Measuring and Predicting Lateral Earth Pressures in Slopes in Soft Clays in Sweden

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Results of a study of the lateral stress distribution in slopes in soft clays is reported. Many slopes in soft clays in the southwestern part of Sweden have a very low factor of safety against failure. Valuable information has been collected over the past years about those slopes, but, as yet, very little is known about the lateral stress distribution and the development of failures. The lateral stress distribution in a slope varies from top to toe of the slope. A better understanding of the behavior of slopes can be obtained with a better knowledge of those stresses and how they change with time and the factor of safety. When a slope is close to failure, the resulting deformations yield higher lateral stresses in the passive zone and lower in the active zone. To take this fully into account in slope modeling, full-scale field tests are imperative. In a research project at the Chalmers University of Technology, measurement of lateral stresses with Glötzl cells in natural clay slopes was started at four sites and will continue over a period of at least 2 years. The results obtained will be compared with the results obtained by analytical and numerical methods to find out whether or not those methods can serve as a reliable means for the prediction of the lateral stress distribution in the slope studied. Up to now, only Janbu's generalized procedure has been utilized. For the slopes investigated, this method has been found to give lateral stresses quite close to those measured.

At Chalmers University of Technology, Göteborg, Sweden, a project named "Slope Stability Analysis Accounting for Stresses, Deformations, and Statistical Variability in Geotechnical Parameters" was started in spring 1988, and it continues. The project is financed by the Swedish Board of Building Research (BFR). So far, the project has focused mainly on lateral stresses in clay slopes in the area around Göteborg.

Many areas in the western part of Sweden consist of soft marine clays. On top of the glacial clays were deposited the more finely grained postglacial clays. The soft clays along valley sides often contain layers of sand and silt.

The water content is generally high and often higher than the liquid limit. The clays have a low hydraulic conductivity owing to the high clay content and also to a low preconsolidation pressure, which implies low undrained shear strength. An undrained shear strength just below the dry crust as low as 10 to 15 kPa is common, and there is usually an increase of shear strength with depth of 1 to 2 kPa/m. Clays with extremely high sensitivity (>400) exist, but, typically, the sensitivity ranges from 10 to 20.

Landslides occur in those soft clays every year. The Göta River valley and its side valleys have been subjected to many slides in modern times (e.g., Göteborg harbor in 1916, Surte in 1950, Göta in 1957, and Tuve in 1977).

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Very few measurements of lateral stresses in natural clay slopes have been carried out through the years. The intention of this project is to measure lateral stresses in at least five slopes in different conditions and to compare the measurements with results obtained from theoretical analyses. So far, measurements have been carried out (and are still going on) in slopes with the following conditions:

- A steep slope in a stiff glacial clay;
- A slope in mostly postglacial clay with a very low factor of safety, which has been stabilized by soil filling in the passive zone (measurements have taken place both before and after stabilization);
- A slope in postglacial clay with a low factor of safety that is to be stabilized by removing masses from the active zone; and
- A slope in postglacial clay in an area where many small slides have taken place.

The ratio of the effective horizontal and effective vertical stress, σ'_h/σ'_v has been determined for all sites. For in situ conditions with no lateral strain (horizontal ground surface) the ratio is usually called K_o. For those slopes with a low factor of safety the ratio σ'_h/σ'_v is designated K.

Theoretical analysis of predicted lateral stress distribution for the slopes has been done by using Janbu's generalized method and will be done by using a finite-difference method later in this paper.

When comparing predicted and measured horizontal stresses, the following classification has been used: A difference of less than 10 percent is classified as very good, 10 to 20 percent as good, 20 to 30 percent as fair, and, if the difference is greater than 30 percent, it is classified as poor (unacceptable).

TYPE OF EARTH PRESSURE CELLS

A pneumatic system was chosen to measure stress cell response in this project (Figure 1). A spade-shaped thin Glötzl cell was used. The cell, 100 mm × 200 mm × 5 mm, consists of two parallel thin steel sheets welded together and is filled with oil. The oil is in contact with a sensitive membrane that shuts a counter-pressure lead. By slowly increasing the air pressure in the counter-pressure lead, the membrane will open at a

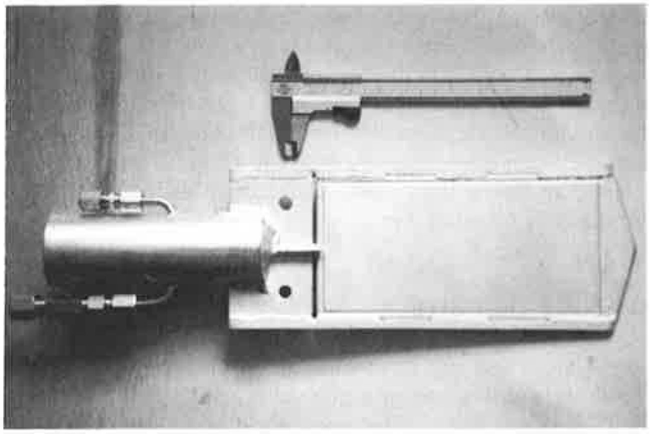

FIGURE 1 Glötzl earth pressure cell.

pressure that slightly exceeds the oil pressure in the cell. This opening pressure can be read on a manometer.

The Glötzl cells have shown to give reasonable lateral stresses in other projects, both at Chalmers and at the Royal Institute of Technology in Stockholm. Larsson (*1*) carried out a comprehensive series of tests both in the field and in the laboratory to determine the lateral stresses in Bäckebol clay. The tests showed good agreement between different kinds of field test methods; that is, Glötzl earth pressure cells, the Ménard pressuremeter, and a self-boring pressuremeter (Cambridge type). Schmidt's empirical relation, $K^{o}_{nc} = 1 - 1.2 \sin \phi'$, was used to calculate the in situ horizontal stresses. The calculated stresses were close to those measured (Figure 2).

A method by which in situ lateral load tests in soft clay can be carried out was developed by Olsson (*2*). The system was used to test earth pressure cells in the field (Glötzl type). Two large, soft flat jacks were pushed down into the soil and inflated by air to the desired pressure. Glötzl earth pressure cells were installed to measure the imposed pressure. The tests showed that the cells give very good measurements of the lateral stresses in the soil and that about 5 days are required after the installation of the cells before the excess pressures have dissipated. The tests also showed that the cells respond very quickly to changes in lateral stresses.

Standard dilatometer (DMT) tests have also been carried out in some of the areas studied. The DMT test is an in situ method used to determine strength and deformation properties by empirical correlations. The coefficient of lateral earth pressure can also be determined (*3*).

