Preloaded Motorway Embankments

an environmentally sound solution for soft soil areas

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Preloaded motorway embankments – an environmentally sound solution for soft soil areas
Remblais autoroutiers préchargés - une solution écologique pour les régions à sols mous

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Keywords: CPTU, embankment, gyttja, laboratory testing, monitoring, motorway, prediction, preloading, site investigation, soft soil.

ABSTRACT: Road construction, particularly involving soft soil replacement, draws very heavily on the scarce resources of sand and gravel. One environmentally appealing alternative to complete soft soil replacement is preloading where the sand/gravel materials may be re-used along the road alignment. The paper describes the first application of the method for motorways in connection with the completion of the Danish motorway infrastructure. To validate the feasibility of preloading an instrumented test embankment was constructed in the alignment. In the paper the extensive site characterisation is described in detail together with 2D FEM predictions of the performance. The predictions are compared with the observations obtained for the test embankment.

RÉSUMÉ: La construction routière, en particulier celle comprenant le remplacement du sol, puise très lourdement sur les ressources de sables et de graviers peu abondantes. Une alternative écologiquement attrayante du remplacement complet du sol mou, est de précharger là où le matériau sable/gravier peut-être réutilisé le long de l,alignement de la route. L,article décrit la première application de la méthode pour des autoroutes qui font partie de la réalisation de l,infrastructure autoroutier Danois. Pour valider la faisabilité du préchargement, un remblai d,essai instrumenté a été réalisé sur l,alignement. Dans l,article, la caractérisation étendue du site est décrite en détail, de même que les prédictions en éléments finis 2D de la performance. Les prédictions sont comparés avec les observations obtenues pour le remblai d,essai.

Figure 1. Areal view of motorway alignment. (a) Top soil removed for placing of embankment fill. (b) Close-up of test embankment.

1 INTRODUCTION

Road construction, particularly involving soft soil replacement, draws heavily on the scarce resources of sand and gravel. This is particularly true in Vendsyssel, the northern part of Denmark, where road construction materials must be transported hundreds of kilometres. One environmentally appealing alternative to complete soft soil replacement is preloading where the sand/gravel materials may be re-used along the road alignment. This method has been successful for a number of embankments for secondary and primary roads over the past 20 years (Jørgensen 1987). Hence, the method was favourably considered when two new motorways were to be constructed. The alignment passes through areas where valleys in the late-glacial landscape were filled with post glacial marine deposits of peat, gyttja and sands/silts during alternating sea transgression and isostatic uplift.

In order to verify the feasibility of preloading a thorough site investigation was carried out. This involved geotechnical borings, CPTU soundings and oedometer and triaxial testing. Furthermore, an instrumented test embankment was constructed in the alignment to provide a means for full scale testing of the performance and power of the predictive tools. Piezometers, settlement gauges and settlement tubes (the instrumentation package for the test embankment) were subsequently installed at several cross sections along the motorway alignment in general to provide data for forecasting and monitoring of the settlement behaviour during preloading and after completion of the motorway.

The project described in the paper was carried out as a Joint Industry Project, involving the owner, Vejdirektoratet, the consulting engineers, Carl Bro as, and the Geotechnical Engineering Group at Aalborg University. In this way the benefits from the project could be maximised in that the need to know commercial approach could be combined with the nice to know scientific approach and shared through networking.

2 GEOLOGY AND SETTING

As a political trade off in connection with the Storebælt link project the Danish motorway infrastructure has been extended with two legs in the northern most part of Denmark, Vendsyssel, as seen in Figure 2a. In this paper only the southern part of the western leg, stage 96 from Aalborg to Brønderslev, will be considered (cf Fig. 2b).

In the area the Pre-quaternary consists of Cretaceous chalk (300-600 m thick) overlain by glacial deposits from the latest ice age, the Weichel glaciation (50,000 to 10,000 B.P.). Late glacial deposits of Aalborg sand and clay were deposited in a late glacial ice sea, the Yoldia Sea, and subsequently exposed during isostatic uplift some 8,000 – 10,000 years B.P. A series of deep valeys and canyons were formed (presently down to level –20 m) due to erosion from rainwater streams from the surrounding hilly glacial landscape. The valleys and canyons were subsequently partly filled with a mixture of post glacial silty sands, peat and gyttja during the Flandrian transgression. Some 7,500 years ago forming the present marine foreland in the motorway alignment (Berthelsen 1987, Jessen 1936).

