The Dutch design guideline for piled embankments

Eekelen, S.J.M., van[1], Jansen, H.L.[2], Duijnen, P.G., van[3], De Kant, M.[4], Dalen, J.H., van[5], Brugman, M.H.A.[6], Stoel, A.E.C., van der.[7], Peters, M.G.J.M.[8]

[1] Deltares, Delft University of Technology, chair person Dutch Task Group Piled embankments [2] Fugro, [3] Movares, [4] Royal Haskoning, [5] Strukton Engineering and Delft University of Technology, [6]) Arthe Civil & Structure, [7] CRUX Engineering, University of Twente, Netherlands Defence Academy, [8] Grontmij

All members of the Dutch Task Group 'Dutch Design Guideline for the Design of Piled Embankments'

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ABSTRACT:
This paper presents the outlines of the Dutch Design Guideline for the design of piled embankments, which was introduced in 2009. For the design of the geosynthetic reinforcement (GR), the Dutch Design Guideline adopts major parts of the German EBGEO. However, constraints are adapted for Dutch circumstances. The choice for the EBGEO design method is – among others – based on measurements in three Dutch piled embankments. A comparison shows that the EBGEO forms a conservative approach of the measurement. For large dynamic loads, the arching-reduction (κ)-model of Heitz is recommended.
In the Netherlands, the load and resistance factors design approach is commonly used. This paper presents the newly determined set of load and resistance factors. Monte Carlo analyses show that the Eurocode reliability index is satisfied with this set of safety factors.
Perpendicular on a road axis, the Dutch Design Guideline recommends calculating with the sum of the spreading forces and membrane forces. The paper describes how to use the finite element method to determine bending moments in piles due to lateral mechanisms, such as for example spreading forces, brake application and centrifugal forces. Finally, deformation differences of the surface can be determined numerically using finite elements, but also an analytical method is suggested, namely a 3D version of Peck's method.

1 INTRODUCTION

In 2009, the Dutch Design Guideline for the design of piled embankments has been introduced. This paper sketches the outlines of this Design Guideline, which follows major parts of the German EBGEO (2009).

The choices made within the Dutch Design Guideline are based on comparisons with and analyses of several field tests, finite element calculations, parameter studies, and work of several authors (like Zaeske, 2001, Heitz, 2006, Farag, 2008 and Love & Milligan (2003)). The BS8006 (1995 and 2009) and the EBGEO have been discussed in great detail.

The constraints of the EBGEO for the applicability of the design rules have been considered and adapted for the Dutch situation. For example the minimum height of the embankment is reduced. Holland is a flat country. The environment asks for relatively low roads, with thin embankments.

2 DESIGN GEOSYNTHETIC REINFORCEMENT

2.1 *Calculation procedure*

We distinguish several calculation steps in the design of the geosynthetic reinforcement (GR).

1. Determination material properties en load- and material factors (set of factors is based on safety philosophy especially for piled embankments).
2. From axle load to uniformly distributed load.
3. Force distribution within the piled embankment.
4. Concentration distributed load into line load.
5. From line load to strain and membrane tensile force $T_{s;membrane;d}$.
6. Include spreading perpendicular on road axis: $T_{s;tot;d} = T_{s;membrane;d} + T_{s;spread;d}$

The calculation is an iterative process. The tensile force depends on the tensile stiffness of the GR. Both ultimate state and usability state (factors = 1,0) are considered. The next sections will consider each of the above calculation steps separately.

2.2 *Step 1: Safety philosophy*

The EBGEO (2009) uses an overall safety factor approach (calculate the representative situation first, and then apply safety factors). The Dutch, however, usually use a load- and resistance factor design approach (factors first, and then calculate).

To adopt the calculation rules of the EBGEO, and also follow the common Dutch safety philosophy, it was necessary to determine a new set of partial factors. Purpose was to find a set that gives a probability of failure (p_f) and the related reliability index β for the piled embankment as prescribed by the Eurocode (table 1). A fault tree analysis results in the related p_f and β for the GR.

