# Piled embankments using geosynthetic reinforcement in the Netherlands: design, monitoring & evaluation

## Remblais sur pieux utilisant un renforcement geosynthetique aux Pays Bas : conception, inspection & évaluation

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ABSTRACT

In 2009, the Dutch guideline for the design of piled embankments is presented. For this purpose, existing design models have been considered and validated. This paper describes parts from that validation: a comparison between several design models and the validation with a field test. Predictions with the German concept-standard EBGEO show the best agreement with numerical calculations and the field test. The Dutch Standard adopts major parts of this EBGEO standard to calculate the tensile forces in the geosynthetic reinforcement, but wants to extend it to lower embankment heights.

RÉSUMÉ

En 2009, la directive hollandaise pour la conception des remblais sur pieux a été présentée. À cette fin, des modèles de conception existants ont été utilisés et validés. Cet article décrit des parties de cette validation : une comparaison entre plusieurs modèles de conception et la validation avec un essai sur le terrain. Les simulations avec le concept-standard allemand EBGEO donnent la meilleure adéquation entre les calculs numériques et l'essai sur le terrain. La norme hollandaise adopte une grande partie de cette norme EBGEO pour calculer les forces de tension dans le géotextile, mais veut le prolonger aux remblais plus bas.

Keywords : piled embankments, field tests, case studies, geosynthetic, geogrid, piles

## 1 INTRODUCTION

For the construction of roads on very soft soils, several construction methods are available. The piled embankment using geosynthetic reinforcement (GR) is one of these methods, becoming more and more popular in the Netherlands. Until 2009, at least 20 piled embankments have been constructed underneath highways and local roads. In 2008, for the first time, a piled embankment was constructed below a Dutch railway. Often a piled embankment is applied under abutments for viaducts or flyovers. This guarantees a sustainable smooth connection between road and construction. The construction of a 14 km long piled embankment started in July 2007, through the soft-soil-polder 'The Krimpenerwaard'.

A piled embankment makes it possible to construct a road rather quickly and settlement-free, which gives relatively low life cycle costs. Furthermore, sensitive constructions next to the piled embankments, such as cables and pipelines, will not be effected by horizontal movements of the soil.

In 2009, a Dutch Standard for the design of piled embankments is presented. For this purpose, the Dutch CUR-committee 'Design Guideline Piled Embankments' considered and compared existing design methods for reinforced embankments on a field of piles.

This paper considers the British Standard BS8006 (199xxx), and the German Draft-Standard EBGEO (2004xxxx). These methods will be validated with numerical calculations and the results of a full-scale test.

This paper only considers the calculation of the tensile forces in the GR due to the vertical loads and the fill arching on the piles. The (often significant) tensile forces in the GR due to the horizontal stresses in the embankment ("spreading") are beyond the scope of this paper.

### 1.1 *What determines the Dutch choices?*

Several design methods have been analyzed. Between other focus points, special attention was paid to the mechanical and mathematical consistency of:

- The distribution of the forces within the embankment (part A transferred directly to the pile caps through arching, part B that is transferred through the reinforcement to the pile caps, and part C resting on the soft subsoil, see figure 1)
- The concentration of the load parts B (and C) onto the reinforcement strips between the pile caps
- How to calculate the tensile force in the reinforcement as a result of load B (and C)
- The influence of dynamic load on arching
- Support of soft soil between piles
- Finally, The Netherlands are really flat; therefore it is important to construct low embankments on the piles.

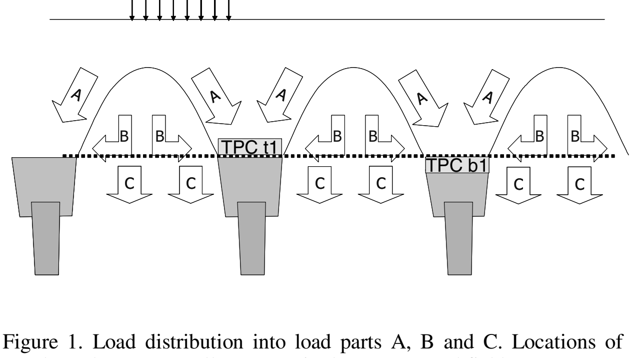


Figure 1. Load distribution into load parts A, B and C. Locations of Total Load Pressure Cells (TPC's) in the Kyoto Road field test

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## 2 DESIGN MODELS

### 2.1 *The British Standard BS8006*

The British code BS8006 makes four assumptions to calculate the load on the GR of a piled embankment:

