Introduction
Near Breda, the Netherlands, Grontmij has planned commercial development on top of the former waste disposal site ‘Bavelse Berg’ (figure 1). Since construction on a waste disposal site is relatively new, parties involved adopted a risk management approach for the feasibility study of the project. The urge was felt to resolve the lack of data for a number of geotechnical mechanisms.

Pilot testing for the determination of settlement parameters has been performed. A worst case approach in stability analysis gave satisfying answers for construction on gentle slopes. This article starts with a short description of the history of landfilling and planned commercial development at the site. Next, it elaborates successively on the risk management approach, and characterization of the waste material. The aspect of foundation design and various stability issues of constructing buildings on the slopes of the landfill are also addressed.

History and commercial development
Until 1968, the project site was used for loam excavation for the brick industry. From 1968 until 1982, the site has been used as a waste dump. Later on, regulations that were more stringent came into practice, and the site has been in operation as a regulated landfill until 1992. Capping the site with a geomembrane and a mineral layer was realized during 3 phases from 1995/1996 to 2000/2001. Everlasting aftercare is guaranteed by Grontmij.

The overall area of the site is approximately 35 hectares. Different types of waste have been dumped, varying from waste with high organic content to waste originating from construction. Gasses emitted from the landfill are actively withdrawn under the capping layers. With these gasses electricity is produced at a local power plant. Leachate is collected and treated in a water treatment plant.

The first elaborated ideas of commercial development emerged in 2003. Early 2008, Grontmij and ING Real Estate agreed on the further development. By 2009 a rough spatial planning of the plan Leisure park De Bavelse Berg was presented (figure 2). Leisure and recreation will focus on...
sports, entertainment and wellness, linked
together by expressions of arts. An indoor skiing
facility is included on the western steeper slopes
of the landfill. Most buildings are planned on top
of the landfill. Some facilities will be constructed
on the upper edges of landfill as well as on the
gentle slopes towards the north. The steeper
slopes accommodate outdoor leisure activities.

Risk management approach
Since construction on a waste disposal site is
relatively new, the stakeholders adopted a risk
management approach for the feasibility study of
the project. This approach was also advocated
during the SufalNet (Sustainable Use of Former
and Abandoned Landfills Network) final confe-
rence in November 2007 [Pereboom, 2007].

In earlier stages of the 'Bavelse Berg' project,
desk studies showed technical feasibility of the
project. Subsequently, expert panels made
inventories of risks and uncertainties. In this
case, the unknown behaviour of the subsoil, and
e specially in this case the waste body, is a major
risk driver in a construction project. Deltares has
developed an easy framework for geotechnical
risk management, known as the GeoQ process
[Staveren, 2006; Pereboom et. al., 2007]. In the
feasibility phase, applicable to the Bavel project,
the GeoQ process particularly concentrated on
its first three steps of gathering information,
risk identification, and quantifying geotechnical
risks.

The following major subsoil related risks were
identified:

- complete saturation of the top layers above
  the sealing layers due to failure or blockage of
  drainage systems affecting bearing capacity
  of the site;
- excessive (differential) residual settlement
  of buildings on the landfill;
- instability of buildings on or near the slopes;
- excessive deformation of the sealing mem-
  brane, and mineral layers, possibly resulting
  in damage.

Of these risks, large deformations caused by
settlement of the landfill and instability of
structures on the slopes impose the largest risks
to the project. In addition, due to effects from
settlements or stability loss, the geomembrane
and the mineral capping layers may be overstret-
ched or severely damaged. Aftercare require-
ments related to proper environmental isolation
of the waste body are very strict and do not allow
any damage of this kind to the capping layers.
The stakeholders involved felt the urge to tackle
the lack of information related to the underlying
geotechnical mechanisms of these risks.

Common geotechnical field and laboratory
testing for deriving settlement properties
(oedometer testing), does not provide a way out
in the highly heterogeneous material setting
of a landfill. Full scale tests by means of placing
loads over the landfill have the advantage of
being able to derive parameters that are repre-
sentative for (a part of) the waste body itself,
including heterogeneity effects. For stability
of structures on the slopes of the landfill,
similar considerations are applicable.

Pilot testing for settlement consisted of the
construction of temporary embankments of 3
m height on top of the landfill. Monitoring and
subsequent interpretation yielded settlement
properties. Results from stability analyses,
including partial or complete saturation of the
top layers yielded information on stability of
slopes and structures, and on deformation of the
sealing membrane and the mineral layers.

