The effect of morphology on the overall physical properties of hydrate-bearing sediments
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Introduction
With the world’s energy demand increasing daily in the midst of climate change concerns, alternative cleaner energy sources are required. Methane gas hydrates are an untapped resource of natural gas. Due to their wide geographical distribution and the estimated staggering magnitude of this resource, methane gas hydrates have stimulated significant international interest due to their potential as a future energy resource, but furthermore as a geotechnical hazard for offshore operations related to hydrocarbon recovery.

Methane gas hydrates are ice-like crystalline solids composed of water and natural methane gas that can only exist under specific thermobaric conditions of low temperature and high pressure restrictions. Due to these conditions, gas hydrates naturally occur in submarine sediments or in on-shore sediments in permafrost regions (Kvenvolden, 1993).

The occurrence of gas hydrate within sediments significantly alters the physical properties of the host sediments. If the pressure-temperature conditions are changed, for instance by climate change, hydrates are destabilised, dissociating into water and methane gas. This would cause seafloor instabilities and foundation failures of offshore works.

To contain this potential geotechnical hazard as well as to tap into this energy resource, the ability to detect and quantify the presence and concentration of gas hydrate in submarine sediments and understand the effect it has on host sediments has become increasingly important.

Due to the metastable nature of gas hydrate, the identification of their insitu presence via the recovery of actual samples has been problematic. Hence the detection and quantification of gas hydrate has been inferred via exploratory seismic surveys, which measure indirectly the bulk dynamic properties of sizeable volumes of sediment insitu. Seismic data are then interpreted using an effective medium model, which employs theoretical assumptions to relate wave velocities to gas hydrate content of the sediment. Wave velocity can then be used to infer hydrate concentration levels.

Methane gas hydrates occur in a variety of sediments ranging from fine-grained clays to coarse-grained sands, each hosting a variety of morphologies, which occur as two basic types: pore-filling and grain-displacing. Pore-filling gas hydrate replaces pore fluid between the sediment grains possibly cementing grains; whereas grain displacing hydrate doesn’t occupy sediment pore volume but instead forces grains apart, forming layers, veins and nodules of pure hydrate.

Grain-displacing morphologies consist of finely disseminated hydrate, nodules, layers, veins and massive hydrate, as shown in Figure 1. The different morphologies will affect the physical properties of the host sediments in different ways and an understanding of this effect, particularly for specific gas hydrate morphologies, is important.

For this work, simple grain-displacing morphologies are considered consisting of nodules and veins.

Hydrate morphologies
Hydrates occur insitu in sediments ranging from fine-grained clays to coarse-grained sands. The lithology of the host sediment influences the growth of gas hydrate and subsequently different gas hydrate morphologies are found within sediment based upon several years of research (Sloan, 1998; Holland et al, 2008).

Holland et al (2008) identified that gas hydrate morphologies occur as two basic types: pore-filling and grain-displacing. Pore-filling gas hydrate replaces pore fluid between the sediment grains possibly cementing grains; whereas grain displacing hydrate doesn’t occupy sediment pore volume but instead forces grains apart, forming layers, veins and nodules of pure hydrate.

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Computational homogenisation
The numerical modelling approach is a multi-scale technique that employs the ideas behind first-order computational homogenisation methods based on work by Smit (1998), van der Sius (2001) and Gitman (2006). Multi-scale approaches consider the material on different scales or levels of

The existing models are predominantly limited to pore-filling hydrate morphologies and there is a lack of modelling techniques that consider grain-displacing morphologies. Thus the effect of hydrate morphology on submarine sediments is poorly understood.

This justifies the need for the development of a new modelling approach that can conceptualise and model more complex morphologies such as grain-displacing morphologies by taking geometry explicitly into account, thus complementing the existing models in the field by providing a means to investigate a larger range of hydrate morphologies.

An alternative modelling approach for gas hydrate-bearing sediments based on first-order computational homogenisation is formulated for specific grain-displacing morphologies. This approach is novel as it applies geotechnical engineering principles along with modelling techniques from the material science field, which have not been implemented in the hydrate-research industry to date.

The aim is to investigate the effect of morphology and hydrate content on the overall stiffness and seismic wave velocity of gas hydrate-bearing sediments.
observation and are based on the fundamental assumption that the material is considered to be homogeneous on the macro-scale and heterogeneous on the micro-scale.

In essence, first-order computational homogenisation consists of determining the constitutive response at a macro-scale point of a heterogeneous material, through the solution of a separate, appropriate boundary value problem formulated at the micro-scale.

The deformation gradient at the macro-scale point is used to “drive” the boundary conditions of the micro-volume, the microstructure of which is modelled explicitly. The resulting stress increment field is averaged over the micro-volume, and it is applied as the stress increment at the corresponding macro-scale point. A graphical illustration of the multi-scale computational homogenisation process is shown in Figure 2.

For the adopted numerical model, the boundary value problem on the micro-scale is formulated by means of a representative volume element (RVE). The RVE is a model of the material that is used to determine the corresponding effective properties of the homogenised macro-scale model and should be large enough to contain sufficient information about the microstructure but much smaller than the macroscopic body (Hashin, 1983). In this context, it is assumed that the wavelength of a propagating seismic wave is greater than the RVE, hence effectively homogenising the material as the seismic wave “sees” in a sense the overall material.

A hydrate morphology is assigned to the RVE and the boundary value problem solved yielding the effective elastic properties for this particular morphology.

