EXPERIMENTAL DATA CONCERNING CLAY SLOPES
DONNEES EXPERIMENTALES CONCERNANT DES TALUS DANS DES ARGILES.

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INTRODUCTION

In Belgium rather deep cuts have been realized, which over a certain height run into overconsolidated clays. Such clays present under large distortions residual strengths which are much smaller than the peak strengths. As has been shown by Skempton [4], Bjerrum [1], because of the progressive character of the deformations, it can be unsafe to check the stability of slopes in overconsolidated clays on the peak strength values.

In order to be able to define calculation methods which should give solutions, which at the same time should be safe and economical, it is worthwhile to dispose over experimental data concerning the progressivity of the deformations with time, and concerning the behaviour of existing slopes.

I. PROGRESSIVITY OF THE DEFORMATIONS.

a. Slopes of a test pit in the Boom clay at Antwerp.

Important excavation works had to be realized in Antwerp for the new E 3 tunnel under the Scheldt river at Antwerp. These excavations run rather deep into the Boom clay. The Boom clay belongs to the oligocene series (Rupelian stage). According to the geologists it was overconsolidated under a weight of about 40 m of neogene sands, which were afterwards partly or totally eroded. The characteristics of the Boom clay at Antwerp are given in Table I.

For solving the problem of the temporary slopes of the construction pits of the ventilation buildings, a deep testpit was realized, which was limited with slopes having different inclinations.

a-1. Vertical slope.

The vertical slope is shown on fig. 1.a. It runs over an height of 11 m into the Boom clay. This slope collapsed after an existence of nearly 50 days. Behind the slope inclinometer wells had been installed. The level at which the maximum dial changes were observed is indicated with the letter M on the figure.

The dial changes at this level are given versus time on the fig. 1.b. Also the dates of the appearance of tension cracks are shown.

It can be observed that the first increases of the dial readings occur in the well IW3, located near the toe of the slope. The appearance of the first tension cracks at the upper surface of the Boom clay occurs with a time lag of 14 days, after the increase of the dial readings.

At the moment the general tension crack located 8 m

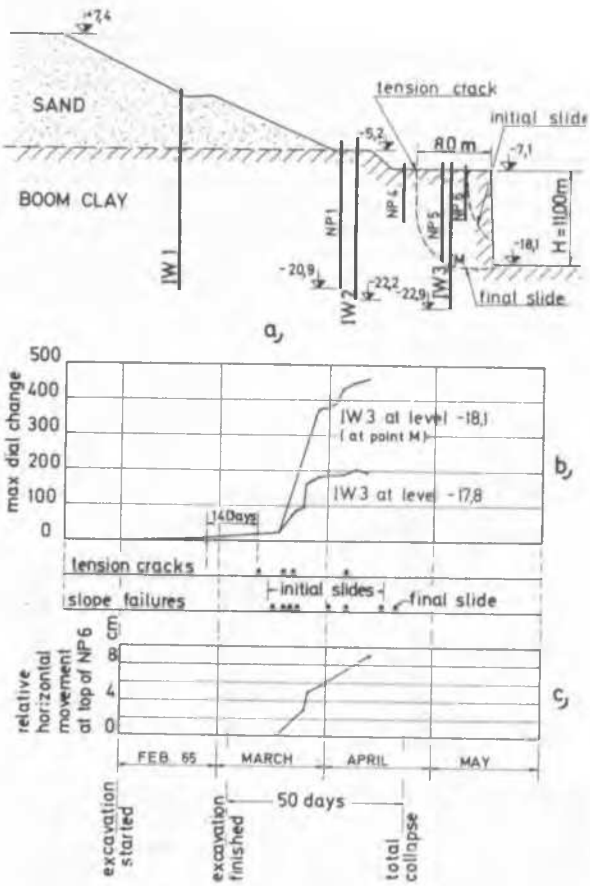


Fig. 1 Vertical slope of the test pit at Antwerp.

behind the crest of the slope occurred, the inclinometer well located in the potential slipsurface indicated already big distortions.

Behind the slope also piezometers had been installed. The horizontal movement of the top of these piezometers were regularly measured. The horizontal movement of piezometer NP6 is shown versus time on fig. 1.c. It can be observed that the horizontal movement starts also with a time lag against the distortions. From these observations can be concluded that the distortions start in the vicinity of the slope, climb gradually upwards, and that the occurrence of the tension cracks is posterior to the large distortions at the toe.

