Predicting land subsidence with a constant-parameter coupled model for groundwater flow and aquitard compaction: the Markerwaard case

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Abstract A constant-parameter coupled model for groundwater flow and aquitard compaction, based on MODFLOW and a special compaction-related IBS module, is used in this paper to predict land subsidence that would occur as a consequence of reclaiming the Markerwaard Polder in The Netherlands. The same case has been analyzed previously in an uncoupled approach, but taking into account stress-dependency of geotechnical parameters. Comparing the new model output with the previous results enables conclusions to be drawn for this particular case regarding the importance of a coupled modelling approach, and regarding the errors made when using constant geotechnical parameters instead of stress-dependent ones. Analysing the performance of the MODFLOW-IBS modelling approach in this case may help appreciate the advantages of a coupled modelling approach and understand under which conditions it is still acceptable to use constant parameters, given a certain accuracy required.

NOTATION

- $C$: compression coefficient, dimensionless
- $C_c$: compression index, dimensionless
- $C_r$: recompression index, dimensionless
- $e$: void ratio, dimensionless
- $e_0$: initial void ratio, dimensionless
- $g$: gravitational acceleration, m s$^{-2}$
- $K_{xx}, K_{yy}, K_{zz}$: hydraulic conductivity, m s$^{-1}$
- $n$: porosity, dimensionless
- $N$: source or sink term, s$^{-1}$
- $p$: hydraulic pressure, Pa
- $S_s$: specific storage coefficient of aquifer, m$^{-1}$
- $S_{sk}$: specific storage coefficient of interbeds or confining bed, m$^{-1}$
- $S_{skE}$: elastic $S_{sk}$, m$^{-1}$
- $S_{skV}$: inelastic $S_{sk}$, m$^{-1}$
- $t$: time, s
x,y,z  spatial coordinates, m
\alpha  volume compressibility, Pa^{-1}
\gamma  specific weight, kN m^{-3}
\phi   hydraulic head, m
\rho   density of water, kg m^{-3}
\sigma  geostatic pressure, Pa
\sigma_s  effective stress, Pa
\sigma_{s0}  initial effective stress, Pa
\sigma_{s1}  terminal effective stress, Pa
\Delta \sigma_s  increment of effective stress, Pa

INTRODUCTION

During the twentieth century considerable parts of Lake Yssel (the former Zuiderzee) in The Netherlands were reclaimed and converted to "new" polderlands, with surface levels a few metres below mean sea level. These projects had a significant impact on the groundwater flow regimes in the adjacent "old land" zones, because keeping the polders dry means a permanent change of boundary conditions to the regional groundwater flow systems. The idea of a possible reclamation of part of the remaining smaller Lake Yssel — which would create the Markerwaard Polder — was studied during the 1980s. Among the studies carried out was a prediction of the land subsidence to be expected in the westward bordering land in the province of Noord-Holland. This prediction was done by first running a groundwater model to predict the changes in hydraulic head (Hebbink & Schultz, 1983), and afterwards using these outputs as an input to a compression model (Delft Geotechnics, 1983).

The flow of groundwater and the compression of layers of peat, clays and silts in response to changing hydraulic heads are coupled processes. Hence, it seems to be preferable to simulate them in a coupled model, rather than simulating flow/piezometry and compression sequentially as mentioned above. In an attempt to obtain a more clear idea of the possible merits of a coupled model, the model prediction done in the past was repeated with an extended version of the well-known groundwater model code MODFLOW, incorporating a so-called Inter Bed Storage Module (IBS) to take care of partly irreversible sediment compression and associated groundwater fluxes. The IBS module used has the limitation that it considers only stress-independent geotechnical parameters ("constant parameters").

The Interbed Storage Package used (IBS1) was originally developed to account for compaction of "interbeds" or lenticular compressive intercalations inside aquifers (Leake & Prudic, 1988). In this paper it is used to simulate compaction of a continuous confining bed. The flow equation as ordinarily used by MODFLOW (McDonald & Harbaugh, 1988):

\begin{equation}
\frac{\partial}{\partial x} (K_{xx} \frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y} (K_{yy} \frac{\partial \phi}{\partial y}) + \frac{\partial}{\partial z} (K_{zz} \frac{\partial \phi}{\partial z}) + N = S_s \frac{\partial \phi}{\partial t}
\end{equation}

assumes specific storativity ($S_s$) to be constant in time, except for the case where a confined aquifer becomes unconfined (or vice versa). To account for changes in storage caused by compaction of interbeds or confining beds, an additional term has to be added to the right-hand side of the equation. This term can be expressed as:
Equation (2) represents an average flow into or out of storage per unit volume of interbed or confining bed and per unit of time. The specific storage value $S_{sk}$ in Equation (2) varies between an "elastic" and an "inelastic" value depending on the relation of the current hydraulic head to the preconsolidation head. The preconsolidation head can also change during the simulation as the model updates it.

