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GROUND MOVEMENTS ASSOCIATED WITH GAS HYDRATE PRODUCTION

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by

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By

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Ground Movements Associated With Gas Hydrate Production

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1. STATEMENT OF GRANT OBJECTIVES

INTRODUCTION

Work under this grant deal with a numerical investigation to evaluate the influence of hydrate production on ground movements near the wellbore and the surface. For planning recovery operations of this energy source, the ground movements and subsidence associated problems must be first investigated.

SCOPE OF WORK

The grantee will evaluate the influence of hydrate production on ground subsidence near the wellbore and the surface. The objective of this research will be achieved by using computer simulations of what is expected in a hydrate reservoir during the production stage as reported by hydrate production models and available data. The model will be based on theories of continuum mechanics, thermomechanics of hydrate production, principles of rock mechanics and geomechanics, and special features of geomaterials under cold temperatures such as those found in permafrost regions. The research work involved in the proposed investigation will be divided into three major tasks; mechanics of subsidence in permafrost regions, modeling of subsidence, and parametric studies.

TASKS TO BE PERFORMED

Task 1: Mechanics of subsidence in Permafrost Regions

The grantee will determine the mechanics of subsidence in permafrost regions by:

- (a) Perform a literature review on the mechanics of subsidence in permafrost regions.

- (b) Identify the major factors which influence the magnitude and extent of subsidence.

Task 2: Modeling of Subsidence

The grantee will perform modeling of subsidence activity which includes the following:

- (a) Establishment of ranges for material properties such as thermo-mechanical properties, thickness of hydrate reservoirs, overburden heights, etc., required for subsidence analysis.
- (b) Formulation of a subsidence model on the basis of information presented in Task 1, based on the primary assumption that the mechanism of subsidence in hydrate reservoir is similar to that found in permafrost regions.
- (c) Performance of parametric studies to establish possible variations in the expected ground movements.
- (d) Comparing the results with available subsidence information in permafrost regions and computed subsidence based on a longwall-analogy.

Task 3: Parametric Studies and Input Parameters

Parametric studies will be performed to investigate the influence of different factors on subsidence by varying them within the limits established in Task 2. Other input parameters such as mechanical and thermal properties will be estimated on the basis of available information.

2. STATEMENT OF TECHNICAL PROGRESS

Task 1:

(a) Literature Survey

The literature survey was completed. Status of this effort is given below.

Several publications [1-54] dealing with the mechanics of subsidence were reviewed. The phenomena that control the mechanical behavior of frozen soils are complex, and has not been fully understood. More caution and judgement must be exercised in applying the laboratory results in practice, because of wide variations in soil structure and in loading and thermal boundary conditions encountered in-situ. The creep of frozen soils is strongly related to the presence of unfrozen water and its movements under the influence of the stress gradient. The behavior of frozen soils under quasi-static loading is usually very different from that of the unfrozen soils because of the presence of ice and unfrozen water films. Frozen soils show creep and relaxation effects, and its behavior is affected by temperature difference. The strength of ice in frozen soil is dependent on many factors, such as temperature, pressure, strain rate, grain size, crystal orientation and density. Movement of water under stress gradients is considered to be an important factor in creep. When water migrates under stress, structural and ice-cementation bonds break and mineral particles slip. These processes, which are time dependent, result in a reduction of shearing resistance. If, during creep, weakening overcomes strengthening, the creep rate accelerates and failure occurs.

(b) Factors Influencing the Subsidence

The following factors were identified. Based on the work during the last quarter, no additional factors were considered.

- (a) Overburden depth
- (b) Extent of dissociated (or depleted) hydrate reservoir
- (c) Rock/frozen soil mechanical properties and strength
- (d) Reservoir compaction characteristics

Task 2: Modeling of Subsidence

(a) Mechanical Properties

In order to compare the results from the present subsidence analysis those obtained from a longwall-analogy, the following

material properties were selected. The values of elastic modulus were determined from experimental data obtained elsewhere under uniaxial condition (i.e. under no confining stress). In order to use this information in computer modeling studies, it is necessary to establish a relationship between the confining pressure and the elastic modulus. This was done by using the commonly used hyperbolic constitutive model¹. In this model, the initial elastic modulus is related to the confining stress as:

$$E_i = K_h P_a (\sigma_3 / P_a)^n \quad (1)$$

where E_i is initial modulus.

K_h and n represent material parameters.

P_a is the atmospheric pressure.

σ_3 is confining stress.

Based on equation (1), the Elastic Modulus, E , corresponding to a different confining stress, σ_3 , can be computed as

$$E = E_0 (\sigma_3 / P_a)^n. \quad (2)$$

The values, E , were computed for different values of confining pressures and the exponent, n . Typical variation of K_h and n values are shown below.

