Abstract

Two major railway lines, the Betuwe Route (BR) and the High Speed Railway Line (HSL), are currently under construction in The Netherlands. Stringent requirements with respect to the construction time and the residual settlements of the future embankments have stimulated new developments in the field of soil mechanics and construction technology. Given the limited construction time and the adverse geotechnical conditions in the western part of the country initial designs tended to focus on the (virtual) elimination of settlements. This was to be achieved by various new systems, all based on the principle of stiff elements transferring the bearing loads to deeper competent strata. High costs of such systems and uncertain performance, however, urged designers to reconsider the options. In the case of the Betuwe Route this resulted in a traditional embankment design supplemented with special measures to accelerate the consolidation process and/or increase the strength of the subsoil. This so-called traditional-plus approach proved to be the most cost-effective solution to meet the contract requirements in terms of both construction time and residual settlements.

For the HSL, dynamic loads as a result of the high velocity of the trains prompted a design comprising concrete slabs founded on piles. Where these slabs rise above the original ground level, embankments of sand are required between the slabs and the ground surface to reduce bending moments in the piles. To avoid large settlements of these embankments the original design included (partial) replacement of the compressible strata. However, further optimisation of the design resulted in the use of accelerated consolidation techniques to enforce full settlement before driving the piles.

Both of these projects have demonstrated that stable sand embankments can be constructed in a relatively short period of time even in areas with underlying very compressible soils.
**Introduction**

The geological setting of The Netherlands is determined by its position on the edge of the North Sea Sedimentary Basin. With Tertiary and older rocks outcropping near its eastern and southern borders the thickness of the sequences of unconsolidated Quaternary deposits increases towards the west and north reaching a maximum thickness of 500 m in the NW. In particular in the western part of the country positioned in the delta of the Rhine, Meuse and Scheldt the Holocene strata comprise soft, highly compressible clays, organic clays and peats of alluvial and marine origin, occasionally intersected by more sandy strata. At depths typically varying between 5 m and 15 m below surface Pleistocene sands underlie these deposits.

**BETUWE ROUTE**

Over the last five years, construction has commenced on several large infrastructural projects in The Netherlands. One of these is the Betuwe Route, a 160 km long electric freight railway line from the Port of Rotterdam to the German border. The Betuwe Route was tendered in sections of which the 22 km section Sliedrecht-Gorinchem, also known as BR1/2, is further described in this paper (Figure 1).

The surficial geology is relatively uniform. The shallow subsurface consists of highly compressible Holocene deposits overlying dense Pleistocene sands. The Holocene deposits essentially comprise a thin cover of agricultural soil (clay) overlying peat and clays. The peat is known locally as Holland Peat while the clays are part of the Gorkum Formation. The Holocene units are generally soft to very soft with undrained shear strengths in the range of 5-15 kPa. The thickness of the Holocene varies from about 10 m in the western part of the BR1/2 section to 8 m in the eastern part.

This section was considered a high-risk section, not in the least because of the combination of poor soil conditions with a tight contractual time frame and strict directives for allowable residual settlement. As a simple solution for all project risks was not obvious, the Owner, ProRail, tendered this section as a Design, Construct & Maintenance contract. After a pre-selection phase, five consortia were asked to prepare detailed bids. Only one consortium, HBSC (Heijmans, Boskalis, Structon, CFE), cared to base its design on a more or less traditional approach using a sand fill embankment and wick drains.

HBSC’s design was much influenced by an innovative approach to the geotechnical design aspects. The risks associated with this approach were perceived to be high but ultimately a consensus was found by adopting an Alliance as contractual form.

This allowed better allocation and control of risk and provided more incentive (for all contractual parties) to identify and realise optimisations. Many of the optimisations were directly related to geotechnical aspects. Some key components of the geotechnical design are described below.

**Overall parameter set**

The results of an extensive suite of field and laboratory tests (see Table I) were included with the tender documents. A geological interpretation was also included, in the form of a longitudinal profile.

Table I. Soil investigation.