Reliability Classes	Piled embankment		GR fails	
Eurocode	β	p_f	β	p_f
RC1	3,3	4,8E-04	3,5	2,0E-04
RC2	3,8	7,2E-05	4,0	3,5E-05
RC3	4,3	8,5E-06	4,5	4,0E-06

Table 1: Probability of failure (p_f) and reliability index β

The analysis was carried out as follows:

1. Choice for a set of load- and resistance factors.
2. Make reference design.
3. Monte Carlo analyses: 20.000 calculations, in which the load- and resistance parameters were chosen on basis of a Gauss distribution. This gives a probability distribution $P(R>S)$ and a probability of failure (p_f).
4. When this p_f satisfies the values given in table 1, the chosen set of factors gives a sufficiently save design.

This set of partial factors does not necessarily give the same design results as EBGEO, as shown in Fig. 1, but the safety constraints of Table 1 are satisfied. Table 2 presents the resulting set of load- and resistance factors, as adopted in the Dutch Guideline.

Parameter		RC1	RC2	RC3
(Dynamic) load *p* (kN/m^2)	$\gamma_{Q;dyn}$	1,05	1,10	1,20
Angle of internal friction *tan* φ (°)	γ_φ	1,15	1,15	1,15
Soil weight (kN/m^3)	γ_γ	0,90	0,85	0,80
Modulus of subgrade reaction *k* (kN/m^3)	γ_k	1,30	1,30	1,30
Axial stiffness GR *EA (kN/m')*	$\gamma_{m;E}$	1,00	1,00	1,00
Strength GR *(kN/m')*	$\gamma_{m;T}$	1,25	1,30	1,40

Table 2. Load and resistance factors Dutch Design Guideline

Figure 1 shows the differences in tensile force between the EBGEO and the Dutch approach (RC2). For RC3 the results of the Dutch method and the EBGEO are almost equal (difference <10%). In the Netherlands, usually RC1 has to be applied for highways and RC3 for rail roads.

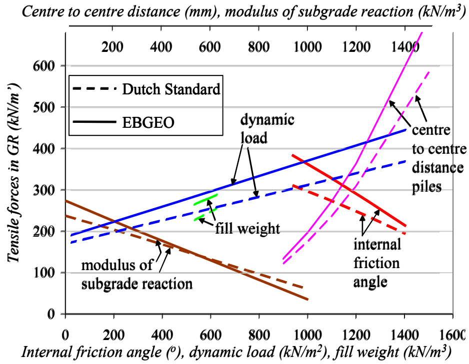

Figure 1. Influence differences safety Dutch and German approach, Lastfall 1 (EBGEO) and RC 2 (Dutch/Eurocode), arching reduction (kappa-model) not included yet.

2.3 *Step 2: From axle load to uniform load*

The Dutch Guideline gives rules how to translate a now and then occurring extreme axle load into a uniformly distributed (input-)load. The axle loads are spread according Boussinesq over the total height of the embankment. The extra spreading capacity of the asphalt top layer may be taken into account with a virtual extra height. The influence of all three axles of a standard truck is summed. Table 3 presents a summary of a larger table that is part of the Dutch Guideline. The stress ($\sigma_{max;ave}$) is the average stress on the maximal loaded pile grid (s_x*s_y), with $s_{x,y}$ (m) the CTC distance between piles.

Height embankment *H* *[m]*	1.5 x 1.5 m² $\sigma_{max;ave}$ $[kN/m^2]$	2.0 x 2.0 m² $\sigma_{max;ave}$ $[kN/m^2]$	2.5 x 2.5 m² $\sigma_{max;ave}$ $[kN/m^2]$
1.0	61.3	51.3	44.8
2.0	33.7	30.0	27.8
3.0	21.1	19.8	19.0

Table 3. Examples: distributed load for a 600 *kN* truck.