Characterization of the material
Geotechnical engineering properties of the
landfill material had to be determined. Based
on information about the type of waste pro-
cessed in the different compartments of the landfill
from 1968 to 1991, the sensitivity regarding
decomposition of the waste could be estimated
per compartment, giving an indication of the
compressibility of the material and settlements
that may be expected.

At Bavel, settlements at 19 boxes covering the
landfill gas collection pumps, which stand out
above the ground level, were measured from
2000 up to now. These settlement data from
locations over the entire landfill were used to
estimate the residual virgin creep settlement
over the landfill (figure 3). In this figure, values
range from less than 0.1 m (green) up to 0.3 m
(dark brown) in 50 years. Extrapolation of the
measured settlement data was based on the
logarithmic rate of strain (LRS) method, being a
fast and simple method to extrapolate creep in
time without actual modelling of soil layers etc.
The expected residual settlement per data point
was interpolated over the entire landfill using the
kripting method.

The slopes of the landfill vary from 1 : 3 to 1 : 8
(vertical : horizontal). The slopes make it possible
to estimate the angle of repose (or angle of inter-
nal friction) of the waste. The minimum angle of
internal friction was estimated at 18°, also being
the minimum value found in literature that may
be expected in view of the waste characteristics.
Conservatively, no effective cohesion was attri-
buted to the waste material.

Test loads
Geotechnical monitoring of test loads was
proposed to determine compressibility and
creep behaviour of waste material for different
sections of the landfill. Implementing these data
in the geotechnical and structural design would
then facilitate the reduction of risks regarding
excessive (differential) settlement of future
buildings.

It was proposed to place several loads on the
landfill, varying from 2x2 m² (2 locations), 4x4 m²

Figure 3 Expected virgin creep settlements
over landfill - ranging from less than 0.1 m
(green) to a maximum of 0.3 m (dark brown)
in 50 years.

Figure 4 Lay out monitoring test loads.
(1 location) and 30x30 m² (2 locations), representing building foundations with loads of 50 kN/m² (figure 4). The 30x30 m² loads were constructed out of a 3 m high embankment of clay. The smaller loads were constructed out of concrete slabs. By carefully monitoring the induced settlements for a period of 9 months, compressibility moduli of the landfill were retrieved. With the application of a fully automatic Total Station connected to a data logger, measurements were carried out 10 times per day. The measurements were stored in a database.

The small 2x2 m² as well as the 4x4 m² loads did not reveal a significant settlement process in time. This can be explained viewing the limited foundation area in relation to large stress distribution within the landfill, only causing a significant stress increase in the upper layers. As these upper layers consist of sandy, relatively incompressible materials, only a limited settlement may be expected. The large 30x30 m² loads, instrumented by a dense grid of settlement plates, caused a significant increase in stress throughout the total landfill height, resulting in (creep) settlements, with a settlement rate decreasing in time.

By removing a part of the load after achieving a certain rate of strain, the effect of preloading was simulated. Preloading can result in a decrease in expected residual settlement.

Time settlement behaviour was modelled after a well known linear strain settlement model using the parameters RR (reloading ratio), CR (compression ratio), $\alpha$ (Coefficient of secondary compression; creep) and $P_c$ (preconsolidation stress).

The preconsolidation stress ($P_c$) in the landfill can be caused by ageing or preloading. The latter results from the method of compaction of the waste, which was done by means of bulldozers. Preloading by means of bulldozers was estimated at 50 kPa ($P_c = 50$ kPa). No preconsolidation caused by ageing was attributed to the waste material.

It is assumed that settlement in time, caused by loading, can be described more or less by a consolidation process (after Terzaghi). An important part of the settlement induced has a character which can be compared with a long term creep behaviour. Creep strain in time was described by an isotach model, according to:

$$\varepsilon = C_{\alpha \varepsilon} \cdot \log \frac{t_{\text{equi}} + \Delta t}{t_{\text{equi}}}$$

in which:
- $\varepsilon$ = linear strain [\]
- $C_{\alpha \varepsilon}$ = creep parameter [\]
- $\Delta t$ = time over which creep is calculated [days]
- $t_{\text{equi}}$ = equivalent age: $t_{\text{equi}} = \frac{P_c}{\sigma'}$ [days]
- OCR = Over Consolidation Ratio = $\frac{P_c}{\sigma'}$ [-]

In an isotach model, creep velocity decreases when overconsolidation increases. This increase in overconsolidation can be caused by removal of a preload or by ageing. Ageing occurs within the preload time and can be regarded as the time (t) after 100% consolidation has occurred. The overconsolidation that is caused by ageing can be calculated from:

$$OCR = \frac{t}{t_{CR-RR}}$$

from the OCR the preconsolidation stress ($P_c$) in the fill can be calculated. When a decrease in effective stress occurs, for example caused by removal of a preload, an updated OCR can be calculated. This OCR can be used to determine the equivalent age ($t_{\text{equi}}$) and the reduced creep strain rate.

