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Calculation Method for a Fabric Reinforced Road

Programme de calcul pour un chemin renforcé par géotextiles

A calculation method has been developed by which the increase of the bearing capacity of a road by geotextile reinforcement can be determined. Different from the existing methods (Nieuwenhuis (1), Bakker (2), Ludwig (3), Barenberg (4), Giroud and Noiray (5), the method presented here fulfills the equilibrium conditions of the geotextile and the subgrade simultaneously. The geotextile is described by a membrane type differential equation: the subgrade equations include a bilinear elastoplastic soil model, in which an elastic analysis based upon a modulus of subgrade reaction is coupled with a rigid plastic analysis based upon a Brinch Hansen type characteristics method. The calculation method is programmed for a pocket calculator. This enables determination of the aggregate height and the required geotextile strength as a function of the properties of aggregate and subgrade, traffic conditions and rutting.

Une méthode de calcul a été développée pour déterminer l'augmentation de la capacité portante d'une route, en utilisant un géotextile. Autrement que les méthodes existantes (Nieuwenhuis (1), Bakker (2), Ludwig (3), Barenberg (4), Giroud et Noiray (5), la présente méthode assure simultanément les conditions d'équilibration du géotextile et du sol. Le géotextile est représenté par une équation différentielle type membrane: les équations du sol comportent un modèle de sol élastoplastique bilinéaire, dans lequel une analyse élastique, basée sur un module de réaction du sol est couplée à une analyse plastique rigide, basée sur une méthode caractéristique type Brinch Hansen. La méthode de calcul a été programmée pour un ordinateur de poche et permet la détermination de la hauteur du remblai et de la résistance requise du géotextil en fonction des propriétés du remblai, du sol, des conditions de circulation et des ornières.

Introduction.

The main functions of geotextiles in high deformation, low volume road construction are assumed to be separation, filtration and reinforcement. Separation is defined as the prevention of aggregate penetration into the subgrade, while filtration is defined as the prevention of subgrade migration into the aggregate. Reinforcement is defined as the action of the geotextile that causes a change in the stress state in the road profile. This paper deals only with this function.

Two types of reinforcement are distinguished: Lateral restraint and membrane action.

Lateral restraint is the restraint of lateral movement of the aggregate over the geotextile. Consequently, the aggregate shows a stiffer behaviour and spreads the traffic load over a wider area. Deformations of the road and stresses and strains in the geotextile are small. The stress-strain properties of the geotextile are rather irrelevant. Lateral restraint is an interaction between the aggregate and the geotextile. It is assumed to be predominant in roads on rather good subgrade.

The second type of reinforcement is predominant in roads on a very weak subgrade. During rutting the fabric is strained like a membrane. The traffic load on the subgrade is spread over a larger area by the vertical components of the stresses induced in the geotextile. The membrane type reinforcement is an interaction between subgrade and geotextile. It is more effective if the geotextile has a high modulus of elasticity. Separation and filtration are well accepted functions of the geotextile. The reinforcement function however used to be more doubtful and less defined. In many test sections reported in literature - e.g. Wilmers (7), Grossman (8), Heijnen and Lubking (9) - it seems to be of minor importance. Other authors - e.g. Blumer (10), Webster and Watkins (6), Webster and Alford (11), Barenberg (12), Le Flaive (13) - find a certain reinforcement which is more distinct as the geotextile is stiffer and the subgrade weaker. Kinney and Barenberg (14), derived similar results from laboratory tests. Potter and Currer (15) performed tests in which the membrane reinforcement was eliminated for the greater part by a special test set-up. They found differences between the test section and a reference section, which may be attributed to lateral restraint effects. Haliburton (16) gives a description of lateral restraint and makes a first step to a physical description.

A mathematical description has not been given yet.