INSTALLATION TECHNIQUE

A good working technique for pushing cells into the ground was developed at the Royal Institute of Technology, Stockholm, in the mid 1970s (*4*). The technique has been modified to work even better and to protect the cells during installation. The cell is protected during installation by a steel cylinder (h = 500 mm, ϕ = 120 mm) connected to piston sampler rods (Figure 3). About 50 cm above the intended measuring level, the cell is pushed out of the protection cylinder by sounding rods inside the piston sampler rods. The cylinder

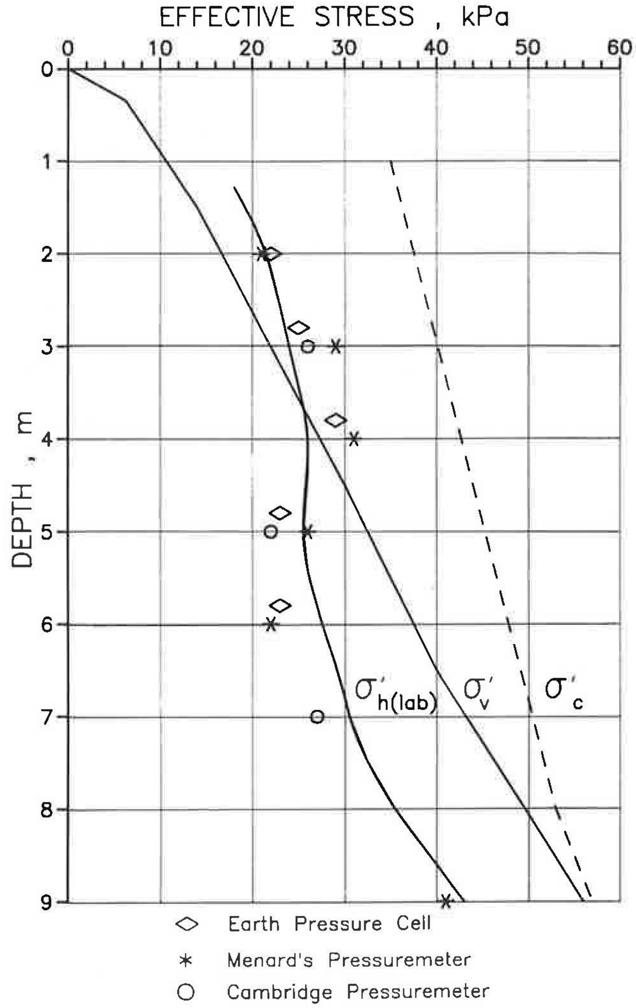

FIGURE 2 Comparison of measured lateral in situ stresses with lateral stresses according to Schmidt's relation [after Larsson (*1*)].

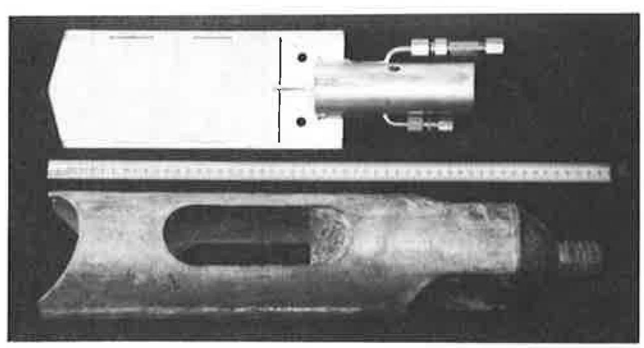

FIGURE 3 Glötzl earth pressure cell and instrumentation tool.

and the rods are then withdrawn. Wires are connected to the cells to make it possible to recover the cells after the measurement period.

By using this method, earth pressure cells can be pushed to great depth with little risk of damage. The dry crust has to be predrilled before pushing the cells into the ground.

JANBU'S GENERALIZED PROCEDURE OF SLICES FOR PREDICTION OF HORIZONTAL STRESS DISTRIBUTION

There are many ways of solving slope stability problems for shear surfaces of any shape. The differences are to be found in the assumptions regarding interslice forces.

Forces acting on the boundaries of a single slice in Janbu's generalized procedure of slices (*5*) are assumed as indicated in Figure 4. By assuming the position of the line of thrust for the total slice force E for the selected shear surface, the average factor of safety and the four unknowns for each slice, E, T, σ, and τ, can be determined by an iterative procedure. All the slopes in this project have been investigated under undrained conditions, and the line of thrust has been placed somewhat below the lower third point in the active zone and somewhat above it in the passive zone.

A computer program, originally made by Grande (*6*), has been used for determination of the interslice stress distribution with Janbu's method for all four test sites.

BÄCKEBOL TEST AREA

The Bäckebol test area, 10 km north of Göteborg, is an almost horizontal field next to the Göta River. The clay is known to be exceptionally homogenous and has been subjected to several investigations. The soil profile comprises a 1-m thick dry crust underlain by a slightly organic gray clay. The undrained shear strength is around 15 kPa.

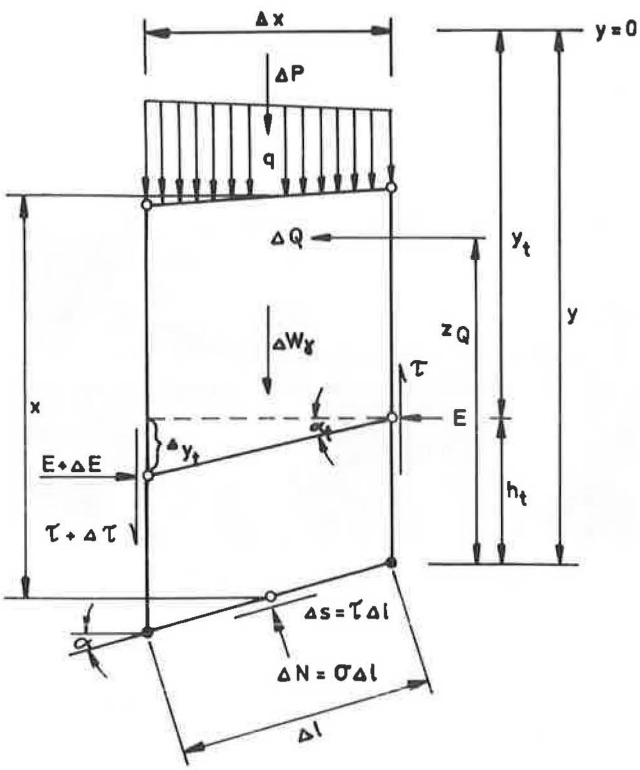

FIGURE 4 Forces acting on the boundaries of a single slice in Janbu's generalized procedure of slices [after Janbu (*5*)].

