Numerical modelling for the detection and quantification of deep-ocean methane hydrates using seismics

Utilisation de modèles numériques pour la détection et quantification d'hydrates de Méthanes de l'océan profond en utilisant des séismiques

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ABSTRACT

Methane gas hydrates have stimulated substantial international interest due to their potential as a future energy resource, but furthermore as a geotechnical hazard for offshore operations related to hydrocarbon recovery. In this context, the ability to quantify and detect the presence and concentration of hydrate in marine sediments and understand the effects it has on these host sediments has become increasingly important. The detection and quantification of gas hydrates and their effect on hydrate-bearing sediments has been inferred via exploratory seismic methods, which measure indirectly the bulk dynamic properties of sizeable volumes of in situ sediment. Traditionally, effective medium models are used to interpret the seismic data by employing theoretical assumptions that relate gas hydrate content within the sediment to wave velocities. Therefore, wave velocity can be used to deduce hydrate concentration levels. The modelling of methane gas hydrate-bearing sediments is relatively new and at present has been based on theories of rock physics and effective medium modelling. A variety of such models exists in the literature. Many effective medium models are not readily transferable to other settings, as they have been calibrated on and tested on specific sites. In addition, many models do not take into account the existence of heterogeneities of the host sediment, or the inhomogeneous distribution or formations of hydrate within the sediment. This paper presents a general review of the existing effective medium models, identifying typical areas for improvement. A new numerical modelling method is presented that can specifically take into account different hydrate morphologies within the host sediment thereby enhancing the existing effective medium models. Preliminary results from the numerical model are presented, portraying the impact of hydrate on the mass seismic properties of the host sediment.

RÉSUMÉ

Les hydrates de gaz de Méthane ont attire énormément d'attention international résultant de leur potentiel de devenir une future forme d'énergie, mais notamment comme un hasard géotechnique des opérations en mer connecte avec le recouvrement d'hydrocarbon. Dans ce contexte, l'habilité de quantifier et de détecter la présence et concentration d'hydrate dans des sédiments marins ainsi que de comprendre les effets qu'il a sur ces sédiments hôtes a grandit considérablement en importance. La détection et quantification des hydrates de gaz et leurs effets sur les sédiments-supports de ces hydrates ont été déduits par des méthodes séismiques exploratoires qui mesurent indirectement la majeure partie des propriétés dynamiques de volumes considérables de sédiments in situ. Traditionnellement, des modèles mediums efficaces sont utilises pour interpréter des données seismiques en employant des hypothèses théoriques qui relient le contenu des hydrates de gaz parmi le sédiment a la vélocité des ondes. Par conséquent, la velocite d'onde peut être utilisée pour déduire les niveaux de concentration d'hydrates. Le modellement de sédiments-hôtes d'hydrates de gaz de Méthane est relativement nouveau et actuellement est base sur des théories de physique de roches et modellement medium efficace. Une variété de tels modèles existe dans la littérature. De nombreux modèles mediums efficaces ne sont pas facilement transférables a d'autres données, parce qu'ils ont été calibres et teste sur de différents sites. Plusieurs modèles ne tiennent pas compte de l'existence des hétérogénéités du sédiment-hôte, ou de la distribution ou formation non-homogène de l'hydrate dans le sédiment. Ce papier présente un compte rendu général des modèles mediums efficaces en existence, identifiant des endroits aillant du potentiel d'amélioration. Une nouvelle méthode de modèle numérique est présente qui prend compte en particulier des différentes morphologies d'hydrates parmi les sédiments-hôtes qui met en valeur les modèles mediums efficaces. Des résultats préliminaires du modèle numérique sont présentes, qui font le portrait de l'impact des hydrates sur les propriétés masse séismiques des sédiments-hôtes.

Keywords : gas hydrates, effective medium modelling, numerical modelling

1 INTRODUCTION

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 deep-ocean sediments or in on-shore sediments in permafrost regions. The occurrence of gas hydrates within sediments significantly alters the physical properties of the host sediments.

As a future energy resource, hydrates have gained significant international interest due to their very high methane content, wide geographical distribution, especially in continental margins, and occurrence at shallow sediment depths within 2,000m of the earth's surface. Hydrate dissociates and loses gas if the thermobaric conditions change. The potentially hazardous consequences of dissociating hydrates on the physical properties of the host sediment, resulting in seafloor instability, have highlighted the immediate concern of gas hydrates as a geotechnical hazard for offshore operations related to hydrocarbon recovery. In this context, the ability to detect and quantify the presence and concentration of hydrate in marine sediments and understand the effect it has on hydrate-bearing sediments has become increasingly important.