The mathematical description of the membrane type reinforcement was first attempted by Nieuwenhuis (1). Nieuwenhuis solved the equilibrium equations of the geotextile (the

membrane equation), but did not give an adequate description of the behaviour of the subgrade. Bakker (2) and Ludwig (3) have a better description of the behaviour of the subgrade, which they assumed to be in a rigid plastic state. However, they did not fulfill the equilibrium conditions of the geotextile. They assumed a rather arbitrary shape of the deformed geotextile, which they gave a prescribed type of deformation.
Giroud and Noiray (5) used essentially the same method, but made a rather good assumption of the type of deformation of the geotextile, as will be shown in the following sections. All authors of mathematical models conclude on a theoretical basis that the application of high modulus geotextiles with sufficient strength may lead to considerable savings or improvement in road construction. The same conclusion was drawn by Barenberg (12), who determined design graphs for low and high modulus geotextiles on a more empirical base. In 1975 Barenberg (11) made already design curves for low modulus geotextiles. They were based on the empirical assumption that a soil-geotextile-aggregate system will only show large deformations at the point of general shear, while roads without a geotextile will start to show large deformations at the point of local shear. Therefore a higher bearing capacity factor (6.2 instead of 3.14) may be taken into account. Steward (17) improved this theory slightly in 1977.
Most of the "reinforcing" effects of this approach must be attributed to lateral restraint and separation. Accurate interpretation of the results of Webster and Watkins (6) confirms this last statement. It is likely that the negative findings of many authors with regard to the reinforcement function of a fabric can be explained by the fact that not real stiff and strong fabrics were used in their test sections.
Because of a distinct feeling that considerable savings were possible by the use of high modulus geotextiles, Nicolon B.V. decided to introduce a range of high modulus wovens, the so called Geolon® wovens. At the same time it was felt necessary to have a sophisticated and safe design method, since these wovens were meant to be essentail structural elements.
The Delft Soil Mechanics Laboratory was committed to develop such a design method and to determine specifications for the Geolon® range.

Calculation method.

The calculation method is mainly set up for low volume roads for which the construction phase is determinative. Figure 1 shows a cross section over such a road reinforced with a geotextile and surcharged by an axle load.
The calculation is actually made for the situation of a truck driving in the centre of the road. However, the solution with minor adeptions is succesfully applied to excentrically loaded roads too.
The calculation is kept two dimensional, assuming a long queue of trucks. The geotextile is considered to behave like a membrane loaded by the axle load and the subgrade reactions.
During the elastic phase of the subgrade the membrane equation is given by the equations (1).

$$S_o \frac{d^2 w}{dx^2} - kw = -q \qquad S = S_o \sqrt{\left(\frac{dw}{dx}\right)^2 + 1} \qquad (1)$$

where,

- S : tensile force in the geotextile
- S_o : horizontal component of S
- w : vertical displacement
- x : horizontal distance from the truck axis
- k : subgrade reaction coefficient
- q : membrane loading

Equation (1) is solved for a constant load q_o distributed by the aggregate; $q_o = F/2(na+2eH)$. The result is the following:

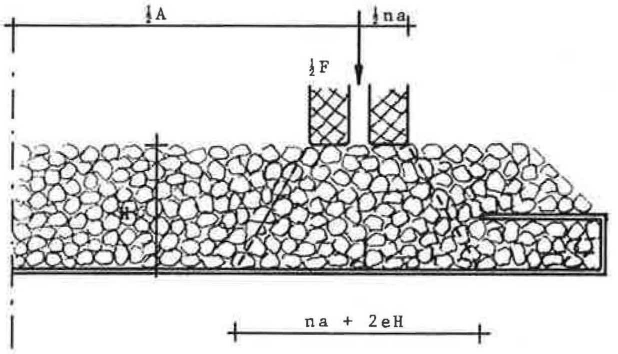
$$\frac{kw}{q_o} = 2\,\mathrm{ch}(\beta-\alpha)\,\mathrm{ch}\xi\,\mathrm{sh}\eta\,/\,\mathrm{sh}\beta$$

$$\frac{kw}{q_o} = 2\,\mathrm{ch}(\beta-\alpha)\,\mathrm{ch}\xi\,\mathrm{sh}\eta\,/\,\mathrm{sh}\beta + 1 - \mathrm{ch}(\xi-\alpha+\eta)$$

$$\frac{kw}{q_o} = 2\,\mathrm{ch}\alpha\,\mathrm{ch}(\xi-\beta)\,\mathrm{sh}\eta\,/\,\mathrm{sh}\beta \qquad (2)$$

with, $\alpha = \frac{1}{2}A\sqrt{k/S_o}$ $\quad \eta = \frac{1}{2}(na+2eH)\sqrt{k/S_o}$
$\beta = \frac{1}{2}B\sqrt{k/S_o}$ $\quad \xi = x\sqrt{k/S_o}$

