INCREASE OF SUBSOIL BEARING CAPACITY BENEATH EMBANKMENTS

AMELIORATION DE LA CAPACITE PORTANTE AU-DESSOUS DES REMBLAIS

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SYNOPSIS: In a study of the consolidation effect on the bearing capacity of normally consolidated clayey subsoils beneath embankments, experimental observations, supported by stability analyses, have shown that, in the case of subsoils with low bearing capacity, this effect is of considerable importance and should be taken into account when designing embankments over such subsoil. In order to obtain a significant increase in the undrained shear strength of the subsoil, it is necessary that the load be applied gradually (over several months or years) and that the drainage conditions be favourable. Over the last ten years several extensive series of field vane tests have been carried out in the subsoil of the Ljubljana Marshlands, where several motorway sections have been built. Vane tests performed in the subsoil beneath test embankments indicated good possibilities for taking into account increased bearing capacity due to this consolidation effect and obtaining more economical solutions to embankment construction. The results obtained in these tests, together with associated stability analyses and other experimental observations, have provided a sufficient basis for the introduction of this improved method for the design of embankments on very soft subsoils. Over the last few years considerable lengths of embankment have been built across the Ljubljana Marshlands and elsewhere in Slovenia on soft subsoils, thus solving various stability problems. In all cases the optimum solution was sought for filling speed, measures for assuring stability, and acceptable post-construction settlement.

INTRODUCTION

According to conventional design methods, when road embankments are constructed over very soft subsoils, fairly wide lateral berms are usually required. These methods take into account the characteristics of the subsoil, usually obtained by vane shear tests carried out before filling is begun. However, if the favourable influence of the consolidation effect is taken into account, then, in the majority of cases, it will be possible to reduce the width and/or height of the berms or even eliminate them altogether. Alternatively, if the berm dimensions are kept unchanged it may be possible to accelerate the pace of construction of the embankment. A third possibility for exploiting the consolidation effect occurs in the case when a pre-loading procedure to reduce post-construction settlements is being considered. In this case, taking into account the increased undrained shear strength of the subsoil, it may be possible to decide in favour of a pre-loading which otherwise would not have been permissible or to make use of a heavier pre-loading than otherwise anticipated. In the case of embankments which are being built over very soft subsoils it is usually necessary to construct vertical wick drains or gravel columns, which accelerate the consolidation process, thus increasing the bearing capacity of the subsoil and the overall stability of the embankment.

In the paper the results of experimental observations concerned with the construction of the Southern Bypass for the city of Ljubljana, constructed over the very soft subsoils of the Ljubljana Marshlands ("Ljubljansko barje") are presented. This is a flat area approximately 25 km long and of varying width, up to about 10 km, covering a tectonic depression and filled with pleistocene fluvial and marsh sediments and holocene lake deposits.

