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EXPERIMENTAL AND NUMERICAL ANALYSIS OF THE BEHAVIOUR OF AN EMBANKMENT STABILIZED WITH VERTICAL DRAINS

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ABSTRACT

The paper deals with the settlement analysis of an embankment founded on soft soil and realized for the construction of a reinforced concrete building in the industrial area of Catania (Sicily, Italy). The solution adopted consisted in the construction of the embankment by stages with thirty-three vertical prefabricated drains disposed under the embankment. Soil consolidation settlements took place since the beginning of the embankment construction. The experimental measurements were carried out since August 2000 up to January 2001. The site was well investigated by means of in-situ and laboratory tests. A significantly correspondence between the values of the geotechnical parameters derived from laboratory and in situ tests was observed. Consolidation was investigated and a comparison between computed results and field measurement is presented. The future performance of the embankment is predicted and the end of consolidation has been estimated in terms of settlements, which must be considered of major interest for the evaluation of the stability of the overlying structure.

INTRODUCTION

Due to the rapid increase in population and associated activities taking place in the last decades, construction activities are more focused on soils which were considered unsuitable in the past. These soft soil deposits have a low bearing capacity and exhibit large settlements when subjected to loading. It is therefore inevitable to treat soft soil deposits prior to construction activities in order to prevent differential settlements and subsequently potential damages to structures.

Different ground improvement techniques are available. Every technique should lead to an increase of soil shear strength and a reduction of soil compressibility. The choice of ground improvement technique depends on geological formation, soil characteristics and experience in the past.

According to Bergado *et al.*, (1996) the ground improvement techniques can be divided into two categories. The first category includes techniques which require foreign materials and utilization of reinforcements. They are based on stiffening columns either by the use of a granular fill (stone columns), by piling elements or by in situ mixing of the soil with chemical agents (deep stabilization). The second category includes methods which are strengthening the soil by dewatering, i.e. preloading techniques often combined with vertical drains.

Preloading is the application of surcharge load on the site prior to construction of the permanent structure, until most of the primary settlement has occurred. Since compressible soils are usually characterized by very low permeability, the time needed for the desired consolidation can be very long, even with very high surcharge load. Therefore, with the application of preloading, a system of vertical drains is often introduced to achieve accelerated radial drainage and consolidation by reducing the length of the drainage paths (Figure 1).

Vertical drains are applicable for moderately to lightly compressible soils, which are usually normally consolidated or lightly over consolidated, and for stabilizing a deep layer of soil having a low permeability. The vertical drams are particularly efficient where the clay layers contain thin horizontal sand or silt lenses.

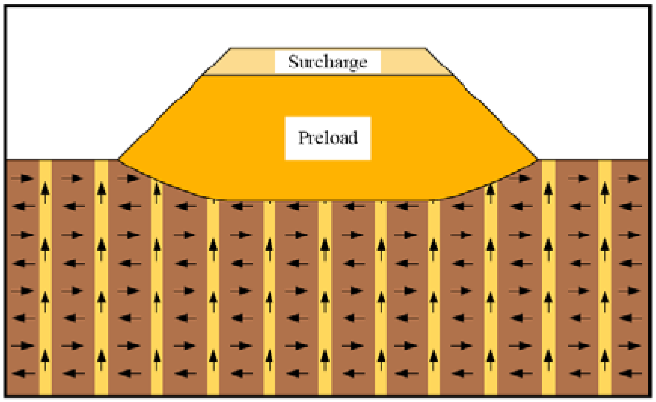


Fig. 1. Preloading with vertical drains.