- Part A of the load is calculated with the equation of Marston (1913) for pipes, adapted for a piled embankment.
- No support of soft soil (load part C = 0, fig. 1).
- The load B is transferred into line-loads $W_T$ on the strips of reinforcement between two pile caps. BS8006 based this on the work of Jones et al (1990), who assumed a 2-dimensional geometry, which means walls in the soil instead of piles. This gives (for partial arching) a much higher tension in the GR. (All the load is carried in only one direction, perpendicular to the walls. In reality, the load is carried in two directions between the piles (especially for biaxial reinforcements)). Many authors however, assume that BS 8006 is meant to be fully 3-dimensional. In comparing studies, they use a wrong pile efficacy. This plus an adapted version of BS8006 is described in Van Eekelen and Bezuijen (2008a), this version is involved in figure 3 of this paper.
- BS 8006 assumes that 'full arching' exists. So, if the embankment is high enough, extra embankment height or traffic load is ignored for the design of the GR.
- Consequence of the last two assumptions, the 2D base of Jones et al, and the full arching, is that there is no vertical equilibrium. This is fully elaborated in Van Eekelen and Bezuijen (2008a).
- The relation between the line-load $W_T$, the strain ε and the tensile force in the GR is given by the catenary equation.

The BS8006 calculates a tensile force in the GR (due to vertical load and arching) that depends on: the geometry of the system, the weight of the embankment, and the surcharge (traffic). No dependence is assumed on other fill properties (e.g. internal friction angle). The angle of internal friction only has influence on the tensile force due to "spreading" near the edges of embankment.

### 2.2 *The German EBGEO, chapter 6.9, piled embankments*

The design concept in the German EBGEO-Draft is based on the work of Zaeske, 2001. The tensile force in the reinforcement due to vertical load and "arching" depends not only on the parameters in the BS8006, but also on the internal friction angle of the fill material φ and the modulus of subgrade reaction k, kN/m³ of the soft subsoil.

EBGEO first calculates the load parts A and (B+C). B generates a strain in the GR, which can be determined with graphs, based on differential equations for an elastically supported membrane. These graphs use, among others, the time-dependent tensile modulus (tensile stiffness) J, kN/m' of GR, and the subgrade reaction modulus k, kN/m³ of the soft soil . The strain, determined with the graphs, gives with J the tensile force F, kN/m'. The rest of the load (C), which is not specifically calculated, is carried by the soft subsoil.

## 3 CASE STUDY

### 3.1 *Specifications of the case study*

Two cases have been considered, see figure 2. Several calculation series have been carried out with BS8006, EBGEO and an axial-symmetric finite elements model (Plaxis), each time varying only one parameter. The EBGEO is only applicable for H>(s-a) and BS8006 for H>0,7($s_x$-a), with $s_{EBGEO}$=sqrt($s_x^2$+$s_y^2$)) and a is pile cap side (BS8006) or pile cap diameter (EBGEO). Therefore, EBGEO is officially only applicable to case 2.

BS8006 uses the strain as input, as the EBGEO and Plaxis use the stiffness of the GR as an input parameter. For the comparing study, the input-strain of BS8006 has been chosen so that the stiffness of the GR is the same as for the other Calculations.

| | **Case 1** | **Case 2** |
|---|---|---|
| No support of soft subsoil | | |
| Centre to centre distance of piles (in x- and y- direction,not diagonal) | $s_x = s_y$ =1,75 m | $s_x = s_y$ =1,00 m |
| (Equivalent) diameter pile caps | a = 0,50 m | a = 0,30 m |
| Volume weight fill material | γ = 20 kN/m³ | γ = 20 kN/m³ |
| Internal friction angle fill material | φ = 37,5 kN/m³ | φ = 37,5 kN/m³ |
| Weight asphalt and foundation | 6 kPa | 6 kPa |
| Surcharge load | 30 kPa | 30 kPa |