Initial Relative Density	K_h	n
60	909	0.490
80	1080	0.516
90	1530	0.600

In this study n values was varied from 0.4 to 0.6. Based on this relationship, the confinement of 3000 psi could increase the models by a factor large as 25. This is very important since the hydrate reservoirs are found at greater depths where the confining stress could be large. In the modeling study performed here, depth up to 3000 ft were considered, and appreciate values of elastic

¹ Details of this model can be found in Reference 7, and the following paper. Duncan, J. M., and Chang, C. Y., "Nonlinear Analysis of Stress and Strain in Soils," J. Soil Mech. Found. Eng., ASCE, Vol. 89, No. SM5, Sept. 1970, pp.1629-1653.

models were used on the basis of the above equation together with the expected overburden stress. The details of the modeling study is presented below.

(b) Simulation of Reservoir Compression

In this study, the problem of subsidence caused by hydrate reservoir depletion is analyzed by assuming plane strain conditions. It is anticipated that the depleted hydrate reservoir will be large in length-to-width ratio, and hence the plane strain idealization is considered as adequate. During the reservoir compaction, the roof of the reservoir moves, which in turn causes the overburden to move. These movements at the reservoir roof cause additional stresses and disturbance in the overburden strata. The ground movements caused by the reservoir compaction propagates towards the surface causing ground subsidence. One of the major objectives of this research work was to evaluate the magnitude of surface subsidence expected during hydrate production. The scope of the study is limited to uniform hydrate formations as opposed to disseminated reservoirs.

In order to evaluate the influence of hydrate production on the ground movements(subsidence), it is necessary to model the reservoir compaction anticipated during hydrate production. The ground movements and additional stresses caused in the overburden by the reservoir compaction can be computed by using the finite element method. In a previous study, the reservoir compaction was simulated by prescribing the displacements at the reservoir roof as a percentage of the reservoir thickness. In other words, the reservoir compaction r_c was expressed as:

$$r_c = \beta t$$

where t is the thickness of the reservoir, and β is called herein as the compaction ratio. The value of β depends on the mechanical properties, overburden stress, and porosity of the depleted hydrate reservoir. This approach was referred to as "longwall analogy", which provides the upper bound solution for ground subsidence.

In the present study, the reservoir compaction is modeled by using the conventional "stress equilibrium" approach. In this approach, the overburden strata move under the influence of body force (i.e. self weight) in response to the "cavity" generated by reservoir depletion. The resulting stresses and ground movements are computed using the finite element method. During the quarter covered by this report, preliminary finite element computations have been performed for different values of overburden depth for the case of 600 ft wide cavity shown in Table 1 using the material properties shown in Table 2. The preliminary results show that the computed subsidence values are much smaller in comparison to those

obtained from the longwall analogy. The present study is expected to provide a lower bound solution to the subsidence caused by hydrate reservoir depletion.

During the next quarter, all of the cases shown below will be analyzed by using the "stress equilibrium" approach discussed in the forgoing section, and the results will be presented in the final report.

(c) Computer Modeling Effort

The first task in the modeling work was to establish possible geometric limits for hydrate reservoirs and overburden strata, for example, the thickness of the hydrate layer and the lateral extent of the hydrate reservoir. In this study, the thickness of the hydrate reservoir was assumed to be 50 feet. The depth of the reservoir was varied as 1500 ft, 2000 ft, 2500 ft and 3000 ft. The time dependence in reservoir depletion was simulated by considering three different values of depleted size. As shown in Figure 1, three different locations of the dissociation front were considered. The geological complexities involved in this problem dictates that the modeling procedure to be numerical in nature. Finite Element Method is a powerful computer-based method which has been widely used in many disciplines of science and engineering.

In this study, the computer code FEAGMEC developed by Siriwardane is used in the computations of ground movements and stresses using the finite element method. This computer code is based on the latest developments in computational mechanics and novel computational algorithms for reliability and efficiency in the analysis of problems unique to geomechanics. Additional stresses developed in the overburden may cause failure in the overburden strata. The failure zone may extend by some distance towards the ground surface, and it is useful to know the extent of this zone in evaluating environmental impact of hydrate production.

In order to perform the finite element analysis of ground movements, geometric extent of the hydrate reservoir needs to be first established. For the purpose of evaluation, several cases are selected. The values of different parameters corresponding to these cases are shown in Table 1. It is planned to perform computations of subsidence profiles corresponding to each case in Table 1. Some of the material properties of hydrate reservoirs are estimated as shown in Table 2.

In addition to ground subsidence, it is also possible to have failure (collapse) in the overburden strata caused by additional stresses generated in the system. There are two mechanisms of such failures: the tensile failure and the shear failures. These failure modes were modeled by using appropriate failure criterion. The failure zones may extend by some distance towards the ground

surface, and it is useful to know the extent of this zone in evaluating environmental impact of hydrate production.

Subsidence problem may be more important for hydrate reservoirs at shallow depths. At greater depths, the subsidence problem may not be pronounced as that expected at shallow depths. In any event, the subsidence differential between the ground surface and the reservoir level could cause additional stresses on the wellbore.