3 SITE INVESTIGATION AND LABORATORY TESTING

To map the geological/geotechnical conditions a preliminary site investigation, with geotechnical boreholes roughly per 100 m length along the alignment, was carried out in 1992-93. This confirmed the above overall picture and showed that the motorway passes a system of formerly deep

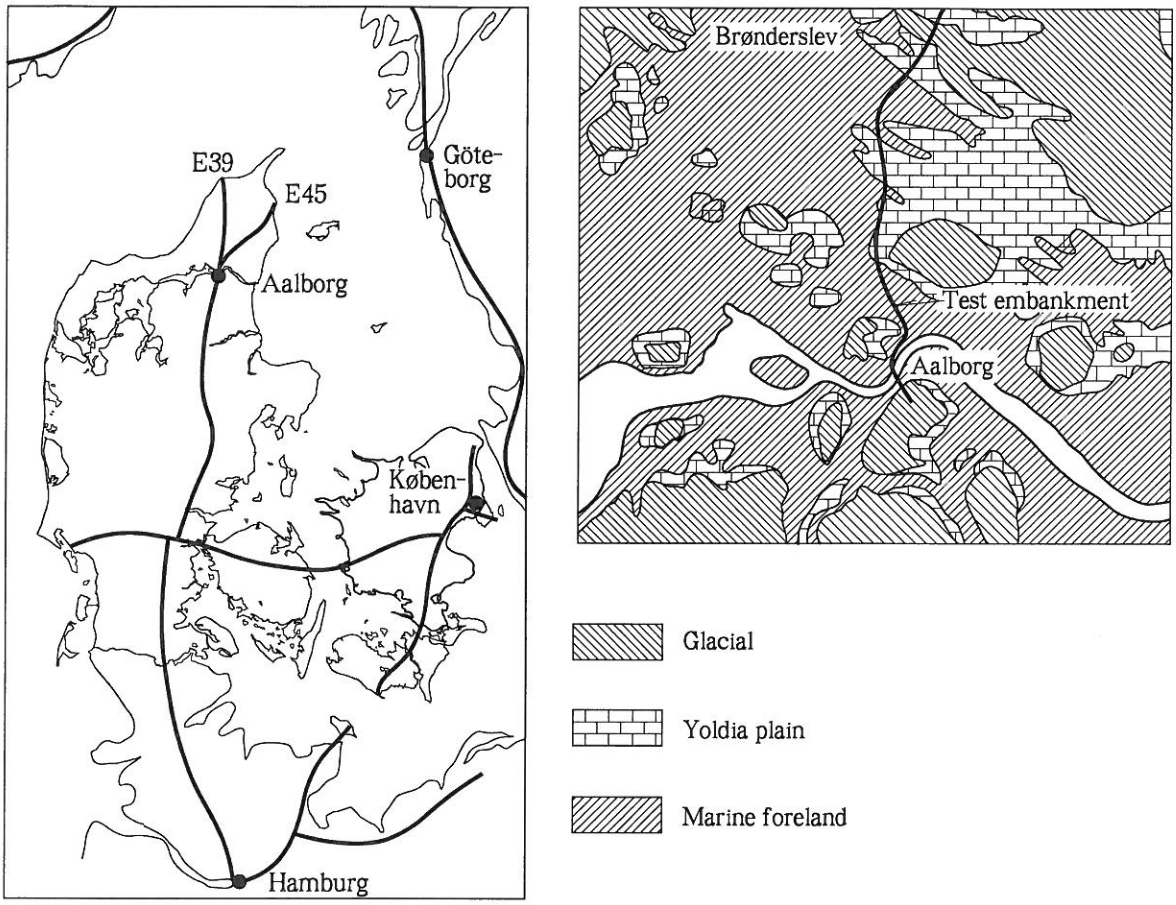

Figure 2. Position of motorway project. (a) Danish Motorway infrastructure; (b) Surface geology of project area.

valleys and canyons.