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dutch Cone</td>
<td>658</td>
</tr>
<tr>
<td>Begeman 66 mm Borehole</td>
<td>51</td>
</tr>
<tr>
<td>Begeman 29 mm Borehole</td>
<td>94</td>
</tr>
<tr>
<td>Laboratory Triaxial Tests</td>
<td>201</td>
</tr>
</tbody>
</table>
According to the provisional geotechnical interpretation supplied with the documents the route was to be divided into a number of geotechnically distinct sub-sections. Suggested values of geotechnical parameters (such as shear strength) were supplied for each sub-section. The number of samples and tests varied considerably from section to section. This implied that the statistical confidence level with regard to parameter values also varied significantly from section to section. The values of some parameters also fluctuated strongly from section to section (for a given soil type). In some cases, the given parameter set was such that it was virtually impossible to design a traditional sand embankment that met all the contractual criteria, notably with regard to allowable construction time.

However, statistical analysis of the available test data showed that there was in fact no reason to assume significant spatial correlation of parameter values. In other words, for a given soil type, the geotechnical properties did not vary from location to location. Thus for each soil type only one overall set of parameters was required for the whole route. This simplification considerably reduced the need for additional geotechnical fieldwork. By combining all the test data it was also much more evident which test results were non-representative (erroneous). Also, by decreasing the number of design variables, the potential for design errors and discrepancies (from section to section) was greatly reduced.

All the embankment design was based on the overall parameter set. This choice has been further validated empirically; embankment construction has been completed and to date there is no evidence suggesting that local parameters should have been used.

**Minimum shear strength**

In the Netherlands, slope stability is traditionally determined with a Bishop method, using drained shear strength parameters (c’ and φ’). This method was in fact specified in the contract. Triaxial Dutch Cell tests showed that the cohesion value for these soils was generally very low (ca. 1-3 kPa). At low effective stress levels (e.g. in the toe of an embankment and beyond), the shear strength predicted along a failure plane is then very low. Calculations with this approach suggested that even an initial sand lift of only 1 m thickness would lead to slope failures, especially if the embankment toe was adjacent to a drainage ditch.

This clearly did not correspond to empirical observations that lifts of 1.5 m and more were quite safe. Slope stability calculations with minimum (undrained) shear strengths (c, about 5 kPa) yielded results that came much closer to actual field practice. Ultimately an approach was chosen which combined a minimum shear strength at low stress levels with drained shear strength parameters at higher stress levels.

In practice, very few stability problems occurred. The problems that did occur were not a result of this approach but always related to an unrecognised local feature. The impact of embankment stability problems on cost and schedule were virtually negligible.

**Wick drains**

During construction, loading the embankments with sand leads to the development of excess pore water pressures in the subsurface soils. These excess pore pressures must be allowed to (partially) dissipate before additional lifts of sand can be placed. The rate of consolidation thus poses a restraint on the attainable rate of embankment construction. Typical for these soils is the combination of a high compressibility with a very low permeability, leading to an extremely low coefficient of consolidation.

It will then be no surprise that, given the contractual specifications with regard to allowable construction time, it was decided to maximise the consolidation rate by installing vertical wick drains (Figure 2). Drains were installed at a center-to-center spacing of about 1 m. Initially serious doubts were raised concerning the validity of the existing design rules (e.g. Kjellman) for such close drain spacing. The results of field monitoring with settlement beacons and water pressure meters (the “observational method”) showed that the drains performed at least as well as predicted. Thus, based on “observational method”, these concerns were shown to be unfounded.

**Geotextile**

Sand was generally placed in lifts of 1-1.5 metres thick. Even with these limited lift heights stability problems...
were anticipated so in fact for most of the embankment a geotextile was placed on the original ground prior to sand placement. Since the wick drains were only installed after a floor of sand had been placed, this meant that the drains perforated the geotextile.

A damage factor based on the drain spacing and grid orientation was included in the geotextile design analysis. In practice very few stability problems occurred. To our knowledge this is the first time that geotextile was used in the Netherlands in this manner and at this scale (Figure 3).

Settlement monitoring
In The Netherlands, creep has long been recognised as having a major influence on settlement. The traditional approach to settlement calculations is based on the Koppejan equation.