Hydrates have been recovered in a variety of sediments ranging from fine-grained clays and silts to coarser-grained

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sediments. The lithology of the host sediment influences the growth of gas hydrate and subsequently different gas hydrate morphologies are found within sediment based upon an overview of several years of research. Gas hydrate morphologies occur as two basic types: pore-filling and grain-displacing (Holland et al. 2008). Pore-filling gas hydrate replaces pore fluid between sediment grains possibly cementing grains; whereas grain-displacing hydrate doesn't occupy sediment pore volume but instead forces grains apart forming layers, veins or nodules of pure hydrate. Grain-displacing morphologies occur over a wide range of sizes, from thin micron-thick veins to massive sheets of hydrate possibly metres in width (Holland et al. 2008). The morphology of gas hydrate has large effects on sedimentary geotechnical and physical properties and will therefore impact the hydrate saturation estimations from seismic in-situ data.

Detection and quantification of gas hydrates and their effect on hydrate-bearing sediments has been inferred via exploratory seismic methods, which measure indirectly the bulk dynamic properties of large volumes of in-situ sediments. In order to quantify gas hydrate concentration using seismic techniques or to determine the physical properties of gas hydrate-bearing sediments, a predictive model is required that relates the amount of gas hydrate within a sedimentary sequence to the seismic velocities. At present for the interpretation of seismic data, effective medium models have been used by employing theoretical assumptions to relate wave velocities to the gas hydrate content within the sediment. Wave velocity can then be used to determine hydrate concentrations within marine sediments. However, various limitations are associated with the applied theoretical assumptions in the models. A brief review of some of the existing gas hydrate effective medium models is presented, focusing on typical areas for improvement. The aim of the research, which is work in progress, is to develop a new numerical modelling method that enhances existing effective medium approaches, by taking explicitly into account different hydrate morphologies within the host sediment. Preliminary results from a set of morphologies are presented.

2 EFFECTIVE MEDIUM MODELLING

2.1 *Overview*

An effective medium is defined as a theoretical medium that has the same overall bulk physical properties (seismic velocity and elastic moduli) as a physical medium which is composed of more than one constituent, each with its own different physical properties. An effective medium model relates the overall physical properties of a medium to the properties of the individual constituents making up the medium. However, the models are not expected to incorporate a detailed description of the microstructure. Such models include empirical and/or physical methods and reproduce many of the characteristics observed for sedimentary rocks. A variety of models have been developed and apply different assumptions to determine either theoretically defined upper and lower bounds or attempt to reach an exact solution.

2.2 *Gas hydrate effective medium models*

The presence of gas hydrates is often associated with higher seismic velocities than those observed for marine sediments. If the wave velocity and gas hydrate concentration relationship for hydrate-bearing sediment is known, the concentration of hydrate can be determined from anomalies in seismic data such as the latter mentioned higher velocities. This concentration/hydrate relationship has been predicted by a range of theoretical approaches, all of which are essentially effective medium models. However, due to the problems associated with in-situ sampling and the lack thereof of calibration data, it is unclear which of the published available methods to apply for the interpretation of seismic velocities for gas hydrate content (Chand et al. 2004).

A general review of the most widely used existing effective medium models for gas hydrate-bearing sediments was conducted by Chand et al. (2004) and the results together with those from an extensive literature review were used to identify areas for improvement. The models differ in the assumptions applied with respect to, for example, the representation of the hydrate-bearing sediment on the particle scale, the exact location of hydrate within the medium and the underlying theories that are applied. Existing gas hydrate effective medium models range from the empirical weighted equation by Lee et al. (2001), three-phase effective medium theory based on rock physics contact models (Helgerud et al. 1999 and Ecker et al. 2000), three-phase Biot theory (Carcione & Tinivella 2000 and Gei & Carcione 2003) and approaches using combinations of self-consistent approximation and differential effective-medium theory (Jakobsen et al. 2000 and Chand et al. 2006).