This fact is very well known by the brickmaking factories. Indeed in the clay-pits for brickmaking the clay is dug under rather steep slopes by a digging machine which runs back and forth along the crest of the slope. An eventual slip involving the machine, could ruin this costly equipment. To prevent this event, the toe of the slope is put under permanent control. As soon as big deformations are observed near the toe, the digging machine is immediately removed. Tension cracks at the upper surface appear with a certain delay after the large distortions at the toe. Shortly after the tension cracks occurs the complete collapse. If the brickmakers should only control the occurences of tension cracks, in many occasions insufficiently time should remain to remove the digging machine.

a-2. <u>Slope 2:1</u>.

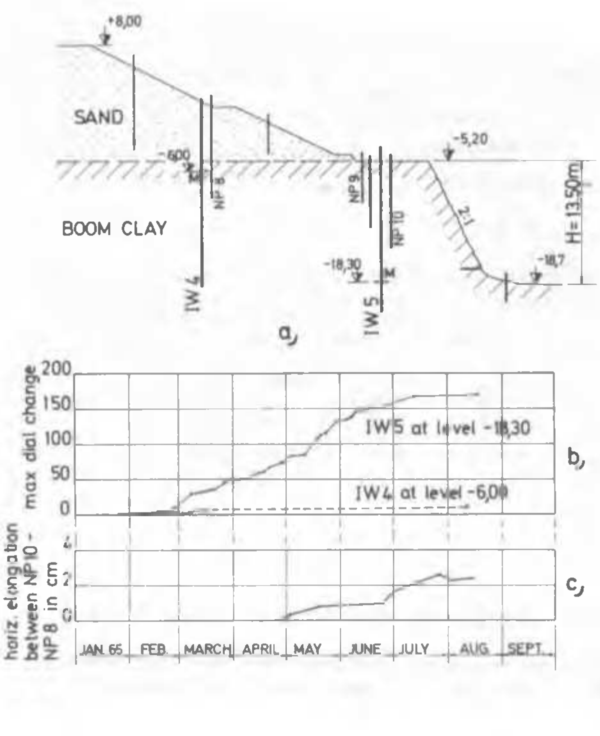


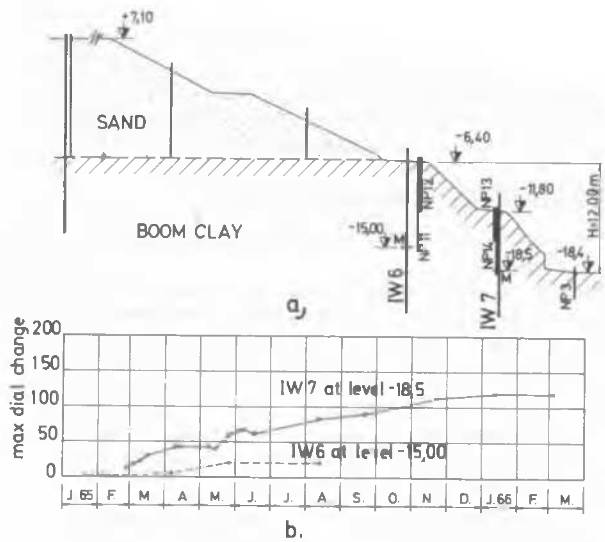
Fig. 2 Slope 2:1 of the test pit at Antwerp.

The slope 2:1 is shown on fig. 2.a. During the 6 months of existence of this slope, no rupture was observed. The variation of the dial changes with time at the levels M (fig. 2.a) of maximum dial change are shown on fig. 2.b. The horizontal elongations between the tops of the piezometers NP10 and NP8 are shown on fig. 2.c. The largest dial changes were observed for the inclinometer IW5 located near the toe of the slope. At the end of the observation time the dial changes of the inclinometer IW5 amounted already to 168 units, to be compared to the amount of 455 units observed in the inclinometer IW3 just before collapse of the vertical slope.

Although large distortions were observed in some of the inclinometers, no tension cracks occurred at the upper surface of the clay.

From the elongations observed between the piezometer-tops it must however be concluded that already an extensive opening of the micro-fissures must have occurred. This opening has a large influence on the permeability and thus on the rate of adaptation of the effective stresses to the unloaded state.

a-3. <u>Slope 1:1</u>.



The slope 1:1 is shown on fig. 3.a. During the 12 months of existence of this slope, no rupture was observed.

The variation of the dial changes of the inclinometers at the levels M (fig. 3.a) of maximum dialchange are shown on fig. 3.b. Again the largest dial changes are observed in the inclinometers located nearest to the toe of the slope. No tension cracks were observed during the life-time of the slope.

