Stability Problems of Slopes in Overconsolidated Clays

Stabilité de Talus dans des Argiles Surconsolidées

E.DE BEER Prof.Dr.ir., Prof. at the Univ. of Ghent, Director General of the State Geotechnical Institute,
E.GOELEN Chief Engineer at the State Geotechnical Institute, Zwijnaarde, Belgium

SYNOPSIS

A railroad cut at Godarville, which has a total height of 21 meters and which runs over most of its height in a stiff fissured clay belonging to the Ypresian stage of the Tertiary age (eocene) has been designed according to the peak shear strength values of the clay, but taking into account the most unfavourable seepage forces which can occur, and adopting a sufficiently large factor of safety in order to be outside the conditions of large deformations, being able to induce a progressive rupture.

Since its realization this cut has been under permanent control, with measurement of the deformations with inclinometers, and of the waterpressures with Warlam piezometers.

The contribution give all details concerning this cut. Conclusions are drawn about the Belgian experience concerning the stability of important cuts in overconsolidated clays.

INTRODUCTION

In Belgium in the past years several important cuts have been realized in overconsolidated clays.

To solve the stability problem of permanent slopes, the question arises if the stability calculations should be based on the residual strength parameters which, as pointed out by Bjerrum, "represents in many cases an unnecessarily conservative and enormously expensive solution". [1]

The Belgian experience seems to show that insofar no earlier slip surfaces exist, stable slopes can be designed, starting from the peak shear strength values, provided the worst possible assumptions concerning the water-pressures are made, and reduced values of the cohesion are introduced.

Based on previous experience on cuts existing since several decades, recently a railroad cut made at Godarville, in order to eliminate an existing railroad tunnel, and dug in tertiary clays has been designed according to these rules. It has thoroughly been observed during and after construction and exists now for about 4 years, without any major trouble.

The same design has been followed for a cut also made in the tertiary Ypresian clay, in order to eliminate a tunnel in the canal connecting the Scheldt and Leie rivers.

Before describing the new railroad cut at Godarville, a brief review is given of the most important existing canal- and railroad cuts in Belgium, and their behaviour.

I. Existing deep cuts in tertiary clays in Belgium.

Among the most important cuts realized in the past years, which over a certain height run into overconsolidated tertiary clays are listed :

- The canal cut at Eigenbilzen in the Albert canal, which runs partly into two clay layers, belonging to the Rupelian stage (oligocene). The cut has a total height of 26 meters and exists now, without any major trouble, for about 37 years.
- The canal cut at Godarville (canal Brussels-Charleroi), with a total height of 43 meters, which runs into clay layers belonging to the Ypresian stage of the eocene age.
- The canal cut at La Fléchère (canal Charleroi-Brussels) with a total height of 19 meters which runs into the Ypresian clay.
- The slopes at the entrance of the E 3 Scheldt tunnel at Antwerp with a total height of 22 meters which run into the Boom clay (oligocene).
- The cut at Godarville (railroad) with a total height of 21 meters which runs into the Ypresian clay.
- The cut in the canal Scheldt-Leie at Moen, with a total height of 38 m which runs in the Ypresian clay.

The characteristics of the tertiary clays in which these cuts run are given in table I.

TABLE I

Physical and mechanical properties

	H (m)	Stage		Physical characteristics: Percentage < 2 μ	Natural water content w %	liquid limit w %	plastic limit w_p %	plasticity index i_p	Mechanical characteristics: Peak strength c' (t/m²)	Peak strength φ'	Residual strength c_r (t/m²)	Residual strength φ'_r
Eigenbilzen	26	Rupelian (oligocene)	$R_{1,c}$ clay	31	22	68	22	46	0,6	26°	0	10° (a)
			$R_{2,c}$ clay	14	21	40	19	21	0,4	32°	0	18° (a)
Godarville Canal cut	43	Ypresian (eocene)	Upper layer	16	34	62	25	37	0,4	32°	0	12°30' (a)
			Lower layer	18	25	48	19,5	28,5	0,6	29°	0	14°30' (a)
La Fléchère	19	Ypresian (eocene)		19-23	19-27	37-50	17-20	20-30	-	-	0	13°
Entrance of the E 3 Scheldt tunnel	22	Rupelian	(oligocene)	49	25-32	73-89,50	25,7-32,4	52,2	1,5	22°	0	22°
Moen Canal cut	38	Ypresian	(eocene)	20 à 30	39	81,4	29,9	51,5	0,2	26°	0	10° (a)
Godarville Railroad cut	21	Ypresian (eocene)	Upper layer	22	33	62	27	35	1,0	24°30'	0	12°30' (a)
			Lower layer	18	26	53	22	31			0	13° (a)

(a) : according to the chart of Bjerrum.