In 1996-97 a more detailed site investigation was carried out revealing that the valleys consist of a southeast-northwest trending main valley with a series of minor connecting valleys. The borings indicated that the southern slopes of the main valley were considerably steeper than the northern slopes. The latter are gentler as solifluction and sliding processes are believed to have been more pronounced on the sun exposed northern slopes in the thawing permafrost landscape.

In general the organic deposits of gyttja (organic clay) and peat are particularly pronounced in narrow zones along the perimeter of the main valley and in the sub-valleys

A typical geotechnical boring from station 4.0 – 5.3 km shows a sequence of topsoil (0.2-0.4m), post glacial marine silt/sand (2-4 m), post glacial marine gyttja (4-20 m), peat (0.5 - 2 m) and late glacial sand (0-5 m) over late glacial plastic Aalborg clay.

Figure 3 shows a longitudinal section along the motorvay, where it crosses the major valley, based on the geotechnical bore holes in the detailed investigation (Jørgensen & Christensen 1996).

The post glacial sand is silty and in places mixed with gyttja and the gyttja/sandy gytja deposits are interlaced irregularly with sandy, silty inclusions. The extent and position of these sand/silt layers are critical for the minimum duration of the preloading period and for the success of modelling and forecasting the settlement behaviour of the short and long time behaviour of the motorway embankments.

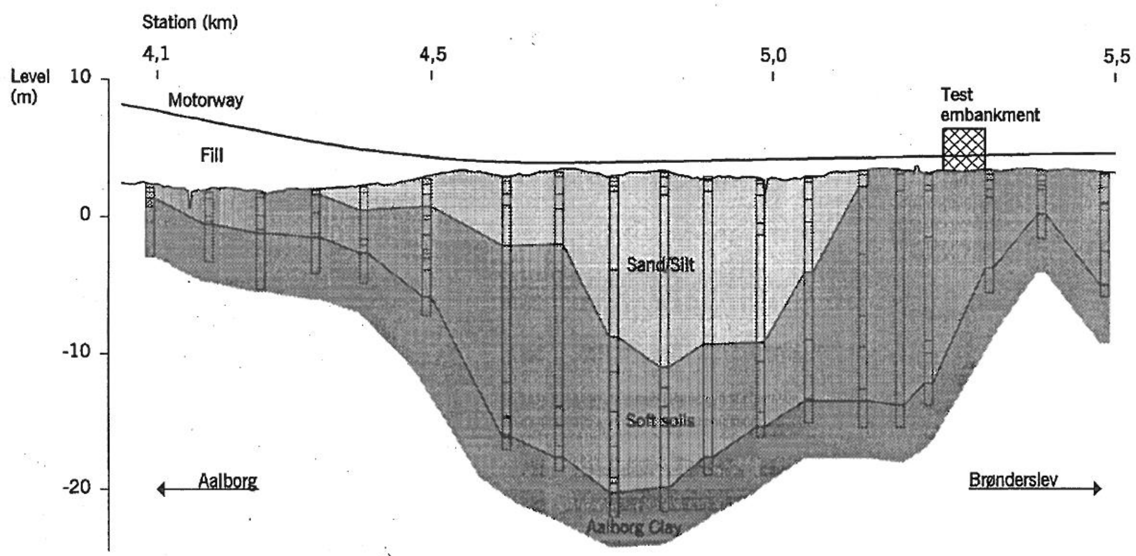

Figure 3. Simplified longitudinal section along motorway alignment at crossing of major valley in late glacial landscape.

Table1. Geotechnical parameters for main layers in general and parameters related to settlement prediction for test embankment in particular.