From the observations of the slope 1:1 the same conclusions can be drawn as for the slope 2:1.

Table I : Physical and mechanical properties.

	Boom clay at Antwerp $R_{2,c}$		Godarville (Ypresian clay) upper layer mean	Godarville (Ypresian clay) upper layer on the spot of the previous slide	Godarville (Ypresian clay) lower layer	Eigenbilzen $R_{1,c}$ clay	Eigenbilzen $R_{2,c}$ clay	La Flèche
percentage < 2 μ	49		16	28	18	31	14	1[illegible] - 23
natural water content w %	25 - 32		34	43	25	22	21	[illegible] - 27
liquid limit w_L %	81 ± 8		62	69	48	68	[illegible]	37 - 50
plastic limit w_p %	29 ± 3		25	29	19,5	22	1[illegible]	17 - 20
plasticity index i_p	52		37	40	28,5	46	21	20 - 30
undrained shear strength c_u (h:depth under soil surface in m)	0,75 + 0,035h (kg/cm^2)							
	(a)	(b)						
peak strength c' (t/m^2)	1,5	0	0,4	3,0	0,6	0,6	0,4	-
φ'	19° - 24°	19°	32°	22°45'	29°	26°	32°	-
residual strength c'_r (t/m^2)	0	0	0	0	0	0	0	0
φ'_r	19° - 24°	10° - 15°	12°30'(c)	12°(c)	14°30'(c)	10°(c)	18°(c)	14° - 1[illegible]° 1[illegible]°(d)

	φ'_r	
(a) samples not cut : depending on laboratory techniques	18°30'	triaxial test : remoulded strength
(b) samples previously cut : depending on laboratory techniques		direct shear test : at least 30 movements back and forth
(c) according to the chart of Bjerrum (fig.8)	22°	sample I
(d) from an actual slip	15°	sample II
	15°	torsion tests : not cut
	[illegible]°30'	previously cut
	15°(d)	

b. <u>Temporary slopes of the construction pit of the ventilation building (Right Bank).</u>

The front-slope of the construction pit of the ventilation building (Right Bank) is shown on fig. 4.a. This front slope had to last for one year. In order to shorten the length of the immersed tunnel this slope had to be as steep as possible. On the other hand a collapse of this slope should have had catastrophic consequences. From the mean waterlevel in the Scheldt river the pit has a total depth of 29 m ; the pit runs 15 m in the Boom clay. The levels of the maximum dial changes of the inclinometers are shown by the letter M on fig. 4.a.

The variation of the dial readings at these levels are shown versus time on fig. 4.b.

It can again be observed that the largest dial changes occur in the inclinometers which are the nearest to the toe of the slope. The inclinometer IW101 located nearest to the cofferdam showed practically no variations during the lifetime of the slope. From the location of the points M of maximum dial change, the shape of the potential slipsurface, shown with a dashed line on fig. 4.a can be deduced.

The readings of the inclinometer IW103, showed at a certain period a rather large rate of increase of the

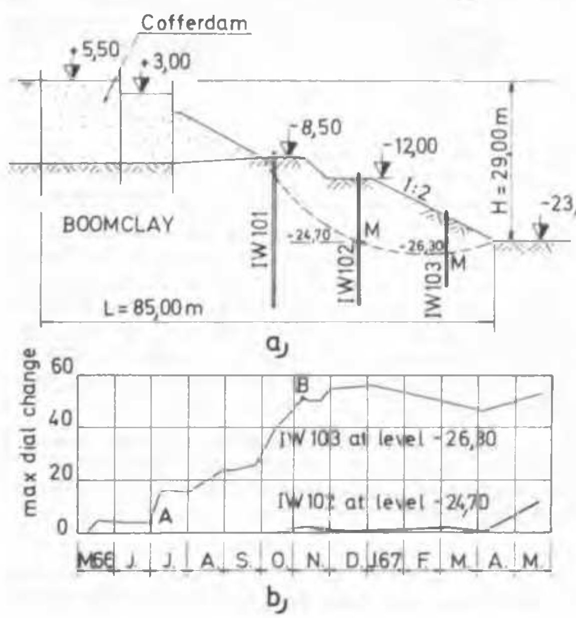


Fig. 4 Front-slope of the construction pit of the ventilation building (R.B.) at Antwerp.

distortions (part AB of fig. 4.b). From point B on this rate decreased because the part of the slope located before the inclinometer IW103, was already partially backfilled. This partial backfilling was made possible, because the excavation of the construction pit on full depth, and also the concreting of the ventilation building was realized in parts, in order to be able to take advantage of the three dimensional effect related to the shortened length of the slopes.