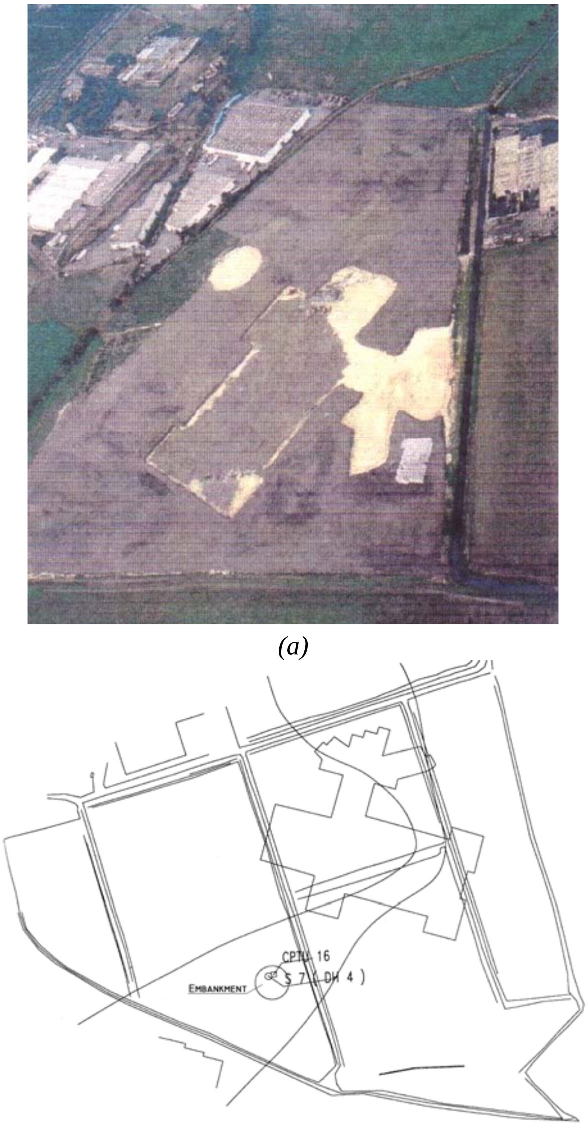
The paper deals with the settlement analysis of an embankment founded on soft soil and realized to investigate on preloading techniques and utilization of vertical drains.

Consolidation was investigated and a comparison between computed results and field measurement is presented. The future performance of the embankment is predicted and the end of consolidation has been estimated in terms of settlements, which must be considered of major interest for the evaluation of the stability of the superstructure.

CASE STUDY

On 5 September 2000 in the industrial area of Catania (Sicily, Italy) started the construction of a reinforced concrete building (Figure 2) on normally consolidated clayey deposits.

The applicability of a preloading technique in improving the compressibility of the soil foundation was investigated by means of the construction of an instrumented circular test embankment with a diameter of 65 meters and 2.50 meters high. Thirty-three vertical prefabricated drains were disposed beneath the embankment.



(a)

(b)

Fig. 2. Plan view of the site a) and embankment b).

Figure 2a shows a plan view of the site and it is possible to individuate the area of the embankment (Figure 2b) and the plan view of the building (Figure 3).

Due to the embankment weight, consolidation started and considerable settlements took place. Several types of geotechnical instrumentation were installed before the construction of the embankment in order to monitor it's performance. Figure 4 shows the scheme of vertical drains installation and the monitoring instruments used to monitor the soil foundation beneath the embankment.

Monitoring is essential to prevent failure, to record changes in the rate of settlement and to verify the design parameters. Performance evaluation is also important to improve settlement predictions and to provide guidelines for the future projects.
In this case assestimeters, placed immediately after the installation of vertical drains, were used to measure the long-term settlements at the original ground surface. Figure 5 shows the profile of the consolidation settlements versus time in the first 150 days. The maximum value of the consolidation settlements recorded is ranging between 8 to 16 cm.

Shallow and deep piezometers were used to monitor the complete pore pressure profiles (Figure 4). The shallow piezometers have two cells collocated at 20 and 34 meters under the ground surface, while the deep piezometers have two cells collocated at 41 and 47 meters under the ground surface.

To complete the equipment and to measure lateral displacements some inclinometers were placed in the body of the embankment. The preloading by an embankment not only cause settlements of the soft subsoil but also generally outward lateral displacements, mainly caused by the shear stress induced by the embankment load. When the shear stress is big the failure within the subsoil occurs (Dunnicliff, 1988; Chu & Choa, 2004).