2.4 *Step3: Load distribution*

The load within the piled embankment is distributed with the arching equations mentioned in de EBGEO (Zaeske, 2001). For comparison reasons we define load parts A, B and C (figure 2) as:

A. Goes directly to the pile caps through arching.
B. Goes through the reinforcement to the pile caps.
C. Resting on the soft subsoil.

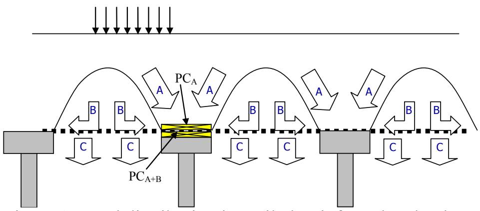

Figure 2. Load distribution in a piled, reinforced embankment

2.5 *Step 4: Conversion into line load*

Load part B(+C) is concentrated into a line load on the reinforcement strips between two pile caps. EBGEO carries out this load step 3D and correctly, resulting in a triangular distributed line load.

2.6 *Step 5: From line load to membrane force*

The line load finally results in a tensile (membrane) force. This can be described with a differential equation (for example Bouma, 2005 or Bezuijen et al, 2010). Zaeske (2001) gave a solution in graphs, from which the strain and thus the tensile stress of the GR can be read out. The Dutch Design Guideline gives an alternative elaboration, which is basically the same as Zaeske's graphs in the EBGEO.

For each project, it is important to determine whether the subsoil will support or not, considering for example the effects of working platforms for the pile installation, left below the GR and future changes in the groundwater table.

2.7 *Step 6: Spreading forces*

The spreading forces are calculated from the lateral earth pressure. It was considered to take the maximum of the spreading force and the membrane force for the tensile force perpendicular to the load axis of the (rail) road, according to the suggestions of Love & Milligan (2003).

An important issue in the considerations was the value of the coefficient for lateral earth pressure. When an arching effect occurs in the embankment, the lateral earth pressure can be higher than active. A positive correlation between the arching effect and the spreading force exists, where the correlation between membrane force and arching effect is reverse.

However, finite element calculations have shown that the spreading forces should be calculated with the active ground pressure, and that spreading forces and membrane forces should be summed.

2.8 *Constraints*

The Dutch Design Guideline prescribes the following constraints:

1. $H/(s\text{-}d) \geq 0{,}66$
2. $p_{dynamic} < p_{embankment\ weight}$ or: apply κ-model of Heitz (2006)
3. $d/s \geq 0{,}15$
4. one layer of GR: $z \leq 0{,}15$ m, two layers of GR: distance between two layers $\leq 0{,}20$ m
5. $2/3 \leq s_x/s_y \leq 3/2$
6. $\varphi'_{fill} \geq 35^{\circ}$ for the lowest layer with height $h^* = 0{,}66(s\text{-}d)$. Above that, $\varphi'_{fill} \geq 30^{\circ}$
7. $T_{r,d} \geq 30$ kPa, in both directions, and $0{,}1 \leq T_{r;x;d}/T_{r;y;d} \leq 10$
8. $k_{s;paal}/k_{s;subsoil} > 10$

Not mentioned before are: z (m) is the distance between GR and pile cap, d (m) is the (equivalent) diameter of the pile cap and $T_{r,d}$ (kN/m') is tensile strength GR (calculation value, without safety factors). All constraints, except number 2, are different from the constraints in the EBGEO.

3 VALIDATION EBGEO / DUTCH

3.1 *Comparison load distribution with field tests*

Between others, comparison of predictions and field measurements was one of the studies carried out to make a choice for a design method. Figures 3 to 5 compare EBGEO predictions with measurements in three monitored piled embankments that have been reported elsewhere: a railway (Van Duijnen et al, 2010), the 'Kyoto Road' (Van Eekelen et al, 2010) and the 14 km long regional road N210 in the Netherlands (Haring et al, 2008).