The observations of the temporary slope of the construction pit show again that the distortions start near the toe of the slope and climb gradually upwards.

c. Slope of the canal cut at la Fléchère.

An existing canal for 300 ton ships had to be deepened and enlarged for 1350 ton ships. At la Fléchère the cut in the divide between the Meuse and Scheldt basins had to be adapted to this new situation. The cut runs generally in an upper loam layer, and in the Ypresian clay. When the 300 ton canal was built in the late eighties rather extensive slips occurred, because too steep slopes had been designed. Thus in many parts of the Ypresian clay previous slipsurfaces exist.

At the location of one of such slipsurfaces inclinometers were placed, after the slope had been flattened according to the contour ABCDEF (fig. 5). At that time the bottom of the canal was still to be deepened from level + 118,90 to level + 117,30, thus about

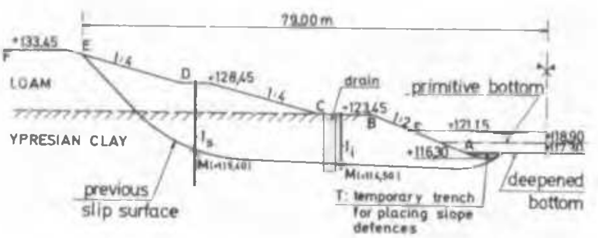


Fig. 5 Canal cut at La Fléchère.
Flattened slop at the location of previous slipsurfaces. Location of the inclinometers.

over 1,60 m. Further to realize the defenses of the canal slopes temporarely a supplementary excavation of 1 m (from level + 117,30 to level + 116,30) had to be provided. During the dredging works the dial readings of the inclinometers steadily increased. The levels of maximum dial changes are shown by the letter M on fig. 5. They correspond nearly with the location of the previous slipsurface.

The increase of the dial readings is shown versus time on the fig. 6. This figure gives also versus time the distance of the dredge to the profile in which the inclinometers are located.

It can be observed that the dial changes occur first in the inclinometer I_i, located nearest to the toe of the slope, and that the increases in the inclinometer I_s located more upward present a time-lag of 11 days to those in the inclinometer I_i. From the readings of the inclinometers could be predicted the time at which discontinuity cracks should become visible at the exit point E of the previous slipsurface. A discontinuity crack became perceptible when it reached a width of 1 to 2 mm.

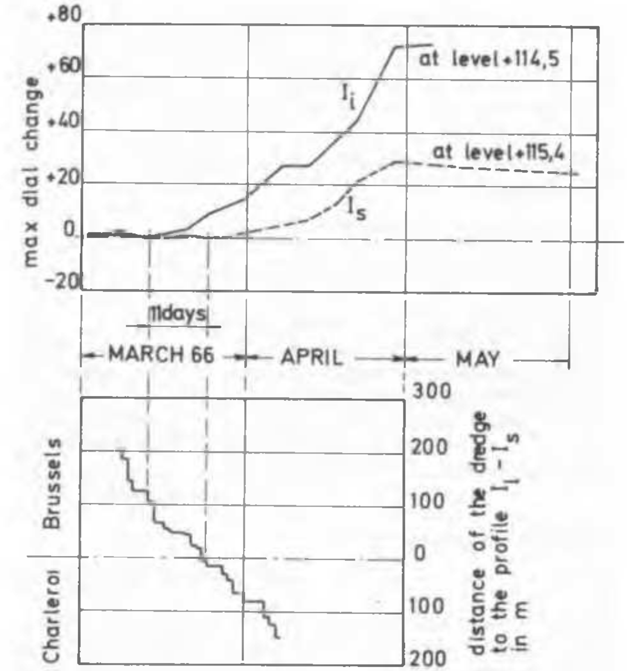


Fig. 6 Dial readings at the canal cut at La Fléchère.

These observations also show that the distortions start in the vicinity of the toe, and progress gradually upward.

II. BEHAVIOUR OF EXISTING SLOPES IN OVERCONSOLIDATED CLAYS.

a. Canal cut at Eigenbilzen.

The fig. 7 gives a cross section of a canal cut at Eigenbilzen, which now exists, without any major trouble, for about 30 years. The total height of this cut amounts to 26,08 m. It runs partly into two clay layers, belonging to the Rupelian stage (oligocene).