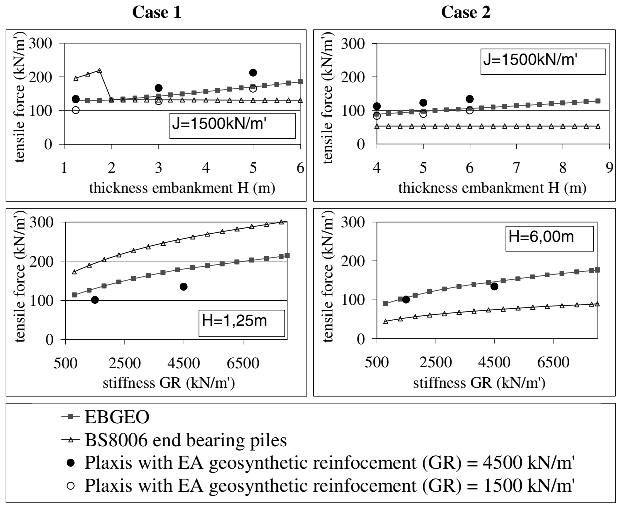


Figure 2. Tensile forces in the geosynthetic reinforcement (GR), for the case study for case 1 and case 2.

### 3.2 *Results of the case study*

The results show calculated tensile force along the road axis, thus due to vertical loading.

For the high embankment (case 2), the results of EBGEO and Plaxis agree very well. For the low embankment (case 1), agreement is found as the GR stiffness is increased in the Plaxis calculation from 1500 to ca. 4500 kN/m'. For example for H = 1,25 m in case 1 with EA = 1500 kN/m', Plaxis gives a circa 20% lower tensile force than EBGEO.

The Plaxis calculations have been carried out with an internal friction angle φ = 37,5 ° and a dilatation angle ψ = 7,5 °, while in EBGEO ψ =0 °. We have recalculated the Plaxis calculations with a ψ =0 ° and found better agreement with EBGEO (less than 8 % difference between EBGEO and Plaxis tensile forces).

At H=1,4(s-a), the BS8006 graph shows a sudden change where the situation changes from partial arching to full arching. Thereafter the tensile force remains constant with increasing H. In this situation of full arching, the entire extra embankment height and surcharge load is supposed to be transferred directly to the piles. Therefore, the reinforcement does not 'feel' extra load any more.

Calculations with Plaxis and EBGEO show an increasing load on the GR with increasing embankment thickness.

For the low embankment (partial arching), the BS8006 finds high tensile forces. This is due to the 2 dimensional configuration as used to determine the line loads on the reinforcement strips between two pile caps. This means that one strip carries considerable more (nearly twice as much) load than in the case a 3 dimensional configuration would have been used.

Not in the figures, but important is that the BS8006 results do not depend on the fill properties, such as the internal friction angle φ. Only the lateral forces due to the slope of the embankment are influenced by φ, as common in soil mechanics.

### 3.3 *Conclusions case study*

The agreements between the EBGEO and Plaxis calculations, and the consistency of the EBGEO-results were arguments (between others) for the Dutch Committee to adopt the design method of the EBGEO in the Dutch design guideline.

BS8006 is not consistent. The lack of vertical equilibrium in the equations and the jump in the tensile forces at the transition from partial to full arching do not increase confidence in this method. Problem with the EBGEO for the Dutch conditions is that it is only valid for embankments higher then the diagonal distance between two piles. The original work of Zaeske (2001) also presents results for lower embankment heights. For the Dutch, an extension of the EBGEO to lower embankment heights is essential.

## 4 THE KYOTO ROAD, A FIELD STUDY

### 4.1 *Specifications of the Kyoto Road*

At this moment, at least three piled embankments are being monitored in the Netherlands; a test field in the 14 km long N210 in the Krimpenerwaard, a piled embankment below a railroad in Houten, and a piled embankment in Giessenburg, called the Kyoto Road. Although they are all involved in the studies for the Dutch guideline, we will focus here on one of these field studies: the Kyoto Road.

The Kyoto Road was constructed on 13 m long wooden piles, concrete pile caps with a height of 0,4 m and a diameter a = 0,3 m. The geogrid reinforcement consisted of two layers uni-axial grid, perpendicular on road axis Fortrac 400/30-30 M and along the road axis Fortrac 350/50-30 M. On top of that a 1,15 m high embankment fill of a 'Hegemann' (sandy) sludge mixture was constructed.

The Hegemann sludge mixture is a mixture of dredged material and additives containing mainly clay and cement with the following properties: average unit weight $\gamma_{average}$ = 18,6 kN/m$^3$, internal friction angle $\varphi$ = 33,8 $^o$ and a cohesion of 11,5 kPa. Usually, non-cohesive granular material is used for embankment fills. The modulus of subgrade reaction of the soft subsoil (peat), determined from compression tests on samples, is k = 477 kN/m$^3$. However, this value will be too low: more than a metre of the top layer was removed before the (quick) installation of the piled embankment. The peat was still swelling when the embankment was constructed. The swell of the peat will give a larger counter pressure from the subsoil acting on the mattress than calculated with k = 477 kN/m$^3$.

