Measured and predicted settlements of the Vaasa motorway

Les tassements mesurés et prévus de l'autoroute de Vaasa

P.Vepsäläinen & K.Kinani – *Helsinki University of Technology, Espoo, Finland*
P.Tolla – *Finnish Road Enterpise, Helsinki, Finland*

ABSTRACT: The aim of the study was to present an example of the longitudinal settlement profile of a 6.5 km long section of the Vaasa motorway four years after the construction of the road and to compare various settlement criteria with the measured results. Furthermore the other purpose was to compare the predicted time-settlement curves with the measured, after-construction settlements.

RÉSUMÉ: La fin de cette étude était présenter un exemple d`un profil longitudinal de tassement d`une longueur de 6,5 kilomètres de l'autoroute de Vaasa quatre ans passés de la construction de la route. Autre fin était comparer critères différents des tassements avec les résultats mesurés, en plus, comparer les courbes de tassements en fonction du temps prédites avec les tassements post construction mesurés.

1 INTRODUCTION

The design of the motorway started with the construction of the instrumented trial embankment in the summer 1989. The embankment was built close to the planned motorway in the center of a two kilometers long and 30 to 40 meters deep in maximum very soft silty clay deposit (Tuovilanjoki soft soil formation). The settlements of the embankment and pore water pressures in the ground were measured during 18 months period. Vepsäläinen & al. (1991), Koehorst & al. (1992) and The in the PLAXIS web-pages have presented the measured results with different computational simulations.

The geotechnical design of the motorway on the soft ground was based on the experience of the behaviour of the test embankment. Because the prevention of settlements by using e.g. embankment piling was found to be too expensive, the main attention was focused to the control of differential settlements and angular distortions by the means of preconsolidation by preloading combined with vertical strip drains and the use of lightweight fills when necessary. The construction of the motorway started in 1991, and the settlements of the road embankment were measured and compared to the estimated ones during the preconsolidation time. On the bases of those comparisons the original estimated preconsolidation time of 24 months was extended to 30 months. The motorway was opened for service in 1994.

The road surface level profile was measured by control levellings at the end of the construction stage in 1994. The final engineering plan and results of the control levellings were kept as an initial state for the later settlements in the time of use. The settled surface level profile of the road pavement was measured four years after construction, in 1998, by GPS measurements with some cross-sectional control levellings. Furthermore there were some cross-sectional levellings on the pavement where the road surface level and settlements were measured quite often during 1994 – 1998.

2 THE LONGITUDINAL SETTLEMENT PROFILE

2.1 *Settlement criteria and the Finnish practise*

The longitudinal profile of the road surface has to be such that the driving is safe and comfortable. Furthermore the uneven settlements during the operational time have to be limited so that the structure of the road remains undamaged. There are different criteria for the allowable longitudinal settlements and derivatives of the settlements in the design stage: The maximum settlement, the differential settlement, the change of inclination, the changed radius of curvature of the road surface, the angular distortion and the imaginary vertical acceleration of the vehicle.

In this paper only the settlement criteria for the design are considered although the IRI-value (IRI: International Roughness Index roughness in meters per kilometer) commonly used during the operational time of the road, can be used also during the de-

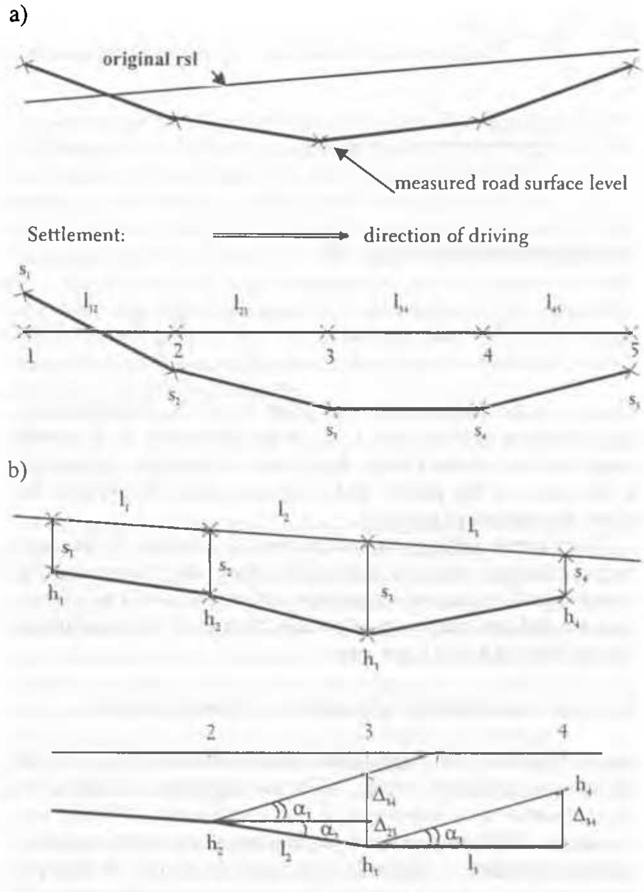

Figure 1. The definition of a) change of inclination, b) angular distortion. Definitions of symbols are presented in the text.

