1 of 1

**Ground Movements Associated
With Gas Hydrate Production**

Final Report

**Hema J. Siriwardane
Bora Kutuk**

Work Performed Under Contract No.: DE-FG21-91MC28080

**For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880**

**By
West Virginia University
College of Engineering
Morgantown, West Virginia 26506**

March 1992

TABLE OF CONTENTS

TABLE OF CONTENTS	i
LIST OF FIGURES	iii
LIST OF TABLES	v
ABSTRACT	vii
CHAPTER 1	1
INTRODUCTION	1
1.1 Introduction	1
1.2 Statement Of The Problem	2
1.3 Objective	4
1.4 Background	4
CHAPTER 2	9
METHODOLOGY	9
2.1 Introduction	9
2.2 Mathematical Formulation	10
2.2.1 Finite Element Formulation	10
2.2.2 Element Stiffness Matrix	15
2.2.3 Element Load Vector	17
2.2.4 Finite Element Program For Subsidence Analysis.	19
2.3 Mechanics Of Subsidence	20
2.3.1 Literature Survey	20
2.3.2 Factors Influencing The Subsidence	22
2.4 Modeling Of Subsidence	23
2.4.1 Mechanical Properties	23

2.4.2	Simulation Of Reservoir Compression	25
2.4.3	Computer Modeling Effort	26
	CHAPTER 3	30
	MODELING RESULTS	30
3.1	Introduction	30
3.2	Results From The Parametric Study	31
	CHAPTER 4	60
	SUMMARY AND CONCLUSIONS.....	60
4.1	Summary and Conclusions	60
	BIBLIOGRAPHY	63

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
2-1	Two Dimensional, 4 Node-Isoparametric Element	12
2-2	Surface Loading On a Two Dimensional Element	18
3-1	Assumed Sizes of Depleted (Dissociated) Reservoir ..	32
3-2	Finite Element Mesh Used For Case 1-a(h=1500 feet)..	33
3-3	Finite Element Mesh Used For Case 1-b(h=2000 feet)..	34
3-4	Finite Element Mesh Used For Case 1-c(h=2500 feet)..	35
3-5	Finite Element Mesh Used For Case 1-d(h=3000 feet)..	36
3-6	Computed Subsidence Profile For Case 1	40
3-7	Computed Subsidence Profile For Case 2	41
3-8	Computed Subsidence Profile For Case 3	42
3-9	Computed Subsidence Profile For Case 4	43
3-10	Normalized Subsidence Profile For Case 1	44
3-11	Normalized Subsidence Profile For Case 2	45
3-12	Normalized Subsidence Profile For Case 3	46
3-13	Normalized Subsidence Profile For Case 4	47
3-14	Comparison of Present Analysis With Longwall Analogy For Case 1-a	48
3-15	Comparison of Present Analysis With Longwall Analogy For Case 2-a	49
3-16	Comparison of Present Analysis With Longwall Analogy For Case 3-a	50
3-17	Comparison of Present Analysis With Longwall Analogy For Case 1-b	51
3-18	Comparison of Present Analysis With Longwall Analogy For Case 2-b	52

3-19	Comparison of Present Analysis With Longwall Analogy For Case 3-b	53
3-20	Comparison of Present Analysis With Longwall Analogy For Case 1-c	54
3-21	Comparison of Present Analysis With Longwall Analogy For Case 2-c	55
3-22	Comparison of Present Analysis With Longwall Analogy For Case 3-c	56
3-23	Comparison of Present Analysis With Longwall Analogy For Case 1-d	57
3-24	Comparison of Present Analysis With Longwall Analogy For Case 2-d	58
3-25	Comparison of Present Analysis With Longwall Analogy For Case 3-d	59

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
2-1	Summary of Cases Considered in the Modeling Study ..	28
2-2	Material Properties for Hydrate Reservoir Strata and Overburden Strata	29
3-1	Summary of Maximum Subsidence Values for Present Data and Longwall Analogy	37

ABSTRACT

Gas hydrates as an energy reserve is very attractive in view of the large amount of gas that can be concentrated in a hydrate; for example, 1 cubic foot of solid methane hydrate contains approximately 160 standard cubic feet of gas. This report deals with a study directed towards a modeling effort on production related ground movements and subsidence resulting from hydrate dissociation.

The goal of this research study was to evaluate whether there could be subsidence related problems that could be an impediment to hydrate production. In almost all cases of man-made underground cavities such as mines, tunnels, gasification chambers, and oil and gas reservoirs located on and off shore, it has been observed that some form of ground movements have occurred. During the production of gas from a hydrate reservoir, it is expected that porous reservoir matrix becomes more compressible which may cause reservoir compression (compaction) under the influence of overburden weight. The overburden deformations can propagate its influence upwards causing subsidence near the surface where production equipment will be located.

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 present study is expected to provide a "lower bound" solution to the subsidence caused by hydrate reservoir depletion. The reservoir compaction anticipated during hydrate production was modeled by using the finite element method, which is a powerful computer modeling technique. The ground movements at the reservoir roof (i.e. reservoir compression) cause additional stresses and disturbance in the overburden strata. In

this study, the reservoir compaction was 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 were computed by using the finite element method. 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.

Based on the parameters used in this investigation, the maximum ground subsidence could vary anywhere from 0.50 to 6.50 inches depending on the overburden depth and the size of the depleted hydrate reservoir. The results also show that the maximum ground subsidence increases with the size of the depleted reservoir. The change in the maximum subsidence appears to be very small with the overburden depth of the hydrate reservoir. The results from the present study can be considered as a lower bound solution to the subsidence caused by hydrate reservoir depletion. Results show that the normalized subsidence profile is not significantly influenced by the panel width at a given overburden height within the range of parameters investigated in this study. However, the normalized subsidence profile is a function of the overburden height.