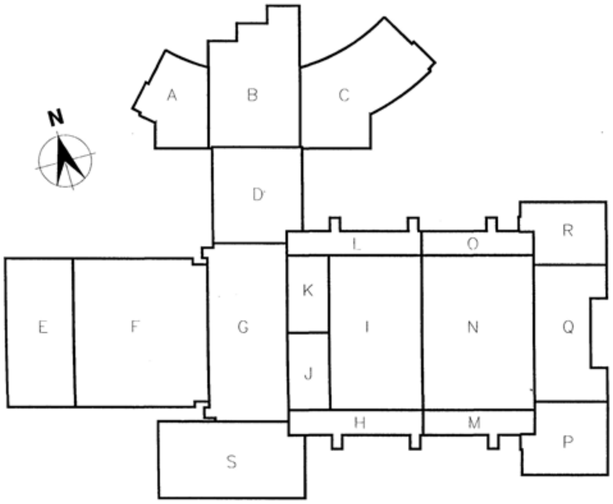


Fig. 3. Plan view of the building.

SOIL PROPERTIES EVALUATION

To determine the geological profile and the geotechnical characteristics of the soil, the site was well investigated by means of in-situ tests such as: boreholes, standard and cone penetration tests, seismic tests, as well as laboratory tests.

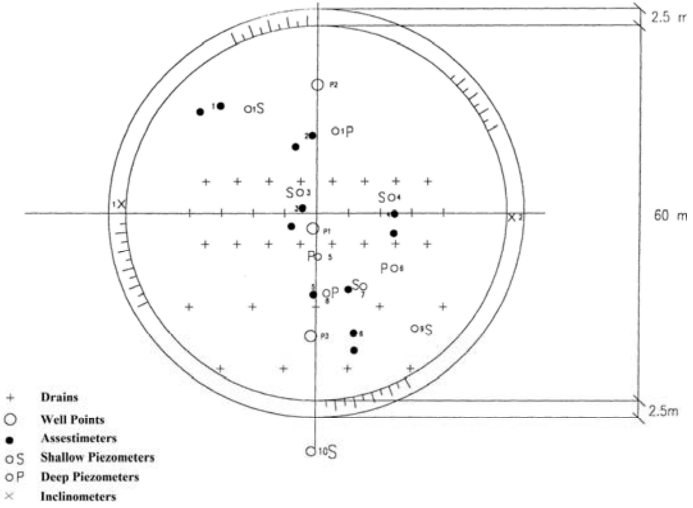


Fig. 4. Cone penetration (CPTU) and seismic tests (D-H).

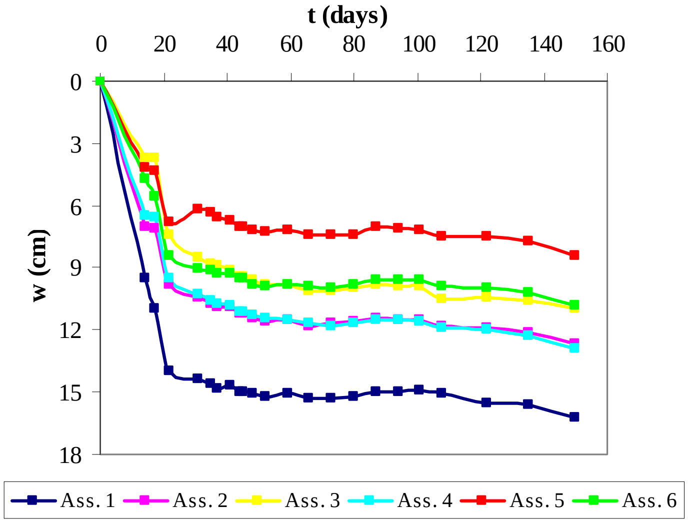


Fig. 5. Experimental values of the consolidation settlements.

The index properties and the mechanical characteristics of the soil foundation derived from the laboratory tests are shown, as function of depth, in Table 1. A good correspondence between the values of the geotechnical parameters derived from the laboratory tests and those derived by the results of the in situ tests was observed.