Calculations show, that if for the slopes of these cuts, the worst assumptions concerning the water pressures are made, and the residual shearing strength parameters are introduced, these slopes cannot be stable.

However all these slopes have until yet shown no signs of distress, although some of them exist since several decades.

There has only been an exception in two cases, where the observed slips, are without any doubt related to previously existing slip surfaces, which explains why their equilibrium was governed not by the peak - but by the residual shear strength values.

These two special cases are the following :

a-1. Canal cut at La Fléchère.

At La Fléchère the existing 300 ton canal Brussels-Charleroi had to be deepened and enlarged for 1350 ton ships.

When the 300 ton canal was built in the late eighties, because the engineers of that time often considered a stiff clay as a very strong material, much too steep slopes were designed, with the consequence that rather extensive slips occured. Thus in many places in the Ypresian clay previous slip surfaces existed.

For the 1350 ton canal the slopes were designed according to the peak shear strength values. However in the parts, where previous slips existed, these slopes started to slide already during the excavation works. Stability calculations of the ruptured masses taking into account the measured water pressures, showed that the equilibrium was governed by the residual values $c'_r = 0$ $\varphi'_r = 13°$ of the Ypresian clay.

Based on these residual values, the slopes in the parts affected by previous slides were flattened and reinforced by bored anchor piles Ø = 1 m placed near the toe of the slope.

a-2. Canal cut at Godarville.

At Godarville the slopes of the cut for the Canal Brussels-Charleroi, with a total height of 43 m, have been designed with the peak shear strength of the Ypresian clay, taking into account the worst possible water-pressures.

The canal cut exists now for about 17 years without any trouble, except for a local slip, near the end of the cut, at a place where the total height is rather limited. At this location, a slip already occured during the excavation works, and the contractor simply restored the situation by an extension of the drainage system and digging away part of the slipped mass. Some eight years after construction, in a very rainy period the same mass failed again.

Equilibrium calculations, based on the measured water pressures showed, that the equilibrium of this local slip is governed by the residual shear strength parameters of the Ypresian clay, and at that location the slopes were flattened and the system of transverse drains adapted, in order to obtain a sufficient factor of safety with respect to the residual shear strength parameters.

Here again the necessity to introduce the residual shear strength parameters is a consequence of the existence of a previous slip.

The experience of the Belgian deep cuts in tertiary clays shows, that if previous geological or historical slips do not exist, the design of the slopes can be based on the peak shear strength values, at the condition that the worst assumptions concerning the water-pressures, and rather large safety factors, especially on the cohesion c' are introduced.

More details have already been given in earlier papers about the cut at Eigenbilzen, the cut at Godarville for the canal Brussels-Charleroi, the cut at La Flechère and the slopes at the entrance of the E3 Scheldt Tunnel at Antwerp [4][5].

This paper is concerned more especially about the slopes of the railroad cut at Godarville.

II. Railroad cut at Godarville.

At Godarville a rather deep cut had to be realized in order to replace an existing one way railroad tunnel.

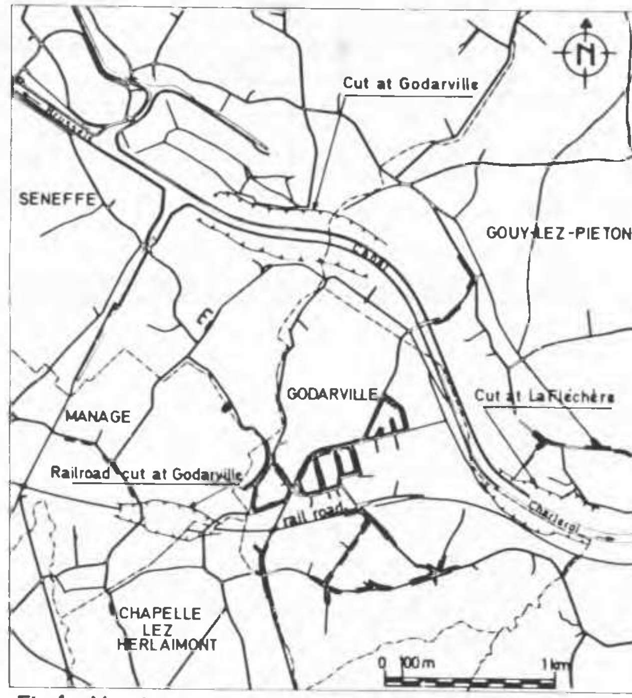


Fig 1 Map indicating the location of the cuts at Godarville and LaFlèchère

The map of figure 1 gives the general location of the site of the new cut. On the same map is also gi-