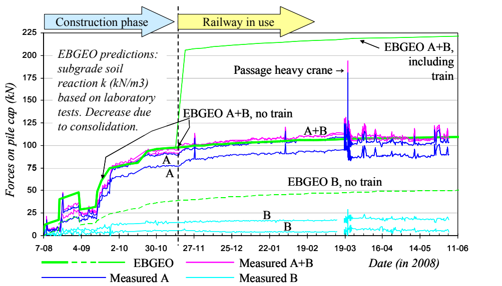

Figure 3. Load distribution below railway in Houten, prediction and measurements (Van Duijnen et al, 2010)

Load part B directly determines the tensile force in the GR. The measured B is 25-40-73 % of the prediction of EBGEO, which is on the save side. The BS8006-prediction of B in Fig. 5 is far too high, as expected for this relatively thin embankment (partial arching).

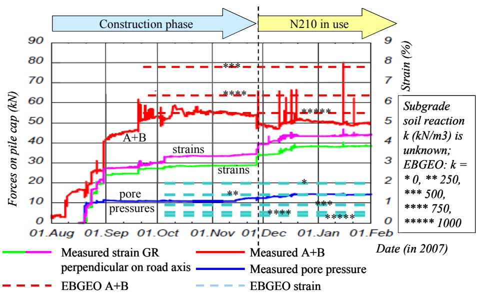

Figure 4. Load distribution in N210, prediction and measurements (Haring et al, 2008)

It is concluded that EBGEO (and thus also the Dutch Standard) gives better predictions for the measurements than all other available design methods.

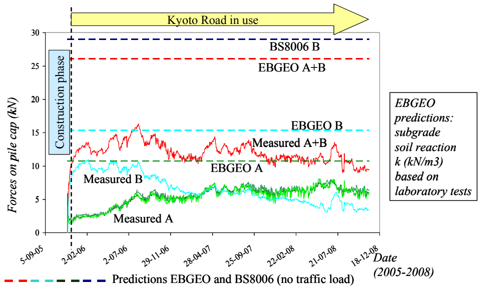

Figure 5. Load distribution in the Kyoto Road, prediction and measurements (Van Eekelen et al, 2010)

3.2 *Thin embankments, influence dynamic loads*

The monitoring programs show that the arching improves in time under operation. This could be caused by the increase of the internal friction angle due to densification, some hydraulic binding, some increase of GR deflection due to creep and subsoil settlement (Van Eekelen et al, 2010).

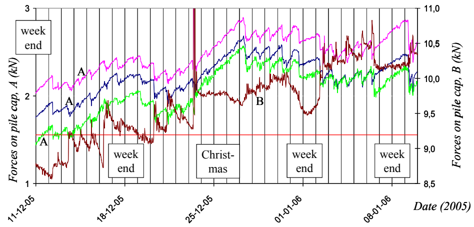

Figure 6. Arching cycle in the Kyoto Road, measurements (Van Eekelen et al, 2010)

A heavy passage, however, can give a sudden decrease of the arching (decrease of A, see the heavy crane passage in figure 2). The Kyoto Road, where traffic only occurs during working days, shows a daily arching reduction during the first passages of the day. After that the arching recovers during the rest of the day or weekend. This recovery mechanism is not yet seen clearly in the N210 and Houten.

The Dutch minimum embankment height $H \geq 0{,}66(s\text{-}d)$ is lower than in EBGEO ($H/(s\text{-}d) \geq 1{,}0$). Heitz (2006) showed with a series of tests that such a low minimum is allowable as long as enough reinforcement is available and the dynamic load is not too large. Therefore the dynamic load is restricted.

So, to prevent a continuous reduction of arching, the Dutch Design Guideline gives the following constraint for the maximum traffic load:

$p_{dynamic} < p_{embankment\ weight}$ or: apply κ-model of Heitz (2006).

When the dynamic load is relatively too large, the Dutch Design Guideline prescribes to use this arching reduction (κ) model of Heitz (2006), who based his model on his unreinforced laboratory tests only. Therefore, the κ model is a conservative model, thus on the save side.