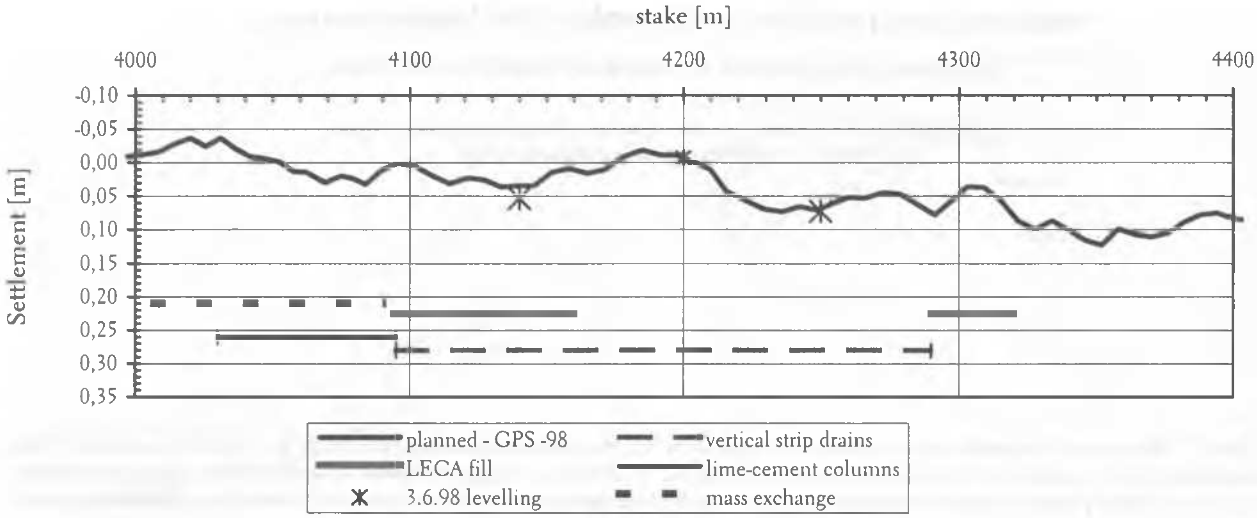

Figure 2. The longitudinal settlement profile of the left driveway of the Vaasa motorway four years after the construction. Beneath the profile the ground improvement areas are defined.

sign stage if the longitudinal settlement profile has been calculated. The definitions for the change of inclination, the changed curvature and the angular distortion are presented in Fig. 1 and in Eq. (1a), (1b), (1c) and (1d).

The change of inclination $\Delta s / l$ (fig. 1a):

$$\frac{\Delta s}{l}=\frac{(s_j-s_i)}{l_{ij}}100\% \qquad (1a)$$

The curvature of the road surface $1/R$ (fig. 1a):

$$\frac{1}{R_j}=\frac{4\Delta s_j}{(l_{ij}+l_{jk})^2} \qquad (1b)$$

$$\Delta s_j=\frac{l_{jk}(s_k-s_i)}{l_{ij}+l_{jk}}+s_j-s_k \qquad (1c)$$

The angular distortion δ (fig. 1b):

$$\delta_k=\frac{\Delta_{jk}}{l_j}-\frac{\Delta_{kl}}{l_k}=\tan\alpha_j+\tan\alpha_k=\frac{s_k-s_j}{l_j}-\frac{s_l-s_k}{l_k} \qquad (1d)$$

where s_i is the settlement at the point i, l_{ij} is the horizontal distance between points i and j, Δ_{ij} is the difference of the settlements between points i and j, h_i are the levels of the road surface at the time t at the point i and R_j is the radius of curvature between the centers of ij and jk.

The Finnish settlement design criteria consists of the maximum settlement and the maximum change of inclination. For motorways the maximum allowable settlement is 400 to 700 millimeters and the maximum allowable change of the longitudinal inclination is 0.4 to 0.6 per cent.