Major soil layer	Water content w [%]	Vane shear strength $c_{u,v}$ [kPa]	Oedometer modulus K_{nc} [kPa]	Coefficient of consolidation c_v $[m^2/s]$
Sand, silty	30 [28]	- *	4000-10,000 [10,000]	- $[1.0\ 10^{-4}]$
Gyttja, sandy	35-50 [38]	30-100 [40]	1000-3500 [1200]	$5\text{-}9\ 10^{-7}$ $[1.0\ 10^{-6}]$
Gyttja, w sandy	50-90 [47]	40-90 [40]	400-1200 [800]	$2\text{-}5\ 10^{-7}$ $[4.8\ 10^{-7}]$
Peat	200-350	50-120	500-800	$1\text{-}4\ 10^{-6}$
Aalborg clay	30-40 [34]	120-150 [150]	8000-12,000 [10,000]	$[1.0\ 10^{-7}]$

* $\varphi = 38^{\circ}$ was used for PLAXIS modelling. Values in brackets are for test embankment.

The geotechnical parameters for calculation of the settlements of the motorway embankments were determined from 17 oedometer tests carried out on specimens from tube samples from the geotechnical borings.

Representative values for Station 4.1-5.2 km are shown in Table 1 for the significant layers. The values used in the Plaxis, type A FEM modelling for the test embankments are shown in brackets. The parameters are assessed based on the evaluation of the oedometer tests and a comparison with general test results and the geological description from the relevant borings.

4 PREDICTION

Before the test embankment was placed a type A settlement prediction was performed using 2D Finite Element Modelling (PLAXIS) with the parameters indicated in Table 1. The soil model is linear-elastic with a Mohr-Coulomb failure criterion. The results showed a total settlement of 0.50 m in the centre of the test embankment (Station 5.280 km) and a consolidation time of some 8-900 days (T=1) on the assumption of one-sided drainage (Jørgensen & Christensen 1996).

In Figure 9 the predicted time settlement curves for the centre line of this station is shown for loads corresponding with the full test embankment.

After completion of the test embankment a type B 2D FEM prediction was performed using DIANA. An elasto-plastic Drucker-Prager soil model with strain hardening on the cohesion was applied for analysis of the total settlements. The material parameters were determined from seven oedometer tests and two CD triaxial tests with area constant consolidation. These calculations lead to a total settlement of 0.53 m, almost the same result as PLAXIS.

For the analysis of time-dependence a 2D non linear transient flow-model was applied leading to a predicted consolidation time of 300 days. The FEM model catches the influence of more permeable inclusions seen from pore pressure developments and CPT tests (Koue & Strandgaard 1996).

5 TEST EMBANKMENT AND INSTRUMENTATION

Based on the geotechnical investigations a 60m long section between stations 5.25 km and 5.31 km was selected as suitable for the test field. The position of the test embankment is seen in Figure 4 together with the geotechnical borings from the detailed site investigation.

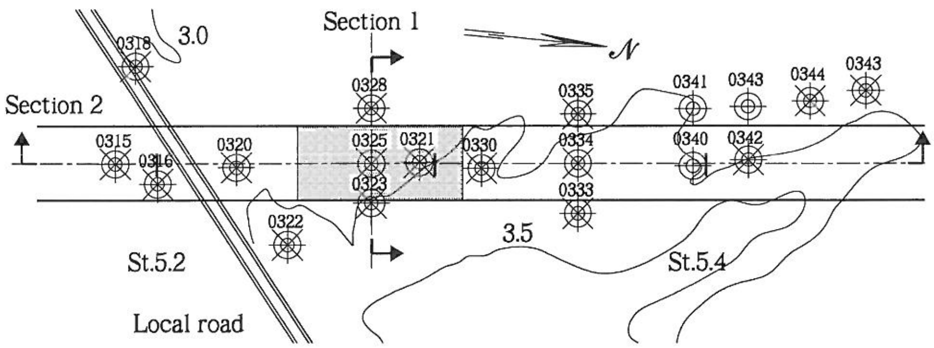

Figure 4. Plan of test embankment (shaded) with detailed geotechnical borings.

Among the further criteria for the choice of test field can be mentioned, that the area was available for the purpose and that it was within easy reach for common vehicles by a local road.