The characteristics of this two clay layers are given on table I. The residual shear strength was not directly measured. However Bjerrum [1], has published a very useful chart giving the residual shear angle against the plasticity index (fig. 8).

The equilibrium calculations were performed against the peak shear strength.

As in stiff fissured clays it is difficult to define exactly the waterpressures, the calculations were based on the worst assumptions concerning these pressures. They consist in admitting that over the whole thickness of a clay layer located between two sand layers the piezometric levels in the clay correspond to the watertable in the upper sand layer, and are not influenced by the drained watertable in the lower sand layer [2].

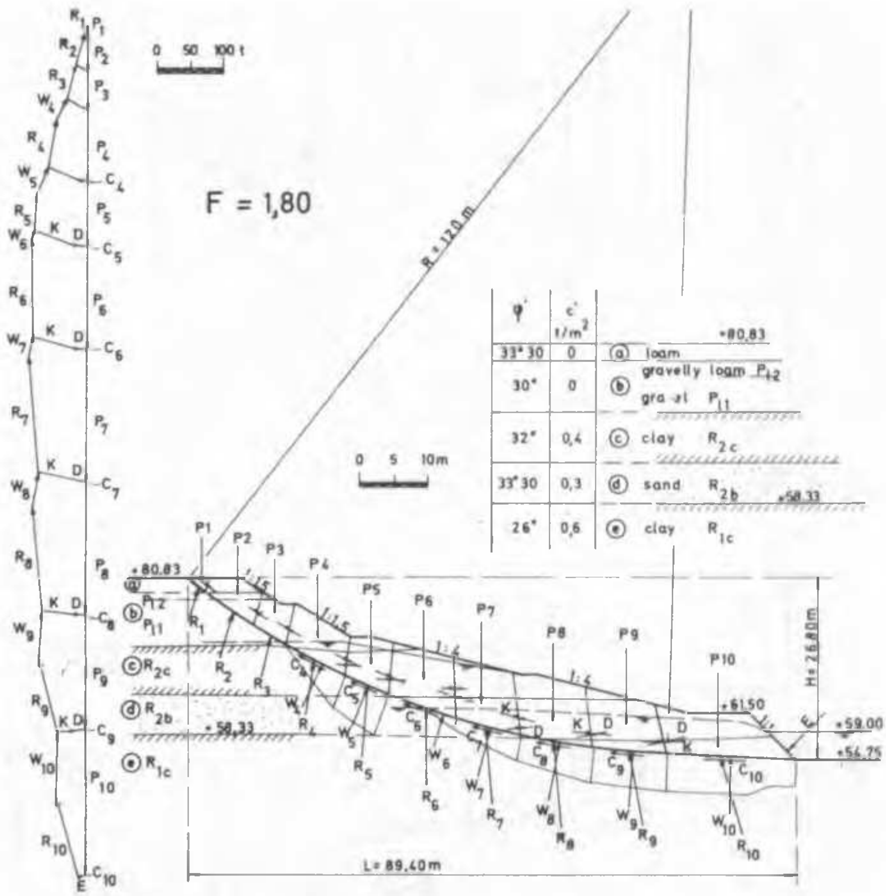


Fig.7 Cross section of the canal cut at Eigenbilzen. Equilibrium calculation related to the peak shear strength.

With these assumptions a factor of safety F = 1.8 was found.

If the residual angles of the chart of Bjerrum are introduced (with $c'_r = 0$), slipsurfaces can be found which are no longer in equilibrium (fig. 9).

As the cut exists now for 30 years, it must be concluded that, either the assumed waterpressures are too large, or that the equilibrium of the slopes which present a very large safety factor against the peak strength, are not governed by the residual angles on previously cut samples.

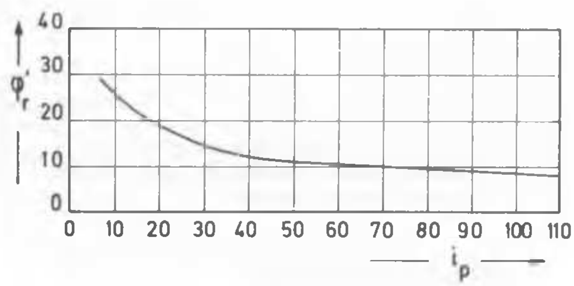


Fig. 8 Residual angle φ'_r versus plasticity index i_p (after Bjerrum).