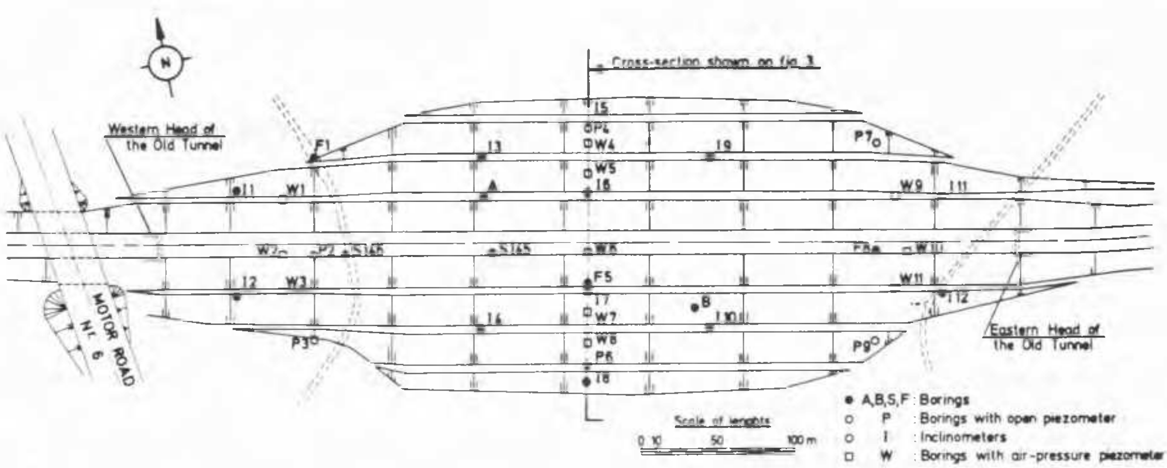


Fig 2 GROUNDPLAN

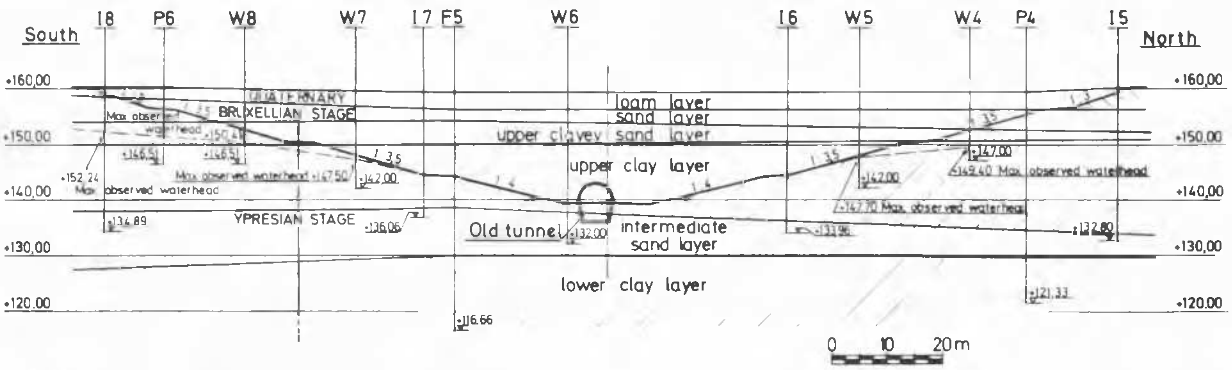


Fig. 3 CROSS SECTION AT LARGEST DEPTH

ven the location of the cut at Godarville for the canal Brussels-Charleroi and the cut at La Fléchère for the same canal.

For the design of the new railroad cut, an extensive investigation program has been performed for determining the physical and mechanical properties of the soil layers involved in the stability problem of the slopes, and in order to determine the water pressures and their seasonal changes.

The figure 2 gives a ground plan of the new cut, with an indication of the performed borings, the placed open and closed piezometers and the placed inclinometers.

The figure 3 gives a cross section there where the cut has its largest depth of 21 meters. This cross section shows that under a cover of quaternary loam and Bruxellian sand, the cut runs into the Ypresian stage of eocene age. At the location of the cut this stage consists of an upper clayey sand layer, an upper clay layer, an intermediate sand layer, and a lower clay layer. This lower clay layer rests on the carboniferous rock at a depth of about 45 m under the soil surface. The cut runs only into the upper clay layer of the Ypresian. The fig. 3 shows also the location of the dismantled one track railroad tunnel.

Typical data concerning the physical properties of the two clay layers are given in table I. These latter shows that these physical properties are practically the same as those for the two corresponding Ypresian clay layers at the nearby canal cut at Godarville.