2.2 *An example of the longitudinal settlement profiles*

As an example, the longitudinal settlement profile of the left driveway is presented in fig. 2. The part examined in this example is situated at the beginning of the Tuovilanjoki soft soil formation. Different ground improvement methods has been used as illustrated in figure 2a, beginning from the left side: Removal and replacement (mass exchange), deep stabilization with lime-cement columns, preconsolidation with preloading combined with vertical strip drains and the use of lightweight fill wedges with expanded clay (LECA). On the right side there is preloading with about 10 kPa surcharge. The initial state for settlements and their derivatives in this example is the road surface level presented in the road construction plans. The maximum settlement after four years is 120 mm (fig. 2). The measured heave in fig. 2 is based partly on the inaccuracy of the pavement work and partly on the variation of GPS measurements.

The derivatives of the settlement profile of this example i.e. the change of inclination, the curvature and the angular distortion are presented in fig. 3. The maximum change of inclination is 0.5 %. When comparing to the Finnish settlement criteria, it seems to be close to the allowable limit. The maximum settlement has not exceeded to the allowable level, but the change of inclination was larger than allowable in some short sections of the studied motorway. The changed curvature of the road surface is presented in fig. 3, and the maximum positive curvature found in this place is $1 / R = 0.3 \times 10^{-3}$ (1/m) (positive is concave, negative is cambered). The maximum angular distortion in fig. 3 is 0.6 %.

The error or variation of the GPS measurements was estimated to be ± 20 millimeters in good conditions. After comparing results of GPS and levelling measurements, we found that the GPS results deviated from the levelling results –20 to +50 millimeters.

3 PREDICTED AND MEASURED SETTLEMENTS

3.1 *Predictions*

The predictions of the time-settlement behaviour of the motorway on the Tuovilanjoki soft soil formation were based on the experience of the behaviour of the Vaasa trial embankment. Predicted time-settlement curves were calculated for some road cross sections situated on soft soil layers before the construction of the road, and the predictions for the operating time of the road were re-checked during the construction time when the more exact load history of road embankments and the preliminary construction-time settlements were found out.

The width on the top of the motorway embankment is about 40 meters with the 15 meters wide central reserve. The height of the embankment varies from 0.6 to 2.0 meters from the ground surface. The ground under higher sections of the embankment was improved by preconsolidation with vertical drains and 1.0 meter thick excess preloading fill. The vertical drains were in 1.0 x 1.0 square grid and their maximum depth was 15 meters.