A comparisons of subsidence profiles computed in the present analysis with those from the "longwall analogy" shows that subsidence values computed in the present analysis are much smaller than the values obtained from the longwall analogy. The maximum subsidence value from the present analysis is about 100-150 times smaller than the value corresponding to the longwall analogy for a panel width of 200 feet. However, for the same overburden height, this ratio is about 20-25 for a panel width of 600 feet.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Under certain conditions of temperature and pressure, gas (methane, ethane etc) and water can form a crystalline, ice-like compound called clathrate hydrate [1,12,15,23,26,51]. Hydrates can occur naturally in permafrost regions and in deep ocean sediments where conditions of stability prevail. This is evident from the presence of large quantities of gas, mainly methane, in ocean sediments recovered during deep sea drilling operations [12]. Methane hydrates are believed to occur in large quantities in Siberia and in the North American Arctic. Hydrates are believed to occur in three types of physical distributions in nature. They are in (a) pure monolithic form, (b) unconsolidated media, and (c) consolidated media. This report deals with a numerical investigation to evaluate the influence of hydrate production on ground movements near the surface. For planning recovery operations of this energy resource, the ground movements and subsidence associated problems must be first investigated. There is no published information on potential ground movements and subsidence problems associated with hydrate reservoirs during production.

Gas hydrates as an energy reserve is very attractive in view of the large amount of gas that can be concentrated in a hydrate;

for example, 1 cubic foot of solid methane hydrate contains approximately 160 standard cubic feet of gas. On the other hand, recovery of hydrates poses severe production problems because of the environmental conditions. A number of conceptual production models have been identified for the recovery of hydrates [2,5,12]. The primary models are thermal injection, depressurization or a combination of the two. The producibility of gas from a hydrate reservoir will depend on the existence of fractures and on the influence of dissociation on the geomechanical structure of the reservoir matrix. A number of assumptions on deformation characteristics of hydrate reservoir materials have been made in these conceptual models, but presently very little information is available on the mechanical behavior of hydrate reservoir matrix. This study was directed towards a modeling effort on production related ground movements and subsidence resulting from hydrate dissociation.

1.2 STATEMENT OF THE PROBLEM

The goal of this research study was to evaluate whether there could be subsidence related problems that could be an impediment to hydrate production. In almost all cases of man-made underground cavities such as mines, tunnels, gasification chambers, and oil and gas reservoirs located on and off shore, it has been observed that some form of ground movements have occurred [6-8,50,54,55]. In the case of oil and gas reservoirs, ground subsidence can be the result

of reservoir compaction during depletion. A well-known example is the Groningen gas reservoir in the Netherlands. In certain cases, ground movements up to nine feet have been reported due to reservoir depletion. Furthermore, it has also been observed that excessive pumping of ground water through porous water-bearing aquifers have caused severe ground movement and subsidence problems near the ground surface. During the production of gas from a hydrate reservoir, it is expected that porous reservoir matrix becomes more compressible which may cause reservoir compression (compaction) under the influence of overburden weight. This can cause the overburden to deform causing changes in state of stress near the wellbore. The overburden deformations can propagate its influence upwards causing subsidence near the surface where production equipment will be located. The reservoir compression could also cause a reduction of fracture permeability. All of the forgoing mechanisms are possible complex scenarios. This can become more complex when deformations and stress changes associated with heat transfer is considered. The possibility of one or more of the aforementioned mechanisms can cause ground movements and subsidence problems which could influence hydrate production. Such problems, if real, could be a serious impediment to the development of extraction technology for gas hydrates. The purpose of this study was to perform a modeling study to investigate the type of ground movement characteristics which can be expected near the wellbore and ground surface over hydrate reservoirs during production stage.

1.3 OBJECTIVE

The primary objective of this research work is to evaluate the influence of hydrate production on ground subsidence near the surface. The objective of this research was achieved by using computer simulations of what is expected in a hydrate reservoir during the production stage as reported by hydrate production models [2,5,28] and available data [23]. The model is based on theories of continuum mechanics, principles of rock mechanics and geomechanics, and special features of geomaterials under cold temperatures such as those found in permafrost regions.

1.4 BACKGROUND

Due to fast growing needs of energy supplies, U.S. Department of Energy has launched an effort to explore the potential of gas hydrates as an energy source for the 21st century. One of the unavoidable consequences of energy extraction from underground geomaterials is the undesirable compaction in the gas reservoir matrix. The magnitude of reservoir compaction depends on factors such as porosity, compressibility of reservoir matrix, overburden stresses, and geologic features in and near the reservoir rock mass. One major consequence of reservoir compaction is the undesirable subsidence (ground movements) in the overburden strata and at the ground surface. Almost all types of underground cavities such as mines, tunnels, and gasification chambers cause ground

subsidence problems [3,6,7,21,32,39,42-44,46,48-50,52]. Moreover, even in cases of excessive groundwater pumping, large geographical areas have undergone subsidence problems. In fact, it has been estimated that about 2.5 million U.S. land acres are affected by subsidence due to mining. In the case of potential subsidence problems associated with hydrate production, damages to wellbore and drilling equipment itself can cost, perhaps, millions of dollars. Moreover, such problems may cause a setback in developing production technology for gas hydrates and affect production potential of hydrate reservoirs. Thus, it appears very logical to investigate potential ground movement problems associated with hydrate reservoirs.

The realization of the problem of subsidence due to underground coal mining has stimulated research on prediction and control of subsidence in many parts of the world. Methods of subsidence prediction used in U.S. coal fields fall into two categories: namely, empirical and continuum approaches. Several empirical methods adopted in this country have been developed on the basis of European experience; for example, the National Coal Board (NCB) procedure [32]. The validity of such empirical methods to different geologic conditions and cavity configurations is questionable. Moreover, its validity for complex situations such as in gas hydrate reservoirs is grossly questionable. The purpose of empirical methods is to provide the engineer with a very simple technique for estimating the magnitude of the problem in hand when

a rigorous analysis cannot be performed.

In the case of hydrate reservoirs, the mechanics of ground movements resulting from the dissociation process become very complex due to complexities in the reservoir compression. A model that incorporates these factors undoubtedly has to be numerical in nature. Most of the continuum approaches on subsidence analysis of coal mines in this country have used Finite Element Method. It has been noted that the accuracy of any Finite Element analysis depends on how the material nonlinearities, rock mass failure, initial stress field and time-dependent cavity growth are modelled. Many previous studies [7,54] on ground subsidence have been based on simplified assumptions such as linear elasticity. Some of the recent research work [40,42-44,48] has addressed these limitations and improved models have been developed for the analysis of ground movement caused by underground cavities.