The extent of the soft soil layers varies along and perpendicular to the alignment as shown in the Figures 5a and 5b, with a thickness of 6m to more than 10m. These layers are characterized as marine deposits of gyttja (organic clay) with varying contents of sand or silt.

Passing the test area the projected motorway was planned to be constructed on a 25m wide and 1m high embankment of sandfill. The test embankment was performed with an extra height of 3.1m, i.e. a total height of 4.1m. The construction period had a duration of 2 weeks starting medio March 1996. For wind-protection the complete embankment was covered with geotextiles (cf. Fig.1).

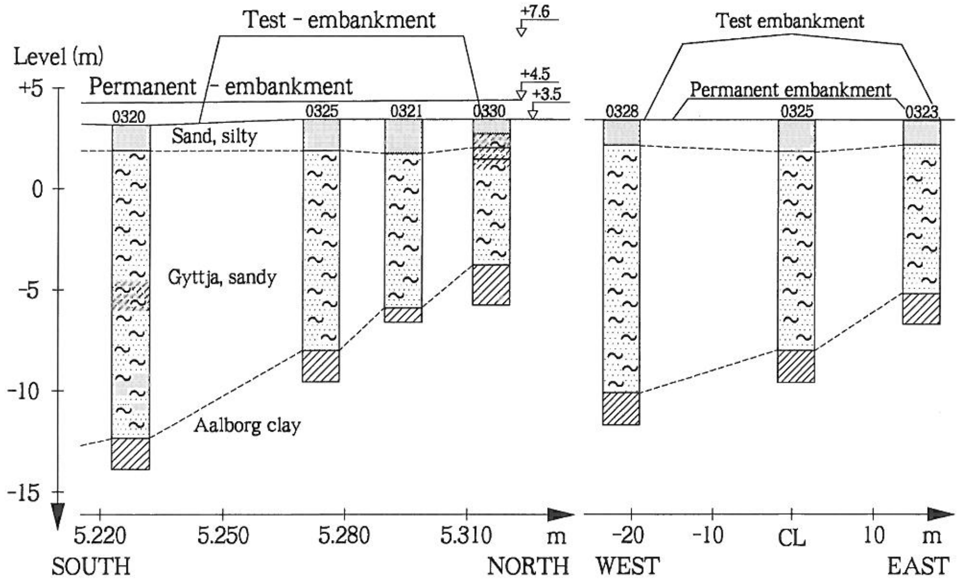

Figure 5. Geotechnical section of test embankment. (a) longitudinal section; (b) cross section.

During the week ahead of the start of construction the chosen measuring instruments were installed. The ground surface was prepared by replacement of 0.4m topsoil with sandfill. A schematic view of the chosen instrumentation is shown in Figure 6.

For observations of the settlement profile of the embankment 3 settlement tubes were placed at different cross sections. The tubes were placed in shallow trenches and covered with sandfill. The vertical movements of the tubes were monitored using hydraulic leveling.

For observations of settlements in the centre line 8 settlement gauges (steel plates) were placed in the sandfill, 4 plates in the bottom and 4 plates in the top of the embankment. The movements of the plates were determined by normal geometric leveling.