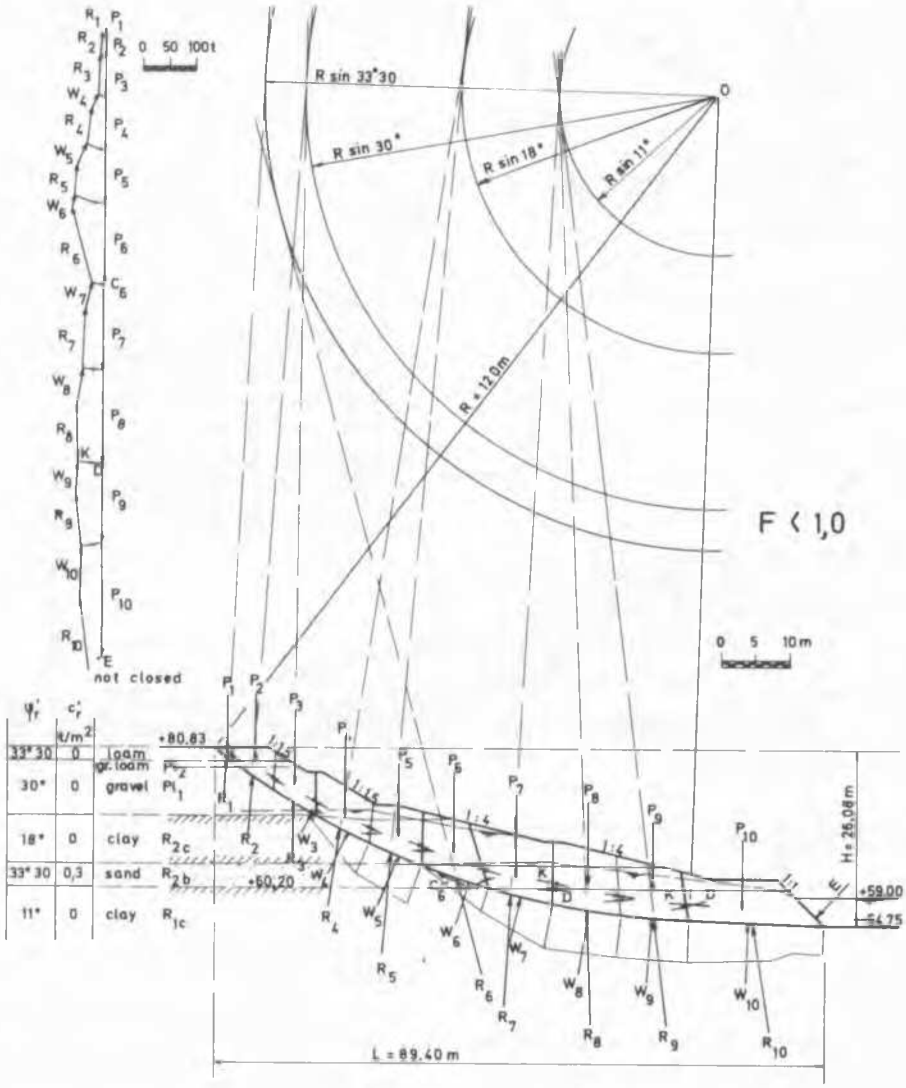


Fig. 9 Canal cut at Eigenbilzen.
Equilibrium calculation related to the residual shear strength.

b. Canal cut at Godarville.

At Godarville a canal cut exists, with a total height of 43,05 m. It runs into clay layers belonging to the Ypresian stage of the Eocene age. The characteristics of the Ypresian clay layers are given on table I.

The equilibrium control performed against the peak shear strength, and assuming the worst waterpressure conditions gives a factor of safety $F > 1.5$ (fig. 10). If the residual shear angles $\varphi'_r = 12°30'$, $\varphi'_r = 14°30'$ according to the chart of Bjerrum are introduced ($c'_r = 0$) some masses should not be in equilibrium.

Now the cut exists for about 10 years, without any trouble, except at one end of the cut. At this end which was not especially studied, because the total