This model displays a number of shortcomings. The first is that the rate of creep is independent of the development of effective stress (i.e. consolidation). In addition, the creep increases not only with time but also with the magnitude of the total stress increment.

The latter is contrary to most international practice.

In the case of stepped load increments, it is quite arbitrarily assumed that the total creep can be calculated by adding the creep components of each load step separately (“superposition principle”). Lastly, the effect of a temporary surcharge (loading followed by unloading) is by no means well defined in this model.

All of these aspects are unsatisfactory. As more emphasis is placed on reducing post-construction settlement it is increasingly important to have a predictive model, which can be used with an acceptable degree of confidence. After due consideration, the Koppejan approach was abandoned and an in-house model based largely on Yin and Graham (Yin et al. 1999) was developed. It must suffice here to say that this model uses the concept of equivalent creep time and isotachs (lines of constant creep strain rate). The compression coefficients used are based on common international practice (i.e. $c_{v}$, $c_{u}$ etc). Both stepped loading and unloading conditions are clearly formulated, including an unambiguous definition of creep time.

Settlement beacons were placed at 50-metre intervals along the axis of the embankment. The Asaoka method (Dykstra et al., 2001) proved to be a useful tool for estimating the actual consolidation coefficient from the field settlement data. Very good fits of the recorded settlements were generally obtained with the isotach model. Based on the derived fit parameters it was possible to predict the post-construction settlement at each beacon location. The model also became an important tool to establish the required finished levels during construction (e.g. prior to placing the ballast bed).

Construction
Sand for embankment construction was brought to the site by barges and unloaded with a barge-unloading dredger. The sand was discharged either directly into the embankment (Figure 4) or into a depot area from where it was trucked to the route (Figure 5). A total of roughly 2.5 million m³ of sand was placed, much of which was “Sea Sand” won in the North Sea. The North Sea sand was desalinated during transport from the winning area to the site. Desalination was so effective that the environmental restrictions concerning the maximum salinity of the placed sand were met.

HSL (HIGH SPEED RAILWAY LINE)

In 1997 the Dutch government took the decision to construct a high speed railway line linking up with the European network of high speed railway lines. Construction of the first line running from the Belgium border near Antwerp via Rotterdam to Amsterdam started in 2000. Most of this railway line passes through the western part of the country with its adverse geotechnical conditions.
As with the Betuwe Route, the construction was tendered in sections. The contract of the most northern section (HSL1) of approximately 16 kilometres between the villages of Hoofddorp and Leiderdorp was awarded to a joint venture of five Dutch contractors known as Bouwcombinatie Hollandse Meren. The contract included not only the foundation of the high speed railway line with its bridges and viaducts, but also widening of a part of one of the busiest highways in The Netherlands: the A4 between Amsterdam and The Hague. This highway runs partly parallel to the new railway line and crosses it. Both the railway line and the highway also have to cross two waterways in this section. Traffic on the highway should not be interrupted or hampered.

Geotechnical conditions and challenges
Poor geotechnical conditions along the proposed alignment comprised below a thin cover of agricultural soil from top to bottom: soft, often clayey peat, soft to very soft organic clay, soft to very soft silty clay, soft to firm peat and finally medium dense Pleistocene sand.

Low to very low shear strengths of the cohesive strata introduced potential stability problems, while high compressibility of these deposits could cause large settlements when loaded. As the proposed railway line transverses various polders these conditions could vary considerably. High groundwater tables and serious limitations to the allowable impact of construction methods on the groundwater regime of the polders further complicated the situation.

Geotechnical design
Strict requirements with respect to the (long-term) settlements of the high speed railway line necessitated a careful design process. Prior to the construction, the Dutch Ministry of Public Works initiated a full scale trial of various new techniques to reduce or eliminate settlements (‘No-Recess’ or ‘New Options for Rapid and Easy Construction of Embankments on Soft Soil’) in areas with poor subsoil conditions.

Embankments founded on stabilised columns, stabilised walls, geotextile-encased sand columns and slender cast in-situ piles were tested by subjecting them to static and dynamic loads. All systems were based on the same principle of transferring the loads by stiff elements to the competent sandy strata of the Pleistocene occurring at a depth of approx. 5-15 m below ground level. None of the tested systems,
however, produced satisfactory results and it was decided to apply a system of concrete slabs founded on conventional driven concrete piles.