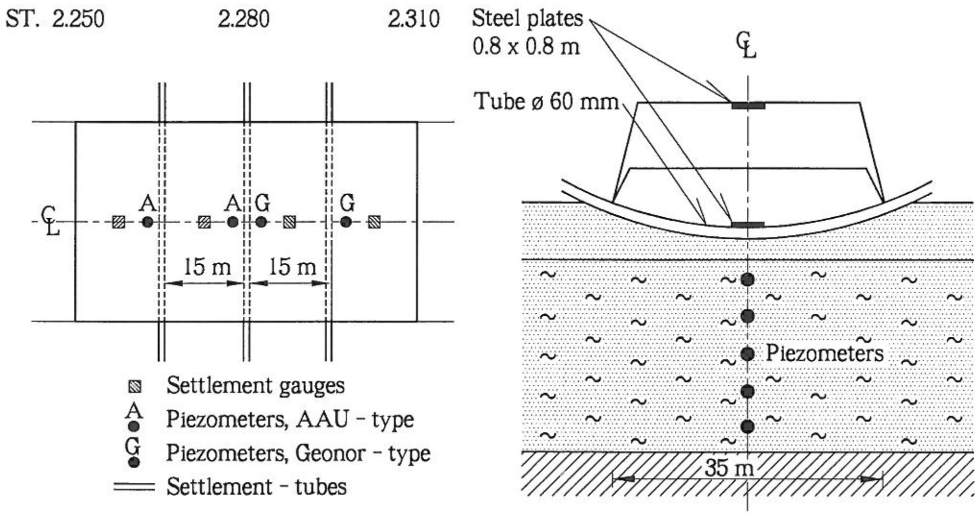

Figure 6. Principle of instrumentation of test embankment. (a) plan; (b) cross section.

For observations of pore pressures two different types of piezometers were installed. Two groups of simple hydraulic piezometers (developed at Aalborg University) were placed as shown in the figures. These instruments were connected to mercury manometers placed in a cabinet outside the embankment and only prepared for manual reading. Furthermore, two similar groups of electrical piezometers (Geonor M600) were installed for continuous logging of pore pressures using an automated data logging set-up.

Finally the instrumentation system included a leveling fixpoint and a well for sounding of water level.

6 MONITORING AND TEST RESULTS

The pore pressures were monitored continuously for a period of approximately 14 months. After this time the pore pressures were monitored manually until September 1998 (Geonor piezometers).

AAU-piezometers were read manually during the whole preloading period. The results from the two types of piezometers are almost identical. The results of the pore pressure from St. 5.280 km (Geonor) are shown in Figure 7.

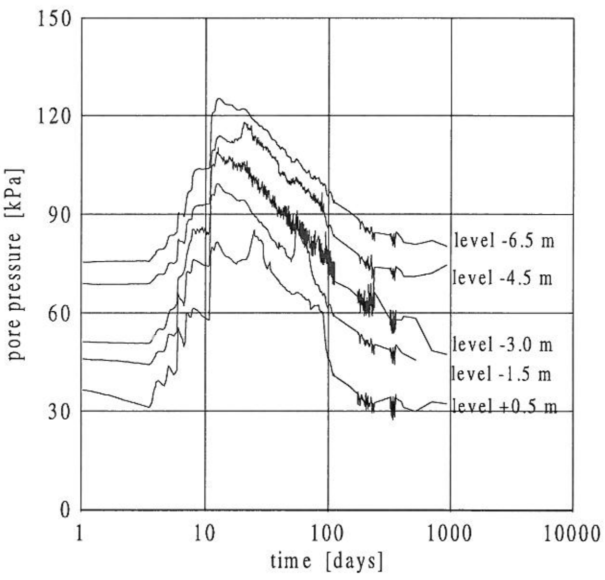

Figure 7. Pore pressure development in Station 5.280 km.

With the water table around level 1.5 m it is seen that the staged completion of the embankment over roughly 10 days allows some dissipation of pore pressure as the maximum surcharge is ~ 70 kPa. All pore pressure transducers show the same principal variation during pore pressure build-up and dissipation.

Figure 8 shows the recorded settlements using settlement gauges and settlement tubes, respectively. From Figure 8(a) it appears that the settlements in the embankment are insignificant. Figure 8(b) shows selected settlement tube recordings from the central cross section in Station 5.280.

It is seen that the maximum values are displaced from the centre line a few metres to the west which is in accordance with the variation of the soft soil layers.

The maximum settlement in the centre line comes very close to the predicted total settlement of 0.50 m.