The first equation holds in $0 < \xi < \alpha - \eta$; the



- B : width of the road
- F : axle load
- A : track
- a : tire width
- n : number of tires
- H : thickness aggregate layer
- e : load distribution factor aggregate

Fig. 1 : Cross section over reinforced road

second in $\alpha-\eta<\xi<\alpha+\eta$; the third in $\alpha+\eta<\xi<\beta$. From solution (2) it is clear that the value of the parameter k/S_o has a strong influence. Its value is relatively large even for the strongest available geotextiles and the softest soils. In that case the displacements outside the area $\alpha-\eta<\xi<\alpha+\eta$ are negligible and therefore the stress state of the subsoil is hardly influenced by the geotextile. This yields the conclusion that geotextiles will hardly reinforce a subgrade that is in elastic stress state.

If one consideres the soil stresses inside the area $\alpha-\eta<\xi<\alpha+\eta$ it appears that these stresses already reach the plastic state for modest loadings. Therefore a plastic state has to be considered. The membrane equation is then simplified to,

$$S_o \frac{d^2w}{dx^2} = -q \qquad S = S_o \sqrt{\left(\frac{dw}{dx}\right)^2 + 1} \qquad (3)$$

where q is the combination of loading and soil stress. The soil failure stress is based on Brinch Hansen's (18) bearing capacity formula,

$$q_l = N_c \left(c + \frac{3}{4} B\bar{\gamma}\, tg^2\varphi\right)$$

where,

- q_l : plastic soil stress
- c : cohesion
- φ : angle of internal friction
- $\bar{\gamma}$: effective unit weight of subsoil
- N_c : bearing capacity factor

The size b of the plastic area is determined by the condition of equilibrium,

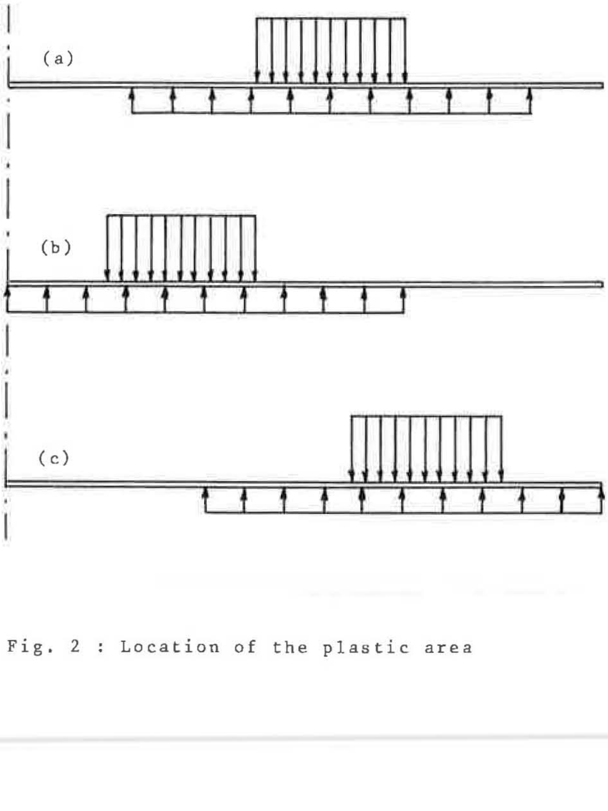


Fig. 2 : Location of the plastic area

$$b = F/2(q_l - \gamma H)$$

with γ being the unit weight of aggregate. For the location of the plastic area of the soil stresses there are three possibilities. They are given in figure 2. In case a) the area is situated centrically under the axle load. This is the normal situation. In case b) a normal situation should cause overlapping of the plastic area's at the truck axis. To avoid this the plastic area is placed against the truck axis. In case c) extension outside the road is not feasible. Here the plastic area is placed against the side of the road. Equation (3) is solved for these three cases. However, the solution still contains the unknown parameter S_o. Its value has to be determined by the compatibility condition of the geotextile. Its length is changed by strain due to tensile stresses. On the other hand the vertical displacements cause the geotextile to stretch. If there is no slip and this requires considerable attention of the side anchoring of the geotextile, then strain and increase of length are compatible. This condition is mainly influenced by the Young's modulus E of the geotextile. The following solution is determined:

$$\Delta s = \frac{1}{4}\,\frac{b - na - 2eH \pm d}{b - na - 2eH}\,\frac{1}{\lambda}$$

$$\lambda^3 = \frac{2E}{3q_l B}\,\frac{(b - na - 2eH)^2 + 3d^2}{b^2} \qquad (4)$$

$$S_m = \tfrac{1}{2} q_l b \sqrt{\left\{\frac{b - na - 2eH \quad d}{b}\right\}^2 + \lambda^2}$$

where,

- Δs : rut depth
- E : Young's modulus
- S_m : maximum tensile stress
- d : location parameter of plastic area
  - d=0 b<A b<B-A
  - d=B-A b>A b<B-A
  - d=B-A-b b<A b>B-A

The solution supplies for $d \neq 0$ two values of Δs and S_m. This is due to the fact that the settlements at both sides of the wheel for $d \neq 0$ are not equal. This is noticed in the test cases.

The result shows the rut depth as function of all the introduced parameters. On the other hand, one may assume a tolerable rut depth and then determine the minimum required Young's modulus and strength of the geotextile. A calculation programme is made on a pocket calculator to determine this.

Calculation programme.

The calculation method described above has been programmed on a pocket calculator. In this interactive programme the following input is asked for:

1. width of the road (B)
2. tire width (a)
3. track (A)
4. number of wheels
5. number of trucks
6. axle load
7. load distribution factor of the aggregate

8. unit weight of the aggregate
9. effective unit weight of the subgrade
10. undrained shear strength
11. angle of internal friction

Output consists of all possible combination of the height of the aggregate (H) and Young's modulus of the geotextile (E), which are given for a certain rut depth. As a standard rut depth three times the elastic rutting is chosen, but other values for the total rut depth can be put in optionally. Apart from E and H which are the main design parameters, information is given about the width of the plastic zone b and the maximum stress in the geotextile S. The latter value should be checked against the tensile strength of the geotextile. An example of the input and output of the programme has been given in fig. 3.

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FABRIC REINFORCED
ROAD CONSTRUCTION

WIDTH ROAD     4,00 m (B)
WIDTH TIRE     0,20 m (a)
TRACK          1,70 m (A)
NUMB WHEELS    2      (n)

NUMB TRUCKS    1
AXLE LOAD    100 KN   (F)
LOAD DISTR     0,50   (e)

HEIGHT AGGREG      H [m]
FABR YOUNG MOD     E [KN/m]
FABR MAX STR       S [KN/m]

condition          s <= b/4
RUT DEPTH          s [m]
elast (el)     plast (pl)
WIDTH PL ZONE      b [m] 2*

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VOL W AGGREG 19,0 KN/m↑3
VOL W EFF     7,0 KN/m↑3
UNDR SH STRG 15,0 KN/m↑2
ANG INT FRIC  0,0 DEGREE