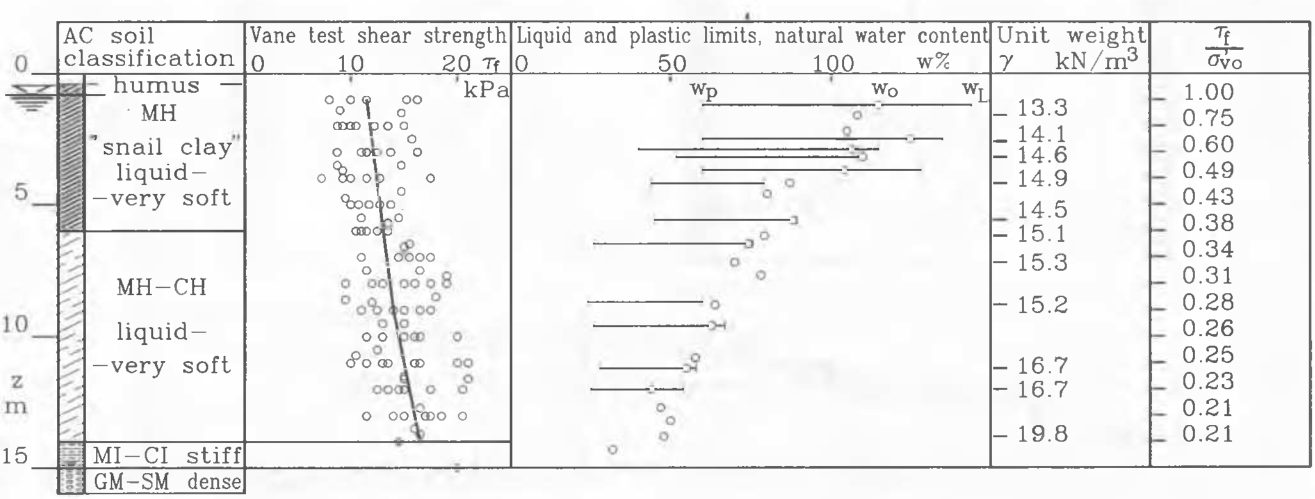

Fig. 1. Geotechnical properties of the subsoil before construction

TYPICAL GEOTECHNICAL CHARACTERISTICS

Typical geotechnical characteristics of the Ljubljana Marshlands before embankment construction along a 4 km long section of the Ljubljana Southern Bypass, are presented in Figure 1. The groundwater table is found at a depth of between 0.5 and 1.0 m, and quite frequently at surface level, depending on the season. Beneath the liquid to very soft clayey silts nearest to the surface, with an average depth of 15 m, are stiffer deposits, consisting of rather dense silty gravels, clayey sands and cohesive soils with a compressibility almost negligible in comparison with the upper subsoils. In Figure 1, to the right of the soil profile can be seen the results of 12 field vane tests, giving the measured and average undrained shear strength τ_f of the subsoil at various depths up to 14 m. It can be seen from the diagram that, within the very soft subsoil strata, τ_f increases from an average value of 12.0 kPa at a depth of 2.0 m below the surface to a value of 17.0 kPa at a depth of 14.0 m. This increase is surprisingly small, but may be explained as follows. The average ratio of the undrained shear strength to the effective overburden stress (σ'_{v0}), taking into account the unit weights of the removed soil samples, decreases fairly uniformly with depth, from a value of 1.0 at a depth of 1.0 m beneath the surface to a value of 0.21 at a depth of 14.0 m. It can also be seen from Figure 1 that the plasticity index, defined by the measured values of the liquid and plastic limits, also decreases with depth. It should, however, be mentioned that the cohesion of the soil layers near the surface can be strongly affected by different physical and chemical processes to those affecting deeper layers, particularly by the changing level of groundwater, so that comparisons between these two effects at shallow depths are not very reliable.

EXPERIMENTAL INVESTIGATION OF CHANGES IN THE UNDRAINED SHEAR STRENGTH

Test Embankment Measurements

Four years before a start was made to the construction of the Ljubljana Southern Bypass, a test embankment without lateral berms was built on the alignment of the future motorway route. The total length of the test embankment, which had three different sections PI, PII and PIII, was 220 m, and its width was 45 m. Along sections PI and PII the subsoil was drained by a triangularly distributed mesh of wick drains, the distance between drains being s = 1.30 m along section PI and s = 1.73 m along section PII. Along section PIII no drains were built.

Embankment filling took place in layers of thickness 0.40 - 0.50 m, and was completed over all three sections in a little more than four years. During the filling fairly frequent measurements were made of the settlement and horizontal deformations of the embankment, and of the pore pressures at various depths. At three roughly equal time intervals during the filling measurements were also made of the in situ undrained shear strength of the subsoil beneath the embankment. The results of the latter measurements are presented for all three observed sections in Figure 2. From this diagram it can be seen that the increase in undrained shear strength of the subsoil is much more significant in the case of drained soils than in the case of undrained soils. The largest effect, with an average increase in undrained shear strength of approximately 150%, was obtained in the case of densely grouped vertical drains (s = 1.30 m). The exceptionally large increase in τ_f in Section PI at a depth of 6.0 - 8.0 metres can be explained by the evidently greater permeability of the subsoil strata at this level.

