

Validation of a theoretical solution through in situ measurements of a consolidation process

Di Filippo Giuseppe¹, Biondi Giovanni², Cascone Ernesto³

¹ *University of Messina, gdifilippo@unime.it*

² *University of Messina, gbiondi@unime.it*

³ *University of Messina, ecacone@unime.it*

Abstract – The settlements induced by preloading with vertical drains have been frequently used to propose, or to validate, semi-empirical procedures able to back-calculate an operative value of the coefficient of horizontal consolidation C_h or to predict the consolidation settlements for a suitable value of C_h . In the paper, the measurements of the settlements induced on a heterogeneous cohesive soil deposit are adopted to validate a generalized theoretical solution which encompasses for radial and vertical consolidation, smear effect and hydraulic resistance of drains. Measurements were normalized with respect to the final consolidation settlement, estimated with the hyperbolic approximation, and compared with the average degree of consolidation provided by the theoretical solution. The comparison is discussed highlighting the effectiveness of the adopted solution despite the remarkable influence of the lithological and mechanical heterogeneity of the soil deposit.

I. INTRODUCTION

In the engineering projects involving preloading with vertical drains unsuccessful ground settlements prediction are frequent in the case of thick and/or heterogeneous soil deposits (e.g. [1]). Observational procedures, mainly devoted to the analysis of the average degree of consolidation from in situ settlement measurements, permit to adjust the predictions, leading to a reliable estimation of the final ground settlement, and, thus, allow savings in cost or time.

In the paper, a large data-set of in situ settlement measurements were back-analyzed to estimate the final consolidation settlements induced by preloading and vertical drains on a heterogeneous cohesive soil deposit where two large steel tanks had to be built. Final consolidation settlements were estimated using the hyperbolic approximation and, to predict the time-settlement relationship, were combined with an average degree of consolidation provided by a rigorous theoretical solution accounting for the radial and vertical consolidation process, induced by a time-dependent loading, for the smear effect and for the effect of the hydraulic resistance of drains. The comparison between

settlement measurements and predictions are presented and discussed highlighting the effectiveness of the adopted solution despite the remarkable influence of the lithological and mechanical heterogeneity of soil deposit.

II. IN SITU MEASUREMENTS AND FINAL CONSOLIDATION SETTLEMENTS

The data-set of measurements consist of the settlement induced by preloading and 20 m long prefabricated vertical drains on a heterogeneous, medium to stiff clayey and silty soil deposit, representing the foundation soils of two large steel tanks and incorporating randomly distributed discontinuous layers of granular soils. At the site a main preloading embankment (9.2 m high, 35 m wide and 96 m long at the top) was built in the area of the tanks, applying an average pressure to the ground surface of about 174 kPa; an adjacent smaller embankment was also realized but it is not considered herein. Figure 1 shows the plan view of the area occupied by the preloading embankments and the location of the geotechnical investigations carried out at the site. The figure also shows the longitudinal cross-section of the site with the soil profile and the profiles of tip resistance q_c and excess pore water pressure u , as obtained from *CPT* and *CPTU* tests. The value of C_h adopted in the analyses presented herein range in the interval $2,4\div5,6\cdot10^{-7}$ m²/s and were obtained by [2] analyzing the rate of dissipation measured during the *CPTU* tests. The geotechnical characterization of the soil deposit, the work sequence and the measurement results are described in [3].

The ground settlements were monitored measuring, by topographic survey, the vertical displacements of 20 platforms (*SP1-20* in Fig. 1) for a period of 284 days, until the embankment was removed; herein the analysis was limited to 200 days. Figure 2 shows the variation of the embankment height with time and the vertical displacements of the platforms *SP4-8* (Fig. 2b), *SP11-13* (Fig. 2c) and *SP16-20* (Fig. 2d) located in the area where the two tanks had to be built and in the centre of the main embankment. Due to the lithological and mechanical heterogeneity of the considered soil deposit ([3]) differences in the final value of settlements are apparent depending on the location of the settlement plates.

