Surface Subsidence in Natural Gas Fields

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ABSTRACT A large volume of ground water, which contained water-soluble natural gas, has been pumped from a certain aquifer system. The volume of pumpage water was increased step by step. Surface subsidence has occurred due to the subsequent decline in groundwater level. A quasi-three dimensional simulating system has been developed and applied to evaluate the aquifer system. The simulating system consists of a quasi-three dimensional finite-element computer program for simulating groundwater flow and an influence function method to estimate the incidental land subsidence. Contour maps of water level and land subsidence can have also been obtained. This system gives useful simulation results based on past, present and future conditions and has contributes for development without environmental hindrance.

INTRODUCTION

In Japan, natural gas is coming into wide use as energy for power plants, public use, and so on. The development of domestic natural gas fields has been accelerated, yet most of natural gas demand in Japan is now served by other countries. The gas field examined in this paper is one of the largest ones in Japan, located in the northern area of the Miyazaki Plain in Kyushu island as shown in Fig.1. During the 16 years, about 50 wells have been developed at intervals of roughly 500m in an area of 40km². The geologic formation of the aquifer system is classified into seven layers, which involves two sandy gas beds, Pliocene age, and intermediate between muddy beds. The sandy ones contain water-soluble natural gas and concentrated iodine. These layers are 180-310m, 400-490m in thickness, respectively. The daily volume of pumpage water has increased from 6,600kl in 1975 to 7,700kl in 1989. The subsequent decline in water level results in a corresponding increase in effective stress on the sandy layer sequence in the aquifer system. The compaction of the permeable layers affects the above layers in succession. As a result, land subsidence has occurred at the surface.

Due to these circumstances, it is necessary to predict the ground movement and to consider how to minimize the movement from the viewpoint of environmental control. In this study, a new environmental
FIG. 1 Distribution of operating and monitoring gas wells and total volume of pumpage water from 1974 to 1988.

A new analytical system which can predict and check surface subsidence is proposed. This analytical method consists of two stages:
(a) Water flow analysis by the finite element technique gives the distribution of water level in a gas seam;
(b) The gas seam deformation is given by the above calculated change of water level head. Nextly, by using Influence function method, the surface subsidence due to the gas seam deformation at arbitrary points can be obtained.

This new analytical system is applied to the Miyazaki gas field.

QUASI-THREE DIMENSIONAL GROUNDWATER FLOW - SUBSIDENCE COUPLING SIMULATION SYSTEM

For a long time, many studies for groundwater flow and land subsidence due to discharge of water have been done at different water withdrawal sites (e.g. Nishida et al., 1981). Evaluating aquifer compaction has been the object of most studies, and the amount of land subsidence was usually assumed to be equivalent to this aquifer deformation. However, land subsidence will occur as a result of three-dimensional propagation of the deformation of aquifer, characterized by an influence factor within a limit angle, as shown in Fig.2. In this paper, groundwater flow, aquifer compaction, and land subsidence are systematically simulated using a quasi-three dimensional simulation system, which is formed by combining the following three stages:
(a) Simulation of groundwater flow and the water-level decline due to
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water pumpage from the aquifer system are given using a quasi-three dimensional finite element computer program. The program can consider the depth of aquifer, which is based on the following equation:

\[ K \frac{\partial^2 H}{\partial x^2} + K \frac{\partial^2 H}{\partial y^2} + Q = 0 \]  (1)

where \( K \) is permeability in the \( x \) and \( y \) directions, \( H(x,y) \) is hydraulic head, and \( Q \) is discharge rate. The model uses a square grid with a certain horizontal spacing. This size of spacing is dependent on the nature of the problem.