For all three sections of the test embankment, calculations were made of the factor-of-safety against slip, based on Bishop's model. The calculations were made taking into account a period of 1000 days after the beginning of construction of the embankment - in the case of Sections PI and PII, and a period of 1250 days in the case of Section PIII. The calculations were carried out for two cases, assuming $\varphi = 0$: firstly, the case when the initial vane shear test results (before construction) were used, and secondly, the case where increased values of the undrained shear strength due to the consolidation effect were taken into account. The results of these factor-of-safety calculations are shown in Table 1, where it can be seen that the factors-of-safety corresponding to the increased values of the undrained shear strength agree well with values obtained using the $c' = 0$, $\varphi' \neq 0$ method, taking into account the measured pore pressures and laboratory-defined drained shear strength of subsoil samples.

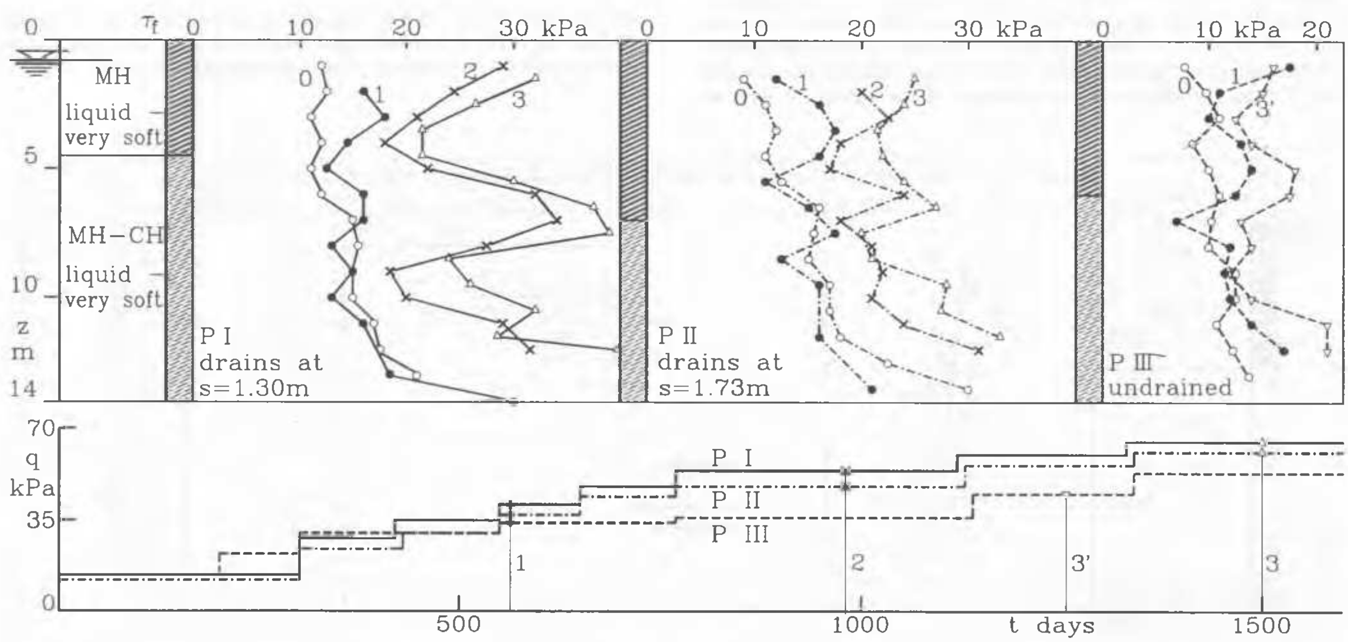

Fig. 2. Vane shear test results and the test embankment loading

Table 1. Results of the stability analyses (test embankment)