      s(el) = 0,046 m
      s(pl) = 0,138 m
      s     = 0,184 m

H     b      E      S

0,26  1,51   2003   125
0,28  1,45   1753   109
0,30  1,40   1475    95
0,32  1,35   1241    83
0,34  1,31   1041    72
0,36  1,27    871    62
0,38  1,23    725    53
0,40  1,20    599    45
0,42  1,17    490    38
0,44  1,14    396    31
0,46  1,11    313    26
0,48  1,08    241    20
0,50  1,06    177    15
0,52  1,03    122    11
0,54  1,01     72     6
0,56  WEDGE WITHIN  ROAD
0,56  0,99     29     3
0,58  ELAST DISPLMT ONLY
1,00  ELAST DISPLMT ONLY
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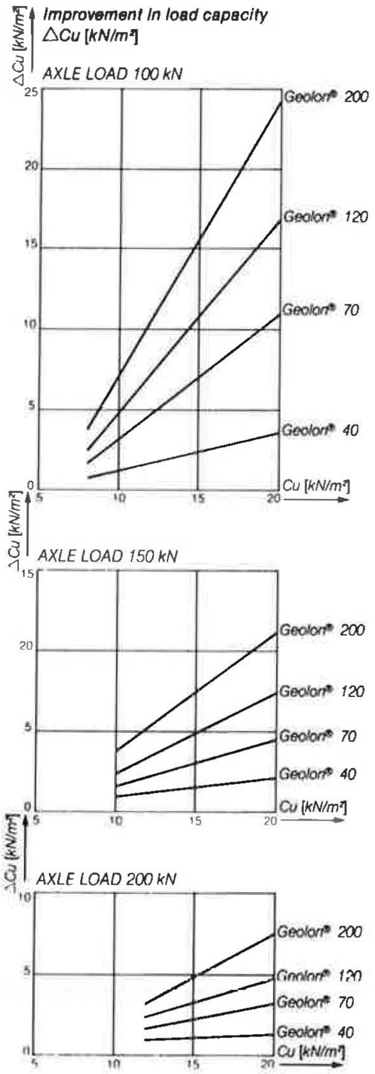

Fig. 3

Design charts.

A great number of calculations has been compressed into design charts (see fig. 3 and 4). In one type of design charts the relative aggregate saving H/H_o is given versus the undrained shear strength of the soil (Cu) H_o is the weight of aggregate that is required without the use of a geotextile. This reduction is based on the additional load spreading of the geotextile. So with a lower aggregate height the same stress will be applied on the subgrade as with the original aggregate height H_o. At low Cu values this saving parameter H/H_o is going to be undetermined, as the road cannot be constructed without a geotextile. A second type of design chart gives the additional shear strength of the subgrade (Cu) versus the original shear strength (Cu). The additional shear strength is the apparent improvement of the subgrade due to the use

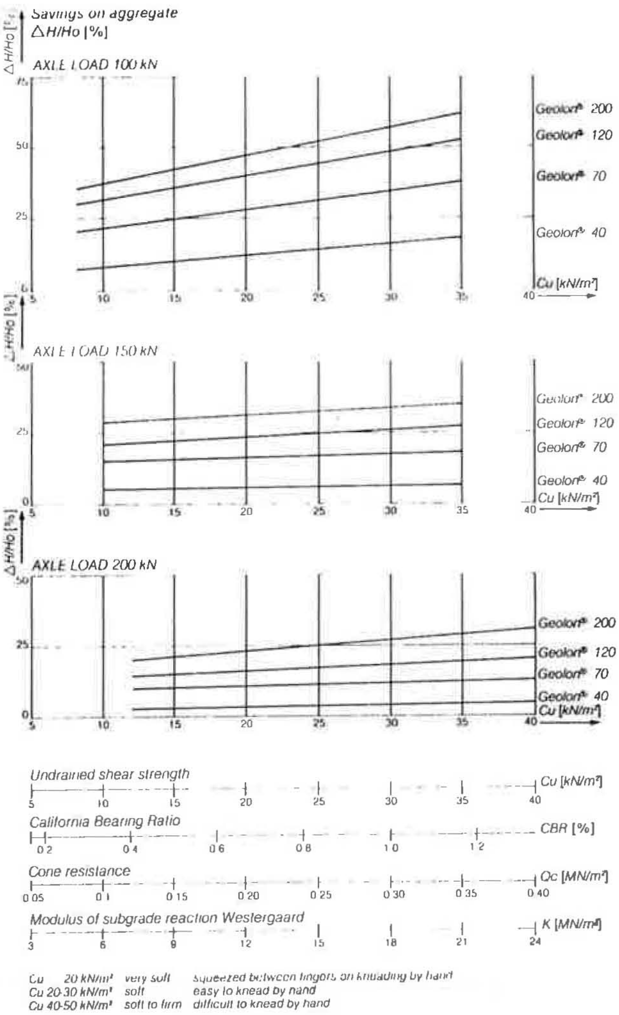

Fig. 4

of a geotextile. In this way the influence of a geotextile may be included in the usual design methods.
Both types of design charts have been given for 3 axle loads (100 kN, 150 kN and 200 kN respectively) and the four strongest wovens from the Geolon® range.