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 [2,5]. The ground movements cause additional stresses in the overburden which may result in rock mass fracture and failure. This, in turn, can cause an increase in permeability for gas flow which may be offset by closure of existing fractures during reservoir compression. The time dependent ground movements which occur at the reservoir level

can change the mechanics of ground movements near the wellbore and at the ground surface. The heat transfer process can make the situation even more complex.

In a previous investigation [49], potential strata movements and subsidence associated with hydrate production was investigated by using an analogy of gob (failed roof) compaction in a typical longwall mine. Even though such an analogy provides upper bound estimates of subsidence easily, the mechanics of subsidence caused by mechanical compression of reservoir materials can be much more complex than assumed. Based on the "longwall mine analogy", it was found [49] that the subsidence could be anywhere from 3 feet to 10 feet depending upon the values selected for reservoir compaction ratio, the size of the depleted reservoir, and the overburden depth. The predicted values of subsidence from the longwall-analogy appear to be unrealistically high. In reality, the subsidence caused by hydrate reservoir compaction can be expected to be similar to that found in permafrost regions.

In the present study, the reservoir compaction was modeled by using the conventional "stress equilibrium" approach [44]. 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. The present study is expected to provide a "lower bound" solution to the subsidence

caused by hydrate reservoir depletion. In this study, the computer code FEAGMEC developed by Siriwardane [41] was 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.

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.

CHAPTER 2

METHODOLOGY

2.1 INTRODUCTION

As stated in the previous chapter, the geological complexities involved in this problem dictates that the modeling procedure be numerical in nature. Finite Element Method [57] is a powerful computer-based technique which has been widely used in many disciplines of science and engineering. In this work Finite Element Method was used in modeling ground movements resulting from hydrate dissociation. An existing computer code [41-44,46,48] was used in the study. This code is based on the developments in computational mechanics and computational algorithms for reliability and efficiency in the analysis of problems unique to geomechanics. This code has been verified by solving a number of problems in geomechanics, mining engineering, and solid mechanics almost over a period of 10 years. The scope of the study was limited to uniform hydrate formations as opposed to a layered or disseminated reservoirs. This was limited due to available production models and the lack of current knowledge on hydrate occurrences. In the following section, details of the mathematical formulation, which provides the basis of the modeling work, is presented.

2.2 MATHEMATICAL FORMULATION

Most all real problems are three-dimensional, but by making certain assumptions depending on the geometric and loading characteristics of the problem, some problems can be idealized as two-dimensional under plane strain or plane stress conditions. In these idealizations, only the stresses and strains in one plane have to be considered. The finite element method is a powerful tool in the analysis of such problems with complex geometry and boundary conditions. In this study, the problem of ground movements caused by hydrate production was analyzed by the finite element method assuming plane strain conditions. Detailed descriptions of plane strain and plane stress idealizations can be found elsewhere [57].

2.2.1 FINITE ELEMENT FORMULATION

The computer program (FEAGMEC), developed by Siriwardane [41], has many capabilities unique to problems in geomechanics. This program has the capability of using either a four-noded or eight-noded finite elements. In this research four-noded elements were used. Therefore, only the formulation of a four-noded element is covered in this report.

The displacements in an element can be defined as u and v in the x - and y -directions, respectively. The displacements within the element can be expressed using interpolation functions and

nodal displacements as follows:

$$\begin{aligned} u &= N_1 u_1 + N_2 u_2 + N_3 u_3 + N_4 u_4 \\ v &= N_1 v_1 + N_2 v_2 + N_3 v_3 + N_4 v_4 \end{aligned} \quad (2-1a)$$

where N_i represents interpolation functions in the local coordinates, and u_i and v_i are the displacements at node 'i'. This can be written in matrix form as:

$$\begin{Bmatrix} u \\ v \end{Bmatrix} = \begin{bmatrix} N_1 & 0 & N_2 & 0 & N_3 & 0 & N_4 & 0 \\ 0 & N_1 & 0 & N_2 & 0 & N_3 & 0 & N_4 \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \\ u_3 \\ v_3 \\ u_4 \\ v_4 \end{Bmatrix} \quad (2-1a)$$

$$\text{or} \quad \begin{Bmatrix} u \\ v \end{Bmatrix} = [N] \{q\} \quad (2-1c)$$

For the four-noded quadrilateral element, the interpolation function can be written as:

$$N_i(r,s) = \frac{1}{4}(1+rr_i)(1+ss_i) \quad (2-1d)$$

where r and s correspond to local coordinates which vary from -1 to +1 as shown in Figure 2-1. The strain ϵ_x , ϵ_y , and γ_{xy} can be written as:

Figure 2-1: Two Dimensional, 4 node-isoparametric element

$$\begin{aligned}
 \epsilon_x &= \frac{\partial u}{\partial x} \\
 \epsilon_y &= \frac{\partial v}{\partial y} \\
 \gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}
 \end{aligned} \tag{2-2a}$$

This can be written in vector form as:

$$\{ \epsilon \} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \end{Bmatrix} \tag{2-2b}$$

Substituting Eq. 2-1 into Eq. 2-2b, the following relationship can be obtained:

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} \frac{\partial N_1}{\partial x} & 0 & \frac{\partial N_2}{\partial x} & 0 & \frac{\partial N_3}{\partial x} & 0 & \frac{\partial N_4}{\partial x} & 0 \\ 0 & \frac{\partial N_1}{\partial y} & 0 & \frac{\partial N_2}{\partial y} & 0 & \frac{\partial N_3}{\partial y} & 0 & \frac{\partial N_4}{\partial y} \\ \frac{\partial N_1}{\partial y} & \frac{\partial N_1}{\partial x} & \frac{\partial N_2}{\partial y} & \frac{\partial N_2}{\partial x} & \frac{\partial N_3}{\partial y} & \frac{\partial N_3}{\partial x} & \frac{\partial N_4}{\partial y} & \frac{\partial N_4}{\partial x} \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \\ u_3 \\ v_3 \\ u_4 \\ v_4 \end{Bmatrix} \tag{2-3a}$$

$$\text{or } \{ \epsilon \} = [B] \{ q \} \tag{2-3b}$$

The matrix $[B]$ is called the strain-displacement transformation matrix. To evaluate the above global derivatives of the interpolation functions, a transformation from local to global

coordinates is necessary. This can be performed by using the chain rule of differentiation as:

$$\frac{\partial N_i}{\partial r} = \frac{\partial N_i}{\partial x} \cdot \frac{\partial x}{\partial r} + \frac{\partial N_i}{\partial y} \cdot \frac{\partial y}{\partial r} \quad (2-4a)$$

$$\frac{\partial N_i}{\partial s} = \frac{\partial N_i}{\partial x} \cdot \frac{\partial x}{\partial s} + \frac{\partial N_i}{\partial y} \cdot \frac{\partial y}{\partial s} \quad (2-4b)$$