Section	Safety factor F		
	$\varphi = 0,\ c \neq 0$		$c' = 0,\ \varphi' \neq 0$
	$\tau_{f\ initial}$	$\tau_{f\ increased}$	
PI	1.73	2.30	2.31
PII	1.85	2.35	2.31
PIII	1.21	1.45	1.56

Measurements along the Ljubljana Southern Bypass, from Km 19.000 to Km 21.000

After the results of measurements on the test embankment were known, it was possible to take into account the observed increase in the undrained shear strength of the subsoil during the preparation of the main design of the Ljubljana Southern Bypass, thus minimizing the extent of lateral berms which might otherwise be necessary. Of course, the motorway embankments had to be built at a faster rate than the test embankment, and were also in some places higher than the latter. In order to help settlements develop mainly during the construction period, as well to achieve a significant consolidation effect, vertical wick drains or gravel columns (where required for increased stability or final settlement criteria) were built. Pre-loading of the subsoil was also carried out, amounting to about 30% of the weight of the final embankment. Settlements were measured at 100 m intervals along the embankment. At the most critical locations the horizontal deformations of the embankment were measured, as well as the pore pressures and undrained shear strength of the subsoil at various depths. The characteristic geotechnical profile presented in Fig. 1 corresponds to the average conditions along this section of the motorway.

An example of how τ_f increased with loading and time is shown in Figure 3, for profile P166 of the motorway. At this profile there were gravel columns of diameter 0.60 m, spaced triangularly at a distance of 2.4 m, but no lateral berms. The vane shear tests were carried out centrally between the gravel columns, first on the undisturbed ground before work was begun and secondly during the pre-loading stage, approximately 1.5 years after construction of the embankment had begun. Maximum embankment height (during pre-loading) was 6.5 m, and final embankment height was 5.0 m (3.0 m above the initial ground surface). Taking into account the shear resistance of the gravel columns and the increased values of τ_f due to consolidation, a minimum factor-of-safety of $F = 1.32$ was determined. If the initial unincreased values of τ_f are taken into account, the result $F = 1.10$ is obtained. Measurements of the horizontal and vertical deformations of the embankment indicated that the former value ($F = 1.32$) is more justified.

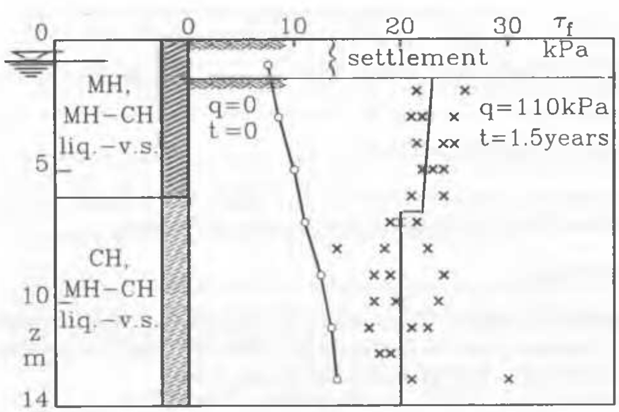

Fig. 3. τ_f during embankment construction at profile P166

Another interesting example is provided by measurements carried out on an embankment carrying the Peruzzi Road up to a bridge across the motorway. At this location vertical wick drains were constructed in the highly compressible subsoil, the rate of filling being similar to that described in the previous example. Figure 4 shows the results of vane shear tests carried out before construction, after 2 years (when the embankment reached a height of 6.5 m) and after 4 years. The full embankment height of 8.0 m was