The boundary value problem is solved by means of a detailed finite element analysis by applying periodic boundary conditions and a load to the RVE and the resulting average stresses and strains determined from the analysis are used to calculate the elastic moduli of the material. Periodic boundary conditions are used to ensure the continuity of stress and displacement fields across the boundaries of the RVE and are applied to the boundary nodes of the RVE mesh in the form of constraint equations. The application of periodic boundary conditions can be checked simply by the deformed shape of the RVE after the analysis where the sides should deform identically, thus RVEs can in theory be stacked together and fit perfectly. This is shown in the deformed RVE for simple shear in Figure 3.

The validity of the RVE assumption for this modelling procedure was checked by comparing the results to those of a discretised model of randomly stacked RVEs forming a structure, and also to the response predicted for the same structure if the calculated effective medium properties are used. All three results are equal showing that the RVE is a valid representation of the material and that the procedure yields an appropriate set of average properties.

This is further supported by the good agreement between the results to those predicted with closed-form analytical approaches appropriate to the morphology used, such as the Kuster-Toksoz (1974) model, Backus (1962) Upscaling and Pariseau’s (1988) NRVE approach.

Numerical results

For the investigated morphologies, a range of seismic wave velocities are predicted for a specific hydrate content depending on morphology and type of seismic wave. This is shown in Figures 5, 6 and 8 (see overleaf) where overall shear wave velocity ($V_s$), compressional wave velocity ($V_p$) and the ratio of the two velocities ($V_s/V_p$) are plotted as a function of hydrate content. For low hydrate contents less than 30%, the effect of the investigated morphologies on overall shear wave velocity is insignificant. However, as hydrate content increases, this effect becomes more pronounced. This is not the case for compressional wave velocity.

Compressional wave velocities are particularly dependent on directional material properties and the orientation of the wave propagation with respect to vein orientation is important. This is shown in Figure 6 where for the same hydrate content and morphology, different compressional wave velocities occur.

The data curve labelled Parallel 0 refers to parallel vein morphologies with a compressional seismic wave propagating perpendicular to the veins. For low hydrate contents less than 30%, the effect of the investigated morphologies on compressional wave velocity is insignificant. However, as hydrate content increases, this effect becomes more pronounced. This is not the case for compressional wave velocity.
» to the veins and Parallel 90 parallel to the veins. This is shown schematically in Figure 7.

The overall compressional wave velocities corresponding to parallel vein morphologies form bounds within which the compressional wave velocities corresponding to nodular and cross-cutting vein morphologies fall. The investigated morphologies clearly have a more pronounced effect on overall compressional wave velocity than on overall shear wave velocity.

For nodular morphology, the \( V_p/V_s \) ratio is approximately 2. This observed value is the same as that observed in the field for nodular hydrate morphologies (Hardage et al, 2006) and can be predicted with a theoretical relationship which has been used extensively in the field of seismic exploration. This relationship links the \( V_p/V_s \) ratio to the Poisson’s ratio \( v \) of the overall material and is only valid when the material is linear elastic, isotropic and homogeneous:

\[
\frac{V_p}{V_s} = \sqrt{\frac{1 - v}{2 - v}}
\]

However, for vein morphologies, this relationship does not apply due to the overall anisotropic material behaviour and the \( V_p/V_s \) ratio is larger than that observed for nodular morphologies. Therefore, if a larger \( V_p/V_s \) ratio than that expected from the theoretical relationship is observed then it is possible that the underlying morphology has a vein-like structure. The \( V_p/V_s \) ratio is also constrained to a region bounded by the \( V_p/V_s \) ratios corresponding to parallel vein morphologies as observed for overall compressional wave velocities. Therefore if two compressional wave velocities taken at directions of wave propagation of 90° to each other can be measured, the two \( V_p/V_s \) ratios determined from these two velocities can be used to constrain the range of ratios that are expected.

**Comment and conclusions**

The application of a multi-scale modelling approach allowed the geometry of underlying morphology to be explicitly modelled. Thus the effect of particular grain-displacing morphologies such as nodules and veins on the overall stiffness and seismic wave velocity of gas hydrate-bearing sediments could be investigated. Results show that morphology has a significant effect on the overall material properties, with the effect being more pronounced on the overall compressional wave velocity than on the overall shear wave velocity.

Due to this effect, knowledge of the particular underlying hydrate morphology when using seismic wave data to estimate hydrate content would assist in constraining the estimation to an expected range of results. In addition, a lower uncertainty in the prediction is obtained when using shear wave velocity.

The ratio of the two velocities \( V_p/V_s \) differs depending on the type of morphology and can provide insight into the underlying morphology by assisting in the differentiation between nodular and vein morphologies. The investigation enhances our understanding of the effect of gas hydrate on the overall material properties.

**Figure 5:** Overall shear wave velocity computed from simulations of nodular, parallel vein and cross-cutting vein hydrate morphologies as a function of hydrate content (where hydrate content is a percentage of the total area).

**Figure 6:** Overall compressional wave velocity computed from simulations of nodular, parallel vein and cross-cutting vein hydrate morphologies as a function of hydrate content (where hydrate content is a percentage of the total area).

**Figure 7:** Schematic illustration of a parallel vein morphology with a compressional wave propagating (a) perpendicular to the veins (0° to the vertical) and (b) parallel to the veins (90° to the vertical).
properties of host submarine sediments by providing a means to investigate a larger range of hydrate morphologies. This contributes to the knowledge required to detect and quantify submarine gas hydrate-bearing sediments for future energy resource planning and geohazard risk analysis.

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References