From settlement plate data stiffness parameters were retrieved. Table 1 summarizes the statistical interpretation. Compressibility parameter values have been back-calculated using the exact dimensions of the pilot test embankments.

<table>
<thead>
<tr>
<th>$RR$</th>
<th>$CR$</th>
<th>$C_{\alpha \varepsilon}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.016</td>
<td>0.14</td>
<td>0.0067</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.0012</td>
<td>0.008</td>
</tr>
<tr>
<td>Variation coefficient $\nu$</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>5% lower boundary</td>
<td>0.014</td>
<td>0.13</td>
</tr>
<tr>
<td>5% upper boundary</td>
<td>0.017</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 1 Stiffness properties waste Bavel.

Unloading / reloading stiffness (RR) of the waste material is approximately 9 times higher than virgin stiffness (CR). Variation is largest for the creep parameter $C_{\alpha \varepsilon}$. Creep also gives the largest contribution to total settlement induced by loads placed on the Bavelse Berg.

The compressibility parameters have been used for:
- assessment of the effect of preloading measures (quantity of preload, preloading time);
- calculation of stresses caused in the sealing membrane by differential settlements;
- analysis of the structural integrity of the shallow...
foundations and its superstructures for buildings to be realized on the Bavelse Berg. Generally, settlements and stresses caused in the sealing membrane by differential settlements are considered acceptable.

Foundation design of buildings
For the foundation design, the following items relating to the subsoil are relevant:
1. The (low) bearing capacity of the landfill.
2. The (high) compressibility of the landfill.
3. Large heterogeneity of the landfill with regard to compressibility.
4. Characteristics of the landfill gathered from the pilot project’s data.
5. Preloading the landfill will decrease residual settlement.
6. Damage to or intrusion into the sealing membrane cannot be tolerated from the point of view of aftercare requirements.

Items 1 and 6 lead to the choice for shallow foundations and light-weight constructions. To deal with low bearing capacity requires large foundation areas. To determine necessary preloading measures for these structures, information on compressibility is required for each building location (items 2 to 5).

Construction of buildings on large shallow plate foundations (dimensions equal to the buildings’ floors) however, will lead to excessive bending moments (item 3 and 4). This will result in an expensive structure for the foundation. However, this option can be an economically feasible option for small buildings with accompanying small loads.

The choice for a foundation in which the bearing members can be vertically adjusted, makes it possible to reduce the bending moments. This type of building foundation will consist of several individual shallow foundations on which the bearing members (columns, beams) can be hydraulically jacked when necessary. In this way, adjustments can be made and vertical differential settlements can be reduced, resulting in a decrease of bending moments in horizontal structural members (figure 5). It is important to minimize the number of times a building has to be adjusted. The following measures can assist in this process:

- A foundation design in which the individual shallow foundations are designed for a specific building load, resulting in more or less the same settlements.
- Carefully monitoring settlements caused by preloading, to make it possible to predict residual settlements.
- Adding additional stiffness to the construction results in distribution of loads and minimizes the effects caused by differential settlements.

Stability of buildings on and near slopes
For landfill De Bavelse Berg one story buildings with an acting load of 20, 30 and 50 kN/m² are foreseen. The buildings will have shallow foundations. Overall stability of the buildings on and near the slopes of the landfill has to be guaranteed for a reliability index \( \beta = 4.3 \).

Based on the construction of the landfill (the presence of different seal and cover layers) (figure 6), the following mechanisms, which could result in instability of the buildings’ foundations, have to be analyzed:

- Sliding over the impermeable layer (after failure of the geomembrane);
- Sliding over the geomembrane;
- Insufficient bearing capacity.

Apart from these mechanisms, a design philosophy for the so-called ‘domino effect’ has to be determined. This effect is described as failure of or excessive damage to a construction initiated by failure of another construction. This can be the case when several buildings are constructed at a limited distance downhill from each other on the slopes of the landfill, in a way that instability of a single building can lead to instability of or damage to the next building downhill.

As the shear strength properties of the soil cover on top of the geomembrane are less favorable than those of the impermeable layer (sand-bentonite with added polymer), sliding over the geomembrane was analyzed. In the following three sections, sliding over the geomembrane, insufficient bearing capacity, and the design philosophy of the domino effect are described.