The above equations can be written in matrix form as:

$$\begin{Bmatrix} \frac{\partial N_i}{\partial r} \\ \frac{\partial N_i}{\partial s} \end{Bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial r} & \frac{\partial y}{\partial r} \\ \frac{\partial x}{\partial s} & \frac{\partial y}{\partial s} \end{bmatrix} \begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \end{Bmatrix} \quad (2-4c)$$

or we may write this by introducing the Jacobian matrix as:

$$\begin{Bmatrix} \frac{\partial N_i}{\partial r} \\ \frac{\partial N_i}{\partial s} \end{Bmatrix} = [J] \begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \end{Bmatrix} \quad (2-4d)$$

The matrix [J] is called Jacobian matrix. In terms of nodal coordinates , [J] can be written as :

$$[J] = \begin{bmatrix} \frac{\partial}{\partial r} (\sum N_i X_i) & \frac{\partial}{\partial r} (\sum N_i Y_i) \\ \frac{\partial}{\partial s} (\sum N_i X_i) & \frac{\partial}{\partial s} (\sum N_i Y_i) \end{bmatrix} \quad (2-5)$$

Now, the [B] matrix in Eq. 2-3b can be evaluated. However, to do this the global derivative of the interpolation functions have to

be known. This can be evaluated by using the Jacobian matrix as shown below:

$$\begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \end{Bmatrix} = [J]^{-1} \begin{Bmatrix} \frac{\partial N_i}{\partial r} \\ \frac{\partial N_i}{\partial s} \end{Bmatrix} \quad (2-6)$$

where $[J]^{-1}$ is the inverse of the Jacobian matrix.

2.2.2 ELEMENT STIFFNESS MATRIX

In order to assemble the element stiffness matrix, we can use the well known principle of minimum potential energy. For stable equilibrium, the potential energy has to be a minimum. The potential energy of a body can be described as the sum of the internal energy (strain energy), potential of body forces, and surface tractions. The general expression for potential energy may be written as [57]:

$$\begin{aligned} \pi_p = & \frac{1}{2} \iiint_V \{q\}^T [B]^T [C] [B] \{q\} dV - \iiint_V \{q\}^T [N]^T \{Y\} dV - \iint_{S_1} \{q\}^T [N]^T [T] dS \\ & + \iiint_V \{q\}^T [B]^T \{\sigma_0\} dV \end{aligned} \quad (2-7)$$

where V = volume

S = surface of the body

$\{q\}$ = displacement vector

$[B]$ = strain-displacement transformation matrix

$[C]$ = constitutive matrix

$[N]$ = interpolation function

$\{Y\}$ = body force vector

$\{T\}$ = surface traction vector

$\{\sigma_0\}$ = initial stress vector

Now, after minimizing the potential energy function, the element equilibrium equation can be found. The element equilibrium equations can be written as [57]:

$$[K] \{q\} = \{Q\} \quad (2-8a)$$

where;

$[K]$ = Element stiffness matrix, and

$\{Q\}$ = Element load vector composed of body forces due to gravity, surface traction and point loads.

These can be expressed as:

$$[K] = \iiint_V [B]^T [C] [B] dV, \text{ and} \quad (2-8b)$$

$$\{Q\} = \iiint_V [N]^T \{Y\} dV + \iint_{s_1} [N]^T \{T\} dS - \iiint_V [B]^T \{\sigma_0\} dV \quad (2-8c)$$

Where $[B]$ is the strain-displacement relationship, $[C]$ is the constitutive relationship, $\{\sigma_0\}$ is the vector of initial stresses such as insitu or tectonic, $\{Y\}$ is the body forces vector, $\{T\}$ is the surface traction vector, $[N]$ is the matrix of interpolation functions, s_1 is the surface on which the surface tractions is applied, and v is the volume of the element.

After establishing the matrices $[B]$ and $[C]$, the integral in Eq.2-8 can be evaluated by using numerical integration techniques.

Gaussian quadrature was used to evaluate the integral. The integral in Eq. 2-8 can now be expressed as:

$$[B]^T[C][B] dV = h \sum_{-1}^{+1} \sum_{-1}^{+1} [B]^T[C][B] \det[J] dr ds \quad (2-9)$$

where r and s represent the local coordinates and h is the thickness of section under consideration. Detailed procedure to perform numerical integration can be found elsewhere in the literature [57].

2.2.3 ELEMENT LOAD VECTOR

The load vector due to uniformly distributed loads, as shown in Figure 2-2, can be calculated by integrating the surface traction term in Eq. 2-8c. For the four-noded isoparametric elements, based on Figure 2-2, the load vector takes the following form:

$$\{Q\} = \begin{Bmatrix} \frac{1}{6}(2P_x + P_x) \\ \frac{1}{6}(P_x + 2P_x) \\ \frac{1}{6}(2P_y + P_y) \\ \frac{1}{6}(P_y + 2P_y) \end{Bmatrix} \quad (2-10)$$

The strain vector at any point can be evaluated after solving the equilibrium equations and determining the displacement vector for each element. The stresses can also be evaluated.