Comparing the output of the new model with the previous results allows conclusions to be drawn for this particular case regarding the importance of a coupled modelling approach, and regarding the errors made when using constant geotechnical parameters instead of stress-dependent ones.

Prediction of land subsidence is confined to part of the province of Noord-Holland, in a belt along the western boundary of the projected Markerwaard polder, because it is there where this new polder is expected to produce significant impacts in terms of land subsidence.

GEOHYDROLOGICAL SETTING AND MODEL SCHEMATIZATION

The study area is underlain by a thick sequence of Quaternary unconsolidated deposits, in an alternation of highly permeable aquifer beds and less permeable aquitards. One of the aquitards forms the top of the system; it is continuous and consists of Holocene sediments. Two semi-continuous aquitards divide the sandy Pleistocene sediments below this Holocene cover into three separate aquifer units. Geometric and hydraulic characteristics of the individual layers are summarized in Fig. 1.

Figure 1 shows the MODFLOW schematization as well: it distinguishes five model layers. The two aquitards dividing the Pleistocene sands into three aquifers are assumed to be able to transmit water, but their capacity to store or release water is considered negligible. For the second model layer (Holocene deposits), on the contrary, change of storage is explicitly taken into account in the model, for reasons mentioned below.

Polder water levels form an upper boundary condition to the system. In the projected Markerwaard zone they are assumed to drop from some 0.25 m below N.A.P. initially (before reclamation) to 6.5-4.5 m below N.A.P. after the polder reclamation would have taken place (see Figs 2 and 3). For simplicity, it is assumed that this drop will take place instantaneously. The drop in polder level will influence the piezometric levels in the Quaternary sediments below, and the effect will spread laterally from the Markerwaard zone towards the surrounding areas (under which the Noord-Holland zone considered). The Pleistocene aquifer complex is underlain by clay, which in the model is assumed to be impervious. The model area chosen is large enough to assume constant-head lateral boundary conditions. It measures 60 km from east to west and 54 km from north to south. The number of model cells used is 2208.

GEOTECHNICAL FEATURES AND SCHEMATIZATION

Preliminary investigations have made plausible that more than 90% of the sediment compaction to be expected in Noord-Holland as a result of polder reclamation will take
place in the Holocene cover (model layer 2). This is because this layer contains highly compressible clays and peat, and the anticipated relative changes in effective stress are much greater there than at greater depths. The compression of the other aquitards is expected to be insignificant compared to that of the Holocene layer. Hence, the model developed focuses on deformation of the confining Holocene layer only, in the before-mentioned zone in the province of Noord-Holland.

The Holocene deposits belong all to the Westland Formation, which includes from bottom to top the following genetically and lithologically distinct sublayers:

- layer 1: base peat: a thin layer of compact peat;
- layer 2: a sand deposit ("sand"), with intercalated clay lenses;
- layer 3: a clay deposit with little silt and gravel ("middle clay");
- layer 4: "Holland peat", a thick compressible peat layer;
- layer 5: a clay cover ("top clay").

The lateral variation of the Holocene series is great, with variable occurrence and thickness of the different sublayers, which makes the Holocene cover with respect to hydraulic and mechanical properties a highly heterogeneous complex.

Data on the lithology and mechanical characteristics of the Holocene cover, as compiled by Xu (1993), are summarized in Table 1. The observed ranges of depths and of present-day pressures and stresses are presented in Table 2.

The deformation of an aquitard can be simulated in the IBS1 package on the basis of a specific storage coefficient $S_{sk}$. This coefficient obtains an inelastic value ($S_{skv}$) or an elastic value ($S_{ske}$) depending on whether the current effective stress is smaller or...
Fig. 2 Polder water level before reclamation.