Drained shear strength parameters.

To determine the drained shear strength parameters a large number of consolidated undrained triaxial tests with measurement of the pore water-pressure were performed.

On the fig. 4 for each of the performed triaxial tests, the differences of the principal stresses is plotted versus the sum of the principal effective stresses. Only the samples taken in the upper Ypresian clay are considered.

There is a rather big scatter in the results, which is however normal for a stiff fissured overconsolidated clay, as is the Ypresian clay.

UPPER YPRESIAN CLAY LAYER

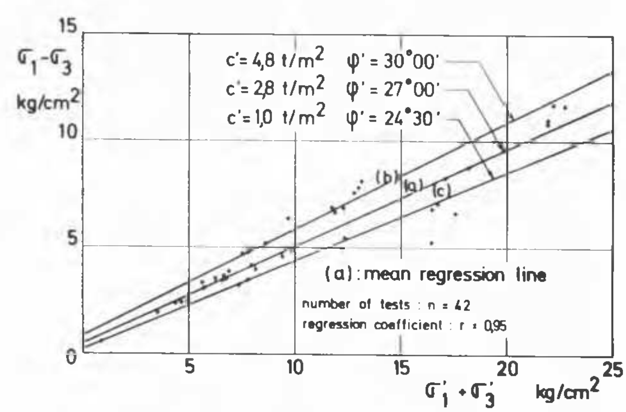


Fig. 4 CONSOLIDATED UNDRAINED TRIAXIAL TESTS

A linear regression analysis gives the following results : $c'_p = 2{,}8\ t/m^2$ $\varphi'_p = 27°00'$

with number of tests n = 42

correlation coefficient r = 0,95.

The line (a) of fig. 4 represents this mean regression line.

For sake of safety, more less characteristics should be taken into account than those determined by the mean regression line.

On fig. 4 two converging lines (b) and (c) are been drawn, making the same angle with the line (a) and with a confidence limit of 2/3. As a supplementary condition was imposed that the point P of the diagram representing the triaxial test at the lowest pressures should be located on the lower confidence line (c).

The parameters corresponding to these two lines are given on the figure.

For sake of safety in the calculations of the stability of the stiff fissured Ypresian clay the parameters corresponding to the lower confidence line (c) have been considered, thus

$$c' = 1 \ t/m^2 \qquad \varphi' = 24°30'.$$

Residual shear strength parameters.

The residual shear strength was not directly measured. However Bjerrum [1] has published a very useful chart relating the residual shear angle to the plasticity index. According to this chart, for the residual strength of the upper clay layer, values $c'_r = 0$ $\varphi'_r = 12°30'$ are deduced.

A thorough study of the equilibrium of existing instrumented slip surfaces of the same clay at the La Fléchère cut, has given the values $c'_r = 0$ and $\varphi'_r = 13°$, which thus correspond quite well with the chart of Bjerrum.

Data concerning the water pressures.

A very important factor for the stability of slopes are the water-pressures. Indeed in most of the cases slopes start to move during or immediately after periods of intense rainfall or after melting of snow, indicating the paramount influence of the water-pressures on the equilibrium.

Data concerning the water-pressures were gathered in the early stage by measurements in open piezometers installed in the intermediate Ypresian sand layer and in the upper sandy and loamy layers.

Long term observation in some open piezometers which, roughly and due to certain circumstances, had their filter point put in the upper and lower clay layers, gave insight on the piezometric head in the clay layers.

Later on, Warlam air-pressure piezometers were put in the upper clay layer to continuously follow the fluctuations of the water-pressures in the clay.

Fig. 5 gives the measurements in function of the time for the piezometers installed in the cross section with largest depth.

On the pressure diagram of fig. 6 are shown the maximum and minimum waterheads measured before and after excavation of the cut.

At the railroad cut at Godarville the water-pressure conditions existing prior to digging the cut, were of course influenced by the already existing railroad tunnel, which played more or less the role of a drain, as could be observed by the water percolating in the tunnel and which is responsible for the lower piezometric head, as can be seen on fig. 6, in piezometer P2, located near the axis of the tunnel.

On the fig. 6 the line AB gives the hydrostatic law of the pressures in the upper loamy and sandy layers before excavation, and the line DE the hydrostatic law of the pressures in the intermediate sand layer of the Ypresian also before excavation.

In the case the upper Ypresian clay layer would be fully homogeneous for its permeability, the water pressures in the clay layer before the excavation works should follow the law BD (fig. 5).