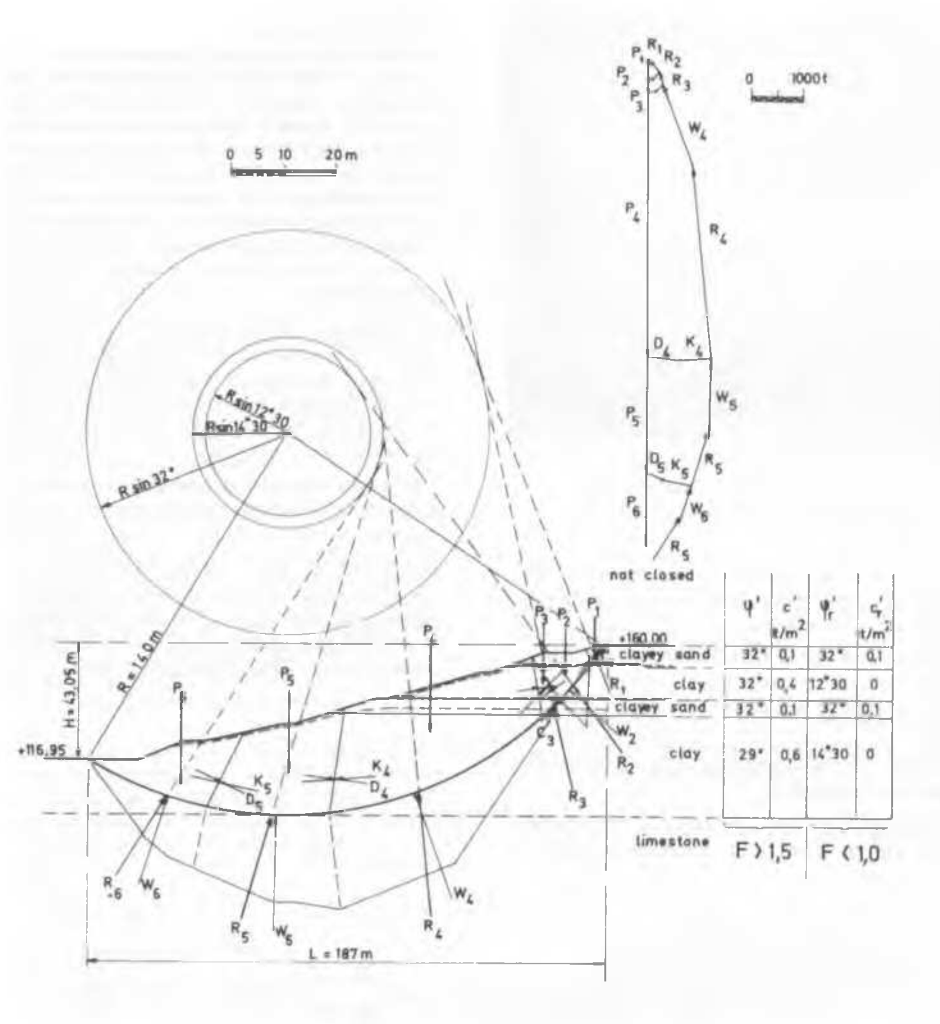


Fig. 10 Canal cut at Godarville.
Equilibrium calculation related to the residual shear strength.

height there is much less than in the central part of the cut, a slip already occurred during the excavation works. Without any study, the equilibrium of the moving mass was restored by the contractor by an extension of the drainage system. Two years ago in a very rainy period the same mass failed again. An aerial view is given on fig. 11. The movement is not perpendicular to the longitudinal axis of the cut but has also a component towards the end of the cut.

Stability calculations show that in the upper Ypresian clay the equilibrium is governed by $c'_r = 0$ and $\varphi'_r = 15°$.

That the mass already started to move during the excavation works, points to the fact that a previous sliding surface existed on that spot. Along this previous sliding surface the equilibrium is governed by the residual shear parameters. The characteristics of the Ypresian clay layers at the spot of the slide are given on table I.

c. Canal cut at La Fléchère.

The fig. 12 gives as "A" the cross section of the original 70 ton canal, as "B" the designed slopes for the 300 ton canal, which failed, as "C" the slo-

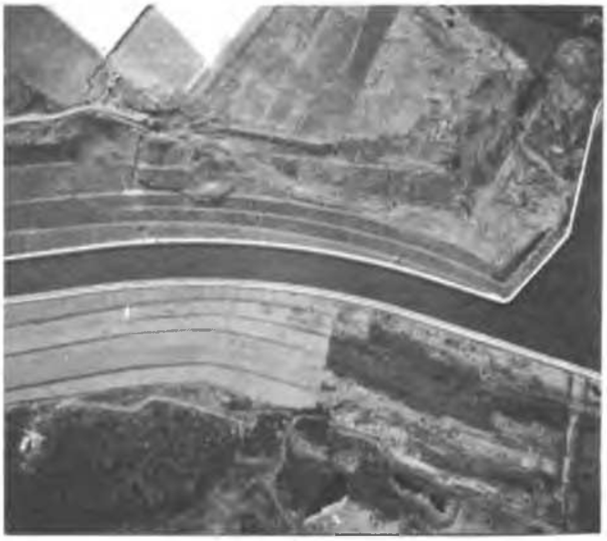


Fig. 11 Aerial view of the cut at Godarville, with a slide at the end of the cut.

pes which finally had to be adopted for insuring the stability of the 300 ton canal, and "D" the slopes designed for the 1350 ton canal.