The empirical weighted equation is site-specific as the equation is fitted to a certain data set. It is limited in its physical meaning, lacks theoretical formulation and is unable to handle anisotropy (Chand et al. 2004). The three-phase effective medium model is based on rock-physics dissemination or cementation models. Hydrate is modeled as either cement at the grain contacts or enveloping the grains; or as part of the pore space or load-bearing matrix. The applied approximation of a random pack of identical spheres for the contact models is unrealistic in representing the heterogeneous nature of the hydrate-bearing sediments. These contact models can not model an anisotropic response. Isotropic assumptions are acceptable for sands; however, they can not always be applied for clay rich sediments (Ellis 2008).

The various effective medium models yield results that differ by orders of magnitude, yet it is unknown which model is the most accurate. This uncertainty is due to the lack of representative samples for calibration with seismic results and comparison with modelling outputs. The equations of the effective medium modelling techniques cannot be expected to incorporate a detailed description of the microstructure limiting their simulation of real in situ behaviour.

The models are calibrated for site-specific conditions and no robust model applicable to all sites with different conditions exists. The different approaches applied to model the gas hydrate location within the pore space and sediment all assume the gas hydrate to be finely and uniformly distributed within the sediment which is not realistic (Holland et al. 2008). The presented models consider hydrate located only on the grain scale and do not consider morphological heterogeneities at a larger scale such as grain-displacing fractures, veins and nodules. Therefore, a new approach to modelling more complex forms of in situ hydrate is required.

3 NUMERICAL MODELLING

3.1 *Approach*

To address the identified limitations we develop a new modelling approach that takes explicitly into account different hydrate morphologies within the host sediments. We take a different approach to that usually followed in constructing effective hydrate-bearing media, and employ the ideas behind first-order computational homogenization methods based on work by Smit (1998), van der Sluis (2001) and Gitman (2006).

First-order computational homogenization is essentially a multi-scale method that is used in material science to model the mechanical response of heterogeneous materials, especially with the method of finite elements. Multi-scale methods 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 homogenization consists of determining the constitutive response at each 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 during the current iteration 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 reported as the stress increment at the corresponding macro-scale point for that iteration. An advantage of the above approach is that the constitutive response of the heterogeneous material need not be defined explicitly but is derived every time through the detailed modelling of its microstructural response. Nevertheless this method can be computationally demanding, as a separate micro-scale boundary value problem must be solved for every macro-scale point at every iteration of the macro-model.

In this work, we retain the idea of deriving the equivalent properties of a heterogeneous material using detailed finite element analyses at the microstructural level 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 homogenized macro-scale model and should be large enough to contain sufficient information about the microstructure but much smaller than the macroscopic body (Hashin 1983). A hydrate morphology is assigned to the RVE and the boundary value problem solved yielding the effective elastic properties for this particular morphology. Different boundary conditions assigned to the RVE will yield different results but a study of recent work suggests that periodic boundary conditions are the most appropriate choice compared with uniform stress or strain conditions (Kaczmarczyk et al. 2007). Therefore, periodic boundary conditions and a load or displacement are applied to the RVE and the resulting average stresses or strains determined from the analysis are used to calculate the effective bulk and shear modulus of the material. 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 were equal showing that the RVE is valid as a representation of the material and that the procedure yields an appropriate set of average properties.

3.2 *Numerical results*

Numerical analyses were conducted using the finite-element software ABAQUS. As a first step, idealized morphologies were created using spheres to represent hydrate inclusions within a sediment matrix. The results predicted for a single sphere within the RVE were compared to those predicted for irregular arrays of spheres of different sizes but corresponding to the same overall hydrate content. The irregular morphologies were created using a random sphere morphology generator for different target hydrate contents, implemented in Matlab. An example of one of these irregular morphologies is shown in Figure 1. The hydrate content is represented by the area occupied by the spheres. However, when comparing data with other effective medium models in the field, cognizance should be taken that these models define hydrate content as the volume of hydrate in the pore space which is also influenced by the porosity of the sediment.