Figure 6 shows the soil profile versus depth of the area where the embankment is located. The profile shows that the underground soil is constituted mainly by clayey-silt and silty-clay up to a depth of $35 \div 40$ meters from ground surface. The water table, determined by piezometers, is located at around -1.5 meters below the ground surface.

The geotechnical investigation was carried out by field and laboratory tests and by the monitoring investigation. The in-situ tests constituted in standard penetration tests *SPT* (boreholes S3-S8 at different depth), cone penetration tests *CPTU* (22 tests), plate loading tests *PLT* (15 tests), down-hole seismic tests (*DH*), and finally spectral analysis of surface wave (*SASW*) with different distance of the source.

The laboratory investigation consisted on characterization tests, oedometer and resistance tests (triaxial *UU* and *CID* and direct shear test). The characterization tests classified the soil as clayey-silt and silty-clay with the following average parameters: liquidity limit w_l varies from 40 up 70% as depth increasing, plasticity limit w_p is about 35%, consistence index I_c varies from 0,7 up 1.4. The values of the natural moisture content w_n prevalently range between 30 and 40% as depth increasing, while the soil unit weight is equal to 18 kN/m^3.

Due to the peculiarity of the geotechnical problem, the vertical consolidation was studied, and by the oedometer tests the characteristic values reported in Table 2 were determined.

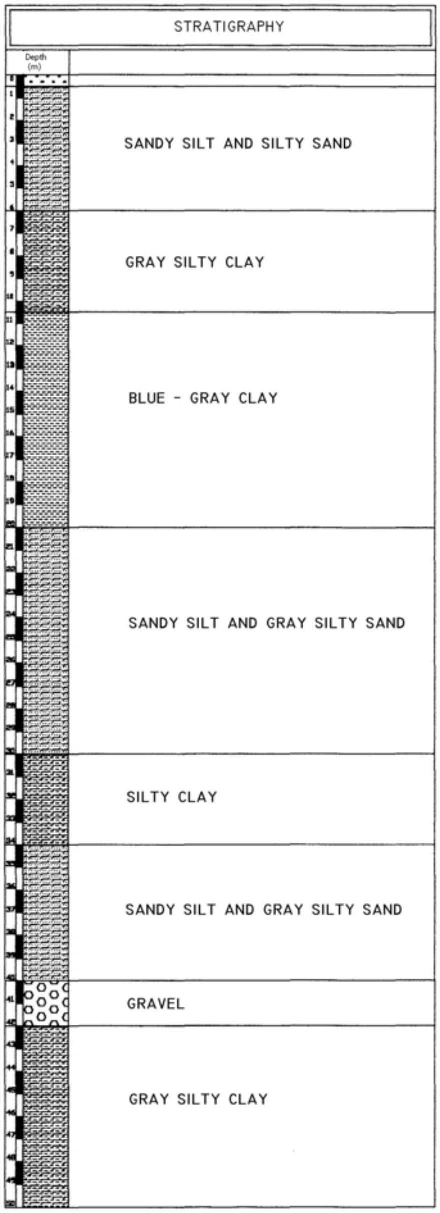


Fig. 6. Soil profile beneath the embankment.

Table 1. Geotechnical soil properties by laboratory tests.

Tests	**Depth (m)**	γ_{sat} **(kN/m^3)**	w_n **(%)**	γ_{dry} **(kN/m^3)**	G_s **(kN/m^3)**	e_o	n	S_r **(%)**	w_l **(%)**	w_P **(%)**	I_c	c_u **(kN/m^2)**
S7 R1	2.45-2.65	19.9	24.17	16.0	26.6	0.66	0.40	97	43	23	0.94	
S7 I1	4.50-5.00	19.5	28.54	15.2	26.7	0.76	0.43	100	45	29	1.02	
S7 R2	8.10-8.30	19.0	32.21	14.4	26.7	0.86	0.46	100	51	33	1.04	42.14
S7 I2	10.50-11.00	18.1	36.39	13.3	26.5	1.00	0.50	97	54	36	0.97	36.69
S7 I3	15.00-15.50	17.5	43.91	12.1	26.6	1.19	0.54	98	60	41	0.84	
S7 R3	19.30-19.50	17.5	44.96	12.1	26.7	1.21	0.55	100	65	38	0.74	
S7 I4	20.00-20.50	17.2	48.25	11.6	26.5	1.28	0.56	100	73	30	0.57	29.03
S7 I5	25.00-25.50	17.1	51.13	11.3	26.7	1.37	0.58	100	77	25	0.49	
S7 I6	28.00-28.50	17.3	47.19	11.8	26.6	1.26	0.56	100	70	41	0.79	32.84
S7 I7	37.00-37.50	17.3	48.27	11.7	26.7	1.28	0.56	100	65	48	0.98	
S7 R4	38.50-38.70	18.9	32.35	14.3	26.7	0.87	0.56	100	61	36	1.14	