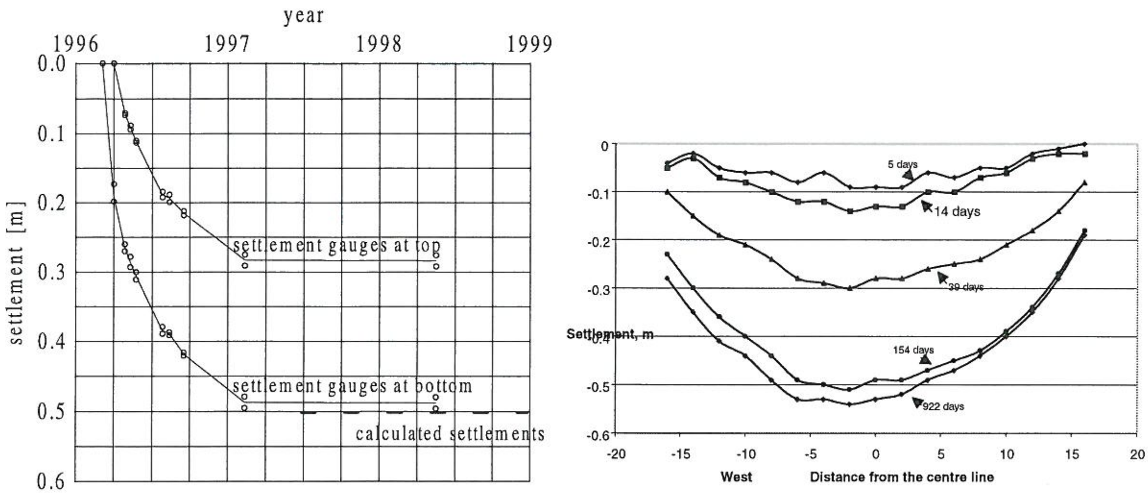

Figure 8. Settlement observations for station 5.280 km. (a) settlement gauges; (b) settlement tubes.

The settlements at the perimeter, 0.20 m at the east side and 0.30 m at the west side, also correspond to the predicted values.

7 EVALUATION

The test embankment has been monitored for a period of 922 days which is long enough to follow a full scale consolidation process corresponding to the one predicted by PLAXIS (type A). This was possible because the constructions and instrumentation of the test embankment were decided and carried out as a special part of the detailed geotechnical investigations one year ahead of the planned more comprehensive preloading projects in the area.

However, the observed data have indicated that the time settlement behaviour has been essentially faster than the first predictions, and furthermore that the initial settlements were overpredicted.

Interpreted from the monitored excess pore pressures the consolidation time t_c (corresponding to U=0.935) is evaluated as 200 days. The settlement curve for gauges at the bottom indicates the same result. The settlement curve observed by the tubes, however, indicates a consolidation time of 100-150 days.

These results can be explained by the presence of permeable inclusions (probably thin sand layers) which reduce the drainage path to half or a third of the total thickness of the soft soil layers. Such layers are often difficult to catch by traditional geotechnical investigations. The CPTU tests seem to be a valuable tool used as a supplement to the geotechnical borings, and had the CPTU-tests been available from the start it might have been possible to pinpoint the more permeable layers decisive for the consolidation time.

Pore pressure measurements are obviously not available in connection with type A predictions. However, during the preloading process the monitoring of excess pore pressures is very important in order to achieve a safe type B prediction, especially if the piezometers are placed sufficiently close. A closer inspection of the actual pore pressure development with depth also indicates the presense of more permeable layers in the lower half of the gyttja.

The creep settlement is apparent from the settlement tubes but not from the settlement gauges. However, the magnitude of creep is small, < 1% of the total settlement.