Figure 2-2: Surface Loading On a Two Dimensional Element

2.2.4 FINITE ELEMENT PROGRAM FOR SUBSIDENCE ANALYSIS

The finite element program [41] used in this study has the capability of using a number of user-selected constitutive models for the geological materials analyzed. These include linear and non-linear and elastoplastic models based on ideal plasticity as well as hardening concepts. Details of derivation of incremental forms of constitutive equations associated with different models and aspects of computational algorithms are presented elsewhere [9,40].

The tensile failure conditions are checked by comparing the computed stress in each element with the corresponding tensile strength of the element. Failure occurs when the tensile state of stress exceeds the tensile strength of the material. This can be expressed as:

$$J_1 = T_{cut} \quad (2-14)$$

where;

J_1 = first invariant of stress tensor; and

T_{cut} = the tension cutoff

Further T_{cut} is related to the tensile strength, σ_y , of the material. The relationship can be expressed as:

$$T_{cut} = 3 \sigma_y \quad (2-15)$$

2.3 MECHANICS OF SUBSIDENCE

Since gas hydrates are considered as a new type of geological material, there is hardly any information on mechanical properties of hydrates in the open literature. Information on mechanical properties of hydrate saturated reservoir materials are necessary as input parameters to the proposed numerical model. It is felt that each hydrate reservoir will have unique material properties, and since the present study is directed towards general hydrate reservoirs rather than any unique case(s), only the ranges of properties would be required for the numerical model study proposed herein. With the known range of properties and production rates, one can perform parametric and sensitivity studies to investigate the range of ground movements expected in the overburden. The range for required input material properties were established on the basis of available information on ice [11,14,29], frozen ground [16,17,18-20,22,24,25,33,35,38,53,56] preliminary data on hydrates [4,45], and ice-sand mixtures used in a previous study [49].

2.3.1 LITERATURE SURVEY

Several publications [3, 4, 6-8, 13, 16, 21, 22, 25, 27, 30, 31, 34, 36, 37, 52, 55] 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. The creep behavior was not included in the present study due to lack of information on gas hydrate bearing strata

It is known that many physical properties of hydrates depend primarily on the lattice structure [23]. As stated in the above reference, because of similarity in crystalline structure of hexagonal ice and hydrates, properties that are currently unknown, at a rough first approximation, can be assumed to be those of ice. Although ice is not normally thought of as a rock, it meets the

definition of rocks [18]. Details of engineering properties of ice can be found elsewhere [11,14,19]. These references provide the range of some mechanical properties of ice over a wide temperature range. It is expected that frozen ground will roughly resemble hydrates in unconsolidated and consolidated media. Detailed information on the mechanical behavior of frozen geological materials under different conditions can be found in a number of references [16,17,18-20,22,24,25,33,35,38,53,56]. For example, the strength of ice-soil mixtures increases with ice content until a certain optimum value of ice content, and then decreases rapidly with any further increase in the ice content. Similar trends were assumed to exist in hydrates formed in geological materials.

2.3.2 FACTORS INFLUENCING THE SUBSIDENCE

The following factors were identified on the basis of the literature survey.

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

2.4 MODELING OF SUBSIDENCE

2.4.1 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 [49] under uniaxial condition (i.e. under no confining stress). In order to use this information in computer modeling studies, it was necessary to establish a relationship between the confining pressure and the elastic modulus. This was done by using the commonly used hyperbolic constitutive model¹ [9,10]. In this model, the initial elastic modulus is related to the confining stress as:

$$E_i = K_h P_a (\sigma_3 / P_a)^n \quad (2-16)$$

where E_i is initial modulus.

K_h and n represent material parameters.

P_a is the atmospheric pressure.

σ_3 is confining stress.

¹ Details of this model can be found in Reference 10, 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.

Based on Eq. 2-16, the Elastic Modulus, E , corresponding to a different confining stress, σ_3 , can be computed as

$$E = E_0(\sigma_3/P_h)^n. \quad (2-17)$$

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 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.

2.4.2 SIMULATION OF RESERVOIR COMPRESSION

In this study, the problem of subsidence caused by hydrate reservoir depletion was 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. This approach was referred to as "longwall analogy", which provides the upper bound solution

for ground subsidence [49].

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.

2.4.3 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 the next chapter (Figure 3-1), four different locations (i.e. 200 ft, 400 ft, 600 ft and 800 ft) 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 [41] was 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. 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 2-1. Some of the material properties of hydrate reservoirs are estimated as shown in Table 2-2. Finite element computations have been performed for different values of overburden depth and cavity width as shown in Table 2-1 using the material properties shown in Table 2-2. The results, which are presented in the next chapter, 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.

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 2-1: 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 2-2: Material Properties for Hydrate Reservoir Strata and Overburden Strata

Material Properties	Hydrate Reservoir Strata	Overburden Strata
Elastic Modulus (psf)	$5.75 \times 10^8 (*)$	2.45×10^8
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	0.15
Cohesion (psf)	2.16×10^5	3.28×10^5
Indirect Tensile Strength (psf)	9.36×10^8	9.36×10^8

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.

CHAPTER 3

MODELING RESULTS

3.1 INTRODUCTION

In order to evaluate the influence of hydrate production on the ground movements(subsidence), it was necessary to model the reservoir compaction anticipated during hydrate production. The ground movements and additional stresses caused in the overburden by the reservoir compaction were computed by using the finite element method as described in the previous chapter.

In the present study, the reservoir compaction was 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.

As presented in the previous chapter, the geometric limits for hydrate reservoirs and overburden strata, for example, the thickness of the hydrate layer and the lateral extent of the hydrate reservoir were first established. 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 3-1, four different location of the dissociation front were considered. For the purpose of evaluation, 16 cases were considered. The values of different parameters corresponding to these cases are shown in Table 2-1. For the comparison purpose, the results of present analysis and longwall analogy on computed subsidence profiles corresponding to each case are shown in Table 3-1.