In the interval of interest the oedometer modulus E_{ed} is ranging between about 1410 up to 4000 kN/m^2 as depth increasing, the consolidation coefficient C_v is ranging between $4.8 \cdot 10^{-9}$ and $4.86 \cdot 10^{-7}$ m^2/sec.

VERTICAL CONSOLIDATION

Because of its low permeability, the consolidation settlement of soft clays takes a long time to complete. To shorten the consolidation time, vertical drains are installed together with preloading either by an embankment.

Vertical drains are artificially-created drainage paths which are inserted into the soft clay subsoil. Thus, the pore water squeezed out during consolidation of the clay due to the hydraulic gradients created by the preloading, can flow faster in the horizontal direction towards the vertical drains.

It is taken advantage of the fact, that most clay deposits exhibit a higher horizontal permeability compared to the vertical. Subsequently, these pore water can flow freely along the vertical drains vertically towards the permeable layers. Therefore, the vertical drain installation reduces the length of the drainage path and, consequently, accelerates the consolidation process.

The performance of vertical drains with preloading can be evaluated by various means including design prediction, field instrumentation, monitoring and in-situ testing, investigated in this research study.

The one-dimensional consolidation settlement behavior of clays can be described by Terzaghi's method (1925). This method when used in conjunction with Barron (1948) and Carrillo (1942) methods can be used for the design of vertical drains. Imai (1995), in particular, had described on the time rate of settlement effect of clays. Many researchers (Choa *et al.*, 1981; Bergado *et al.*, 1991; Hansbo, 1997; Bo *et al.*, 2003; Indraratna *et al.*, 2001) had reported consolidation behavior of clays by using prefabricating vertical drains. Holtz *et al.* (1988; 1991) had given an in-depth coverage of the study of vertical drains, which included the method of installation of vertical drains, static penetration or vibratory driving, types of mandrels and type of shoes. In addition, Hausmann (1990) had also described the theories and mechanisms of vertical drains, while Onoue (1988) suggested a simplified formula for the average degree of consolidation with respect of radial flow.

The behavior of earth structures built on soft clay stabilized with vertical drains can be predicted reasonably. With the rapid development of the numerical methods in Geotechnical Engineering a comprehensive analysis of the behavior of the soft clay can now be conducted effectively.

Finite element technique is based on the discretization of a continuum into a number of elements, which are connected at nodal points. The deformation response of each element is defined by element shape, the displacement variation within each element and the stress-strain behavior (constitutive model) employed to represent the behavior of the element.

Researchers (Brenner & Prebaharan,1983; Onoue, 1988) developed finite difference methods for vertical drains, in which either "explicit" or "implicit" solutions have usually been adopted. A rigorous study between these two methods concluded that the implicit method provides a better numerical stability, although a set of simultaneous equations need to be solved at each time step (Desai & Christian, 1977).

The main advantage of numerical analysis is that the settlement and stresses within the soil are coupled, and therefore more realistic soil behavior can be simulated.

In the paper the numerical analysis has been carried out by means of the finite element program CRISP^{2D} (Sage Crisp Consortium Ltd, 2004), which is able to perform drained, undrained and time dependent analysis of static problems under monotonic loading/unloading conditions.

The finite-element mesh used for the numerical analysis is shown in Figure 7. Considering the symmetry of the models only ½ of the embankment has been modeled.