Van Eekelen and Bezuijen (2008b) describe the Kyoto Road more detailed. This paper considers the monitored total pressures just above the piles, both on top of the reinforcement as well as below the reinforcement, as shown in Figure 1. The measurements will be continued for several years. This paper presents the results of the first 3 years of measurements.

### 4.2 *Distribution of the load*

Figure 1 shows how each design model starts with the distribution of the total load into three parts: A, B and C. The total pressure cell on top of the GR measures A. The total pressure cells below the GR measures A+B. The total load of the embankment is known (115 kN/pile area). Part C equals the total load minus (A+B).

EBGEO calculates B+C together and A separately. With the stiffness $J_x$ = 3920 kN/m of the GR (determined with the isochrone curves for Fortrac M with an assumed strain of 2,5 %) and a subgrade reaction k = 477 kN/m$^3$, EBGEO calculates the tensile force in the GR, and implicitly distinguishes B and C. Figure 3 gives the results.

It is possible to calculate the pressure that would be measured if no arching would occur at all. In that case the entire load is being transferred strictly vertically and the load is $\gamma$*H (+p) = (18,6 * 1,15 + p) = 21,39 + p kPa. Without extra loading (p) this results in a load on each pile cap of $A_p$ * 21,39 = 1,5 kN. On the geotextiel/subsoil this gives B+C = $A_g$*21,39 = 33 kN. The surcharge load is only sometimes accidentally measured. As soon as arching occurs, the load is transferred partly laterally to the piles and we measure an A larger than 1,5 kN and a B+C smaller than 33kN. For this Kyoto Road case, EBGEO calculates B+C= 24 kN. The difference between 33 and 24 kN is due to arching.

Figure 3 shows that it took a long time for the arching to develop completely (due to settlements in the embankment and cementation of the fill material). From July 2006 onward, the measurements are more or less constant. The fluctuations are mainly due to fluctuations in the weather and in moisture content, and the alternation of periods with heavy traffic and without traffic. Van Eekelen et al (2007) describe these influences more specifically.

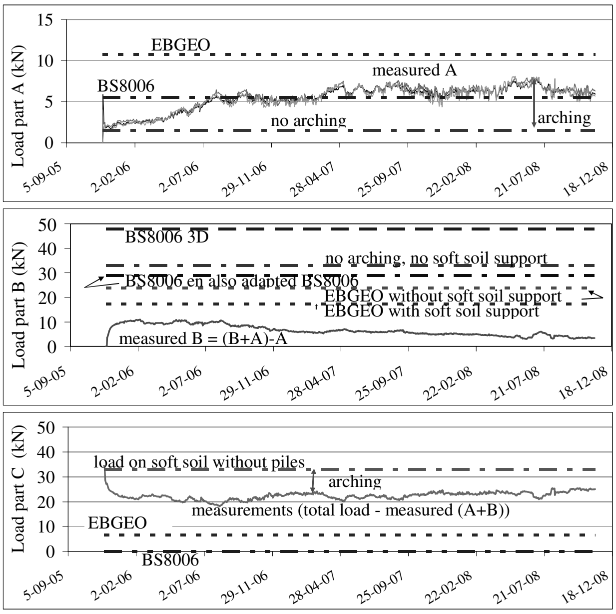


Figure 3. Comparison of measurements in the Kyoto Road and predictions with EBGEO and BS8006

The prediction of BS8006 for the load directly on the pile (A) agrees better with these measurements than the predictions of EBGEO. Apparently, the BS8006-equations based on Marston, predict the arching quite well. The calculation of the load on the piles is necessary to calculate the load on the GR. For the load on the pile to be used for the design of the pile itself, usually the total load is taken.

Load part B (second picture in figure 3) shows the load part that is transported by means of tensile forces in the GR to the piles. The figure shows that EBGEO, when taking into account the support of the subsoil, gives the best approach of the measurements. This is important, as this load directly determines the predicted tensile forces in the GR. When the subsoil is supposed to carry a part of the load, the EBGEO prediction approaches the measurements best.

