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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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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.

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2. STATEMENT OF TECHNICAL PROGRESS

The literature survey was continued, and a brief summary of this effort is given below. A poster-session paper was presented at the contractor's review meeting held at METC on May 5, 1992, and a paper was submitted to METC to be included in the proceedings (see attached).

Task 1:

(a) Literature Survey

Several publications [1-10] dealing with the mechanics of subsidence in permafrost regions 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[2]. 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[2].

(b) Factors Influencing the Subsidence

The following factors have been identified.

- (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, and the results are shown in Table 1. As could be seen from this Table, 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.

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.

In the modeling study performed here, depth up to 3000 ft were considered, and appropriate values of elastic models were used on the basis of Table 1 together with the expected overburden stress. The details of the modeling study is presented below.

(b) 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 reservoir compression, r_c , was varied as 0.2, 0.3 and 0.4. 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.

In order to evaluate the influence of hydrate production on the ground movements (subsidence), it is necessary to model the reservoir compaction anticipated during the hydrate dissociation. The ground movements and additional stresses caused in the overburden by the reservoir compaction is computed by using the Finite Element Method. In this study, the computer code FEAGMEC developed by Siriwardane is used in the computations of ground movements and stresses. 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 2. It is planned to perform computations of subsidence profiles corresponding to each case in Table 2. Some of the material properties of hydrate reservoirs are estimated as shown in Table 3.

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.

Table 1: Variation of Elastic Modulus with Confining Pressure

n=0.40		n=0.45	
Confinement (psi)	E/E0	Confinement (psi)	E/E0
200	2.81	200	3.24
400	3.75	400	4.42
600	4.41	600	5.31
800	4.95	800	6.04
1000	5.41	1000	6.68
1200	5.82	1200	7.25
1400	6.19	1400	7.77
1600	6.53	1600	8.25
1800	6.84	1800	8.70
2000	7.14	2000	9.13
2200	7.42	2200	9.53
2400	7.68	2400	9.91
2600	7.93	2600	10.27
2800	8.17	2800	10.62
3000	8.40	3000	10.95

Table 1: Variation of Elastic Modulus with Confining Pressure
(continued)

n=0.50		n=0.55	
Confinement (psi)	E/E0	Confinement (psi)	E/E0
200	3.69	200	4.20
400	5.22	400	6.16
600	6.39	600	7.69
800	7.38	800	9.01
1000	8.25	1000	10.19
1200	9.04	1200	11.26
1400	9.76	1400	12.26
1600	10.44	1600	13.19
1800	11.07	1800	14.08
2000	11.67	2000	14.92
2200	12.24	2200	15.72
2400	12.78	2400	16.49
2600	13.30	2600	17.23
2800	13.81	2800	17.95
3000	14.29	3000	18.64

Table 1: Variation of Elastic Modulus with Confining Pressure
(continued)

n=0.60	
Confinement (psi)	E/E0
200	4.79
400	7.26
600	9.26
800	11.01
1000	12.58
1200	14.04
1400	15.40
1600	16.68
1800	17.90
2000	19.07
2200	20.19
2400	21.28
2600	22.32
2800	23.34
3000	24.33

Figure 1: Assumed Sizes of Depleted (Dissociated) Reservoir

Table 2: Summary of Cases Considered in the Modeling Study

	Case No.	Depth (ft)	Range (ft)	Reservoir Compaction (β)
1.	Case 1a	1500	200	0.2
2.	Case 1b	1500	200	0.3
3.	Case 1c	1500	200	0.4
4.	Case 2a	1500	400	0.2
5.	Case 2b	1500	400	0.3
6.	Case 2c	1500	400	0.4
7.	Case 3a	1500	600	0.2
8.	Case 3b	1500	600	0.3
9.	Case 3c	1500	600	0.4
10.	Case 4a	2000	200	0.2
11.	Case 4b	2000	200	0.3
12.	Case 4c	2000	200	0.4
13.	Case 5a	2000	400	0.2
14.	Case 5b	2000	400	0.3
15.	Case 5c	2000	400	0.4
16.	Case 6a	2000	600	0.2
17.	Case 6b	2000	600	0.3
18.	Case 6c	2000	600	0.4

Table 2: Summary of Cases Considered in the Modeling Study
(continued)

	Case No.	Depth (ft)	Range (ft)	Reservoir Compaction (β)
19.	Case 7a	2500	200	0.2
20.	Case 7b	2500	200	0.3
21.	Case 7c	2500	200	0.4
22.	Case 8a	2500	400	0.2
23.	Case 8b	2500	400	0.3
24.	Case 8c	2500	400	0.4
25.	Case 9a	2500	600	0.2
26.	Case 9b	2500	600	0.3
27.	Case 9c	2500	600	0.4
28.	Case 10a	3000	200	0.2
29.	Case 10b	3000	200	0.3
30.	Case 10c	3000	200	0.4
31.	Case 11a	3000	400	0.2
32.	Case 11b	3000	400	0.3
33.	Case 11c	3000	400	0.4
34.	Case 12a	3000	600	0.2
35.	Case 12b	3000	600	0.3
36.	Case 12c	3000	600	0.4

Table 3: 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 Table 4-6.