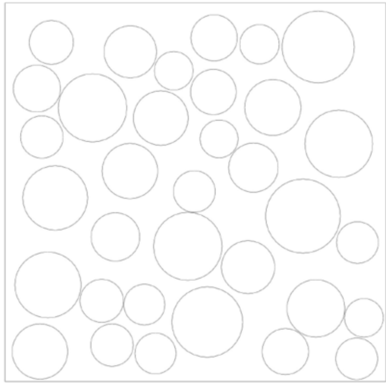

Figure 1. An example of the irregular morphology for 52% hydrate content

The effective material was assumed to be isotropic and elastic with perfect bonding between the two phases. Six-node quadratic plane strain triangles were used in the finite element mesh. The properties of the constituent materials are shown in Table 1 with the sediment properties taken for a depth below the seafloor of approximately 300 to 400m. K represents bulk modulus, G, shear modulus, E, Young’s (elastic) modulus and v, Poisson’s ratio.

Table 1. Constituent material properties

Material	K (MPa)	G (MPa)	E (MPa)	v
Sediment	490	188	500	0.33
Pure methane hydrate	7195	3000	7900	0.317

Figure 2 and 3 show the numerical results obtained for the single sphere and irregular sphere morphologies compared with the Reuss and Voigt theoretical bounds for two phase materials. Figure 2 represents the normalized bulk modulus and Figure 3 the normalized shear modulus plotted against the area of hydrate content within the RVE. The Reuss and Voigt bounds are the simplest defined bounds representing constant stress and constant strain and there is no way that nature can produce a mixture of constituents that is more elastically soft or stiff than these bounds. The numerical results are consistent with these bounds as the data falls within them. However, the results fall close to the Reuss bound at very low hydrate contents and gradually move away from it as the hydrate content increases.

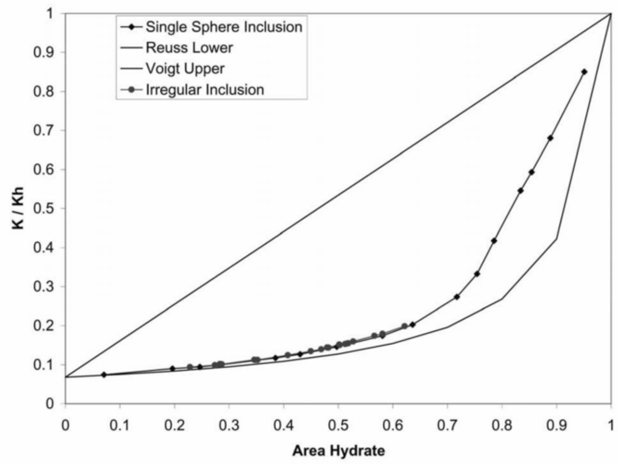

Figure 2. Normalized bulk modulus versus hydrate content within the sediment

The single sphere line in both figures has a kink which is more pronounced for the shear modulus at approximately 0.79 area of hydrate, representing the point where the sphere touches the edge of the RVE and hence the hydrate forms a load-bearing skeleton. The effective moduli for the irregular morphologies are larger in value than those for the single spheres. This observation is consistent with results from Bystrom's (2003) comparison of random and periodic distributions when the inclusions have a higher modulus than the matrix phase. Ellis (2008) stated that the effect of gas hydrate saturation is far more pronounced on the shear modulus than the bulk modulus.

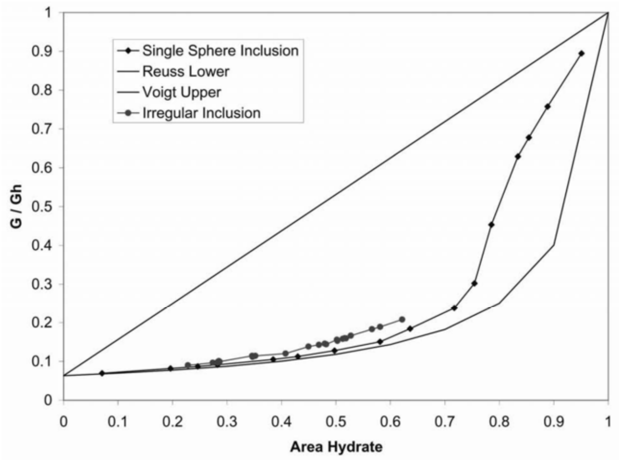

Figure 3. Normalized shear modulus versus hydrate content within the sediment

This trend is observed in Figures 2 and 3 where the bulk modulus of the irregular morphologies seems to follow that for single sphere morphologies, whereas the shear modulus for irregular morphologies is higher than that for a single sphere. Therefore the morphology of the hydrate within the sediment seems to only have an effect on the shear modulus whereas for the bulk modulus the hydrate content appears here to be the only influencing factor. The statistical equivalence of the irregular morphologies such as the average radii and number of spheres will be considered in future work to determine their influence on the elastic effective properties.