3.2 RESULTS FROM THE PARAMETRIC STUDY

Figures 3-2 to 3-5 show the finite element meshes, which were used for overburden heights of $h=1500$ ft, 2000 ft, 2500 ft and 3000 ft, respectively. The results from the present analysis on computed subsidence profiles corresponding to each case in Table 3-1 are shown in Figures 3-6 to 3-9. As could be seen from these figures, the maximum ground subsidence could vary anywhere from 0.50 inch to 6.50 inches depending upon the overburden depth and the size of the depleted hydrate reservoir. Relative to those obtained from the longwall analogy [49], these maximum subsidence values are very small. Also, it can be seen from Figure 3-6 to 3-9 and Table 3-1 that the maximum ground subsidence increases with the size of the depleted reservoir. The change in the maximum subsidence appears to be very small with the overburden depth of the hydrate reservoir. These figures also show that the subsidence curve over the depleted reservoir is fairly flat, and

Figure 3-1: Assumed Sizes of Depleted (Dissociated) Reservoir

Figure 3-3: Finite Element Mesh Used for Case 1-b ($h = 2000$ feet)

Figure 3-4: Finite Element Mesh Used for Case 1-c (h = 2500 feet)

Figure 3-5: Finite Element Mesh Used for Case 1-d (h = 3000 feet)

Table 3-1: 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	-

that the subsidence influence propagates beyond the limits of dissociation front.

Figures 3-10 to 3-13 show the normalized subsidence profiles for different overburden depths. As can be seen, the values of $S/S_{\max}$ for different panel widths decrease with increasing distance. This ratio drops to somewhere around 0.6 at a distance of 800 feet for the overburden height of 1500 feet. For the overburden height of 3000 feet, this ratio drops to a value of about 0.8 at a distance of 800 feet. These figures show that the normalized subsidence profile is not significantly influenced by the panel width at a given overburden height within the range investigated. However, the normalized subsidence profile is a function of the overburden height as shown in these figures.

The computed subsidence profiles corresponding to each case in Table 3-1 for the overburden height of 1500 feet are compared with the results corresponding to the "longwall analogy" as shown in Figures 3-14 to 3-16. As can be seen from these figures, the subsidence values computed in the present analysis are much smaller than the values obtained from the longwall analogy. The maximum subsidence value from the present analysis is about 100 times smaller than the value corresponding to the longwall analogy for a panel width of 200 feet at the overburden height of 1500 feet. However, for the same overburden height, this ratio is about 20 for a panel width of 600 feet.

A comparisons of subsidence profiles computed in the present analysis with those from the longwall analogy are shown in Figures 3-17 to 3-19 for three panel widths at the overburden height of 2000 ft. Similar comparisons corresponding to the overburden heights of 2500 and 3000 feet are shown in Figures 3-20 to 3-22 and 3-23 to 3-25, respectively. All these comparisons also show that subsidence values computed in the present analysis are much smaller than the values obtained from the longwall analogy. The maximum subsidence value from the present analysis is about 100-150 times smaller than the value corresponding to the longwall analogy for a panel width of 200 feet. However, for the same overburden height, this ratio is about 20-25 for a panel width of 600 feet.

Subsidence problem appears to 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. This problem appears to be more important at shallow depths.

Figure 3-6: Computed Subsidence Profile for Case 1

Figure 3-7: Computed Subsidence Profile for Case 2

Figure 3-8: Computed Subsidence Profile for Case 3

Figure 3-9: Computed Subsidence Profile for Case 4

S = Computed Subsidence
S_{max} = Computed Maximum Subsidence
Overburden Height, H=1500 ft

Figure 3-10: Normalized Subsidence Profile For Case 1

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

Figure 3-11: Normalized Subsidence Profile For Case 2

S = Computed Subsidence
Smax = Computed Maximum Subsidence
Overburden Height, H=2500 ft

Figure 3-12: Normalized Subsidence Profile For Case 3

S = Computed Subsidence
Smax = Computed Maximum Subsidence
Overburden Height, H=3000 ft

Figure 3-13: Normalized Subsidence Profile For Case 4

Ground Subsidence

Overburden Height = 1500 ft

Figure 3-14: Comparison of Present Analysis With Longwall Analogy For Case 1-a

Ground Subsidence

Overburden Height = 1500 ft

Figure 3-15: Comparison of Present Analysis With Longwall Analogy For Case 2-a

Ground Subsidence

Overburden Height = 1500 ft

Figure 3-16: Comparison of Present Analysis With Longwall Analogy For Case 3-a

Ground Subsidence

Overburden Height = 2000 ft

Fig 3-17: Comparison of Present Analysis With Longwall Analogy For Case 1-b

Ground Subsidence

Overburden Height = 2000 ft

Fig 3-18: Comparison of Present Analysis With Longwall Analogy For Case 2-b

Ground Subsidence

Overburden Height = 2000 ft

Fig 3-19: Comparison of Present Analysis With Longwall Analogy For Case 3-b

Ground Subsidence

Overburden Height = 2500 ft

Figure 3-20: Comparison of Present Analysis With Longwall Analogy For Case 1-c

Ground Subsidence

Overburden Height = 2500 ft

Figure 3-21: Comparison of Present Analysis With Longwall Analogy For Case 2-c

Ground Subsidence

Overburden Height = 2500 ft

Figure 3-22: Comparison of Present Analysis With Longwall Analogy For Case 3-c

Ground Subsidence

Overburden Height = 3000 ft

Figure 3-23: Comparison of Present Analysis With Longwall Analogy For Case 1-d

Figure 3-24: Comparison of Present Analysis With Longwall Analogy For Case 2-d

Ground Subsidence

Overburden Height = 3000 ft

Figure 3-25: Comparison of Present Analysis With Longwall Analogy For Case 3-d

CHAPTER 4

SUMMARY AND CONCLUSIONS

4.1 SUMMARY AND CONCLUSIONS

The primary objective of the research investigation was to evaluate the influence of hydrate production on ground movements at the surface. To accomplish this objective, the reservoir compaction anticipated during hydrate production was modeled by using the finite element method, which is a powerful computer modeling technique. The ground movements at the reservoir roof (i.e. reservoir compression) cause additional stresses and disturbance in the overburden strata. In this study, the reservoir compaction was 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 were computed by using the finite element method.

The first task in the modeling study 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 four different values of depleted size. Four different locations of the dissociation front were considered.