Measurements of in situ lateral earth pressure have been made with Glötzl earth pressure cells (*1*). DMT tests have been carried out (*7*) in the area. The K_o values are presented in Figure 5. The values decrease with depth from 0.8 close to the ground surface down to 0.6 at 10 m of depth. The agreement between earth pressure cells and DMT is very good at 5 and 7 m below the ground surface, but an unacceptable difference is found at 3 m of depth.

ALAFORS TEST SITE

The Alafors test site is situated about 25 km northeast of Göteborg and is a part of a side valley, the Sköld valley, to the Göta River valley. The investigated area of the valley is narrow, just about 130 m wide, and the difference in altitude between the slope crest and the Sköld stream is 12 m. A slide occurred just 30 m to the east of the test site in 1901.

The soil in the area consists of soft clay, which is about 25 m thick in the center of the valley. The undrained shear strength is 10 to 15 kPa just below the dry crust and then increases with depth (1 kPa/m). The dry crust is 1 to 2 m thick. Thin silt layers (not continuous ones) and quick clay are found in some places. Noncohesive soil of different thickness underlies the clay (Figures 6 and 8).

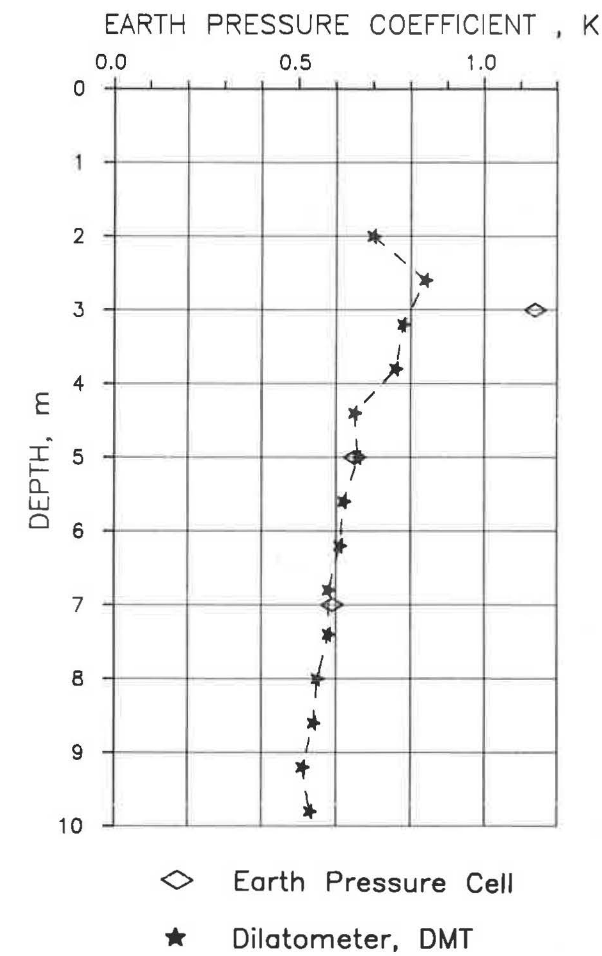

FIGURE 5 *K* values determined by earth pressure cells and DMT at the Bäckebol test site.

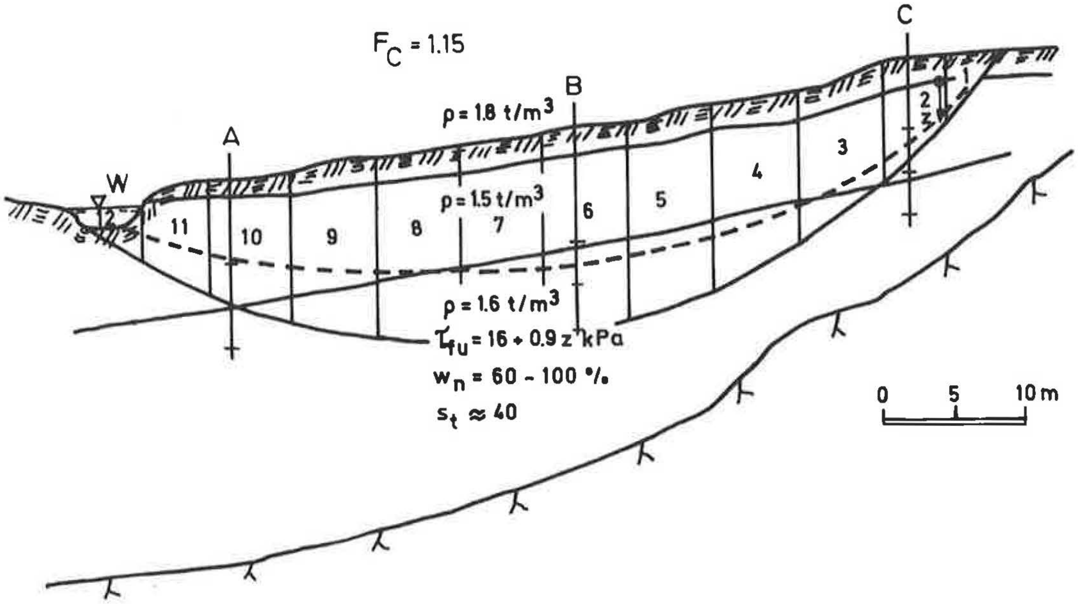

FIGURE 6 Profile with geotechnical parameters, shear surface, and line of thrust used for the Alafors test site before stabilization.

Stability calculations in the late 1970s indicated that the factor of safety of the slope was very low, F_c = 1.07. The slope was stabilized through a 2-m thick clay fill in the passive zone, and the stream was relocated in a culvert (Figure 7).

Predicted Lateral Earth Pressures

Predictions of lateral earth pressures at the Alafors test site have been done by assuming undrained conditions both before and after the stabilization. The same, noncircular, 16-m-deep shear surfaces were used in both analyses. The shear surfaces and lines of thrust are presented in Figures 6 and 7. The calculations gave reasonable values of the lateral earth pressures and *K* values. In the passive zone the lateral earth pressures were higher in the stabilized slope than in the original slope (Tables 1 and 2).

The lateral pressures in the active zone at the shear surface were also higher in the stabilized than in the original, which was not expected. Accordingly, the K_o values were calculated to be higher throughout the slope after the stabilization (Tables 7 and 8).