Although generally running just above ground level, the line is elevated over existing infrastructure (roads, waterways and other railway lines). To avoid excessive bending moments in the piles as a result of braking forces of the high-speed train the design of the approaches to the abutments of bridges and viaducts included earth embankments between the concrete slab and existing ground level. The construction of these embankments introduced a number of geotechnical problems in terms of stability and long-term settlements. Tight planning did not allow enough time for conventional consolidation methods of the highly compressible, cohesive subsoil. In addition, excessive long-term deformations (creep) could introduce unacceptable bending moments in the piles carrying the concrete slabs.

In the final design it was foreseen to remove 3-4 m of highly compressible clays and peat and replace it with sand. Reducing the thickness of the compressible layers increased stability and reduced the (residual) settlements (Figure 6).

In the area where the railway line and the highway run parallel, excavation of the cohesive sediments immediately adjacent to the high embankment of the existing highway was considered to be too risky. Instead it was decided to apply alternative techniques to accelerate the consolidation process, not only increasing the shear strength of the cohesive strata, but also reducing the long-term settlements (creep). One of these techniques was a new vacuum consolidation system, the BeauDrain system, recently developed by Boskalis Westminster.

**BeauDrain system**

The BeauDrain system combines the well-established technique of vacuum consolidation with an innovative installation procedure illustrated in Figure 7. Through a specially designed plough that is pulled by a hydraulic crane, prefabricated vertical (wick) drains are installed and cut at predefined depths below ground level. While the plough is moving a horizontal collection drain is placed at a depth of approx. 3 m below ground surface and is connected to the vertical drain. Before it leaves the plough, the horizontal drain is also covered by an impervious geomembrane in order to ensure a proper sealing between the horizontal drain and the atmospheric conditions.

The whole system, which is usually referred to as a drainage curtain, consists of a row of vertical drains,
a horizontal drain and seal. It is placed in a single pass of the plough. After passage of the plough the compressible soil usually closes in on itself above the horizontal drain creating a natural seal that augments the geomembrane. The total system consists of a number of drainage curtains connected to vacuum pumps.

The net effect of the introduction of a vacuum in the subsoil is an additional atmospheric surcharge, which will ensure an early attainment of the required settlement, and an increased shear strength favouring the stability (accelerated loading schemes, steeper slopes in areas with limited space).

**Embankment construction**

Although most of the embankments could be constructed using the traditional method of replacing part of the cohesive strata by sand, a number of critical sections are being raised using this new method to accelerate consolidation. Not only does it save surcharge sand, it also allows for a reduced construction time and has eliminated the risk of a failure of the embankment of the existing highway.

The degree of consolidation at any time during construction and predictions of post-construction settlements are based on fits of the actually measured settlements using the same in-house developed settlement model discussed before. The consolidation degree is used to monitor the stability of the various lifts, while the prediction of post-construction settlements determines the moment the residual settlements meet the settlement criteria.

**Conclusion**

A 22 kilometre embankment section of the Betuwe Route freight railway line has been designed and built by an alliance of ProRail (Dutch railway infra manager) and HBSC (a combination of four large Dutch and Belgium contractors) in an area of highly compressible soils. The contractual form of an alliance was chosen to maximise synergy between the various contractual parties. In November 2003, four years after the start of the alliance, the project will be completed within the contractual time frame and well within the original project budget. The contractor’s geotechnical design was especially a major contribution to the success of the project.

Like the Betuwe Route, the HSL is being constructed in an area with very poor subsoil conditions. The potential stability problems of the existing embankment of one of the busiest highways in The Netherlands running immediately adjacent to the new railway line have been solved by locally using the BeauDrain system, a new, innovative combination of conventional vertical and horizontal drains and the existing technique of vacuum consolidation.

These projects demonstrate that improvements in embankment design and construction do not necessarily require completely new, revolutionary ideas, but can well consist of innovative use of existing knowledge and techniques.

**References**