It is worthwhile to notice that the slopes of the 300 ton canal were finally stabilized by the construction of heavy anchor walls at the toe of the slopes.

The characteristics of the Ypresian clay at La Fléchère are gathered on table I.

In the locations where previous slides of the slopes of the 300 ton canal existed, the designed slopes "D" (fig. 12) of the 1350 ton canal started to slide during the excavation works. Equilibrium calculations showed that there the equilibrium was governed by the values $c'_r = 0$ $\varphi'_r = 13°$ in the Ypresian clay.

On the locations of the previous slides the designed slopes of the 1350 ton canal were flattened as indicated on fig. 5. The flattened slopes had a factor of safety of nearly one, if the bottom of the canal was dredged to its final situation. The temporary dredging of a trench T needed to place the slope defenses, should bring the safety factor under one. This was proven by the dial changes of the inclinometers and the formation of fissures at the exit point E (fig. 5). The temporary trench was therefore made in parts, and immediately filled with the material of the slope defenses, reestablishing a safety factor somewhat larger than one.

In order to obtain the necessary safety factor (F = 1.2) bored anchor piles Ø = 1 m have been placed near the toe of the slope at intervals of 4 m. In the regions where no previous slides existed, the designed slopes D (fig. 12) of the 1350 ton canal have not been altered.

The works are now finished for about 2 years. Inclinometers have been placed which are under permanent control.

Until yet no dial changes have been observed neither in the zones without previous slides, as in the zones with previous slides, where to insure the stability a flattening of the original designed slopes and anchor piles have been provided.

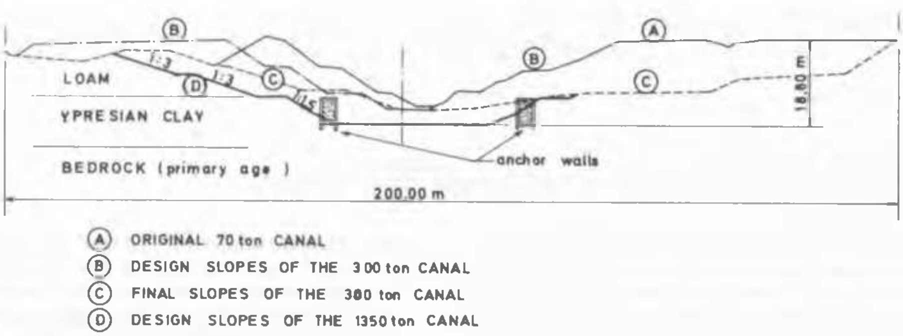


Fig. 12 Canal cut at La Fléchère.

CONCLUSIONS.

From the experimental data gathered in Belgium in relation with slopes in overconsolidated clays the following conclusions can be drawn.

1°) The distortions along potential slipsurfaces start in the vicinity of the toe of the slope and progress gradually upward. Tension cracks at the exit of the slipsurface present a time lag against the large distortions at the toe. This can be explained by the fact that the region of maximum shearing stresses is located near the toe, as is also clearly shown by Haefeli [3].

2°) The equilibrium along previously existing slipsurfaces is governed by the residual shearing strength parameters, determined on previously cut samples.

3°) The chart of Bjerrum [1] relating the residual shear angle to the plasticity index, is a very useful tool to obtain a first idea of the value of the residual angle.

4°) From the gathered experience cannot be concluded that in the regions where no previous slides exist, the final stability is necessarily governed by the residual parameters $c'_r = 0$ φ'_r. If this should be the case, one should for many problems come to solutions which are no longer economically acceptable. The Belgian experience seems at the contrary to show that if the peak shear strength parameters corresponding to the unloaded stress state of the clay are adopted stable slopes can be designed, provided that :

   1°) no previous sliding surfaces exist

   2°) the worst possible assumptions concerning the waterpressures are made

   3°) large safety factors (for instance F = 2 on the cohesion, F = 1.5 on the friction) are introduced. Indeed the larger the safety factors, the smaller the distortions, all other parameters being equal.

5°) The use of anchor walls or anchor piles, as they prevent the distortions, make it possible to use with a larger confidence the peak strength values in the design of slopes in overconsolidated clays.

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