Figure 1: Assumed Sizes of Depleted (Dissociated) Reservoir

Table 1: Summary of Cases Considered in the Modeling Study

Depth-ft (H)	Width-ft (W)	Output
1500	200	Case1-a
	400	Case2-a
	600	Case3-a
	800	Case4-a
2000	200	Case1-b
	400	Case2-b
	600	Case3-b
	800	Case4-b
2500	200	Case1-c
	400	Case2-c
	600	Case3-c
	800	Case4-c
3000	200	Case1-d
	400	Case2-d
	600	Case3-d
	800	Case4-d

Table 2: Material Properties for Hydrate Reservoir Strata and Overburden Strata

Material Properties	Hydrate Reservoir Strata	Overburden Strata
Elastic Modulus (psf)	* 5.75E7	2.45E8
Poisson's Ratio	0.23	0.23
Density (pcf)	159.0	159.0
Angle of Internal Friction (deg)	29.27	29.27
Coefficient of Earth Pressure at Rest, K ₀	0.5	0.5
Cohesion (psf)	2.16E5	3.28E5
Indirect Tensile Strength (psf)	9.36E4	9.36E4

Reservoir Thickness = 50 ft

* This value corresponds to a depth of 1500 feet. The values of Elastic Modulus varies with the confinement (or depth) according to the Equation 1.

Task 3: Parametric studies and Input Parameters

Most of the work in this has been completed as described in the previous section. The results for the parametric study are shown in Table 3 and Figures 1 to 20; these figures are self-explanatory and a commentary is not included herein. However, a discussion of these Figures will be included in the final report.

Table 3: Summary of Maximum Subsidence Values for Present Data and Longwall Analogy

Depth-ft (H)	Width-ft (W)	Output Name	Present Data [Smax] (inches)	Longwall Analogy [Smax] (inches)
1500	200	Case1-a	-0.63	-54.51
	400	Case2-a	-1.87	-75.47
	600	Case3-a	-3.60	-93.08
	800	Case4-a	-5.81	-
2000	200	Case1-b	-0.68	-42.32
	400	Case2-b	-2.00	-59.36
	600	Case3-b	-3.81	-74.24
	800	Case4-b	-6.09	-
2500	200	Case1-c	-0.71	-34.15
	400	Case2-c	-2.08	-48.26
	600	Case3-c	-3.95	-60.84
	800	Case4-c	-6.27	-
3000	200	Case1-d	-0.73	-28.24
	400	Case2-d	-2.14	-40.08
	600	Case3-d	-4.04	-50.81
	800	Case4-d	-6.39	-

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Figure 1: Computed Subsidence Profile for Case 1

Figure 2: Computed Subsidence Value for Case 2

Figure 3: Computed Subsidence Profile for Case 3

Figure 4: Computed Subsidence Profile for Case 4

S = Computed Subsidence
Smax = Computed Maximum Subsidence
Overburden Height, H=1500 ft

Figure 5: Normalized Subsidence Profile For Case 1

S = Computed Subsidence
Smax = Computed Maximum Subsidence
Overburden Height, H=2000 ft

Figure 6: Normalized Subsidence Profile For Case 2

S = Computed Subsidence
 S_{max} = Computed Maximum Subsidence
Overburden Height, $H=2500$ ft

Figure 7: Normalized Subsidence Profile For Case 3

S = Computed Subsidence
S_{max} = Computed Maximum Subsidence
Overburden Height, H=3000 ft

Figure 8: Normalized Subsidence Profile For Case 4

Ground Subsidence

Overburden Height = 1500 ft

Figure 9: Comparison of Present Analysis With Longwall Analogy For Case 1-a

Ground Subsidence

Overburden Height = 1500 ft

Figure 10: Comparison of Present Analysis With Longwall Analogy For Case 2-a

Figure 11: Comparison of Present Analysis With Longwall Analogy For Case 3-a

Ground Subsidence

Overburden Height = 2000 ft

Fig 12: Comparison of Present Analysis With Longwall Analogy For Case 1-b

Ground Subsidence Overburden Height = 2000 ft

Fig 13: Comparison of Present Analysis With Longwall Analogy For Case 2-b

Ground Subsidence

Overburden Height = 2000 ft

Fig 14: Comparison of Present Analysis With Longwall Analogy For Case 3-b

Ground Subsidence

Overburden Height = 2500 ft

Figure 15: Comparison of Present Analysis and Longwall Analogy For Case 1-c

Ground Subsidence

Overburden Height = 2500 ft

Figure 16: Comparison of Present Analysis and Longwall Analogy For Case 2-c

Ground Subsidence

Overburden Height = 2500 ft

Figure 17: Comparison of Present Analysis and Longwall Analogy For Case 3-c

Ground Subsidence
Overburden Height = 3000 ft

Figure 18: Comparison of Present Analysis and Longwall Analogy For Case 1-d

Ground Subsidence

Overburden Height = 3000 ft

Figure 19: Comparison of Present Analysis and Longwall Analogy For Case 2-d

Ground Subsidence

Overburden Height = 3000 ft

Figure 20: Comparison of Present Analysis and Longwall Analogy For Case 3-d

Figure 22 Finite Element Mesh Used for Case 1-b (h = 2000 feet)

Figure 23 Finite Element Mesh Used for Case 1-c (h = 2500 feet)

Figure 24 Finite Element Mesh Used for Case 1-d (h = 3000 feet)

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