible. Hence, fines act as gas barriers and migration is spatially restricted to sandy soil layers, faults and fractures.

A more detailed understanding of the gas-influenced soil mechanical behaviour is indispensable to develop constitutive models for gassy soils on the basis of which numerical stability analyses can be performed.

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