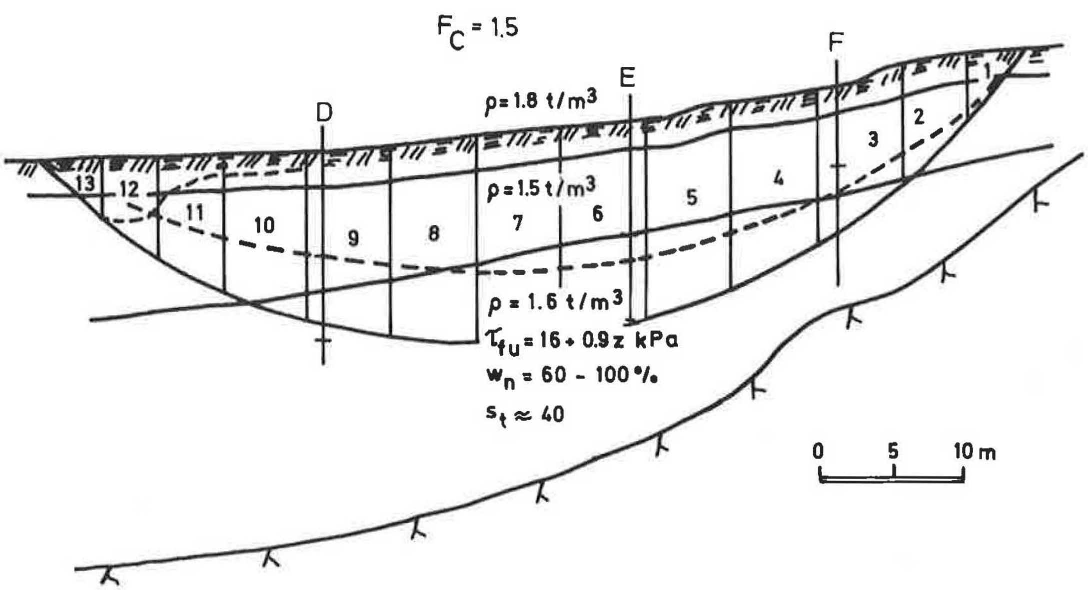

FIGURE 7 Profile with geotechnical parameters, shear surface, and line of thrust used for the Alafors test site after stabilization.

TABLE 1 PREDICTED LATERAL EARTH PRESSURES AND *K* VALUES AT THE ALAFORS TEST SITE BEFORE STABILIZATION

Slice inter-section	Lateral pressure at the ground level σ_{hg} (kPa)	Lateral pressure at the shear surface σ_{hs} (k a)	K -values at the shear surface
1-2	-10.9	33.3	0.11
2-3	-26.5	97.7	0.40
3-4	-30.9	171.2	0.96
4-5	-16.2	194.7	0.78
5-6	-0.2	206.9	0.81
6-7	-0.2	216.7	0.89
7-8	23.7	185.8	0.68
8-9	25.2	176.2	0.75
9-10	27.3	148.6	0.83
10-11	16.0	111.6	0.78
11-12	41.7	55.8	0.77

TABLE 2 PREDICTED LATERAL EARTH PRESSURES AND *K* VALUES AT THE ALAFORS TEST SITE AFTER STABILIZATION

Slice inter-section	Lateral pressure at the ground level σ_{hg} (kPa)	Lateral pressure at the shear surface σ_{hs} (kPa)	K -values at the shear surface
1-2	-13.4	49.0	0.28
2-3	-30.9	114.0	0.67
3-4	-35.4	194.2	1.26
4-5	-18.4	220.2	1.06
5-6	0	242.4	1.19
6-7	6.4	241.2	1.10
7-8	21.4	219.6	0.87
8-9	39.3	210.1	1.01
9-10	36.0	179.6	0.91
10-11	34.3	148.3	0.95
11-12	23.8	118.8	1.07
12-13	37.4	65.2	0.80

Comparison Between Predicted and Measured Lateral Earth Pressures

Measurements with earth pressure cells have been carried out both before and 10 years after the stabilization. Before the stabilization, cells were installed in section A at 6, 9, and 12 m depth; in section B at 8, 11, and 14 m; and in section C at 5, 8, and 11 m depth (see Figure 6). After the stabilization, cells were installed in section D at 7.4 and 13.4 m depth, in section E at 8 and 14 m, and in section F at 5.5 m depth (see Figure 7). The measurements indicated the same results as the prediction with increasing pressures and *K* values from the crest to the toe of the slope. However, the difference between the pressures in the passive zone before and after the stabilization was not as high as was predicted (Tables 3 and 4).

The agreement between the measured and predicted pressures and *K* values was good in the case of the original slope but not as good (some unacceptable values) in the case of the stabilized slope (Tables 3 and 4).

TABLE 3 COMPARISON BETWEEN MEASURED AND PREDICTED LATERAL EARTH PRESSURES AND *K* VALUES AT THE ALAFORS TEST SITE BEFORE STABILIZATION

Section	Depth z(m)	Total lateral earth pressure			K -values		
		Mea-sured (kPa)	Pre-dicted (kPa)	$\Delta\sigma$ (%)	Mea-sured	Pre-dicted	ΔK (%)
A	6	91	89	2	0.95	0.89	6
	9	124	124	0	0.73	0.73	6
	12	175	160	9	0.86	0.63	27
B	8	104	119	14	0.61	0.88	44
	11	139	162	16	0.55	0.87	58
	14	175	205	17	0.51	0.84	65
C	5	56	46	18	0.50	0.30	40
	8	70	89	14	0.18	0.45	150
	11	-	132	-	-	0.55	-

TABLE 4 COMPARISON BETWEEN MEASURED AND PREDICTED LATERAL EARTH PRESSURES AND *K* VALUES AT THE ALAFORS TEST

Section	Depth z(m)	Total lateral earth pressure			K -values		
		Mea-sured (kPa)	Pre-dicted (kPa)	$\Delta\sigma$ (%)	Mea-sured	Pre-dicted	ΔK (%)
D	7.4	103	124	20	0.70	1.04	49
	13.4	181	198	9	0.65	0.84	29
E	8.0	99	142	43	0.58	1.26	117
	14.0	171	246	44	0.50	1.24	148
F	5.5	74	79	7	0.67	0.79	18

LÄRJEÅN TEST SITE

The Lärjeån test site in the Lärje stream valley is situated 10 km northeast of Göteborg. The Lärje stream has cut its way down 15 m into the clay layers and has formed many steep slopes (some with an inclination as high as 1–2) and a meandering stream line. Many small slides occur in this area every year.

The investigated slope has an altitude between the slope crest and the slope toe of 14 m and an inclination of 30 to 35 degrees in its steepest part. A slide occurred in the slope early in 1988, and the investigations and measurements have been made only after the slide.

The soil consists of clay overlying noncohesive soil on the rock. The rock surface is found 31 m below the ground level at the slope crest and is almost lateral. The undrained shear strength is 40 kPa right below the dry crust and increases with depth, 2.5 kPa/m. The dry crust is 5 m thick at the top of the slope and 2 m thick at the toe (Figure 8). The pore pressure is hydrostatic with a zero value at the lower part of the dry crust.

