GROUND MOVEMENTS CAUSED BY MINING ACTIVITIES IN THE NETHERLANDS

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Abstract
The mining activities in the Netherlands consist of coal mining from the beginning of this century to mid seventies and in the present the production of oil and gas on- and off-shore, particularly from the major Groningen gas reservoir.

Small and deeply buried gas reservoirs are hardly capable of producing notable subsidence, in contrast to extremely large gas reservoirs at great depth, like the major Groningen gas reservoir, that may be potential candidates for ground movements.

Subsidence results from the interaction between the compacting reservoir and its visco-elastic surroundings. This displacement interaction can be calculated for a disc-shaped reservoir using the theory of poro-elasticity.

An outline is given of the subsidence due to coal mining in the past. After the termination of the coal extraction and the ceasing of the pump-activities, the mine water level has gradually risen to the surface.

Surface movements above the mine water reservoir result from the interaction between the dilating reservoir and its elastic surroundings, which are mutually connected. The surface rising is treated as a typical problem in elasto-mechanics, where the mine water reservoir dilates in a half space, with a traction-free surface, due to an increase in pore-pressure up to hydrostatic level.

General
The last twenty years the domestic energy supply of the Netherlands changed dramatically. This change has been strongly determined by the discovery of the Groningen gasfield with an expected reserve of 2500 \( \times \) 10^6 m^3. Until the end of the fifties the energy needs of the Netherlands were mainly supplied by coal of national origin. Coal mining was concentrated in the South of the Netherlands, with an average annual production of 12 \( \times \) 10^6 metric tons. The total exploited quantity of coal amounted to 600 \( \times \) 10^6 tons, and was mainly exploited from 1900 to 1975.

This coal-mining caused substantial land subsidence which in several places amounted to more than 10 meters and in many cases it lead to heavy mine-damage. For an overview of the total surface subsidence due to coalmining see figure 1.

Since 1965, the Groningen gasfield is in production and the total exploited quantity of gas comes to more than 800 \( \times \) 10^6 m^3. This quantity of gas is extracted from a reservoir with a thickness of 150 m, at a depth of 3000 m and with an extention of nearly 900 km^2. In 1975, the NAM (Nederlandse Aardolie Maatschappij) in cooperation with KSEPL (Koninklijk Shell Exploratie en Produktie Laboratorium) published the results of an extensive investigation, which shows that the surface subsidence above the Groningen gasfield amounts to more than 25 cms in the far future. This slight surface subsidence still makes it necessary to make provisions for
maintaining the vulnerable water-management in the polder-region of the Groningen province, most of it being situated below mean sealevel. For the Groningen reservoir see figure 2.

For the Groningen gasfield a comparison is made between the prediction of the subsidence on the basis of an elastomechanic calculating model and
the results of an annual large scale levelling survey. Additionally this levelling survey, subsidence is controlled by shallow compaction recording, by means of a cable-measurement method, and by monitoring of radio-active bullets for measuring the in-situ reservoir compaction.

After the abandonment of the Limburg coalmines, the pumping of mine water has ceased and the old workings, covering an area of 160 km² and in depth reaching from the surface to nearly 1000 m, are gradually being flooded. The rising of mine water is mainly caused by a workflow from greater depth which causes a surface rising by a pressure-build up in the subsurface. The pressure-build up will in the end rise to the hydrostatic level and it is anticipated that a surface movement of 20 to 30 cms will develop.

In order to make the necessary provisions in time as well above the Groningen gasreservoir as above the mine water reservoir in Limburg, a reliable prediction of the subsidence or surface rising to be anticipated is necessary. In both cases, a phenomenological prediction-model is used; where an isolated volume - the reservoir - shrinks or dilates in a half-space with a tractionfree surface due to a reduction, or build up in pore-pressure.

The displacement can be calculated for arbitrary geometrical reservoir conditions applying the theory of pore-elasticity.