Comparison of GEOL-savings with full scale tests of Webster & Watkins.

Webster & Watkins have done full scale tests on an unpaved road with a.o. three different sections. One section with a woven membrane with E = 200 kN/m, one section with a non woven with E = 70 kN/m and one control section without a geotextile. These sections are respectively mentioned item 7,6 and 5.
The road sections were loaded by a truck with 80 kN axle load and graphs were made of the number of coverages versus rut depth.
The following data are listed for rut depths of 0,28, 0,15 and 0,075 m:

S.1 - The GEOL-savings based on calculations with the really occured axle loads.
S.2 - The GEOL-savings based on calculations with the equivalent standard axle of 80 kN.
S.3 - The savings as determined by Webster and Watkins in relation to a design formula.
S.4 - The savings as determined by Webster and Watkins in relation to a design formula, but now diminished by the performance savings of the section without geotextile in relation to the same design formula.

These field tests are not representative for GEOL, which is based on the construction phase of a road and not for a number of coverages exceeding 20.000. However, an attempt comparison has been made in table 1 and 2.

Evaluation.

1. The savings calculated with GEOL, based on stress reduction on the subgrade alone, are for most of the cases on the safe side, compared with the performance savings of Webster and Watkins.
2. The trend that a greater rut depth corresponds with a greater saving based on stress reduction due to membrane type support only, exists in item 6 of Webster and Watkins and not in item 7.

Field test Study Centre for Road Construction (SCW).

The Study Centre for Road Construction has conducted a field test on an unsurfaced road in the construction phase using geotextiles. Elongations have been measured with the use of electric strain gauges. From the preliminary results it can be seen that the maximum strain in the geotextile coincides reasonably well with the maximum strain calculated with GEOL. In this field test a non woven is used under an aggregate layer of 50 cm on a subgrade with Cu is about 15 kN/m2. The number of passes is about 250, the axle loads 110 kN.

Further research on field tests.

The next step will be a field test using a Geolon 200 woven fabric in two sections with aggregate thickness savings of 10 and 20 cm with factors of safety 2 and 1. The original design thickness in this location is 50 cm which will be represented by a section without a geotextile.

Number of coverages.

One of the most interesting parameters is the number of coverages for which the physical in situ conditions meet the output of the calculation programme. These physical conditions are aggregate thickness, rut depth and load characteristics. For the woven membrane section of Webster and Watkins the number of coverages of the 80 kN axle is about 10.000 and for the non woven section about 600.
For the non woven sections of the field tests of the Dutch Study Centre for Road Construction the number of coverages of an 80 kN axle is also about 600. This seems to indicate that the number of coverages needed to meet the in situ conditions is related to the elastic modulus of the fabric.

Evaluation.

These numbers of coverages show that the calculation programme is at least valid during the construction phase of the road.

Conclusions.

1. The here presented calculation method seems to be a good and safe design method for low volume roads which are loaded most heavily during construction.
2. The use of high modulus geotextiles may lead to considerable savings or improvement in low volume road construction.
3. The absolute saving of aggregate increases with the value of the modulus of elasticity of the geotextile. This increase faints off at higher values of E. The use of geotextiles with moduli over 1500 kN/m makes little sense considering savings on aggregate due to membrane type reinforcement.
4. The absolute saving of aggregate decreases with increasing strength Cu of the subsoil. The use of a geotextile on subgrades with a Cu value exceeding 30 kN/m2 has little effect as a structural reinforcement membrane.
5. The modulus of elasticity of the geotextile is the most determining factor in aggregate saving. However, it should be checked that the geotextile has sufficient strength.
6. Using a geotextile as a structural reinforcement, proper design calculations are absolutely necessary to avoid mishaps.

Table 1

	S.1			S.2		
	rut depth					
	0,28	0,15	0,075	0,28	0,15	0,075
	Savings in % of the design thickness					
item 6	30	9	4	30	9	1
item 7	37	11	3	56	17	3

Table 2

	S.3			S.4		
	rut depth					
	0,28	0,15	0,075	0,28	0,15	0,075
	Savings in % of the design thickness					
item 6	27	20	18	21	12	10
item 7	48	49	52	42	41	44

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