The soil foundation was represented by an assembly of axi-symmetric quadrilateral elements and the analyses were conducted under axi-symmetric conditions with the soil, loading and boundary conditions. The stress-strain-strength behavior of the soil was simulated by a simple elastic-perfectly plastic model, with a Mohr-Coulomb failure criterion, in order to reduce the uncertainties about the interpretation of the results.

Usually, the identification of the parameters of a constitutive model is carried out from laboratory tests, which allow an evaluation of the numerical values to be used in the numerical analyses. In this work, thanks to the great quantity of available field and laboratory data, the approach followed was: the calibration took place on the basis of the experimental results, changing, in a suitable way, some of the values of the parameters in order to obtain time-settlement curves adherent to the experimental ones.

The results of the numerical analysis are summarized in the Figures 8÷10 representing the computed pore pressure and settlements distribution, and the soil settlements beneath the embankment. The comparison between numerical results (in terms of vertical settlements) and those measured (Figure 11), shows that the proposed analysis can be used successfully for the numerical modeling of the behavior of an embankment built on soft clay and stabilized with vertical drains, if model parameters are evaluated properly.

Table 2. Soil compressibility by oedometer tests.

z **(m)**	**k_v** **(m/s)**	**c_v** **(m^2/s)**	**E_{ed}** **(kN/m^2)**
3	3,37.10-9	4,86.10-7	1413
8,3	4,05.10-10	7,49.10-8	1815,8
15,3	1,02.10-10	2,43.10-8	2347,8
25	3,14.10-11	9,87.10-9	3085
32	1,70.10-11	6,27.10-9	3617
37	1,18.10-11	4,80.10-9	3997

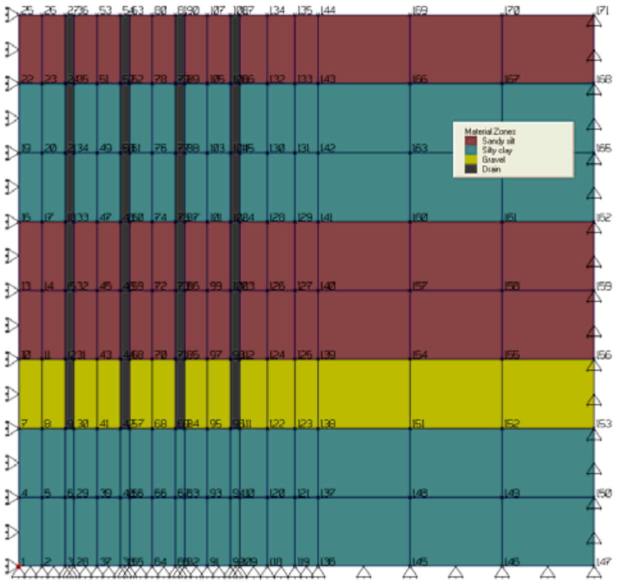


Fig. 7. Finite-element mesh.

CONCLUDING REMARKS

The paper deals with the settlement analysis of an embankment founded on soft soil and realized to investigate on preloading techniques and utilization of vertical drains.

Consolidation was investigate and the comparison between computed results and field measurement is presented. Numerical modeling for vertical drains has been developed for axi-symmetric condition, simulating the consolidation of the soil foundation beneath the embankment.

The comparison between measured and computed results shows that the proposed analysis can be used successfully for the numerical modeling of the behavior of an embankment, and provide a reliable evaluation of the future performance.