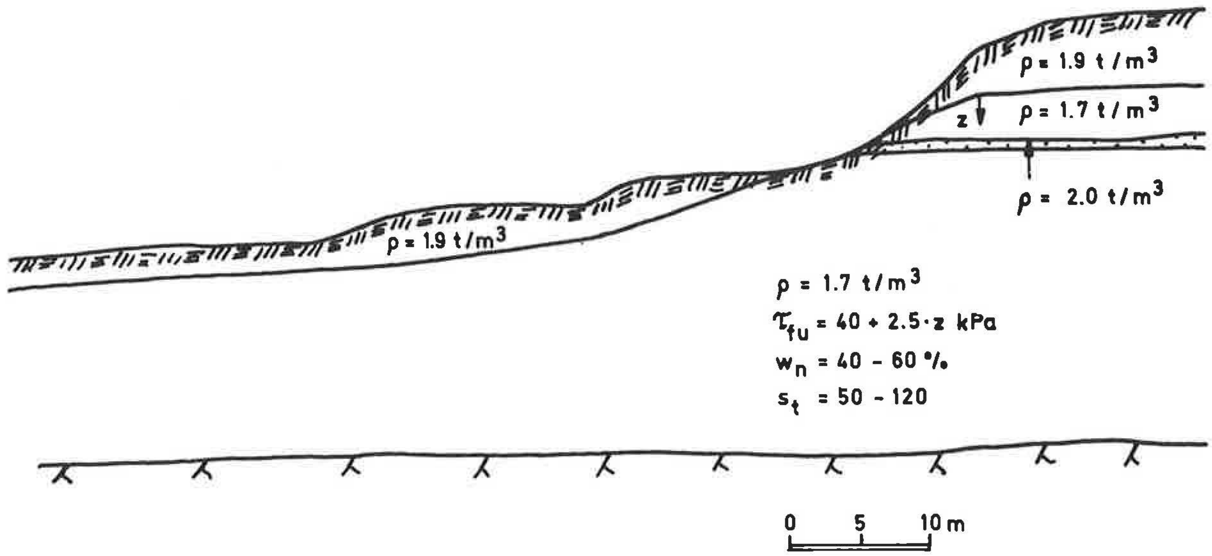

FIGURE 8 Profile with geotechnical parameters for the Lärjeån test site.

Predicted Lateral Earth Pressures

For the Lärjeån test site two different, noncircular, shear surfaces were assumed in an attempt to predict the stress distribution. A 14-m-deep shear surface in the upper part and a 10-m-deep shear surface in the lower part of the slope were applied. The two shear surfaces were chosen to obtain stresses at the places where pressure cells had been installed. The calculations indicate very high lateral pressures and *K* values in the passive zone. *K* values as high as 2.7 to 3.1 were found (Tables 5 and 6).

Comparison Between Predicted and Measured Lateral Earth Pressures

Measurements of lateral earth pressures have been performed with two earth pressure cells. The cell was installed at a depth of 7.25 m in section A and at a depth of 12 m in section B (Figures 9 and 10). The agreement between the measured and predicted earth pressures and *K* values was found to be very good (Table 7).

Two DMT soundings were done with the blade perpendicular to the slope in section D1 and D2 (Figures 9 and 10). Those tests also showed high *K* values but not as high as those obtained by the pressure cells. The results from the DMT

TABLE 5 PREDICTED LATERAL EARTH PRESSURES AND *K* VALUES AT THE LÄRJEÅN TEST SITE IN THE UPPER PART OF THE SLOPE SITE AFTER STABILIZATION

Slice inter-section	Lateral pressure at the ground level σ_{hg} (kPa)	Lateral pressure at the shear surface σ_{hs} (kPa)	K -values at the shear surface
1-2	-3.8	13.4	0.51
2-3	-12.0	199.2	0.60
3-4	-29.4	250.6	0.76
4-5	-24.3	343.9	1.56
5-6	13.0	357.4	2.86
6-7	16.7	316.7	2.01
7-8	29.5	281.1	2.13
8-9	29.8	227.2	1.81
9-10	30.0	163.6	1.84

TABLE 6 PREDICTED LATERAL EARTH PRESSURE AND *K* VALUES AT THE LÄRJEÅN TEST SITE IN THE LOWER PART OF THE SLOPE

Slice inter-section	Lateral pressure at the ground level σ_{hg} (kPa)	Lateral pressure at the shear surface σ_{hs} (kPa)	K -values at the shear surface
1-2	-5.9	33.8	0.68
2-3	-19.8	99.0	0.84
3-4	-16.8	184.4	2.05
4-5	-27.5	260.3	3.02
5-6	-28.9	262.3	2.13
6-7	-18.1	288.9	2.47
7-8	-0.2	240.4	1.60
8-9	42.9	213.9	2.41
9-10	38.3	183.1	1.98
10-11	40.8	139.0	2.19

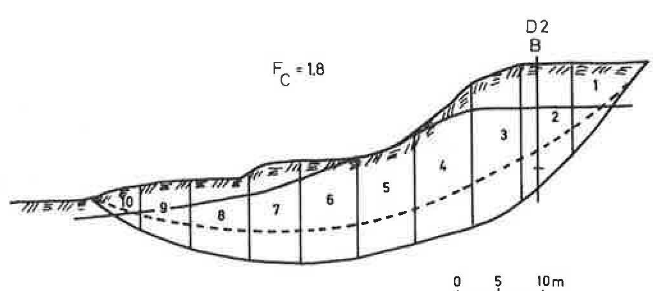

FIGURE 9 Shear surface and line of thrust used for the Lärjeån test site in the upper part of the slope.

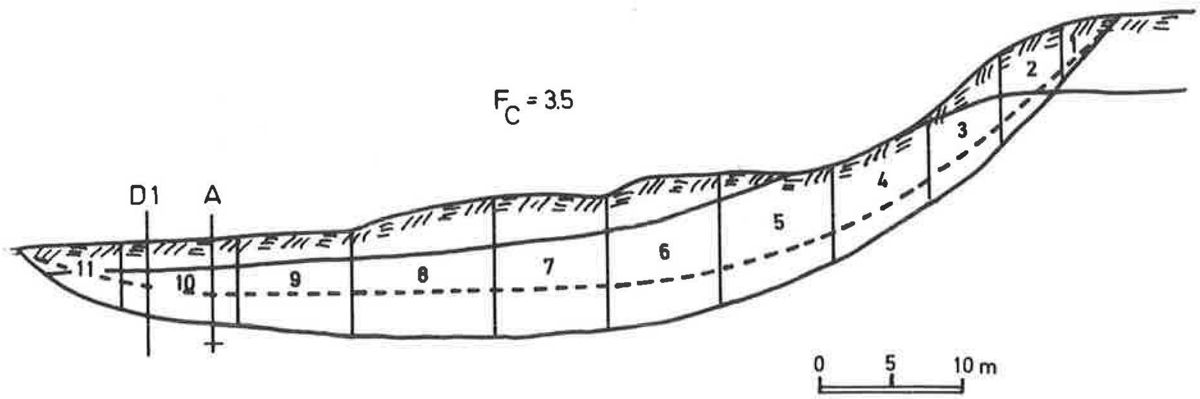

FIGURE 10 Shear surface and line of thrust used for the Lärjeån test site in the lower part of the slope.