Compaction or dilatation of disc-shaped reservoirs

The mechanism of reservoir compaction or dilatation can be explained as follows. The pressure of producible gas or incoming water is mainly dependent on the depth of the accumulation. The degree of compaction or dilatation depends on the strength of the formation matrix which is related to the effectiveness of the cementation of the rock-matrix. The total compaction or dilatation \( \Delta h \) is therefore related to the deformation properties of the rock, the reduction or increase in the gas- or fluid-pressure \( \Delta p \), and the thickness \( h \) of the formation. The geometry for the determination of the displacement field around a disc-shaped reservoir in the half-space, is given in figure 3. In order to predict the compaction or dilatation behaviour the following information is required:

- a map, showing the full extent of the reservoir area and also indicating the reservoirthickness ( \( h \) ),
- a prediction of the reservoir pressure reduction or increase ( \( \Delta p \) ) at a given time,
- the uni-axial compaction coefficient \( c_m \) or the uni-axial dilatation coefficient \( d_m \) of the rock, i.e. the compaction or dilatation per unit stress.

Hence the total compaction or dilatation at a given time and place can be calculated from the formula:

\[
\Delta h = (c_m \text{ or } d_m) \times \Delta p \times h
\]

The surface subsidence or rising above the centre of a disc-shaped reservoir amounts to:

\[
u_z (0,0) = \frac{2}{\pi} (1-\gamma)(1-C/\sqrt{1+C^2}) \times (c_m \text{ or } d_m) \times h \times \Delta p
\]

where \( C = c/R \) then \( c \) is the depth and \( R \) the radius of the disc-shaped reservoir and \( \gamma = 0,25 \) the Poisson-ratio. For a complete mathematical treatment of the problem see ref. Geertsma J. a.o.-

A linearly changing stress \( S(t) \) is applied to a substance, which is elastic in hydrostatic compaction or dilatation and behaves as a Kelvin substance in shear.

With the application of the Correspondence principle from rheology and the theory of the Laplace transforms, the solution for the surface subsidence
Geometry for the displacement field around a disc-shaped reservoir in the half-space

$Z$-AXIS $r, \theta$

FREE SURFACE

$U_r(r, 0)$

$U_z(r, z)$

NUCLEUS OF STRAIN

Relationship between the elastic and visco-elastic deformation above a disc-shaped reservoir

$U_z = \frac{U_z}{2(1-\nu)(1-C/1+C')h(\sigma_m \text{ or } \sigma_m)}$

$\frac{dU_z}{dt} = S_1$

$k + 3K = T_m = \text{RETARDATION TIME}$

FIGURE 3

FIGURE 4
or rising in the visco-elastic half space can easily be written down from the solution in the elastic half space:

\[ u_{z}^{(0,0)}_{\text{visco-elastic}} = u_{z}^{(0,0)}_{\text{elastic}} \left\{ t - T_{M} \left( 1 - e^{-t/T_{M}} \right) \right\} \]

and \( T_{M} \) is the retardation time in years, see figure 4, ref. Jaeger J.C. and Cook N.G.W.

For practical prediction of subsidence or surface rising an accurate determination of the uni-axial compaction or dilatation coefficient is needed.
This can be done by analysing a series of levelling results in connection with the pressure reduction for the Groningen area or the mine water rising in the former coal-district.

The geometry of the gas- and mine water-reservoir

The subsidence or rising of a bench-mark on ground surface is strongly dependent on the shape, the extent and the depth of the reservoir, expressed in the geometry-factor \( f = \frac{1 - C/\sqrt{1 + C^2}}{C} \). The subsidence or the rising is maximum with an infinite extended reservoir \( C = 0 \).

The vertical ground movement of a disc-shaped reservoir with a radius equal to the depth of the reservoir \( C = 1 \) amounts to 28% of the movement by a reservoir with an infinite radius. On the basis of the foregoing a rotation symmetrical integration-net has been drawn-up in which the percentages of influence change from 28% by \( C = 1 \) to 4% by \( C = 0,2 \), see figure 5. For practical use this integration-net is subdivided in octants, making it possible to determine, in an accurate way, the geometry-factor of a reservoir with an arbitrary shape.