If at the contrary, a much less permeable film should exist at the base of the upper clay layer the water-

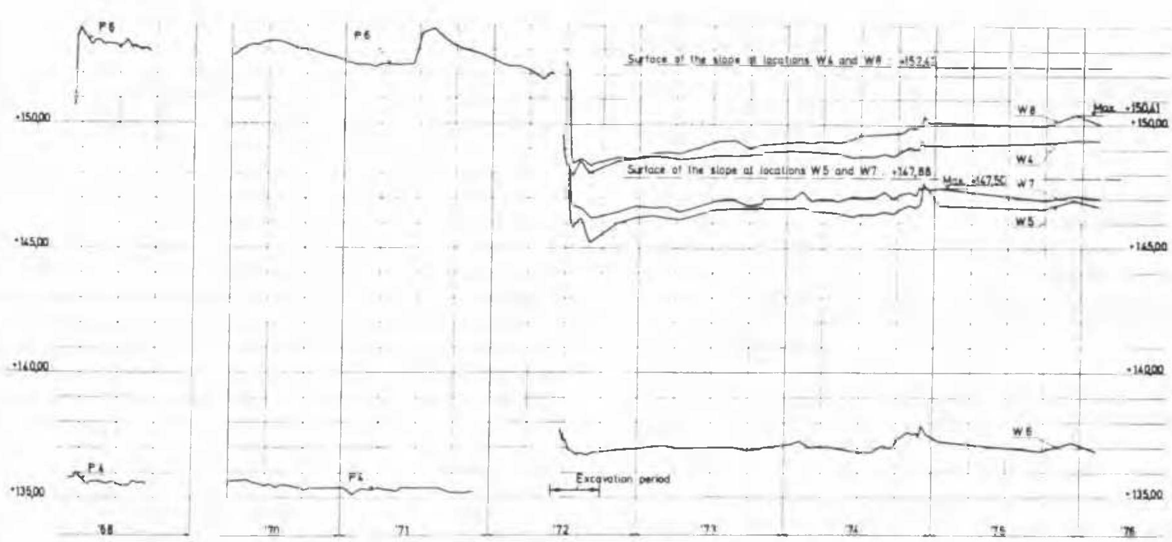


Fig. 5 PIEZOMETRIC LEVELS

pressures in the clay layer should follow the law BF, i.e. the continuation of the law of the hydrostatic pressures in the upper loamy and sandy layers (fig.6).

Unless one or more sandy inclusions in the clay would be in contact with higher upstream levels, the line BF represents the worst possible water-pressure in the upper Ypresian clay layer, before the excavation works.

For the design calculations of the slopes the following assumptions for the water-pressures were made, based on the maximum known water-pressures at the moment of the calculations (fig. 6):

- in the sandy and loamy overlying soils, the water-pressure has been taken corresponding to the highest observed level + 153,00 (line AB, fig. 6)
- in the upper Ypresian clay the water-pressures have been taken as hydrostatic corresponding to the piezometric level in the overlying sandy and loamy soils (line BF, fig. 6)
- in the intermediate Ypresian sand the water pressures have been taken corresponding to the level + 138,00 (line CE, fig. 6).

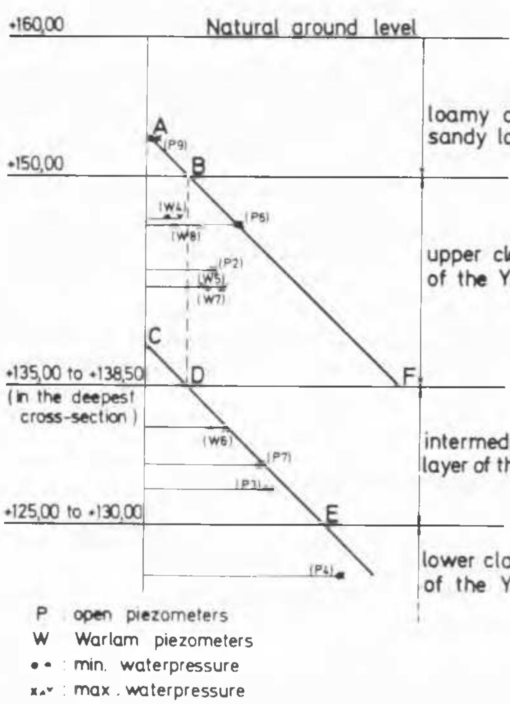


Fig. 6 DIAGRAM OF THE WATERPRESSURES

Later on, after a three years observation period of the piezometric levels, prior to the realization of the cut, the highest observed level in the overlying sandy and loamy layers has been noted as + 154,81.

As this observed water level was higher than that introduced in the design calculations, check calculations based on the actually observed levels were made afterwards.