TABLE 7 COMPARISON BETWEEN MEASURED AND PREDICTED LATERAL EARTH PRESSURE AND *K* VALUES AT THE LÄRJEÅN TEST SITE, MEASUREMENTS WITH EARTH PRESSURE CELLS

Section	Depth z(m)	Total lateral earth pressure			K -values		
		Mea-sured (kPa)	Pre-dicted (kPa)	$\Delta\sigma$ (%)	Mea-sured	Pre-dicted	ΔK (%)
A	7.25	214	202	5	2.78	3.01	8
B	12.0	140	146	4	0.56	0.64	14

TABLE 8 COMPARISON BETWEEN *K* VALUES MEASURED WITH DMT AND EARTH PRESSURE CELLS AT THE LÄRJEÅN TEST SITE

Section	Depth z(m)	K -values		
		Dilato-meter	Earth pres-sure cell	ΔK (%)
D1, A	7.25	1.5	2.78	85
D2	12.0	0.8	0.56	30

soundings are shown in Table 8. The difference between the DMT results and those obtained by the earth pressure cells was unacceptable.

KVIBERG TEST SITE

The Kviberg test site (see Figure 11) is situated in the eastern part of Göteborg. The area consists of a ravine where the Utby stream meanders its way down in a north-south direction. The slope inclination within the area varies between 1–5 and 1–10 except next to the stream where it can be higher. The soil consists of 2 to 3 m of dry crust and soft clay underlain by a silty clay with silt and sand layers. The depth to rock was not investigated but is greater than 20 m at the crest and more than 15 m at the toe of the slope. The undrained shear strength varies between 20 and 30 kPa and increases somewhat with depth. The groundwater level is 1.5 to 2.0 m below the ground level in the upper part of the slope. At the toe of the slope the groundwater is artesian. The sensitivity is rather low (20 to 30). The water level in the Utby stream varies a great deal and causes erosion and many small slides.

Predicted Lateral Earth Pressures

Prediction of the lateral earth pressure distribution at the Kviberg test site was based on the assumption of a noncircular 12-m-deep shear surface (Figure 11). The calculations showed increasing lateral earth pressures and *K* values from the crest

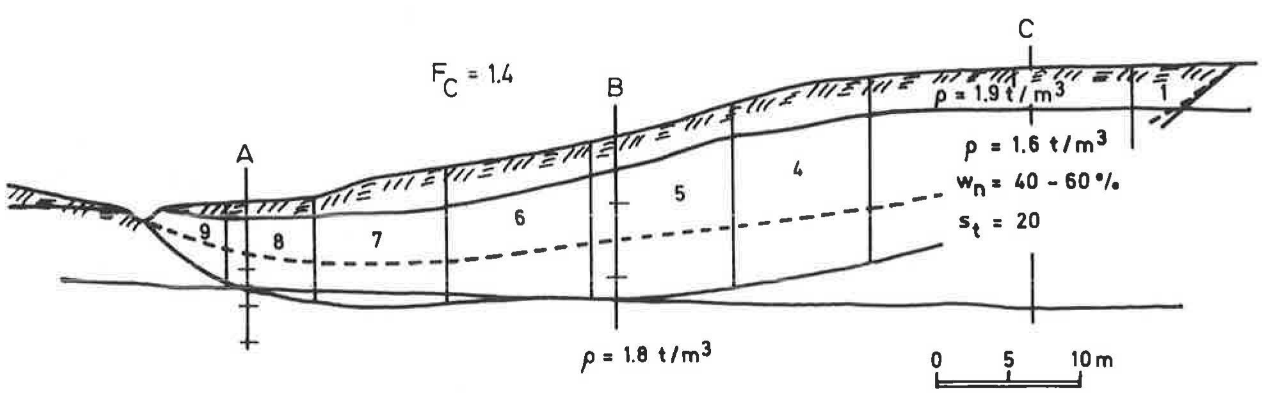

FIGURE 11 Profile with geotechnical parameters, shear surface, and line of thrust used for the Kviberg test site.

to the toe of the slope (Table 9). The differences in *K* values between the active and passive zone were of the same order as at the Alafors test site.

Comparison Between Predicted and Measured Lateral Earth Pressures

Seven earth pressure cells were installed at three sections of the slope: at the toe, at the crest, and in the middle (Figure 11). The cells were installed at depths of 5, 7.5, and 10 m in sections A and C and at depths of 5 and 10 m in section B. The results show increasing *K* values from the top to the toe of the slope but the values were not as high in the passive zone as those found at the Alafors and Lärjeån test sites (Table 10). The agreement between the measured and the predicted values was good (Table 10).

TABLE 10 COMPARISON BETWEEN MEASURED AND PREDICTED LATERAL EARTH PRESSURES AND *K* VALUES AT THE KVIBERG TEST SITE

Section	Depth z (m)	Total lateral earth pressure			K -values		
		Mea- sured (kPa)	Pre- dicted (kPa)	$\Delta\sigma$ (%)	Mea- sured	Pre- dicted	ΔK (%)
A	5	79	99	25	0.83	1.47	77
	7.5	136	136	0	1.26	1.26	0
	10	194	173	11	1.38	1.02	26
B	5	83	87	5	0.92	0.99	48
	10	148	171	16	0.73	1.05	44
C	5	74	51	31	0.73	0.40	45
	7.5	95	79	17	0.50	0.28	44
	10	109	109	0	0.30	0.30	0

UGGLUM TEST SITE

The Ugglum test site is in an area with postglacial clay in the eastern part of Göteborg. The Säve stream, which is an affluent to the Göta River, passes through the site. Rather flat slopes with a height of about 6 m have been formed by the stream. Quick clay can be found in some areas next to the stream and have caused many slides through the years.

The soil consists of soft, homogenous clay capped by a dry crust 1 to 2 m thick overlying noncohesive soil rock. The undrained shear strength is about 10 to 15 kPa right under the dry crust and increases with depth, 1 kPa/m (Figure 12). The groundwater is hydrostatic from the ground level.