4 PILES

4.1 *Type of construction*

The Dutch Standard distinguishes 2 different design approaches:

1. Settlement Free Construction (SFC), settlements < ca. 3 cm. The piles are designed to carry the entire load. For the design of the GR, load part C (subsoil) can be assumed zero, dependent on the local circumstances. The piles underneath are end-bearing piles.
2. Settlement Reduction Construction (SRC). Some settlement of the piled embankment is accepted. The total load is carried by both the piles and the subsoil. The piles underneath are end bearing piles or friction piles.

The second design approach results in less construction costs.

4.2 *Bearing capacity piles*

The vertical bearing capacity of the end-bearing piles is determined using the common Dutch design guidelines.

For the bearing capacity of the friction piles in a SRC, a so-called 'Interaction Model' is presented. This model is an elasto-plastic spring model. Piles and subsoil are modelled as 2 separate beams (without bending stiffness). Multi-linear springs take into account the interaction between the pile and the subsoil. Koppejan is used for the compressibility of the subsoil. The pile is elastic, according to Hooke. The model is iterative. Nodes 1 and 11 are related by the differential settlements between the pile head and the subsoil in between. Fig. 7 presents the model.

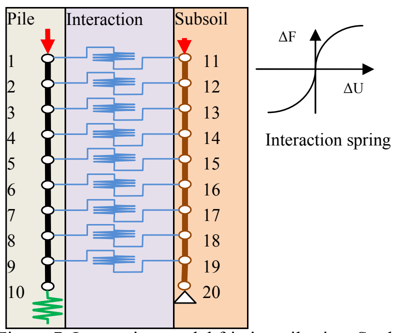

Figure 7. Interaction model friction piles in a Settlement Reduction Construction

4.3 *Horizontal loading on piles*

In the first stage of the design of piled embankments, the efforts are usually limited to calculations for the GR and the bearing capacity of the piles. Lateral loading of the piles, however, can be caused by for example vehicle loads or asymmetry of the embankment. These lateral loads can cause relatively large bending moments in the foundation piles of the embankment. Because the piles and steel reinforcement in the piles significantly contribute to the costs of the piled embankment, determination of the displacements, lateral forces and bending moments plays an important role in the design process.

FEM calculations form the only reliable method to determine the influences on sensitive adjacent structures and bending moments in the piles. For example the FEM program PLAXIS is used for this purpose (Slaats & Van der Stoel, 2009). Although complex geometries principally call for a 3D FEM approach, 2D FEM is still preferred because of the limited calculation time. To be able to assess the validity of 2D calculation for the 3D situation, a comparison has been made between a 3D and 2D FEM model for the Houten case, using Plaxis 3D Tunnel and Plaxis 2D v9 respectively. The models are shown in Figure 8 (2D) and Figure 9 (3D).

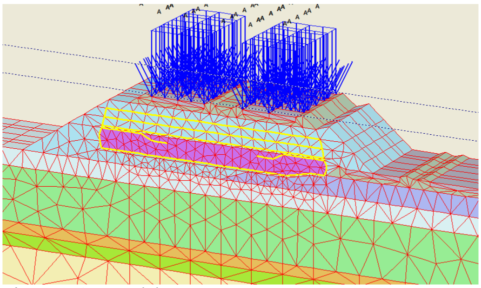

Figure 8. 3D Model

The bending moments in the piles have been determined from a set of calculations, in which the traffic loads and the soil support have been varied.

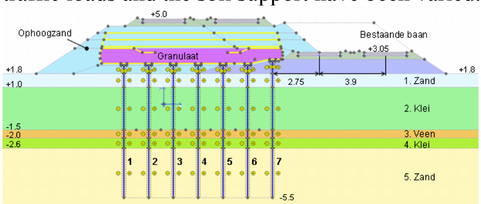

Figure 9. 2D Model

Figure 10 compare the 2D and 3D results for one of the cases. The following conclusions can be drawn:

- The bending moments generally occur at the same locations for the different piles, although piles 2 and 3 show a deeper location of the extreme bending moment;
- The extreme bending moments per pile do not differ significantly.