(b) The decline in water level is directly related to the increase in effective stress, while the total stress on the solid phase of the ground remains constant. So the gas seam compaction is caused by this increase of effective pressure. While most analytical methods for predicting subsidence are based on the well-known Terzaghi's consolidation theory which is suitable for cases of relatively shallow and/or unconsolidated strata such as soft clay, the proposed method is based on the assumption that elastic behavior dominates for the relatively deep and/or compact strata. In other words, the calculation of the gas seam deformation is based on generalized Hooke's law:

\[ d = \left( \frac{m}{E} \right) (1-2\nu) \gamma g \Delta H \]  (2)

where \( s \) is deformation of gas seam, \( m \) is thickness of gas seam, \( E \) is young's modulus of gas seam, \( \nu \) is Poisson's ratio of gas seam, \( \gamma g \) is unit weight of water containing natural gas, and \( \Delta H \) is the amount of water level decline in the aquifer system. This is for a single seam. If there are multiple gas seams, we have to sum up the effects of each gas seam deformation.
Surface subsidence is not proportional to the decline in water level in the aquifer system, while the gas seam deformation is. This is because the influence of gas seam deformation at a certain depth propagates and spreads three-dimensionally to surface. Surface subsidence attributed to gas seam compaction is obtained by the influence function method, which is a three-dimensional method that can be used to obtain displacement at a large number of points and distribution of subsidence both accurately and efficiently (Esaki et al., 1987).

\[ s = e \times a \times d \times z \]

where \( s \) is land subsidence at a point, \( e \) is an influence factor, \( a \) is coefficient of subsidence, \( d \) is amount of seam compaction, and \( z \) is a time factor. And when analyzing a gas field in which many wells have been developed one by one, time factors should also be considered. Surface subsidence increases over long periods of time, while the change in water level is small except for the initial steep loss of head. It is shown that surface subsidence is related to both the change in water level and the time since development. The time factor should be used appropriately.

PRACTICAL APPLICATION

In Japan since 1932, groundwater containing natural gas has been pumped in different places, such as Hokkaido, Chiba, Niigata, Miyazaki, and Okinawa. Following the advance of industry, the amount of pumpage water and extracted natural gas have increased rapidly. The overdevelopment of groundwater and natural gas has resulted in a type of mining damage, i.e. land subsidence. Especially in Niigata, subsidence has exceeded 50cm per year, and in Chiba the total subsidence since 1961 amounts to over 100cm. However, the subsidence phenomena have decreased steadily since 1970 when laws and ordinances restricting the groundwater usage were established (Yamamoto & Kobayashi, 1984).

The area studied here is located in the northern portion of the Miyazaki Plain in Kyushu, southern Japan. This area is alluvial lowland, approximately 20km long and 2km wide facing the Pacific Ocean in the east and divided by the river Hitotsuse into northern and southern regions. The typical geological sequence underlying this area is shown in Table 1.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Bed</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>surface-300m</td>
<td>Takanabe</td>
<td>muddy</td>
<td>impermeable</td>
</tr>
<tr>
<td>300-600m</td>
<td>Sadohara</td>
<td>sandy</td>
<td>permeable (gas seam)</td>
</tr>
<tr>
<td>600-1100m</td>
<td>Niinazume</td>
<td>muddy</td>
<td>impermeable</td>
</tr>
<tr>
<td>1100-1500m</td>
<td>Uryuno</td>
<td>sandy</td>
<td>permeable (gas seam)</td>
</tr>
<tr>
<td>1500-</td>
<td>Ikime</td>
<td>muddy</td>
<td>impermeable</td>
</tr>
</tbody>
</table>
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FIG. 3-a Measured contour map of subsidence from 1974 to 1978.

FIG. 3-b Measured contour map of subsidence from 1974 to 1988.
That is, this geological formation has packed groundwater containing water-soluble natural gas and allows no natural recharge to the aquifer system. The locations of 47 operating wells are shown in Fig. 3-a and Fig. 3-b. Each well is located at intervals of roughly 500m, at depths of 400-1,300m. In 1989, the daily volume of pumpage water and extracted natural gas amounted to 7,700kl and 11,300Nm³, respectively. The subsequent decline in water level results in a corresponding increase in effective stress on the sandy layer sequence in the aquifer system. The compaction of the permeable layers affects the above layers three dimensionally. As a result, shown in Fig. 3-a and Fig. 3-b, land subsidence has occurred in the vicinity of well field.

First, the distribution of water level decline was evaluated using a quasi-three dimensional computer program, under the following conditions:

(a) initial condition: water level at all nodes is the surface.
(b) boundary condition: water level at boundary nodes is the surface.