This is in agreement with load part C, that is carried by the soft subsoil, see the last picture of figure 3. Part C is considerable, even larger than calculated with EBGEO. As described in section 4.1, this was expected. Table 2 shows that the influence of a larger subgrade reaction. The table shows that the subgrade reaction (2000 kN/m$^3$) was apparently larger than the 477 kN/m$^3$ measured in laboratory test on samples taken in the field. This is what we expected due to the construction procedure in the field.

Table 2. EBGEO Predictions with varying subgrade reactions

| k | kN/m$^3$ | 0 | 250 | 477 | 850 | 1150 | 1500 | 2000 | 2500 |
|---|---|---|---|---|---|---|---|---|---|
| B | kN | 24 | 21 | 19 | 16 | 14 | 12 | 10 | 8 |
| C | kN | 0 | 2 | 4 | 7 | 10 | 12 | 14 | 16 |

It is necessary to calculate with the support of subsoil to find an agreement with the measurements until now. However, for each case it is necessary to justify the assumption that the subsoil support will remain throughout the pile embankment's lifetime or not.

### 4.3 *Influence of dynamic loads*

The PhD study of Heitz (2006) on the effects of dynamic loads on arching concludes that dynamic loading can decrease the arching effect. A dynamic loading has more influence on arching when:

- the relative thickness of the embankment (H/s or H/(s-a)) becomes smaller
- the dynamic load is larger in comparison with the total load (static + dynamic)

Heitz concludes that the effects of the dynamic load can be either positive or negative for the GR. Two mechanisms can be important. First, the subgrade reaction can reduce under dynamic loading (see for example page 46 of Heitz). Second, the arching effect can change. In for example his figure 5.31, Heitz finds that both B and C are increasing with increasing number of load cycles. Increasing load B gives a higher tensile force in the GR.

Table 3, comparison Kyoto Road and Heitz test Z04

| | H | D | $s_x=s_y$ | s | h/s | h/(s-d) |
|---|---|---|---|---|---|---|
| | m | M | m | m | - | - |
| Kyoto Road | 1,15 | 0,30 | 1,27 | 1,80 | 0,6 | 0,77 |
| Heitz test Z04 | 0,35 | 0,18 | 0,50 | 0,71 | 0,5 | 0,66 |

Heitz' test number Z04 is most comparable with the Kyoto Road, they are both in the range that influence of the dynamic load on the arching can be expected. The Kyoto Road is only loaded during working days (mainly with heavy trucks), which is shown in figure 4. The Kyoto Road indeed shows that the load on the GR decreases after the daily passages. However, during the periods without traffic, the GR has the opportunity to restore again. Therefore: the dynamic load does influence the arching and the tensile stress in the GR. However, the arching can be restored in this case, and will build up further.

## 5 CONCLUSIONS

In both the case study and the measurement in the Kyoto Road, the EBGEO gives a better prediction than BS8006. Furthermore, the BS8006 has some problems with the vertical equilibrium and the transition from partial to full arching. Therefore, the Dutch made the choice to adopt major parts of the EBGEO.

However, some adaptations are made, to make the method also applicable for low embankments. The influence of dynamic loads on the piled embankment using geosynthetic reinforcement is still being considered, and will be reported more extensively elsewhere.

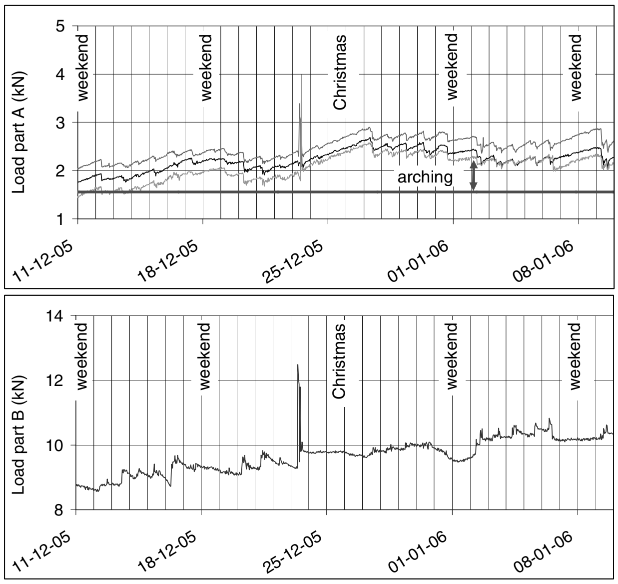


Figure 4, detail of Kyoto Road measurements. The arching is reduced due to the truck passages, but during rest periods (weekends, Christmas), the arching restores and develops further.

## ACKNOWLEDGEMENTS

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