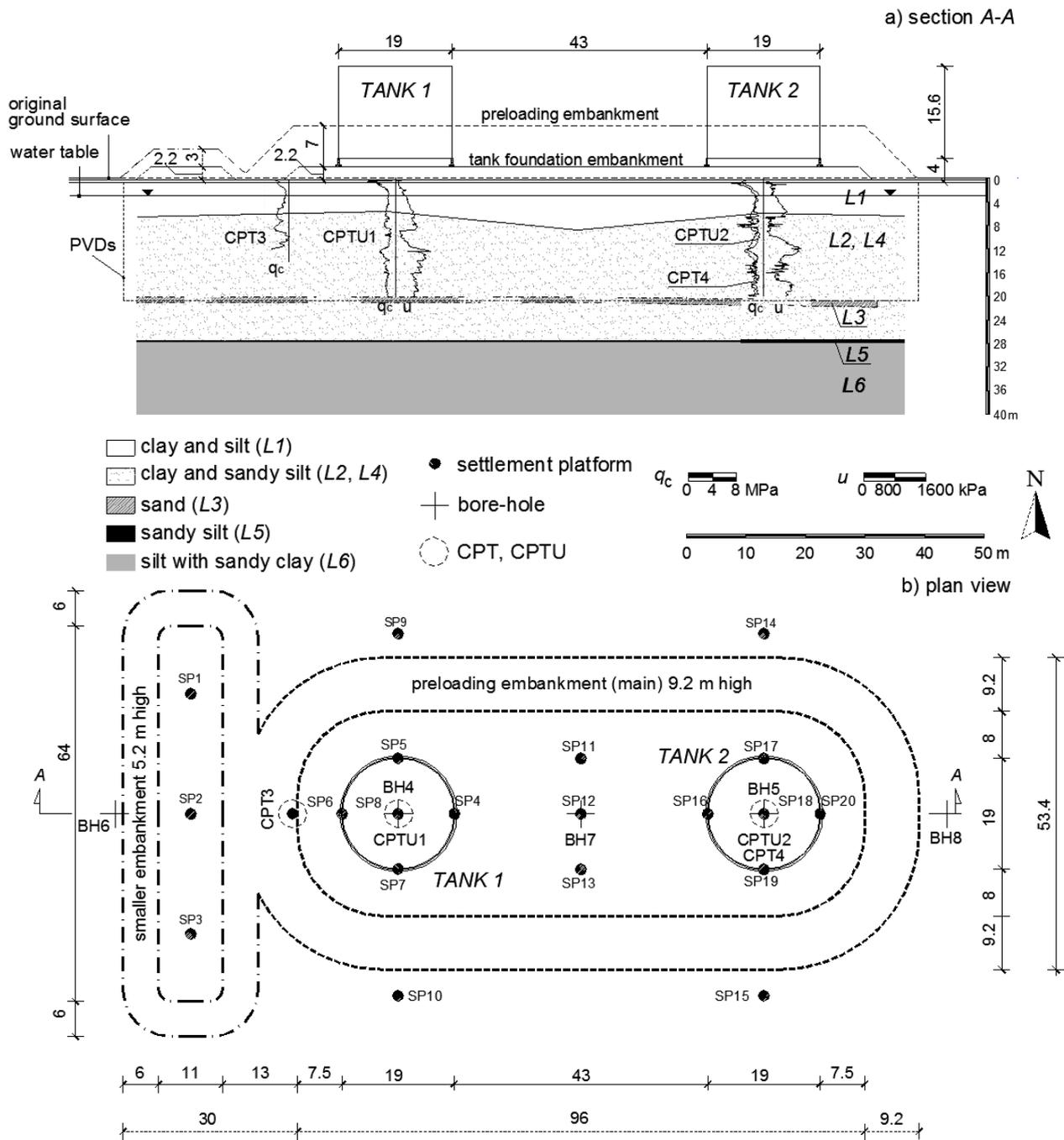


Fig. 1. a) Longitudinal cross-section of the site; b) plan view of the preloading embankment, location of the geotechnical investigations and of settlement platforms (adapted from [2,3]).