REFERENCES

1. BROWN W.G. and JOHNSTON G.H., "Dikes On Permafrost: Predicting Thaw and Settlement", Canadian Geotechnical Journal, Vol.7, 1970.
2. JOHNSTON G.H., Permafrost Engineering Design And Construction, John Wiley, 1981.
3. KONRAD J.M. and MORGENSTERN N.R., "Frost Heave Prediction Of Chilled Pipelines Buried In Unfrozen Soils", Canadian Geotechnical Journal, Vol.21, 1984.
4. LADANYI B., "An Engineering Theory Of Creep Of Frozen Soils", Canadian Geotechnical Journal, Vol.9, 1972.
5. MACKAY J.R. and BURROUS C., "Uplift Of Objects By An Upfreezing Ice Surface", Canadian Geotechnical Journal, Vol.16, 1979.
6. MICHEL B., "A Numerical Model Of Creep Of Polycrystalline Ice", Canadian Geotechnical Journal, Vol.15, 1978.
7. NIXON J.F., MORGENSTERN N.R. and REESOR S.N., "Frost Heave Pipeline Interaction Using Continuum Mechanics", Canadian Geotechnical Journal, Vol.20, 1983.
8. SENSENY P.E., "Creep Properties Of Four Rock Salts", published in the Proceedings Of The Second Conference On The Mechanical Behavior Of Salt, Hanover, Federal Republic Of Germany, September 1984.
9. TSYTOVICH N.A., The Mechanics Of Frozen Ground, McGraw Hill, 1975.
10. WEAVER J.S. AND MORGENSTERN N.R., "Simple Shear Creep Tests On Frozen Soils", Canadian Geotechnical Journal, Vol.

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CONTRACT INFORMATION

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Period of Performance	August 27, 1992 to August 26, 1992

ABSTRACT

Gas hydrate as an energy reserve is very attractive in view of the large amount of gas that can be produced. Vast amounts of natural deposits of hydrates have been identified and a number of conceptual models have been developed for recovery of this resource. In the development of extraction technology for gas hydrates, it is necessary to have an understanding of the geomechanical behavior of hydrate reservoir and the overburden.

An obvious consequence of hydrate dissociation is the compression of reservoir matrix causing displacements in the surrounding area. The reservoir compression is a time-dependent process which depends on the production rate. The ground movements cause additional stresses in the overburden which may result in rock mass fracture and failure. Rock failure may cause rubble formation or bulking in the fracture zone. This in turn can cause an increase in permeability for gas flow which may offset the reduction in permeability caused by closure of existing fractures during reservoir compression.

Potential strata movements and subsidence associated with reservoir compaction during hydrate production has been investigated by using an analogy of gob compaction in a longwall mine. In this study, the thickness of the hydrate reservoir was assumed to be 50 feet. The depth of the reservoir was varied as 1,500 feet and 2,500 feet. Based on

this modeling study with realistic ranges for geometric parameters, it was found that the subsidence could be between 3 ft to 10 ft depending upon the values of reservoir compaction ratio, the size of the depleted reservoir, and the overburden depth (see Figures 1 and 2). These large values appear to provide the upper bound for subsidence, since the computations were based on the analogy of a longwall mine with gob (roof) compaction. In reality, subsidence due to hydrate reservoir compaction can be expected to be similar to that found in permafrost regions, and hence the magnitude of the problem may not be severe as that predicted by the longwall-analogy.

The mechanics of ground movements during hydrate production can be more closely simulated by considering similarities with ground movements associated with subsidence in permafrost regions. The purpose of this research work is to investigate

the potential strata movements associated with hydrate production by considering similarities with ground movements in permafrost regions. The work primarily involves numerical modeling of subsidence caused by hydrate dissociation. The investigation is based on the theories of continuum mechanics, thermomechanical behavior of frozen geo-materials, and principles of rock mechanics and geomechanics. It is expected that some phases of the investigation will involve the use of finite element method, which is a powerful computer-based method which has been widely used in many areas of science and engineering. Parametric studies will be performed to predict expected strata movements and surface subsidence for different reservoir conditions and properties of geological materials. The results from this investigation will be useful in predicting the magnitude of the subsidence problem associated with gas hydrate production. The analogy of subsidence in permafrost regions may provide lower bounds for subsidence expected in hydrate reservoirs. Furthermore, it is anticipated that the results will provide insight into planning of hydrate recovery operations.

H = Overburden Height
W = Size of Depleted Reservoir
BETA (β) = Reservoir Compaction Ratio

Figure 1: Computed Subsidence Profile Based on Longwall Analogy for Overburden Depth of 1500 Feet.

H = Overburden Height
 W = Size of Depleted Reservoir
 BETA (β) = Reservoir Compaction Ratio

Figure 2: Computed Subsidence Profile Based on Longwall Analogy for Overburden Depth of 2500 Feet.

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