In the case of the rising mine water, reservoirs are situated on top of each other, depending on the number of extracted coal-seams. It is justified to assume that the rising surface, as a consequence of the inflowing mine water, is in relation with the subsidence caused by coal-mining in the past.

This subsidence is maximal by extracting a circular area with a radius equal to the seam-depth, the critical area.

This critical area is also subdivided in 5 zones and 8 sectors, by which the subsidence from the extraction of a coal-seam of irregular shape can be determined in a reasonable and accurate way, see also figure 5.

In predicting the surface rising in relation with the flooding of the coal workings, the assumption is made that the thickness of the delating reservoir corresponds with the original coal-seam thickness. This assumption of course influences the determination of the uni-axial dilatation coefficient, but has in the end no influence on the prediction of the surface rising.

Figure 5 shows, in the form of a nomogram, the relation between the subsidence in the past and the anticipated surface rising in the near future. For example: the extraction of a coal-seam, with a geometry-factor coal of 30%, and a geometry-factor water of 57%, and a depth of 250 m, will cause a surface rising of 11% of the subsidence through coal extraction in the past. It is to be expected that the surface in several regions of the former coal-district in Limburg will rise to more than 25 cms depending on the subsidence in the past due to coal extracting.
SUBSIDENCE VERSUS SURFACE-RISING

\[ h = \text{seam-thickness} \]
\[ v = 0.25 \]
\[ C = \frac{h}{R} = 0.80 \]

\[ \beta = \text{Limit angle} \]

\[ A = 3.5\% \]
\[ B = 3\% \]

\[ d_m = 1.45 \times 10^{-3} \text{ cm}^3/\text{kgf} \]

\[ \text{Perc.} = \frac{\text{surface-rising}}{\text{subsidence}} \]

\[ \text{GC} = \text{Geometry Coal extraction} (\%) \]
\[ \text{GW} = \text{Geometry Water-rising} (\%) \]

FIGURE 5
The uni-axial compaction of the Groningen gas reservoir

The phenomenon of reservoir compaction is controlled by the volumetric changes in a porous rock as a result of the change of in-situ stresses that accompany the production of reservoir fluids or gasses. Various measuring techniques have been developed for determining rock deformation under external pressure. The tri-axial compaction test with zero-lateral strain is used for the determination of the uni-axial compaction coefficient $c_m$. Taking into account the different compaction behaviour of the formation-samples, an average value $c_m = 1.45 \times 10^{-8}$ cm$^2$/kgf was obtained. The individual measurements were within a range of an $0.5 - 4.5 \times 10^{-8}$ cm$^2$/kgf.

As a consequence of the inhomogeneous composition of the gas reservoir and the anisotropy of the Rotliegendes sandstone, the determination of the $c_m$ value in the laboratory shows a wide spread. Therefore, it is to be preferred to determine the uni-axial compaction coefficient in an indirect way, by comparing the predicted and measured surface subsidence. For this comparison and for the calculating results, see figure 6. Two geo-mechanical hypotheses are tested:
- a linear-elastic model $c_m = 0.35 \times 10^{-5}$ cm$^2$/kgf, and
- a visco-elastic model, with the same compaction coefficient and a retardation time $T_m$ of 1 year.

The best adjustment is reached by the assumption that the surface reacts to the visco-elastic model, with the $c_m$ and $T_m$ values already mentioned.

This $c_m$ determination on the basis of field-observations differs significantly from that of laboratory-investigations and has resulted in a reduction of the predicted surface subsidence.

A dilating mine water reservoir

The uni-axial dilatation coefficient for the surface rising, in relation with the rising mine water in the former coal-district of the Netherlands, is determined by field-measurements with respect to surface rising and direct gauging of rising mine water in former shafts. For prediction of long term surface rising 3 geo-mechanical models are tested:
- a linear-elastic model, assuming the mine water rising in the Carboniferous-strata goes by a constant velocity and is not influenced by the coal extraction in the past. The best adjustment between recent observations and the prediction is obtained with an uni-axial dilatation coefficient $d_m = 0.5 \times 10^{-5}$ cm$^2$/kgf. The ultimate rising according to the linear-elastic model amounts to 16 cms for the benchmark 60 D 099, see figure 7.
- a visco-elastic model with a retardation-time of 2 years. The uni-axial dilatation coefficient in this model is equal to $0.75 \times 10^{-5}$ cm$^2$/kgf. Testing the visco-elastic model gives a better smooth adjustment between the observed and predicted surface rising than a linear elastic model, see figure 7.