These results represent sphere morphologies which are idealized shapes for nodules of gas hydrate occurring within a sediment matrix. These models are being extended to represent veins and layers of hydrate. This type of morphology creates preferential directions in the material and anisotropy will eventually have to be considered. Therefore, factors such as vein thickness, orientation and spacing are expected to affect the effective elastic properties, and will systematically be explored using the modelling approach presented.

4 CONCLUSIONS

A new numerical modelling technique is presented that enhances existing effective medium models by taking explicitly into account different hydrate morphologies. Results for irregular configurations of spheres and single sphere distributions are compared with the Reuss and Voigt bounds. The models are being extended for hydrate morphologies containing veins or layers. Ultimately, based on the numerical results, we aim to produce an "empirical" analytical description of the constitutive response which, although not a mathematically rigorous equivalent, will be sufficiently accurate for practical purposes. The analytical description will aim to give the constitutive response in terms of measurable physical parameters, such as hydrate content, vein thickness, orientation and spacing. Therefore, it will be possible to use seismic data in conjunction with this analytical description to determine the underlying hydrate morphology and concentration.

REFERENCES

Bystrom, J. 2003. Influence of the inclusions distribution on the effective properties of heterogeneous media. *Composites Part B: Engineering* 34: 587-592.

Chand, S. Minshull, T.A. Gei, D. & Carcione, J.M. 2004. Elastic velocity models for gas hydrate-bearing sediments – a comparison. *Geophysical Journal Institute* 159: 573-590.

Chand, S. Minshull, T.A. Priest, J.A. Best, A.I. Clayton, C.R.I. & Waite, W.F. 2006. An effective medium inversion algorithm for gas hydrate quantification and its application to laboratory and borehole measurements of gas hydrate-bearing sediments. *Geophysical Journal International* 166: 543-552.

Carcione, J.M. & Tinivella, U. 2000. Bottom-simulating reflectors: seismic velocities and AVO effects. *Geophysics* 65(1): 54-67.

Ecker, C. Dvorking, J. & Nur, A. 2000. Estimating the amount of gas hydrate and free gas from marine seismic data. *Geophysics* 65(2): 565-573.

Ellis, M. 2008. Joint seismic/electrical measurements of gas hydrates in continental margin sediments. PhD Thesis. University of Southampton, United Kingdom.

Gei, D. & Carcione, J.M. 2003. Acoustic properties of sediments saturated with gas hydrate, free gas and water. *Geophys. Prospect.* 51: 141-157.

Gitman, I.A. 2006. Representative volumes and multi-scale modelling of quasi-brittle materials. PhD Thesis. Technische Universiteit Delft, Netherlands.

Hashin, Z. 1983. Analysis of composite materials – a survey. *J. Appli. Mech.* 50: 481-505.

Helgerud, M.B. Dvorkin, J. Nur, A. Sakai, A. & Collett, T. 1999. Elastic wave velocity in marine sediments with gas hydrates: effective medium modelling. *Geophysical Research Letters* 26(13): 2021-2024.

Holland, M. Schultheiss, P. Roberts, J. & Druce, M. 2008. Observed gas hydrate morphologies in marine sediments. *Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008)*, Vancouver, British Columbia, Canada, July 6-10, 2008.

Jakobsen, M. Hudson, J.A., Minshull, T.A. & Singh, S.C. 2000. Elastic properties of hydrate-bearing sediments using effective medium theory. *Journal of Geophysical Research* 105(B1): 561-577.

Kaczmarczyk, L. Pearce, C.J. & Bicanic, N. 2007. Scale transition and enforcement of RVE boundary conditions in second-order computational homogenization. *International Journal for Numerical Methods in Engineering* 74(3); 506-522.

Lee, M.W & Collett, T.S. 2001. Elastic properties of gas hydrate-bearing sediments. *Geophysics* 63(5); 1659-1669.

Smit, R.J.M. 1998. Toughness of heterogeneous polymeric systems. PhD Thesis.

Van der Sluis, O. 2001. Homogenisation of structured elastoviscoplastic solids. PhD Thesis. Technische Universiteit, Eindhoven, Netherlands.