Possible existence of slip surfaces prior to the realization of the cut.

At the site of the railway cut at Godarville, the railway track passed earlier in a one way tunnel located nearly at the same level as the base of the actual cut.

No evidence has been observed or reported concerning the possible existence of any possible slide on the site, having occured during or after the construction of the railroad tunnel.

In the case of the railway cut at Godarville the cut was realized starting from the natural ground surface, i.e. there have not been any excavation works done earlier at the site wich could have "damaged" the site in the sense of lessening the shear strength characteristics of the Ypresian clay as in the case reported elsewhere [4],[5] of the canal cut at La Fléchère at about 1 km from the railway site.

Calculation of the stability of the slopes.

In accordance with the principles exposed before, the slopes were calculated starting from the drained peak shear strength characteristics of the Ypresian clay layer.

On the fig. 7 is given an example of the design calculations for the slopes at the railroad cut for the cross-section where the cut shows its largest depth.

On the figure are shown, for the different layers involved
1°) the adopted water-pressures
2°) the adopted shear strength parameters c' and φ'.

Adopting the method of the friction circles, a safety factor F = 1.3 on cohesion and tg φ' was asked for.

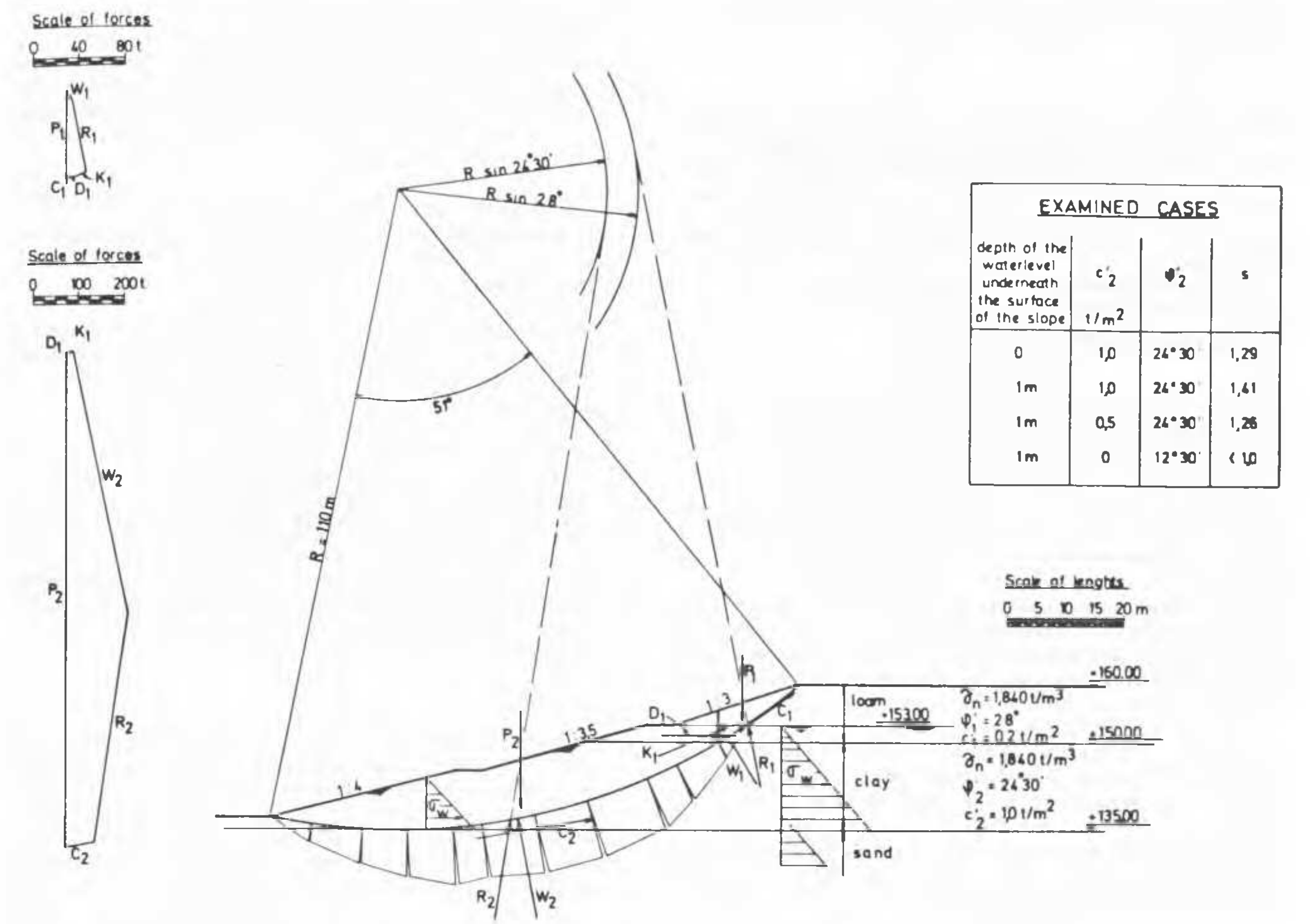
The calculations were made with the worst conditions for the water-pressures as shown on the figure i.e. with the piezometric level at the surface of the slope and limited to the maximum waterhead known at the moment of the design calculations of + 153,00.