Maximum settlements of about 36-39 cm occurred along the longitudinal axis of the embankment (SP8, SP12, SP18) and a stiffer response of the northern preloading area was observed with differences in measured settlements of about 6.6 cm between SP5 and SP7 and of about 7 cm between SP17 and SP19. Starting from settlement measurements, the final values w_f of the consolidation settlement were estimated through

the hyperbolic approximation [4,5]: table 1 list the obtained values together with the equation used to fit the data and the corresponding values of the regression (α and β) and correlation (R^2) coefficient. Consistently with measurements, larger values are predicted along the longitudinal axis (SP8, SP12, SP18) of the main embankment and the heterogeneity of the soil deposit is reflected in the distribution of final settlements.

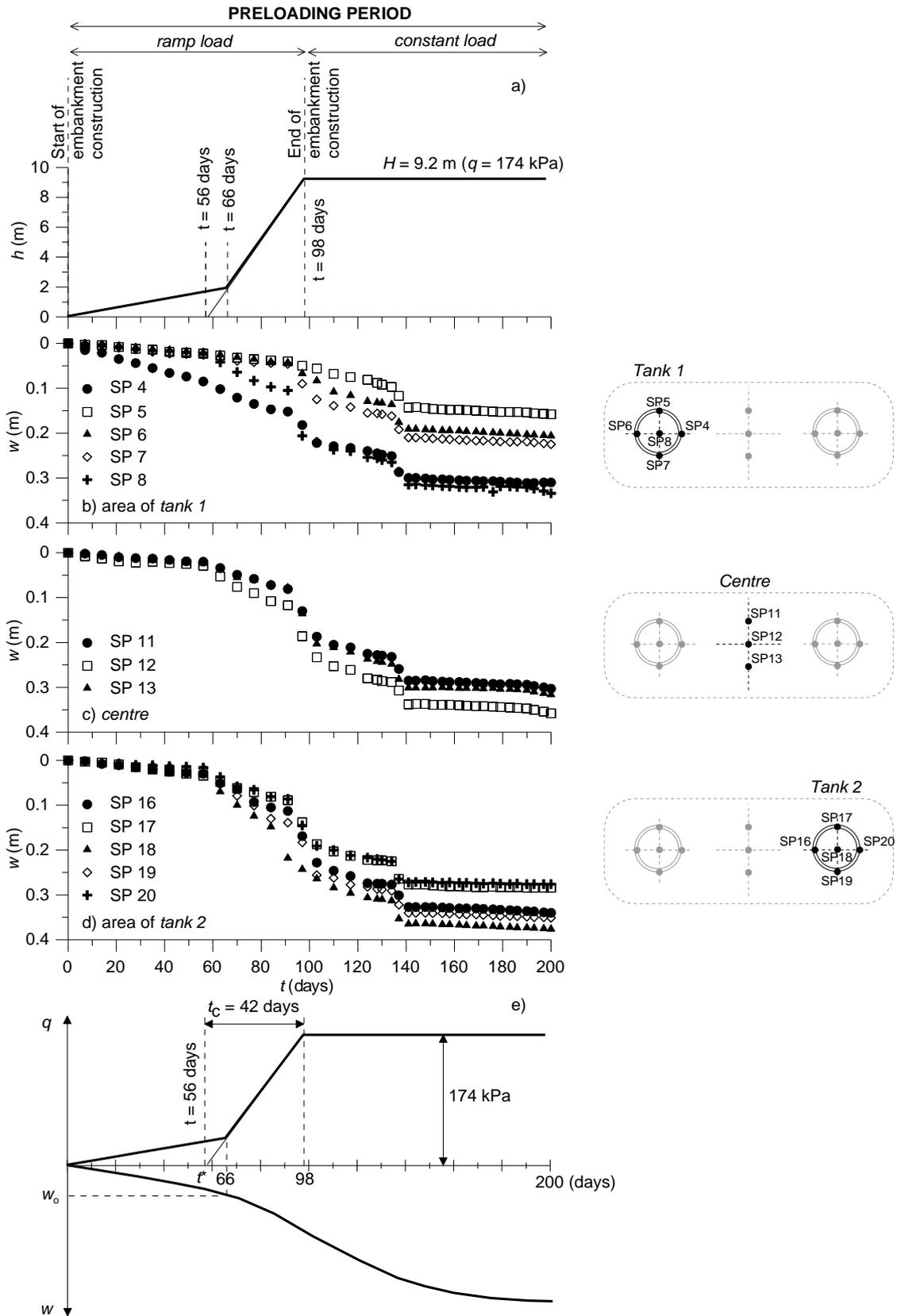


Fig. 2. Time histories of embankment height (a) and of measured settlements (b-d); e) scheme adopted for predictions.

In the area where the two tanks had to be built w_f ranges in the intervals 20–35 cm (SP4-8) and 30–40 cm (SP16-20), with an average variability of about 75% and 33% respectively, whereas in the central area, w_f vary between 33 and 38 cm with a lower variability.

Table 1. Final consolidation settlements (see Fig.2e).

		$w = t/(\alpha + \beta t)$		$w_f = w_0 + 1/\beta$		
		α	β	R^2	w_0 (m)	w_f (m)
Tank 1	SP 4	63,693	7,132	0,9993	0,182	0,322
	SP 5	108,252	8,459	0,9992	0,050	0,168
	SP 6	67,583	6,694	0,9986	0,067	0,216