Based on the parameters used in this investigation, the maximum ground subsidence could vary anywhere from 0.50 to 6.50 inches depending on the overburden depth and the size of the depleted hydrate reservoir. Relative to those obtained from the longwall analogy [49], these maximum subsidence values are very small. The results also show that the maximum ground subsidence increases with the size of the depleted reservoir. The change in the maximum subsidence appears to be very small with the overburden depth of the hydrate reservoir. These figures also show that the subsidence curve over the depleted reservoir is fairly flat, and that the subsidence influence propagates beyond the limits of dissociation front. In comparison to those obtained from the longwall analogy, the computed subsidence values are much smaller. The results from the present study can be considered as a lower bound solution to the subsidence caused by hydrate reservoir depletion.

Results show that the normalized subsidence profile is not significantly influenced by the panel width at a given overburden height within the range of parameters investigated in this study. However, the normalized subsidence profile is a function of the overburden height as shown in Chapter 3 of this report.

A comparisons of subsidence profiles computed in the present analysis with those from the longwall analogy shows that subsidence values computed in the present analysis are much smaller than the values obtained from the longwall analogy. The maximum subsidence value from the present analysis is about 100-150 times smaller than the value corresponding to the longwall analogy for a panel width of 200 feet. However, for the same overburden height, this ratio is about 20-25 for a panel width of 600 feet.

The subsidence problem may be more important for hydrate reservoirs at shallow depths. At greater depth, the subsidence problem may not be severe as that expected at shallow depths. Additional stresses developed in the overburden may cause failure in the overburden strata causing well bore stability problems.

5. BIBLIOGRAPHY

1. Baker, P. E., "Experiments on Hydrocarbon Gas Hydrates in Unconsolidated Sand," in Natural Gases and Marine Sediments (Ed. I. R. Kaplan), Plenum Press, New York, 1974.
2. Bayles, G.A., Sawyer, W.K., Anada, H.R., Reddy, S., and Malone, R.D., "A Steam Cycling Model for Gas Production From a Hydrate Reservoir," Paper presented at the Am. Inst. of Chemical Engineers Winter National Meeting, Atlanta, Georgia, 1984.
3. Berry, D. S., "The Ground Considered as a Transversely Isotropic Material," Int. J. of Rock Mechanics and Mining Sciences", Vol. 1, 1964, pp. 159-167.
4. Brown, W. G and Johnston, G.H., "Dikes on Permafrost: Predicting Thaw and Settlement," Canadian Geotechnical Journal, Vol.7, 1970, pp. 365-371.
5. Burshears, M., O'Brien, T.J. and Malone, R.D., "A Multi-Phase, Multi-Dimensional, Variable Composition Simulation of Gas Production From a Conventional Gas Reservoir in Contact With Hydrates," SPE Paper 15246, Louisville, Kentucky, 1986.
6. Cording, E. J., T. D. O'Rourke, and M. Boscardin, "Ground Movements and Damage to Structures", Proc. Int. Conf. on Evaluation and Prediction of Subsidence (ed. S. K. Saxena), Pensacola, Florida, ASCE, 1978, pp. 516-537.
7. Dahl, H. D., D. S. Choi, "Some Cases of Mine Subsidence and its Mathematical Modeling," Proc., Fifteenth Symposium on Rock Mechanics, Custer, State Park, S. D., 1973, pp. 1-21.
8. Dahl, H. D., "Two and Three Dimensional Elastic-Elasto Plastic Analysis of Mine Subsidence," Proc., Fifth Int. Strata Control Conference, London, 1972.
9. Desai, C. S., and Siriwardane, H. J., Constitutive Laws for Engineering Materials with Emphasis on Geologic Materials, Prentice-Hall, 1984.
10. 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.
11. Dykins, J. E., "Tensile and Flexural Properties of Saline Ice," Physics of Ice, Proc. of Int. Symp. on Phys. of Ice, Munich, Germany, 1968.

12. Gas Hydrate Project Report, DOE/METC/SP-214, February, 1984.
13. Gioda, G., "Some Remarks on Back Analysis and Characterization Problems in Geomechanics," Proceedings, 5th International Conf. on Numerical Methods in Geomechanics, Nagoya, Japan, 1985.
14. Hobbs, P. V., Ice Physics, Oxford University Press, 1974.
15. Holder, G. D. and Hand, J. H., "Multiphase Equilibria in Hydrates from Methane, Ethane, Propane and Water Mixtures," AIChE Journal, Vol. 28, No. 3, 1982.
16. Hwang, C. T., Murray, D. W., and Brooker, E. W., "A Thermal Analysis for Structures on Permafrost," Canadian Geotechnical Journal, Vol. 9, 1972, pp. 33-46.
17. Johnston, G. H., Permafrost Engineering Design And Construction, John Wiley, 1981.
18. Jumikis, A. R., Rock Mechanics, Gulf Publishing, 1983.
19. Jumikis, A. R., Thermal Soil Mechanics, Rutgers University Press, 1966.
20. King, M. S. and Garg, O. P., "Compressive Strength and Dynamic Elastic Properties of Frozen and Unfrozen Iron Ore from Northern Quebec," Proceedings, 4th Canadian Permafrost Conference, 1982.
21. King, H. J., and J. T. Whetton, "Mechanics of Mine Subsidence," Proc. European Congress on Ground Movement, Leeds, England, 1957, pp. 27-38.
22. Konrad J. M. and Morgenstern, N. R., "Frost Heave Prediction of Chilled Pipelines Buried in Frozen Soils," Canadian Geotechnical Journal, Vol. 21, 1984, pp. 100-115.
23. Kuusteraa, V. A. and Hammershaimb, E. C., "Handbook of Gas Hydrate Properties and Occurrence," Report, DOE, MC/19239-1546, 1983.
24. Ladanyi, B., "An Engineering Theory of Creep of Frozen Soils," Canadian Geotechnical Journal, Vol. 9, 1972, pp. 63-80
25. Mackay, J.R. and Burrous, C. " Uplift of Objects by an Upfreezing Ice Surface, "Vol. 16, 1979, pp. 609-613.
26. Makogon, Y. F., Hydrates of Natural Gas, Nedra, Moscow, 1974.