Fig. 3 Polder water level after reclamation.
Table 1 Basic mechanical data of the Holocene sublayers.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Lithology</th>
<th>( p ) (kN m(^{-3}))</th>
<th>( n )</th>
<th>( e )</th>
<th>Mean ( e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>top clay</td>
<td>13-14</td>
<td>0.74-0.80</td>
<td>2.85-4.00</td>
<td>3.42</td>
</tr>
<tr>
<td>4</td>
<td>Holland peat</td>
<td>10.6</td>
<td>0.85</td>
<td>5.67</td>
<td>5.67</td>
</tr>
<tr>
<td>3</td>
<td>middle clay</td>
<td>14-16</td>
<td>0.62-0.74</td>
<td>1.63-2.85</td>
<td>2.24</td>
</tr>
<tr>
<td>2</td>
<td>sand</td>
<td>18-19</td>
<td>0.43-0.50</td>
<td>0.75-1.0</td>
<td>0.88</td>
</tr>
<tr>
<td>1</td>
<td>base peat</td>
<td>11.0</td>
<td>0.75</td>
<td>3.00</td>
<td>3.00</td>
</tr>
</tbody>
</table>

Table 2 Ranges of initial geostatic pressure, water pressure and effective stress in the Holocene cover.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth (m - surface)</th>
<th>( \sigma ) (kPa)</th>
<th>( p ) (kPa)</th>
<th>( \sigma_s ) (kPa)</th>
<th>Mean ( \sigma_s ) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.7-7.8</td>
<td>15-110</td>
<td>0-60</td>
<td>15-50</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>0.7-10.4</td>
<td>10-130</td>
<td>0-80</td>
<td>10-50</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>1.5-16.2</td>
<td>20-240</td>
<td>0-140</td>
<td>20-100</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>4.2-17.1</td>
<td>60-290</td>
<td>20-160</td>
<td>40-130</td>
<td>85</td>
</tr>
<tr>
<td>1</td>
<td>8.7-16.3</td>
<td>130-270</td>
<td>75-155</td>
<td>65-115</td>
<td>90</td>
</tr>
</tbody>
</table>

greater than the preconsolidation stress. The specific storage coefficient is related to effective stress as follows (Neuman & Preller, 1982; Leake, 1991):

\[
S_{skv} = \frac{C_c \rho g}{2.3(1+e_0)\sigma_s} \quad (3)
\]

\[
S_{ske} = \frac{C_r \rho g}{2.3(1+e_0)\sigma_s} \quad (4)
\]

Fig. 4 Compression coefficient vs. effective stress for Holocene cover in North Holland:
1. peat, \( \gamma = 10-11 \text{ kN m}^{-3} \); 2. clay, \( \gamma = 13-14 \text{ kN m}^{-3} \); 3. clay, \( \gamma = 14-16 \text{ kN m}^{-3} \); 4. sand, \( \gamma = 18-19 \text{ kN m}^{-3} \) (Delft Geotechnics, 1983).
Table 3 Specific storage coefficient of the sublayers of the Holocene cover (present situation).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Lithology</th>
<th>$\sigma_z$ (kPa)</th>
<th>C</th>
<th>$\alpha$ (Pa$^{-1}$)</th>
<th>$S_{skv}$ (m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>top clay</td>
<td>33</td>
<td>13.5</td>
<td>0.0224E-4</td>
<td>0.0224</td>
</tr>
<tr>
<td>4</td>
<td>Holland peat</td>
<td>30</td>
<td>7.0</td>
<td>0.0476E-4</td>
<td>0.0476</td>
</tr>
<tr>
<td>3</td>
<td>middle clay</td>
<td>60</td>
<td>14.5</td>
<td>0.0115E-4</td>
<td>0.0115</td>
</tr>
<tr>
<td>2</td>
<td>sand</td>
<td>85</td>
<td>38.0</td>
<td>0.0031E-4</td>
<td>0.0031</td>
</tr>
<tr>
<td>1</td>
<td>base peat</td>
<td>90</td>
<td>6.0</td>
<td>0.0185E-4</td>
<td>0.0185</td>
</tr>
</tbody>
</table>

Following general practice in soil mechanics in The Netherlands, we use here a compression coefficient $C$ (Koppejan, 1948), which is related to the compression index $C_c$ in the following way:

$$C = \frac{2.3(1 + e_0)}{C_c}$$

A plot of the compression coefficient vs. effective stress determined for samples of Holocene sediments in Noord-Holland (Delft Geotechnics, 1983) is shown in Fig. 4. In combination with Table 2, this figure allows an average value of $S_{skv}$ to be estimated for...
each of the lithological sublayers within the Holocene cover in Noord-Holland. These estimates are presented in Table 3. By summing the products of specific storage coefficient and thickness for each sublayer, inelastic storage coefficients were obtained for 497 grid points (Xu, 1993). A map of this storage coefficient of the Holocene cover (model-layer 2) is shown in Fig. 5.