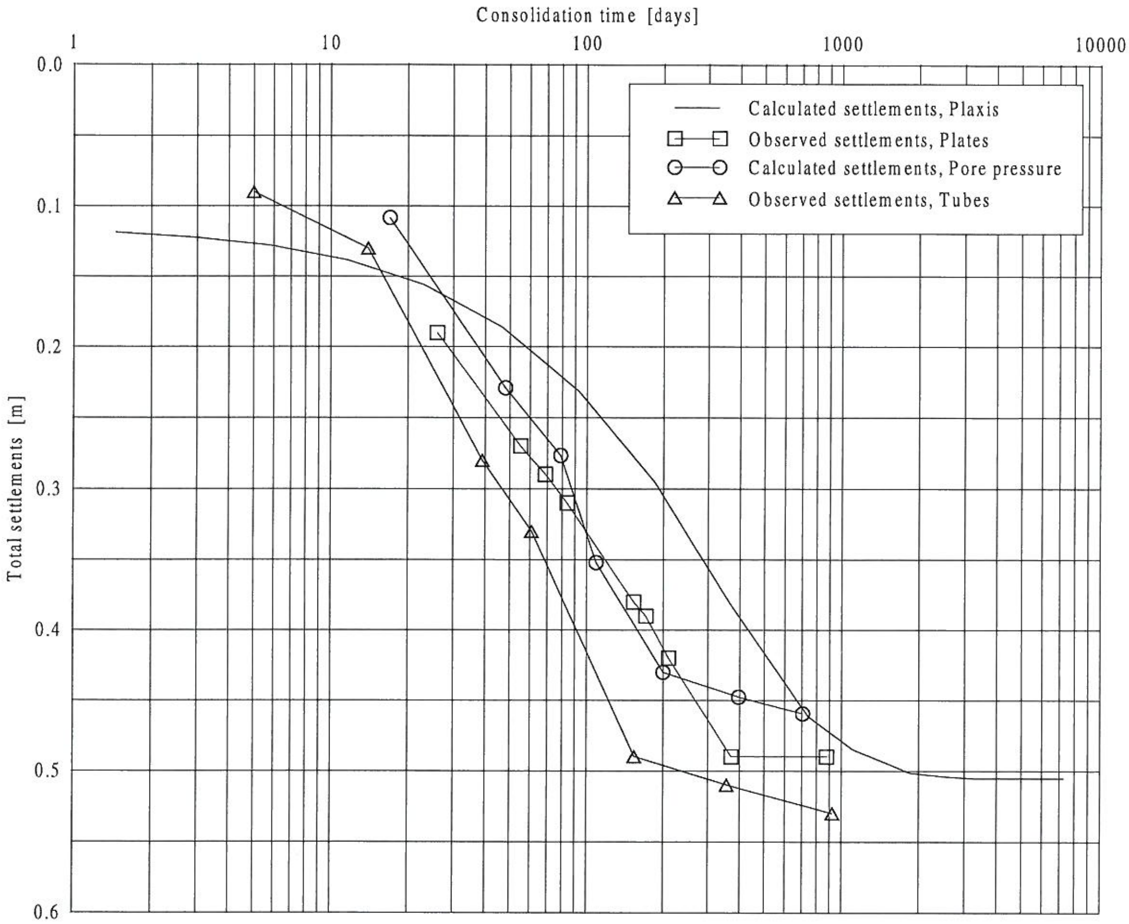

Figure 9. Comparison of predicted (type A) and measured settlement development.

8 CONCLUSION

In order to avoid complete replacement of soft soil deposits with sand and gravel a preloading scheme was prepared for the extension of the motorway net in Vendsyssel, Denmark.

To validate the positive experience with preloading from secondary and primary roads (Jørgensen 1987) an instrumented test embankment was constructed in the motorway alignment with a representative soft soil occurrence. The validation involved the magnitude of settlements and their time wise development.

The test embankment had an overheight of 3.1 m over the 1 m final motorway embankment. Due to a delay in the motorway construction a 30 months monitoring period was available (as opposed to the anticipated 6 months). This allowed a complete picture of the consolidation and creep behaviour for the site to be revealed.

The result of the monitoring of the test embankment showed a maximum total settlement of 0.50 m, very close to the type A prediction. However, the presence of more permeable inclusions (not positively identified in the original site investigation) lead to a time for primary consolidation of 150-200 days as opposed to the conservative prediction of 800-900 days.

Based on these findings it has been possible to plan the progress of preloading for the remaining motorway embankments with reduced heights and reduced preloading periods. As the incurred settlements are well in excess of the settlements for the final embankment height alone the soil condition below the embankments will correspond to swelling when the motorway is in use. This will ensure negligible settlements (heave) and extremely long delays of creep settlements.

Based on the close cooperation between owner, consulting engineer and researchers the data from the project will be available for more general purposes. Moreover, it will be possible to monitor the settlements and pore pressures during unloading and subsequent use of the motorway. This will provide additional knowledge about the pore pressure response to traffic loading and to the swelling behaviour of the organic clay.

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