Input data for water head decline at each of the wells were modified according to Thiem's equation:

\[
\Delta h_w = \frac{Q}{2\pi K r m} \ln \left( \frac{R}{r} \right)
\]

where \( \Delta h_w \) is local drawdown, \( Q \) is discharge rate, \( K \) is a permeability index, \( r \) is radius, and \( R \) is the influence limit. In the case that the upper seam of the aquifer system is of low permeability, the water level in the vicinity of well will decline locally and intensively (as shown in Fig. 4). Some input data are modified according to the interval of grids.

Hydraulic properties used as input data were deduced from laboratory tests, which are shown in Table 2.

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**FIG. 4** Schematic diagram showing variation in drawdown curve due to the extraction of water containing natural gas.
TABLE 2 Hydraulic properties.

<table>
<thead>
<tr>
<th>Seam</th>
<th>m(m)</th>
<th>E(kg/cm²)</th>
<th>ν</th>
<th>K(cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sadohara</td>
<td>240</td>
<td>2x10⁶</td>
<td>0.25</td>
<td>4x10⁻⁵</td>
</tr>
<tr>
<td>Uryuno</td>
<td>480</td>
<td>4x10⁶</td>
<td>0.25</td>
<td>4x10⁻⁵</td>
</tr>
</tbody>
</table>

Interactively, a contour map of water level, which was obtained by the post-processing program, was proportional to the contribution of gas seam deformations. This was done because water level withdrawal will lead the increase of effective stress in the aquifer system, and gas seam compaction will be caused by the stress increase. The gas seam deformation was estimated by equation 2.

Next, land subsidence caused by the seam compaction was obtained using an influence function method. The program used is performed in three steps:
(a) a pre-processor for data input together with a digitizer, accurately reproduces the irregular layout of the water level contour map;
(b) a main-processor calculates the influence coefficient of each point on the surface, at 25m intervals;
(c) a post-processor graphically displays the computed results.

Fig.5-a shows the contour map for the predicted land subsidence four years after development in 1978. Fig.5-b is after 14 years, 1988. The shape of the contour lines is fairly similar with one of the field data in Fig.3-a and Fig.3-b.

As shown in Fig.5-a and Fig.5-b, subsidence is large where the volume of pumpage water is relatively large(Fig.1). Even if the pumpage volume is similar, the time lag since development may affect the subsidence phenomena. In order to cope with this condition, a time factor was applied, according to the period since development and the decline in water level. This procedure was also applied to the two profiles shown in Fig.6 and Fig.7, which compare field data and predicted subsidence in 1988, according to cross sections A-A' and B-B'. This system provides the simulation of land subsidence in the aquifer system appropriately. The differences in shape of two profiles, can be attributed to local variance in the local geological structure, e.g. small faults or the depth of alluvium.

SUBSIDENCE MONITORING AND ENVIRONMENTAL CONTROL

In order to protect surface affairs from subsidence and to develop valuable domestic resources in agreement with local inhabitants, the Technical Committee for natural gas development has been established at Kyushu Branch of MITI in 1974, just before development of the Miyazaki field. By recommendation from the committee, level surveying(126 measuring points over a total length of 53km), measuring of ground water level at the monitoring wells(four wells: one 1300m and three 60m), and prediction of subsidence have been carried out in collaboration with the authorities and the mining company every year.
FIG. 5-a Calculated contour map of subsidence from 1974 to 1978.

FIG. 5-b Calculated contour map of subsidence from 1974 to 1988.
The progress of ground water withdraw and subsidence has been checked and the simulation system also has been modified several times following the field data. During the 14 years since the beginning of operation, subsidence has been restricted to within 30mm per year and withdraw of each well has also within 200m from sea level. In the next decade, 20 new wells are planning in the northern field. The committee will continue to make efforts at environmental control by the use of monitoring system.

CONCLUSION

The interrelation between the volume of pumpage water, groundwater flow, aquifer compaction, and land subsidence can be clarified and simulated according to an aquifer system with dominantly elastic character. This system will also be able to predict the future conditions, which is useful for developing new wells in the northern field.

ACKNOWLEDGMENT

The authors are much indebted to the staffs of the Ministry of
International Trade and Industry in Japan and Ise Chemical Industries Co. Ltd. for providing the valuable data and to Associate Professor M. Nishigaki, Okayama University, offering us PC-GWAPG computer program.

REFERENCES