SIMULATION RESULTS

According to expectation, the simulation results show that the declines of the piezometric levels in the second and third aquifer are much smaller than those in the first one. The final (i.e. steady state) drawdown in the first aquifer after polder reclamation is presented in Fig. 6. The final subsidence in the zone adjacent to the polder is presented in Fig. 7. The general trend is a greater subsidence at smaller distance to the polder; the maximum simulated value is 13.1 cm.

At most locations it takes about 30 years for the compaction process to be completed. Approximately 25% of the final compaction is reached within one year after reclamation, 60% at 5 years, 80% after 10 years, and more than 90% after 20 years.

Fig. 6 Final drawdown in first aquifer (in m).
The simulation results agree very closely with the ones obtained in the earlier study (Delft Geotechnics, 1983). This is clear by comparing the predicted land subsidence according to both studies (Figs 7 and 8); the simulated piezometry of the aquifers shows little difference either (Xu, 1993). Careful analysis indicates that the land subsidence predicted in the current study is slightly larger than that of the previous study. The local maximum of subsidence predicted in the previous study is 12.0 cm.

Given the fact that both studies basically have used the same field data, it is concluded that the two different methodologies (uncoupled/stress-dependent parameters vs. coupled/constant parameters) produce in this case results that are almost identical.

ERRORS DUE TO THE USE OF CONSTANT PARAMETERS

Compressibility and specific storage coefficients decrease with progressing compaction. Hence, applying constant storage coefficients estimated for initial conditions may lead to overestimating land subsidence. By integrating equation (3) over effective stress and

Fig. 7 Final land subsidence after reclamation (in cm).
dividing by the increment of effective stress, a time-averaged specific storage coefficient during the compacting process can be derived:

\[
\bar{S}_{skv} = \frac{C_c \rho g \ln(\sigma_{sl}/\sigma_0)}{2.3(1 + e_0)\Delta \sigma_s}
\]

which allows the errors due to assuming a constant storage coefficient to be assessed. Differences between initial and time-averaged storage coefficients for each of the

**Table 4** Comparison of the average specific storage coefficient with the initial one.

<table>
<thead>
<tr>
<th>Layer</th>
<th>( \sigma_0 ) (kPa)</th>
<th>( \Delta \sigma_s ) (kPa)</th>
<th>Initial ( S_{skv} ) (m(^{-1} ))</th>
<th>Average ( S_{skv} ) (m(^{-1} ))</th>
<th>Percentage error</th>
</tr>
</thead>
<tbody>
<tr>
<td>top clay</td>
<td>33</td>
<td>5</td>
<td>0.0224</td>
<td>0.0209</td>
<td>7.40</td>
</tr>
<tr>
<td>Holland peat</td>
<td>30</td>
<td>5</td>
<td>0.0476</td>
<td>0.0440</td>
<td>8.12</td>
</tr>
<tr>
<td>middle clay</td>
<td>60</td>
<td>5</td>
<td>0.0115</td>
<td>0.0110</td>
<td>4.11</td>
</tr>
<tr>
<td>sand</td>
<td>85</td>
<td>5</td>
<td>0.0031</td>
<td>0.0030</td>
<td>2.91</td>
</tr>
<tr>
<td>base peat</td>
<td>90</td>
<td>5</td>
<td>0.0185</td>
<td>0.0180</td>
<td>2.75</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.0209</td>
<td>0.0209</td>
<td>5.05</td>
</tr>
</tbody>
</table>

Fig. 8 Land subsidence predicted in the previous study.
Predicting land subsidence with a constant-parameter coupled model

Holocene sublayers, expressed as percentages of the former, are listed in Table 4 for a 5 kPa increment in effective stress (which corresponds to the average predicted piezometric drop). These percentages indicate the percentage of error in the predicted land subsidence, as far as caused by using a constant storage coefficient. Note that the error decreases with increasing depth. Taking into account these errors explains most of the already slight differences between Figs 7 and 8.

CONCLUSIONS

MODFLOW in combination with the ISB1 package is an adequate tool for simulating land subsidence in the case presented. The coupled approach offers significant practical advantages over an uncoupled approach. In principle, it also calculates groundwater fluxes more accurately, because of taking into account the additional fluxes due to change of storage in the compacting layer; but the effect appears insignificant in the current case. The error due to assumed constant storage coefficients is small in the case studied: this is because the relative changes in effective stress were only small. To judge whether the MODFLOW-IBS1 modelling approach would be satisfactory for any other case as well, an error assessment like the one shown above may provide guidance.

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REFERENCES