27. Marshall, G. J., and D. S. Berry, "Calculation of the Stress Around an Advancing Longwall Face in Viscoelastic Ground," Proc., First Congress, Int. Society of Rock Mechanics, Vol.II, 1966.
28. McGuire, P. L., "Recovery of Gas From Hydrate Deposits Using Conventional Technology," SPE/DOE 10832, VGR Symposium of SPE, Pittsburgh, PA., 1982.
29. Michel B., "A Numerical Model Of Creep Of Polycrystalline Ice", Canadian Geotechnical Journal, Vol.15, 1978.
30. Mozumdar, B. K., "A Mathematical Model of Ground Movement Due to Underground Mining," Ph.D. Dissertation, Pennsylvania State University, August, 1974.
31. Munson, D. E., and W. F. Eichfeld, "European Empirical Methods Applied to Subsidence in U.S. Coal Fields," Report, SAND80-1920, Sandia National Laboratories, 1980.
32. National Coal Board, Subsidence Engineers Handbook, London, 1975.
33. Nixon, J.F., Morgenstern, N. R., and Reesor, S. N., "Frost Heave-Pipeline Interaction Using Continuum Mechanics," Canadian Geotechnical Journal, Vol. 20, 1983, pp. 251-261.
34. Pariseau, W. G., and H. D. Dahl, "Mine Subsidence and Model Analysis," Transaction of the Society of Mining Engineers of AIME, Vol. 241, 1968, pp. 488-494.
35. Pharr, G. M. and Merwin, J. E., "Effects of the Brine Content on the Strength of Frozen Ottawa Sand," Cold Regions Science and Technology, Vol. 11, 1985.
36. Ranson, B. B., E. O'Rourke, and P. H. Rey, "Design and Demonstration of Subsidence Monitoring System," Report, Woodward-Clyde Consultant, sponsored by U. S. Department of Energy, 1982.
37. Salamon, M. G. D., "Elastic Analysis of Displacements and Stresses Induced by the Mining of Seam or Reef Deposits," South African Institute of Mining and Metallurgy Journal, Part I, Vol. 64, November 1963, pp. 128-150; Part 2, Vol. 64, January, 1964, pp. 197-218; Part 3, Vol. 64, March, 1964, pp. 468-500; Part 4, Vol. 65, December, 1964, pp. 319-341.
38. 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.

39. Shadbolt, C. H., "Mining Subsidence-Historical Review and State of the Art," Proc. of the Conference Held at the University of Wales Institute of Science and Technology, Cardiff, July, 1977, pp. 705-748.
40. Siriwardane, H.J., and C. S. Desai, "Computational Procedures for Nonlinear Three-Dimensional Analysis with Some Advanced Constitutive Laws," Int. J. of Numerical and Analytical Methods in Geomechanics, Vol. 7, No. 2, 1983.
41. Siriwardane, H. J., "A Computer Code for Nonlinear Two-Dimensional Finite Element Analysis of Some Geotechnical Problems", 1982.
42. Siriwardane, H. J., and J. Amanat, "Prediction of Subsidence in Hilly Ground Terrain Using Finite Element Method," Proc., 2nd International Conference on Stability in Underground Mining, AIME, Lexington, Kentucky, August 1984.
43. Siriwardane, H. J., and J. Amanat, "Finite Element Analysis and Prediction of Subsidence Caused by Underground Mining," Report, CE/GEO-83-2 Department of Civil Engineering, West Virginia University, Morgantown, WV, 1983.
44. Siriwardane, H. J., and J. Amanat, "Analysis of Subsidence Caused by Underground Mining, International Journal of Mining Engineering, Vol. 2, 1984.
45. Siriwardane, H. J. and Lawson, W. F., "Mechanical Behavior of Gas Hydrates in Unconsolidated Media," Presented at the Symposium on Gas Hydrates at the North American Chemical Congress, Toronto, Canada, 1988.
46. Siriwardane, H. J., and J. Amanat, "Analysis and Prediction of Subsidence in Hilly Ground Terrain using Finite Element Method," Submitted to the Int. J. on Num. and Analy. Methods in Geomechanics, 1984.
47. Siriwardane, H. J. and Lawson, W. F., "Synthesis of Methane Gas Hydrates in Unconsolidated Media," Under Review by the International Journal of Cold Region Science and Technology, 1991.
48. Siriwardane, H. J., and L. K., Moulton, "Direct and Indirect Influence of Mining Related Subsidence on Structural Damages: A Case Study," Proc., Int. Conf. on Case Histories in Geotechnical Engineering, St. Louis, Missouri, 1984.
49. Siriwardane, H. J. and W. S. Tsai, "Ground Movements Associated With Gas Hydrate Production in Geologic Media", Report Prepared for the U.S. Department of Energy under the Grant No: DE-FG-21-MC24051, 1989.

50. Starfield, A. M., and S. L. Crouch, "Elastic Analysis of Single Seam Extraction," Proc., Fourteenth Symposium on Rock Mechanics, Pennsylvania State University, University Park, PA, 1972, pp. 421-440.
51. Stoll, R. D., "Effects of Gas Hydrates in Sediments," in Natural Gases in Marine Sediments (Ed. I. R. Kaplan), Plenum Press, New York, 1974.
52. Tandanand, S., and L. R. Powell, "Assessment of Subsidence Data from the Northern Appalachian Basin for Subsidence Prediction," RI8630, U. S. Bureau of Mines, 1982.
53. Tsytovich, N. A., The Mechanics of Frozen Ground, McGraw-Hill Book Company, New York, 1975 (Translated from Russian).
54. Voight, B., and W. Pariseau, "State of the Predictive Art in Subsidence Engineering," J. of the Soil Mechanics and Foundations Division, Proc. ASCE, Vol. 96, No. SM2, 1970, pp. 721-750.
55. Wardell, K., "Some Observations on the Relationship Between Time and Mining Subsidence," Trans. of Inst. of Mining Engineers, Vol. 113, 1953.
56. Weaver J.S. and Morgenstern N.R., "Simple Shear Creep Tests On Frozen Soils", Canadian Geotechnical Journal, Vol.
57. Zienkiewicz, O. C., The Finite Element Method in Engineering Science, 3rd Edition, McGraw-Hill, London, 1977.

**DATE
FILMED**

10/27/93

END