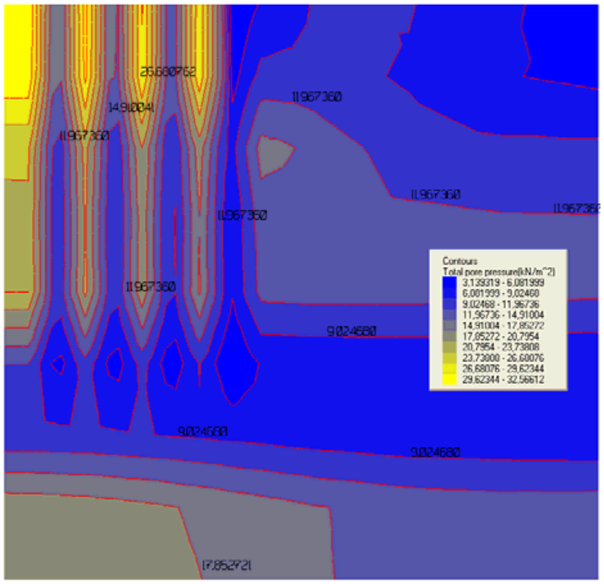


Fig. 8. Computed pore pressure distribution.

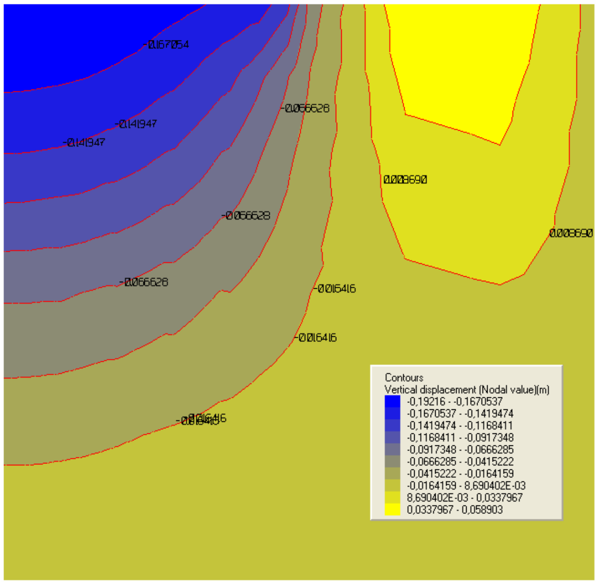


Fig. 9. Computed soil settlements distribution.

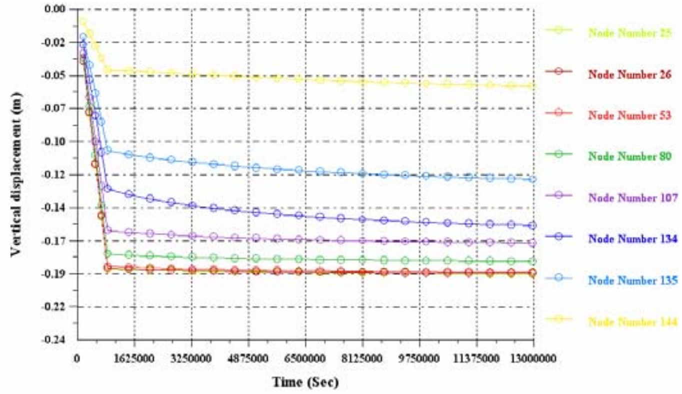


Fig. 10. Computed settlements beneath the embankment.

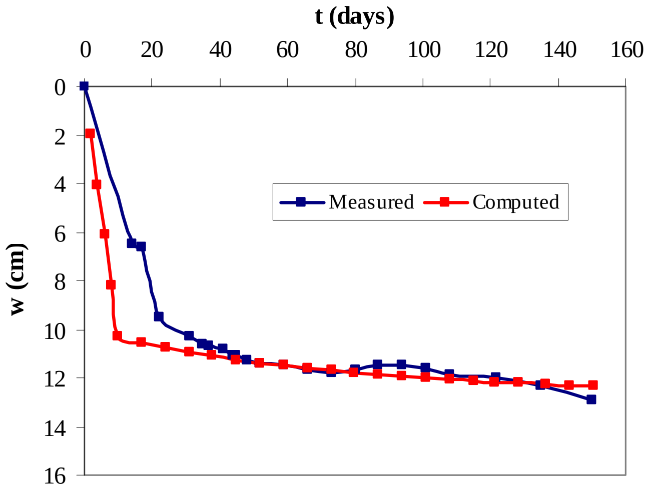


Fig. 11. Comparison between computed and measured settlements beneath the embankment.

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