On the basis of the tested visco-elastic model, the maximum rising in 60 D 099 will amount to 24 cms about 1990, one year after the mine water has risen to the surface.

The coal extraction in the past is related to the recent rising of mine water. Due to the long-wall caving system and the movement on a large scale that is connected with it, an additional porosity and permeability has been created. The pressure build up caused by rising mine water shapes a dilating reservoir in the old workings. The rising of the surface is, among other things, determined by the depth and the thickness of the expanding reservoir. On the basis of in-situ observations the assumption is justified that the
SUBSIDENCE VERSUS PRESSURE-DROP: SIDDEBUREN

Surface rising versus pressure rising benchmark 60 D 099

Uz (mm)

Pressure rising
Levelling results
Elastic seam-model
Elastic

d_m = 1.45 \times 10^{-3} \text{ cm}^2/\text{atm}
d_m = 0.5 \times 10^{-5} \text{ cm}^2/\text{atm}

\begin{align*}
\text{TOP CARBON} & \quad 272 \text{ M.L.} \\
\text{III} & \quad 537 \text{ M.L.} \\
\text{IV} & \quad 401 \text{ M.L.} \\
\text{V} & \quad 316 \text{ M.L.} \\
\text{VI} & \quad 272 \text{ M.L.} \\
\text{0 m N.A.P} & \quad +105 \text{ m N.A.P}
\end{align*}

\begin{align*}
0 \text{ m N.A.P} & \quad 316 \text{ M.L.} \\
401 \text{ M.L.} & \quad +105 \text{ m N.A.P}
\end{align*}

\begin{align*}
730 \text{ M.L.} & \quad \text{I}
\end{align*}

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thickness of the reservoir is proportional to the seam-thickness of the coal excavation in the past. In determining the uni-axial dilatation coefficient the foregoing assumption must be taken into account, and therefore a direct comparison with the coefficients in the preceding geomechanical models is impossible.

- In the model on the basis of the excavated coal-seams only a linear-elastic hypothesis with respect to the ground movements is tested, by which the pressure build-up in the reservoirs is derived from the gauging in the former mine-shafts. The best fit between observations and prediction results in an uni-axial dilatation coefficient of $1.45 \times 10^{-5}$ cm$^2$/kgf.

The maximum rising of the bench-mark 60 D 099 will amount to 23 cms and is nearly the same as in the linear elastic model with a constant rising of the mine water and a dilatation coefficient of $0.75 \times 10^{-5}$ cm$^2$/kgf and a reservoir thickness including the total Carboniferous-strata.

Conclusions

Summarising, it can be said that for the prediction of the subsidence, resulting from gas production as well as the rising of the surface by a dilating mine water reservoir, the use of a linear-elastic deformation model has to be preferred. The retardation times are very short in comparison with the total duration of the geo-mechanical processes.

In the case of the Groningen gas-reservoir, the most probable value of the uni-axial compaction coefficient is equal $0.35 \times 10^{-5}$ cm$^2$/kgf. On the basis of this compaction coefficient, the maximum subsidence above the centre of the reservoir amounts to 25 cms. This subsidence will be reached around the year 2025, under normal production progress.

The most reliable prediction for the rising above the Limburg mine water reservoir is obtained by using the so-called "coal-seams model" with a linear-elastic deformation and an uni-axial dilatation coefficient of $1.45 \times 10^{-5}$ cm /kgf. The maximum surface rising is dependent on the coal excavations in the past and in several places will amount to more than 25 cms. It is obvious that this surface rising, in relation with the gradual and smooth nature of the movement, does not cause any new mine damage.

References:


Pöttgens J., 1982, Forty years of Thought, Feestbundel ter gelegenheid van 65 ste verjaardag van Professor Baarda p. 570-588.