In September 1989 a new railway bridge was built in the area. Since the factor of safety is low, $F_{c\phi} \approx 1.2$ to 1.3, the investigated slope had been stabilized by removing masses from the active zone. Measurements of lateral earth pressures with cells are still going on and continued during and after the stabilization.

TABLE 9 PREDICTED LATERAL EARTH PRESSURES AND *K* VALUES AT THE KVIBERG TEST SITE

Slice inter- section	Lateral pressure at the ground level σ_{hg} (kPa)	Lateral pressure at the shear surface σ_{hs} (kPa)	K -values at the shear surface
1-2	-8.5	59.9	0.18
2-3	-8.0	113.2	0.24
3-4	-12.0	153.6	0.35
4-5	-13.2	174.0	0.60
5-6	3.6	181.4	1.02
6-7	11.1	185.1	1.75
7-8	28.6	142.8	1.51
8-9	27.6	102.8	1.36

Predicted Lateral Earth Pressures

A noncircular 9-m-deep shear surface was used to predict the stress distribution at the Ugglum test site (Figure 12). From the results of the calculations it can be seen that the earth pressures and *K* values constantly increase from the crest to the toe of the slope (Table 11). The *K* values were in the same range as the values at the Alafors test site.

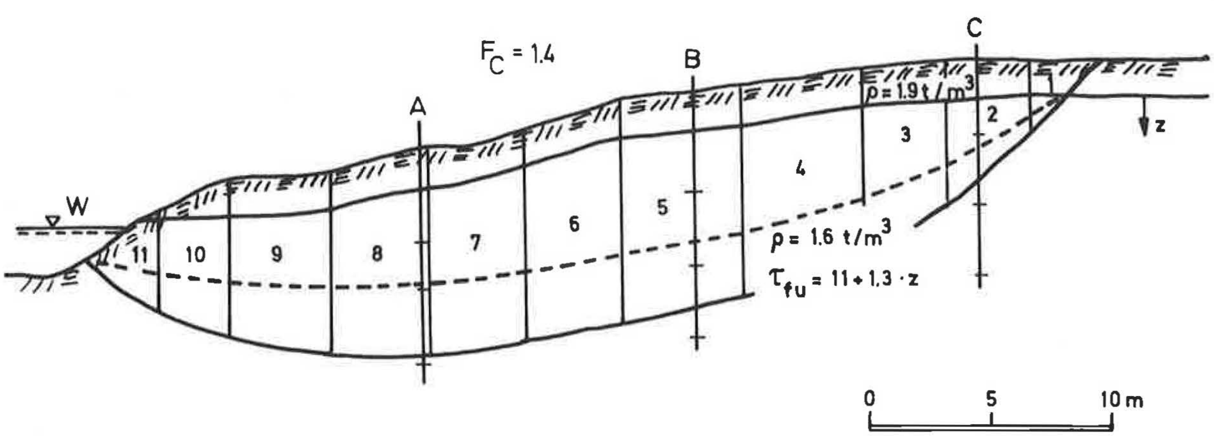

FIGURE 12 Profile with geotechnical parameters, shear surface, and line of thrust used for the Ugglum test site.

TABLE 11 PREDICTED LATERAL EARTH PRESSURES AND *K* VALUES AT THE UGGLUM TEST SITE

Slice intersection	Lateral pressure at the ground level σ (kPa)	Lateral pressure at the shear surface σ (kPa)	K-values at the shear surface
1-2	-8.4	36.2	0.28
3-2	-8.1	75.1	0.44
3-4	-14.5	104.9	0.60
4-5	-8.1	124.5	0.71
5-6	-9.1	128.3	0.59
6-7	-2.9	134.7	0.83
7-8	4.7	129.7	0.82
8-9	12.3	117.1	0.88
9-10	9.9	94.3	0.71
10-11	19.4	71.0	1.11

Comparison Between Predicted and Measured Lateral Earth Pressures

Nine earth pressure cells were installed in three sections of the slope: close to the Säve stream, in the middle, and at the crest.

In section A, cells were installed at depths of 4, 6, and 9 m; in section B at 4.35, 7.35, and 10.35 m; and in section C at 3, 6, and 9 m. The measurements showed increasing *K* values from 0.60 in the active zone to 0.98 in the passive zone (Table 12). A very good agreement between measured and predicted lateral earth pressures was noted (Table 12). The earth pressure cell at 4.35 m of depth in section B gave a very low earth pressure value, which probably was not correct.

DMT soundings with the blade perpendicular to the slope have been carried out in all three sections. The results are shown in Figures 13–15. The agreement between measured *K* values with DMT and earth pressure cells was very good in sections B and C and good in section A.

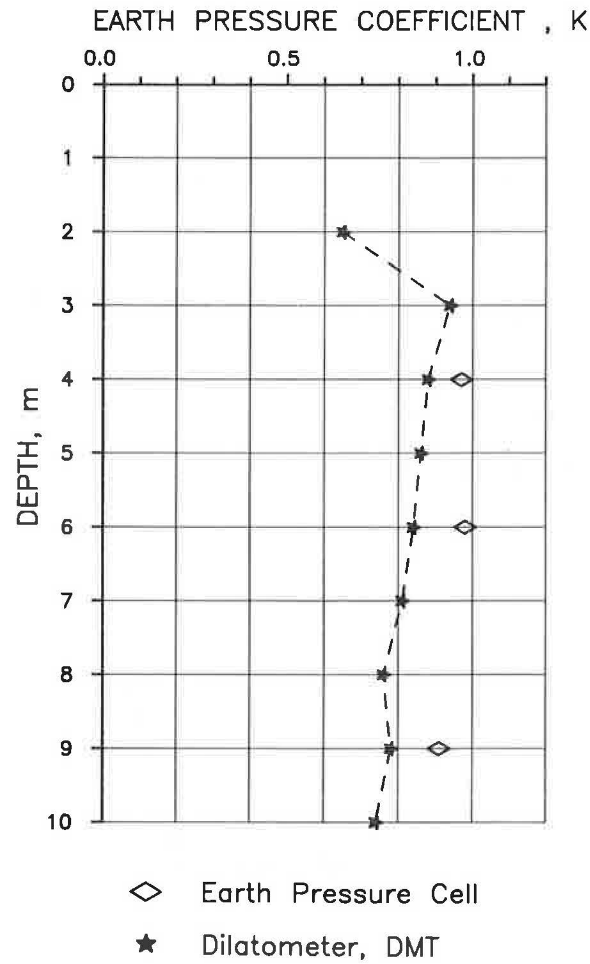

FIGURE 13 Earth pressure coefficient *K* determined by earth pressure cells and DMT at the Ugglum test site in section A.