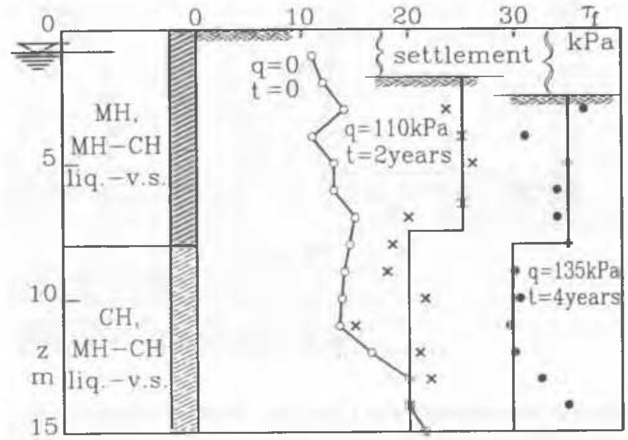

Fig. 4. τ_f during and after construction at Peruzzi Road

reached after about 2.5 years (pre-loading was not applied). The cross-section and critical circular slip surface for both states of the embankment when the measurements of τ_f were carried out are shown in Figure 5. Factors-of-safety have been calculated. using the $\varphi = 0$, $c \neq 0$ method, for both embankment heights (6.5 and 8.0 m), taking into account the initial and/or increased undrained shear strength of the subsoil beneath the embankment and the unincreased undrained shear strength of the subsoil outside the drained area. They are presented in Table 2.

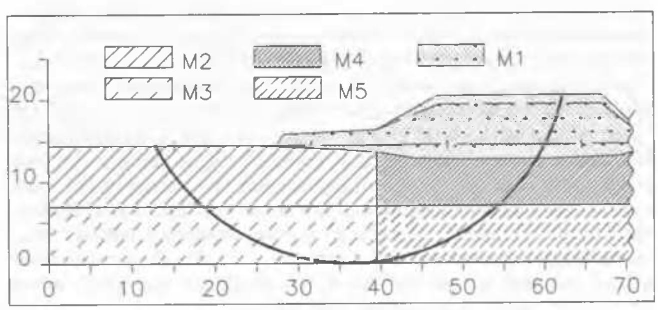

Fig. 5. Stability analysis of the Peruzzi Road embankment

Table 2. Results of stability analyses (Peruzzi Road)

Embankment height	M1	$\tau_{f\ initial}$ / $^*\tau_{f\ increased}$ M2	M3	M4	M5	Factor of safety
6.5 m	$c = 0$	13	16	13	16	1.10
	$\varphi = 36°$	13	16	*25	*20	1.28
8.0 m	$c = 0$	13	16	13	16	0.91
	$\varphi = 36°$	13	16	*35	*30	1.32