Sliding over the geomembrane
Sliding of the foundation including the soil cover over the geomembrane (figure 7) as well as bearing capacity of the soil cover just beneath the building load have been analyzed using constitutive models. Mechanisms have been verified using the FEM computer program Plaxis.

The driving force is the part of the load of the building parallel to the slope. The majority of the resisting force is the mobilized friction between the grains of the cover soil and the membrane, when no (limited) passive resistance is taken into account.
The interface friction angle ($\delta$) can be determined from Direct Simple Shear tests in which the maximum friction between the cover soil and an interface is determined. (Test data on the interface friction angle was not yet available at the time of writing.)

Important aspects regarding the safety factor against sliding are, besides the steepness of the slope, the degree of water saturation of the cover soil layer and the interface friction properties between the cover soil and the geomembrane. Improper maintenance of or damage to the drainage in the soil cover may cause a situation in which the soil cover is fully saturated. A fully saturated cover soil layer has been assumed. The interface friction angle was estimated at $\delta = 20^\circ$. Although regarded as a conservative value, additional laboratory testing (Shear tests) was recommended to verify this assumption.

With a fully saturated cover soil layer, calculations (figure 9) show that slopes steeper than 1:8 do not meet the stability requirement. For a 50 kN/m$^2$ load, squeezing becomes critical over sliding for slopes 1:8 to 1:5.

### Design philosophy domino effect

It is important to determine a design philosophy to deal with risks associated with a geotechnical failure at one single building (e.g., sliding, tilting) triggering a failure at another building (figure 11), the so-called ‘domino’ effect. To consider if this effect is possible at all, the spatial planning of the site should be available.

The following design philosophy was worked out in an example, assuming that consequences associated with multiple buildings being unstable are larger than the consequences associated with a single building being unstable.

Risk = Likelihood x Consequence

For the sake of simplicity, it is assumed that the probability of geotechnical failure of all structures affected should be $n$ times smaller when the consequences are $n$ times larger. In this way, the risk remains at a same level.

Probability of failure for single building ($\beta = 4.3$):

$$P_f = \left( \frac{1}{\beta \sqrt{2\pi}} \right) \exp\left( -\frac{\beta^2}{2} \right) = 9 \times 10^{-4}$$

Probability of failure for several buildings:

$$P_r = \frac{9 \times 10^{-4}}{n}$$

In which $n$ is the total number of possibly affected buildings.

To determine the partial material factors associated with a higher reliability index, the following formula can be used.

$$f_{\beta} = \frac{\gamma_{\beta \beta}}{\gamma_{\beta \beta 0}} = \exp(\alpha_{\beta} + \beta(1 - \beta 0) * \sqrt{\ln(1 + P_r^2)})$$
\[ f_{\beta} = \text{correction factor on partial material factor;} \]

\[ Y_{R; \beta 1} = \text{partial material factor associated with reliability index } \beta_1; \]

\[ Y_{R; \beta 0} = \text{partial material factor associated with reliability index } \beta_0; \]

\[ V_R = \text{coefficient of variation;} \]

\[ \alpha_R = \text{influence factor shear strength (assumed at 1.0; conservative)} \]

The resulting material safety factors have been listed in table 2 and should be used for the geotechnical design of all structures that could trigger a ‘domino’ effect.

**Conclusions**

A risk driven approach in accordance with GeoQ was used to identify risks associated with constructing buildings on a former waste disposal. Risks related to geotechnical aspects were considered important and additional analyses were required to quantify these risks in order to determine the (geo)technical feasibility.

Preloading of locations where building foundations will be constructed is essential to minimize settlements and to quantify residual settlements. Settlements can be accommodated by using adaptable foundation frames in which the bearing members can be vertically adjusted.

A reasoned worst case assumption of waste characteristics, full saturation of the cover layer of the landfill combined with stability analyses led to the conclusion that one storey high buildings can be constructed on the gentle slopes of the landfill and deformation of the sealing membrane is limited. Higher material safety factors were determined in order to deal with the ‘domino’ effect.

Nevertheless, if areas of the landfill with steeper slopes will be used, there is a need to further clarify uncertainties and assumptions relating to the friction characteristics between the grains of the cover soil and the membrane, and between the membrane and the trisoplast (sandbentonite with added polymer). Risk remediation measures such as additional laboratory testing have been proposed to complete this data gap.

**Acknowledgements**

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**Literature**