DISCUSSION OF RESULTS

The investigation showed that the lateral earth pressures and *K* values increased from the crest to the toe of a slopes. This was found both through direct observations and by Janbu's generalized procedure of slices. The *K* values were about 0.4 to 0.7 in the active zones and about 0.8 to 1.4 in the passive zones. In one very steep slope with a low factor of safety, *K* in the passive zone reached values close to the passive earth pressure coefficient K_p ($K \approx 3$).

TABLE 12 COMPARISON BETWEEN MEASURED AND PREDICTED LATERAL EARTH PRESSURES AND *K* VALUES AT THE UGGLUM TEST SITE

Section	Depth z(m)	Total lateral earth pressure			K-values		
		Measured (kPa)	Predicted (kPa)	Δσ (%)	Measured	Predicted	ΔK (%)
A	4.0	65	63	3	0.97	0.91	6
	6.0	97	93	4	0.98	0.90	8
	9.0	140	137	2	0.91	0.86	5
B	4.35	38	54	42	(0.30)	0.64	113
	7.35	97	98	1	0.63	0.64	2
	10.35	143	143	0	0.68	0.67	1
C	3.0	35	35	0	0.60	0.60	0
	6.0	75	76	1	0.58	0.60	3
	9.0	110	95	14	0.46	0.23	50

A good or very good agreement between measured and calculated total earth pressures was found. The differences were less than 20 percent except for the Alafors test site after stabilization. At the Alafors site the differences were about 20 to 50 percent. The explanation to those results may be that the Janbu's generalized procedure only works for natural slopes and not for stabilized ones. This hypothesis will be further investigated when masses from the active zone at the Ugglum test site have been removed.

The *K* values obtained by DMT soundings and the pressure cells were in good agreement at two sites but were unacceptably different at one site.

The calculations with Janbu's generalized procedure have only been done for undrained conditions, though. Lateral stresses obtained from calculations in drained conditions will be studied in the near future.

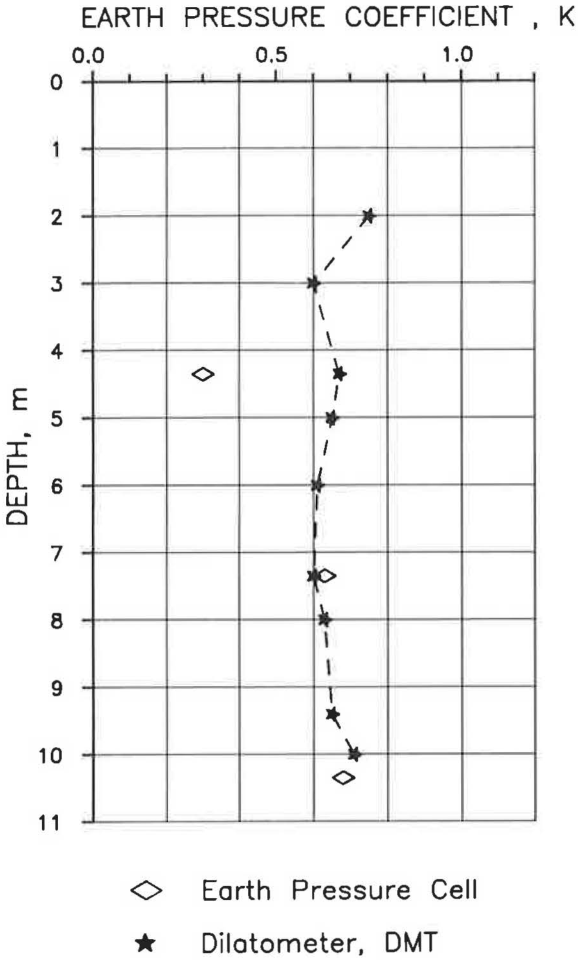

FIGURE 14 Earth pressure coefficient *K* determined by earth pressure cells and DMT at the Ugglum test site in section B.

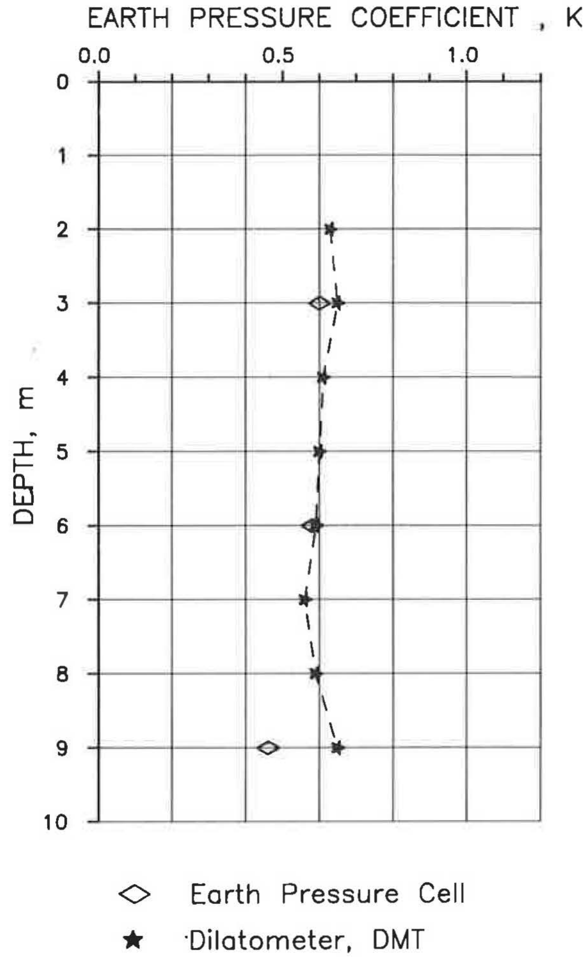

FIGURE 15 Earth pressure coefficient *K* determined by earth pressure cells and DMT at the Ugglum test site in section C.

The effect of the position of the line of thrust on the predicted earth pressures will be investigated more thoroughly in the second phase of this project. The effect on the lateral stresses at a given point of shear surfaces reaching different depths will also be investigated.

The measurements at the Alafors test site did not show any large differences in lateral earth pressures before and after the stabilization. The differences in the stabilized zone were around 10 kPa but were not noticeable in the other parts of the slope.

Predictions of lateral earth pressures will also be made by using numerical methods. An investigation with the finite-element method will start during autumn 1989.

CONCLUSIONS

The following conclusions can be drawn from the investigation:

1. Lateral earth pressures and *K* values increase from the crest to the toe of slopes.
2. *K* values can be extremely high ($K > 3$) in the passive zone of the steep slopes with a low factor of safety.
3. Janbu's generalized method of slices gives acceptable values of the existing lateral earth pressures in natural slopes.
4. Glötzl earth pressure cells have been found to be very reliable in soft clays.

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