The calculations were made with the shear strength parameters $\varphi' = 24°30'$ and a reduced value of the cohesion of $c' = 1\ t/m^2$ (line c of fig. 4).

The safety factor obtained in these conditions for the most critical slip circle is shown on the fig. 7 and is F = 1,29 on cohesion and tg φ'.

The table on fig. 7 shows further the results of the complementary calculations in which the water table is taken at a depth one meter below the surface of the slope, i.e. at the bottom of the drainage mat which has been put on the slopes of the cut. As indicated on the table of fig. 7, the safety factor for that case amounts to 1,41 on cohesion and tg φ'.

In order to get an idea about the sensitivity on the results of a variation of the parameters involved, a calculation has also been performed with a reduced value of the cohesion, namely $c' = 0,5\ t/m^2$. In that case a safety factor of s = 1,26 is obtained on cohesion and tg φ'.



EXAMINED CASES

depth of the waterlevel underneath the surface of the slope	c'_2 t/m²	φ'_2	s
0	1,0	24°30'	1,29
1m	1,0	24°30'	1,41
1m	0,5	24°30'	1,28
1m	0	12°30'	< 1,0

Fig. 7 Railroad cut at Godarville Equilibrium calculations

The check calculations based on the highest observed piezometric level of + 154,81 were performed with a computer program based on the method of Bishop. Adopting c' = 1 t/m² and φ' = 24°30' one gets a factor of safety of 1,274.

Control of the stability of the designed slopes introducing the residual values of the clay layers.

If instead of introducing the peak shear strength values c'_p = 1 t/m² φ'_p = 24°30', the residual shear strength values c'_r = 0 φ'_r = 12°30' are considered, and the water-pressures shown on fig. 7, one gets a safety factor less than one as indicated on the table of fig. 7.

Even for slopes as flat as 1:4, the safety factor obtained by considering these residual values, is much smaller than unity.

If one should base the design of slopes in the Ypresian clay on its residual value, one should come to slopes, so flat, that they become anti-economical, and furthermore do not longer correspond to the behaviour of steeper slopes, which behaved without trouble since several decades.

Realized slopes.

The slopes have been realized according to the design calculations but a supplementary intermediate bank has been put in the slope which flattens still a little the mean value of the slope.

The dashed line of fig. 8 shows the slopes considered in the design calculations. On the same figure the full line gives the slopes as they were actually realized.

The cut exists now for about four years and it is worthwhile to calculate the value of the safety factor for the conditions of water-pressures observed after excavation of the cut.

The fig. 5 shows the water-pressures observed in the Warlam piezometers. The maximum observed levels are + 150,41 in W8 and + 147,50 in W7 (Southern slope).

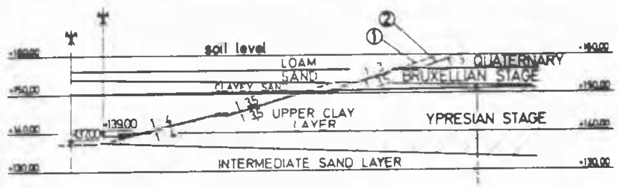


Fig. 8 REALISED SLOPE

These maximum water-pressures are indicated on the cross section of fig. 3.

On the same figure are indicated the maximum observed water-levels in the inclinometer tube I8 (+ 152,24) in the same cross section.

Assuming that the water level in this tube corresponds to the waterhead in the overlying sandy and loamy layers and to the piezometric level in the upper clay, an interpolation is made, by a parabolic law, as shown on fig. 3.

A computer control has been made for the realized slopes with the waterpressures corresponding to the parabolic law deduced from the observations.

Introducing the peak shear strength characteristics $c' = 1\ t/m^2$ and $\varphi' = 24°30'$, a safety factor s = 1,465 is obtained on cohesion and tg φ'.

Measures taken during the excavation works.

In order to secure the permanent slopes deduced from the peak shear strengths, it is not sufficient to control that no previous slides (historical or geological) exist in the area of the cut, but it is also necessary to prevent the occurence of local slides during the excavation works themselves.