Therefore it is concluded that although 2D calculation asses the maximum occurring bending moment quite accurately, some reserve should be made when using 2D model to determine the location of the extreme bending moments.

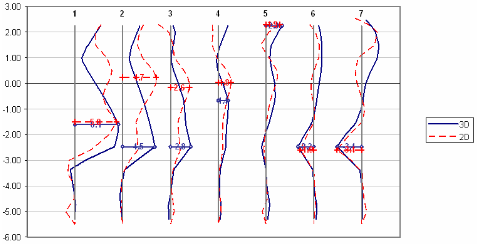

Figure 10. Bending moments in2D and 3D calculations

5 DEFORMATIONS

It is important to limit the differential settlements of the surface of a (rail)road. Due to the sagging of the geosynthetic reinforcement between the piles, settlements at the surface of the (rail)road may occur. Four methods predicting the surface settlements have been compared:

1. BS 8006, section 8.4, describes a cavity that spreads linearly through the embankment, based on a constant volume approach, both 2D and 3D
2. Peck (1969) describes a cavity that spreads with a Gauss distribution through the embankment, based on a constant volume approach, only 2D
3. The 'Peck'-method extended to 3D
4. Finite element calculations

For detailed design purposes, FEM-calculations will yield the most satisfying results with regard to deformations. However, in the preliminary design stage, a quick estimation of the differential settlements at the surface is valuable.

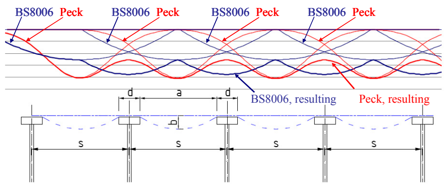

Figure 11. Deformation of the surface according to Peck (extended to 3D) and BS8006 – section 8.4

Methods 1 to 3 are based on a single disturbance in the subsoil. In the case of the piled embankment a sequence of subsurface deformations occurs, which will cause interference of the settlement troughs at the surface. Due to this, method 1, BS8006 results in an interference pattern with maximum settlements above the piles and minimum settlements in the space between the piles. The method of Peck (extended to 3D) gives opposite results with a minimal settlement above the piles, which is comparable (qualitatively) with finite element calculations.

The analytical methods are based on the constant volume approach, so that mechanisms as dilatancy are not taken into account. The method of Peck (extended to 3D) can be useful for a first indication of the differential settlements for preliminary design purposes.

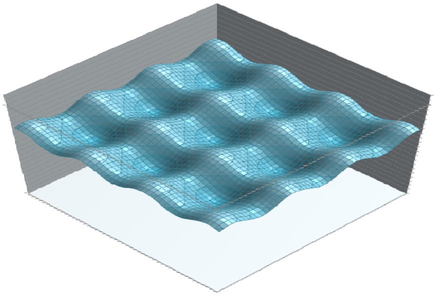

Figure 12. 3D-representation of the surface settlements resulting from Peck (extended to 3D)

6 CONCLUSIONS

The new Dutch Design Guideline for the design of piled embankments is strongly based on the design rules in the EBGEO. A different safety philosophy is applied and a set of a load- and resistance factors have been assembled. Several constraints have been chosen differently, partly to make it possible to construct thinner embankments, as needed in the flat Dutch country. The Dutch Guideline further gives rules how to calculate the uniformly divided load traffic from a standard truck load, the possibility to optimize pile and geosynthetic reinforcement by accepting some settlements of the piled embankment, where the total load is carried by both the piles and the subsoil. Furthermore, Peck's model (extended to 3D) is suggested to get a first indication of the differential settlements. Finally, suggestions are given how to carry out finite element calculations to calculate pile moments and deformations.

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