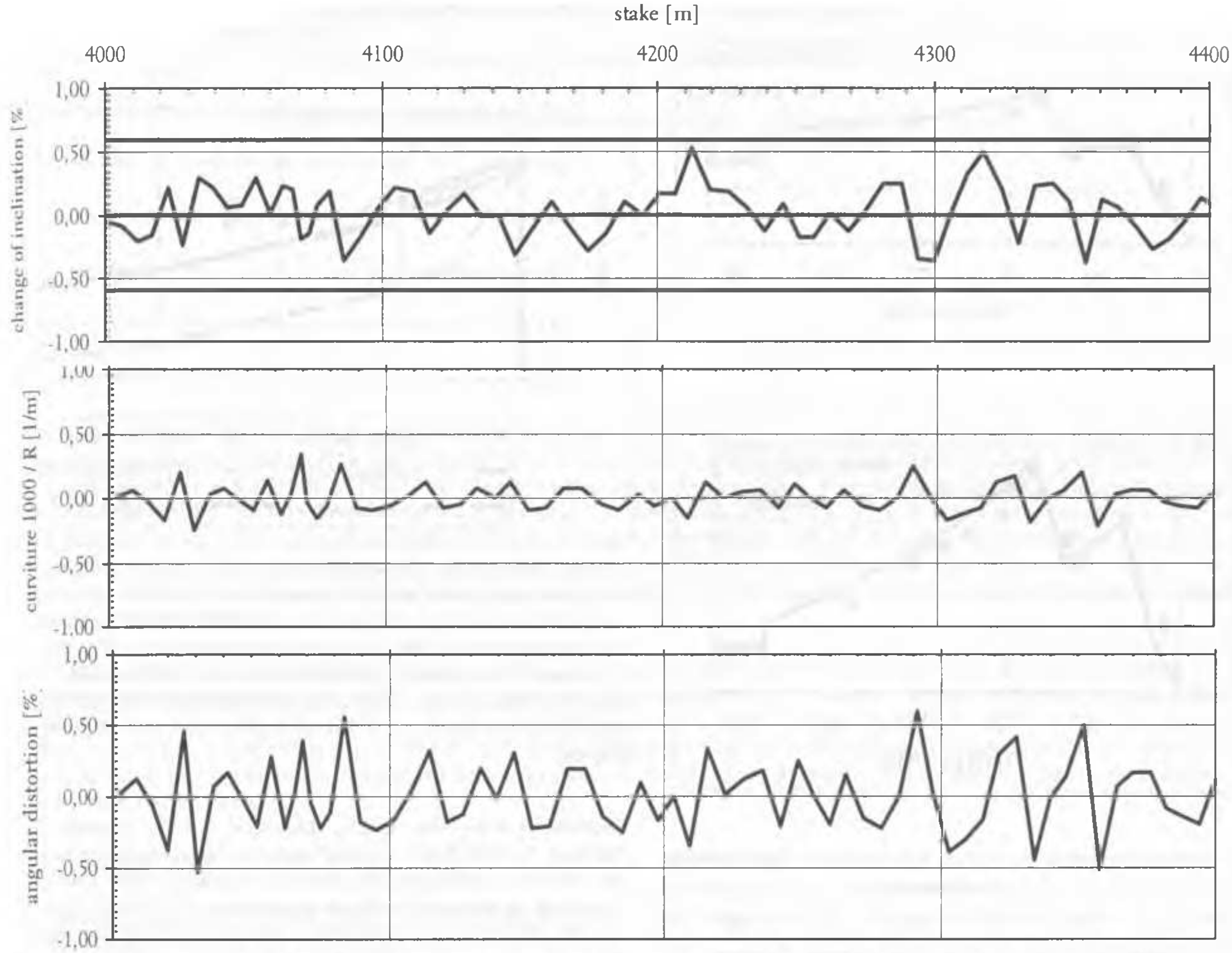

Figure 3. Longitudinal profiles of the change of inclination, the curvature and the angular distortion four years after the construction.

3.2 *Comparisons*

An example of the predicted and re-checked time-settlement behaviour for the construction stage on station number 4280 is presented in fig. 4. In this case the ground was improved to the firm bottom by vertical Mebra strip drains to the depth of 10 meters below the ground surface. The loading history of the embankment during the construction stage is presented in fig. 4a (the unit weight of the fill is 20 kN/m^3). The calculated and measured pore-water overpressures are in fig. 4b and the settlements during the construction time in fig. 4c. The estimated settlement after the preconsolidation was 1.38 meters. The calculations were based on the radial consolidation theory presented by Hansbo (1981) and modified by Vepsäläinen (1989) for arbitrary load history. The mean coefficient of consolidation was 0.5 m^2/a, the diameter of the smeared zone 150 mm and the relationship between undisturbed and disturbed zone coefficients of permeability was 3. Other parameters used in the calculation were the same as in the analysis of the Vaasa trial embankment.

Predictions for the in service settlements were based on the calculations mentioned above. The secondary consolidation was calculated according to the theory of Buisman (1936). Predicted and measured settlements during four years after the end of construction are presented in fig. 5.

There were two predictions for settlements during the operating time: First it was supposed that there might be a slight effect of the primary consolidation according to the pore overpressure estimation in fig. 5, but later, and looking more sharply at the pore overpressure measument results in fig. 4b, the secondary consolidation settlement might dominate the development of settlements from the beginning of the time of use.

The measured time-settlement curves in fig. 5 were based on the cross-sectional levellings on the pavement. For the comparison the results of the GPS-measurements are presented also in fig. 5. The measured settlements for four years after the end of construction were 60 mm on the left driveway and 85 mm on the right driveway. The predicted settlements are quite near to the measured ones. The situation is the same also in other points at the Tuovilanjoki soft soil formation where the time-settlement behaviour was predicted using the knowledge of the behaviour of the Vaasa trial embankment: Predicted and measured settlements during the operating time of four years were even closer to each other than in this example.

4 CONCLUSIONS

Definitions for the longitudinal settlement criteria have been presented together with examples of the longitudinal settlement, the change of inclination, the curvature and the angular distortion profiles. The data for settlements are based on the GPS-measurements with some cross-sectional control levellings. The measured results are compared to the Finnish practice of the allowable maximum settlement and change of inclination. Although the presentation in this paper is focused to the handling of the measured information, the possibilities to estimate longitudinal settlement profiles beforehand in the design stage are nowadays quite good as presented by Vepsäläinen & al (2000).