Indeed during the excavation works very often the excavation front is much steeper than the permanent slopes to be realized. Furthermore during these works the water-pressure conditions can be worse than in the final situation after the works. For both reasons, if no care is taken, local slips can occur, which can cause a series of regressive failures, which finally entail the soil mass located behind the final slopes to be realized. Along these regressive slip surfaces no longer the peak shear strength but the residual strength is prevalent.

In order to prevent such slip surfaces during the excavation works it has been specified that the excavation had to proceed in nearly horizontal layers over the full width of the cut, and that never nor at any site the slope, be it temporarily, may be steeper than the inclination of the final slopes to be realized.

Because of this specification, no local slides occured during the excavation works.

Control during excavation.

During the excavation works and thereafter, systematic measurements were made at the air-pressure piezometers (Warlam) placed in the upper clay layer and in the inclinometer tubes which reached whithin the intermediate sand layer.

The maximum piezometric levels observed since the excavation of the cut are shown in the cross section of fig. 3. These maxima have occured after a very rainy period.

The maximum water levels observed correspond nearly to the levels of the slope showing that the assumptions made concerning the water pressures introduced in the calculations were not excessive.

During the lifetime of the cut, at regular intervals inclinometer readings have been taken. During and after rainy periods, corresponding to maximum levels in the piezometers, the inclinometer readings are made at shorter intervals. However the readings have never shown differences larger than 5 digits, which correspond to the precision with which successive readings can be made. Therefore it can be concluded that no movements have been detected.

Conclusions.

Except forsome cuts or part of them where earlier slip surfaces existed and where obviously the stability was governed by the residual shear parameters of the clay and studied on that base, the considered cuts in the tertiary clays were basically studied taking into account the peak shear strength corresponding to the unloaded state of the clay.

In the calculations the worst assumptions were made concerning the water-pressures in the clay.

A safety factor F of at least 1.3 is asked for, in order to stay sufficiently away from the region of large distortions, which include the danger of progressive rupture.

The recent railroad cut at Godarville has been designed and realized on that base and exists now since four years without any trouble.

From the gathered experience cannot be concluded that in sites where no earlier slip surfaces exist, the stability of slopes in overconsolidated tertiary clays, is necessarily governed by the residual parameters.

The Belgian experience seems at the contrary to show that adopting the peak shear strength parameters corresponding to the unloaded state of the clay and insofar as no previous slip surfaces exist, stable slopes can be designed provided that the worst assumptions are made concerning the water-pressures in the clay and a sufficiently large factor of safety is respected, in order to be outside the conditions of large shear strains, which include the danger of progressive rupture.

Acknowledgements.

We gratefully acknowledge the collaboration of Prof. E. Lousberg, which as engineer at the State Belgian Geotechnical Institute, made the stability calculations and to Mr. Quinet, engineer at the Belgian Rail Road Company which intensively contributed to the field measurements and gave the authorization for this publication.

BIBLIOGRAPHY

BJERRUM L. (1968) : Progressive Failure in Slopes of overconsolidated Plastic Clay and Clay Shales, Norwegian Geotechnical Institute, Oslo, Publication n° 77, p. 1-29.

BJERRUM L. and AITCHISON G.D. (1973) : Problems of soil mechanics and construction on soft clays and structurally unstable soils (collapsible, expansive and others), General Report Session 4, 8th International Conference on Soil Mechanics and Foundation Engineering, Moscow, Proceedings, Vol.3, pp. 111-190.

DE BEER E. (1967) : Shear strength characteristics of the "Boom clay", Proceedings of the Geotechnical Conference, Oslo, Vol. 1, p. 83.

DE BEER E. (1969) : Experimental data concerning clay slopes, Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico, Vol. 2, p. 517.

DE BEER E. (1969) : Stability problems of slopes in overconsolidated clays and shists, Proceedings of the conference "New advances in soil mechanics", Prague, Vol. 1, p. 53.

SKEMPTON A.W. and HUTCHINSON J. (1969) : Stability of natural slopes and embankment foundations, 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico, State of the Art Volume, pp. 291-340.

TER-STEPANIAN G. et al. (1973) : Investigation of creep of clay soils at shear, Proceedings of the 8th International Conference on Soil Mechanics and Foundation Engineering, Moscow, Vol. 1.2, pp. 433-438.

TER-STEPANIAN G. (1973) : Problems of soil mechanics and construction on soft clays and structurally unstable soils, Discussion Main Session IV, Proceedings of the 8th International Conference on Soil Mechanics and Foundation Engineering, Moscow, Vol. 4.2, pp. 119-120.