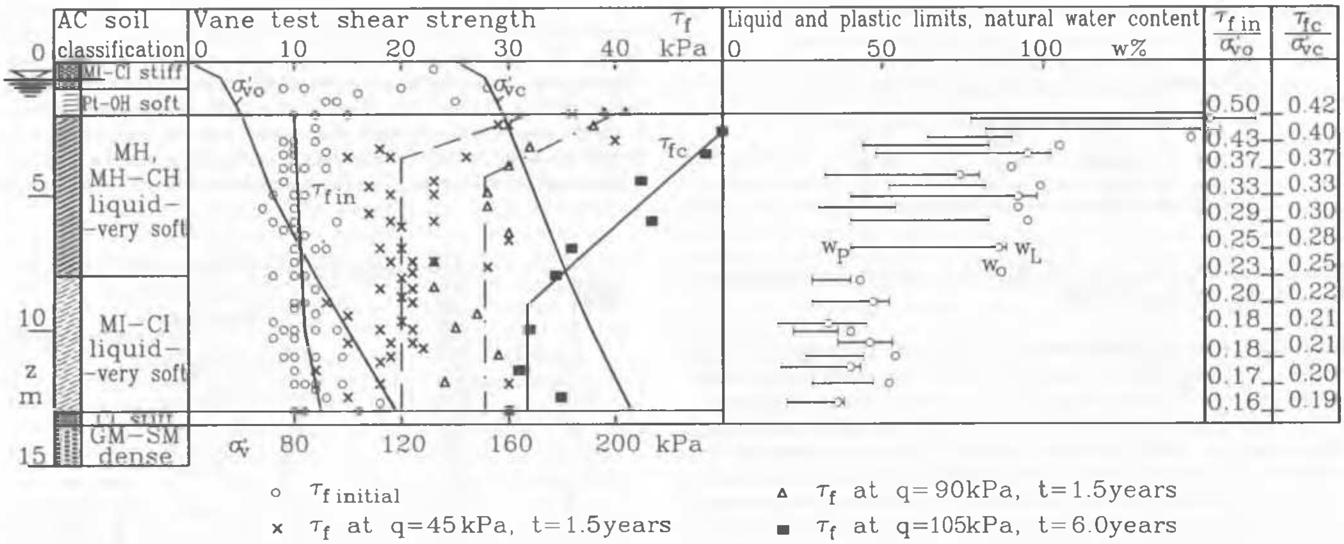

Fig. 6. Changes in τ_f during embankment construction (km 17.600-18.600)

Measurements along the Ljubljana Southern Bypass, from Km 17.600 to Km 18.600

Along this section vertical wick drains at a distance of 1.5 m were applied in order to accelerate the consolidation process. The geotechnical profile for this section (see Fig. 6) is similar to that shown in Fig. 1, but at the surface there is first a 1.0 m thick layer of stiff clay, followed by a 1.0 m thick layer of peat and organic clay (these two layers are heterogeneous and therefore not included in the analysis of changes in τ_f). Fig. 6 includes the results of 18 in situ vane tests of the undisturbed subsoil, and the results of further vane tests carried out at various stages during the embankment construction, indicating very significant increases in τ_f.

In Figure 6 the results at three locations along this motorway section have been combined for two loading stages during construction (after 1.5 years) and one final series of measurements (at the end of 1992) after 6 years (4 years after embankment completion). The increases in τ_f amount, for this very soft subsoil, to about 200% after 1.5 years and up to 400% after 6 years. Comparing these results with those in Fig. 1 (τ_f/σ'_{v0}), and disregarding the first three metres below original ground level, it can also be seen that in the case of this motorway section the values of the ratio τ_f/σ'_{v0} (for undisturbed subsoil) are somewhat smaller, indicating the probable influence of reduced average plasticity indices. Most interestingly, the values of the ratio τ_{fc}/σ'_{vc} (for the consolidated subsoil beneath the embankment) are similar to the initial values for depths equal to or greater than 3.0 m.

CONCLUSIONS

From the results of the field tests and stability analyses carried out during the design and execution of several lengths of motorway embankment built over very soft subsoils (the liquid and very soft clays of the Ljubljana Marshlands), the following conclusions can be drawn:

- depending on drainage measures and the size and rate of increase of applied ground pressure due to embankment construction, an important increase occurs due to the consolidation effect in the undrained shear strength of the subsoil, τ_f. It is therefore recommended that, for such subsoils, this increase be taken into account during the design process, thus reducing the need for lateral berms.

- The ratio τ_f/σ'_v appears to depend, for the soils before embankment construction as well as for the consolidated subsoil beneath the embankment, on the plasticity index I_P. This agrees, in general, with observations made concerning the behaviour of normally consolidated undisturbed clay soils by Bjerrum (1972) and Leonards (1968). The correlations between the ratio τ_f/σ'_v and plasticity index I_P are shown in Fig. 7.

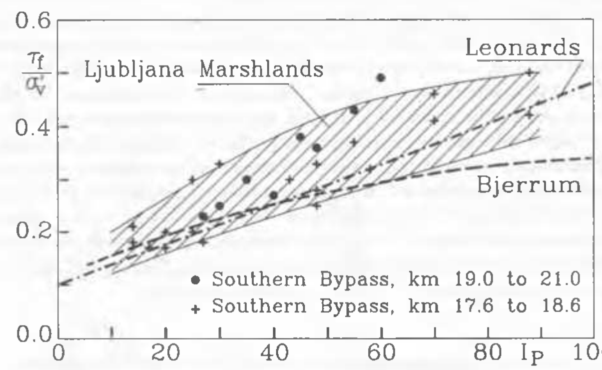

Fig. 7. Relationship between the ratio τ_f/σ'_v and plasticity index

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