Comparisons of the predicted and measured settlements during the four years time of use showed quite good compatibility. It was found that the information of the Vaasa trial embankment behaviour was necessary for succesful geotechnical design in the difficult ground conditions. It was also found that during the

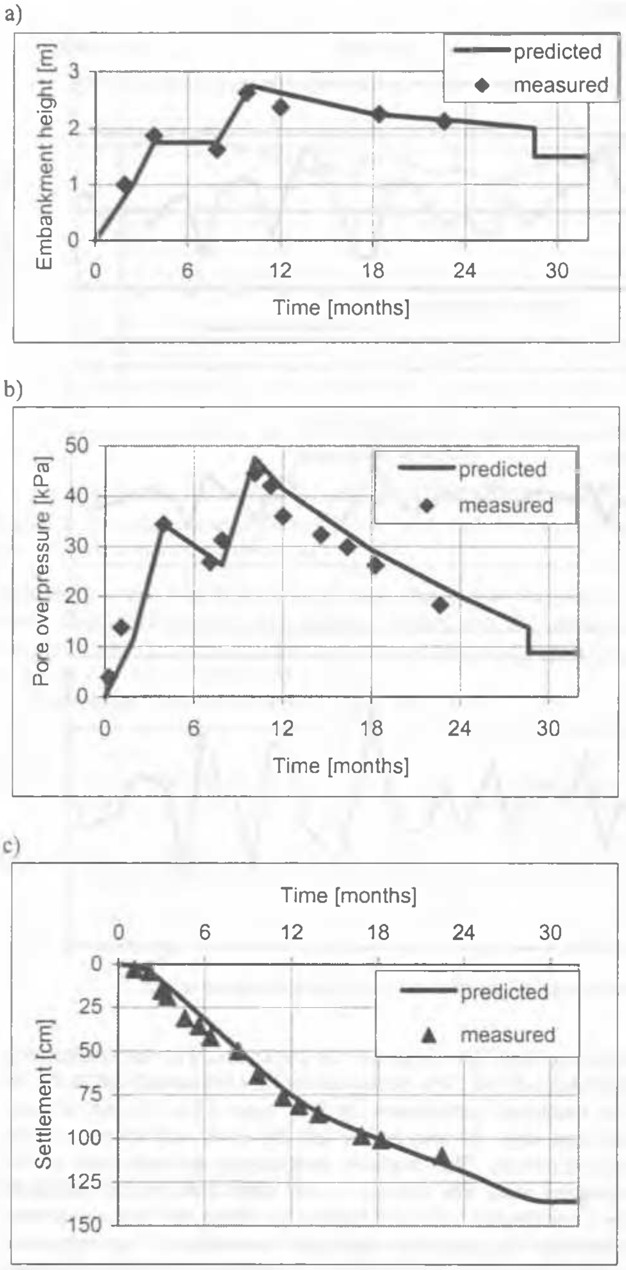

Figure 4. Predictions and measurements during the preconsolidation time at stake 4280. a) Loading history of the embankment, b) pore water overpressure dissipation, c) time-settlement behaviour during the preconsolidation time.

roads service life the secondary settlements might play an important role specially when the ground is improved by vertical drains.

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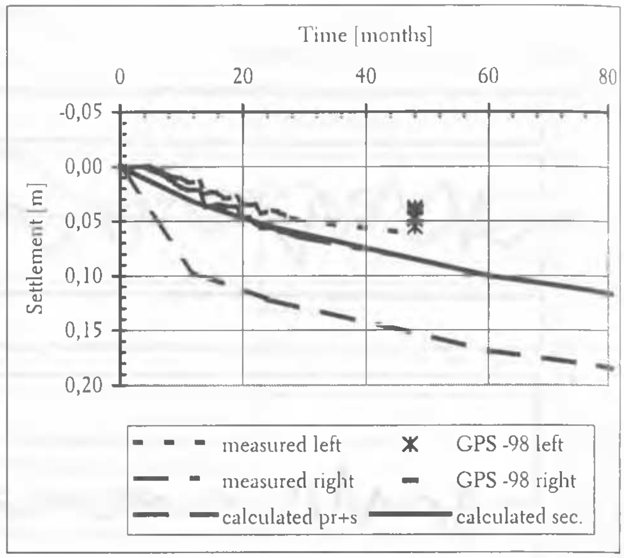

Figure 5. Predicted and measured time-settlement behaviour during the operational time 4 years after the construction at stake 4280. Left means the left driveway and right the right driveway. GPS –98 are the results of GPS mearurements in 1998. Calculated pr+s means that a small amount of primary consolidation has taken into account and calculated sec. means that the pore water overpressure had dissipated at the end of construction and secondary consolidation dominates the time-settlement behaviour.

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