	SP 7	59,662	7,064	0,9995	0,090	0,232
	SP 8	34,939	8,338	0,9978	0,206	0,326
Centre	SP 11	35,922	5,733	0,9994	0,130	0,304
	SP 12	37,930	5,860	0,9989	0,186	0,357
	SP 13	25,435	5,645	0,9991	0,136	0,313
Tank 2	SP 16	33,292	5,686	0,9989	0,169	0,345
	SP 17	29,889	6,533	0,9996	0,138	0,291
	SP 18	57,119	7,117	0,9986	0,243	0,384
	SP 19	34,041	5,697	0,9994	0,183	0,359
	SP 20	31,296	7,312	0,9996	0,145	0,282

III. THEORETICAL PREDICTIONS

Theoretical time-settlement relationships were obtained combining the obtained values of w_f with a rigorous theoretical solution providing the average degree of consolidation U for the problem of radial and vertical consolidation process induced by a ramp loading history in a soil deposit with fully penetrating prefabricated vertical drains: $w(t) = w_f \cdot U(t)$. The solution (details can be found in [2]) refers to an equivalent cylindrical block of soil, having a diameter $d_e = 2 \cdot r_e = 1.05 \cdot s_d$ (s_d is the drain spacing); U depends on a non-dimensional time-factor $T_h = t \cdot C_h / d_e^2$ and is given by:

$$U(T_h) = \frac{T_h}{T_{hc}} - \sum_{m=1}^{\infty} \sum_{n=1,3,5,\dots} A_{m,n} \cdot [1 - \exp(B_{m,n} \cdot T_h)] \quad (1)$$

$$U(T_h) = 1 - \sum_{m=1}^{\infty} \sum_{n=1,3,5,\dots} A_{m,n} [1 - \exp(B_{m,n} T_{hc})] \cdot \exp(B_{m,n} T_h)$$

if $T_h \leq T_{hc}$ or $T_h > T_{hc}$, respectively, being T_{hc} the values of T_h at the end of the ramp loading ($t = t_c$, Fig. 2). In eq. (1), $A_{m,n}$ and $B_{m,n}$ are numerical parameters depending on the following non-dimensional factors:

$$N = \frac{r_e}{r_w} \quad L = \frac{C_v \cdot r_w^2}{C_h \cdot L_m^2} \quad s = \frac{r_s}{r_w} \quad \eta^2 = \frac{C_h}{C_{hs}} \quad (2)$$

were L_m is the maximum vertical drainage path, r_w is the equivalent radius of the drain, r_s and C_{hs} are the radius and the horizontal consolidation coefficient in the smear zone and C_v is the vertical consolidation coefficient. In the analyses a drain spacing ratio $N = 24.7$ was assumed, the values of C_h were associated to each area

according to the distance with the test location (Fig. 1a), the smear effect was examined assuming $C_{hs} = C_v$, consistently with [6] and [7], and, finally, the smear ratio was varied in the range $s = 1 \div 3$ according to [8] and [9].

Table 2 lists the values of C_h , C_{hs} and η^2 considered in the analyses. The use of different pairs of the parameters s and η^2 and the comparison with field data, allowed back-estimating the proper values of the diameter $d_s = 2 \cdot r_s$ describing the smeared zone and the relevance of the smear effect on the rate of consolidation.

Due to the significant differences in the values of C_v and C_h and to the geometry of the problem (r_w , L_m), L is in the range $(1.25 \div 2.90) \cdot 10^{-6}$ making negligible the influence of the vertical drainage on the overall consolidation process. Finally to estimate the average degree of consolidation U a conventional initial time $t^* = 56$ days (Figs. 2a,d) was assumed for the second loading ramp and the first loading ramp ($t = 0-66$ days) was neglected in the settlements prediction. Thus the conventional duration t_c^* of the second ramp is equal to $98-56 = 42$ days (Figs. 2a,d) leading to the values of the non-dimensional time factor T_{hc} listed in Table 2.

Table 2. Parameters adopted in the theoretical analyses.

C_h (m ² /s)	z (m)	T_{hc}	C_{hs} (m ² /s)	η^2
$5.56 \cdot 10^{-7}$	8.90 (CPTU1)	0.807		8.02
$2.39 \cdot 10^{-7}$	12.38 (CPTU1)	0.351	$6.93 \cdot 10^{-8}$	3.45
$3.60 \cdot 10^{-7}$	6.32 (CPTU2)	0.528		5.19

IV. MEASUREMENTS VERSUS PREDICTIONS

Theoretical predictions were compared with in situ measurements starting from $t = 66$ days when field settlements had already attained the value w_0 (Fig. 2 a, e). The comparison results is shown in Figures 3 where the theoretical average degree of consolidation U and the ratio $w(t)/w_f$, computed for different values of C_h and s , are superimposed.

For *Tank1* (Fig. 3a,b) most of the data are bounded by the curves obtained for $s = 1$ and $s = 3$. Regardless C_h , the final values ($w/w_f = 1$) of the ground settlement is well predicted assuming no smear effect ($s = 1$); however, the overall settlement history is more accurately predicted with the combinations $C_h = 2.39 \cdot 10^{-7}$ m²/s with $s = 1$ (Fig. 3a) and $C_h = 5.56 \cdot 10^{-7}$ m²/s with $s = 1.5$ (Fig. 3b).

In the *central area* (Fig. 3c,d,e) and in the area of *Tank2* (Fig. 3f), the curves of the normalized field measurements are close to each other and, independently of C_h , are bounded by the theoretical solutions obtained for $s = 1$ and 1.5.

The best agreement are obtained using $s = 1.3$ and C_h in the range $(3.6 \div 5.56) \cdot 10^{-7}$ m²/s, for the *central area*, and $C_h = 3.6 \cdot 10^{-7}$ m²/s (the only value which was considered suitable for the analyses) with s in the range $1 \div 1.3$, for the area of *Tank2*.

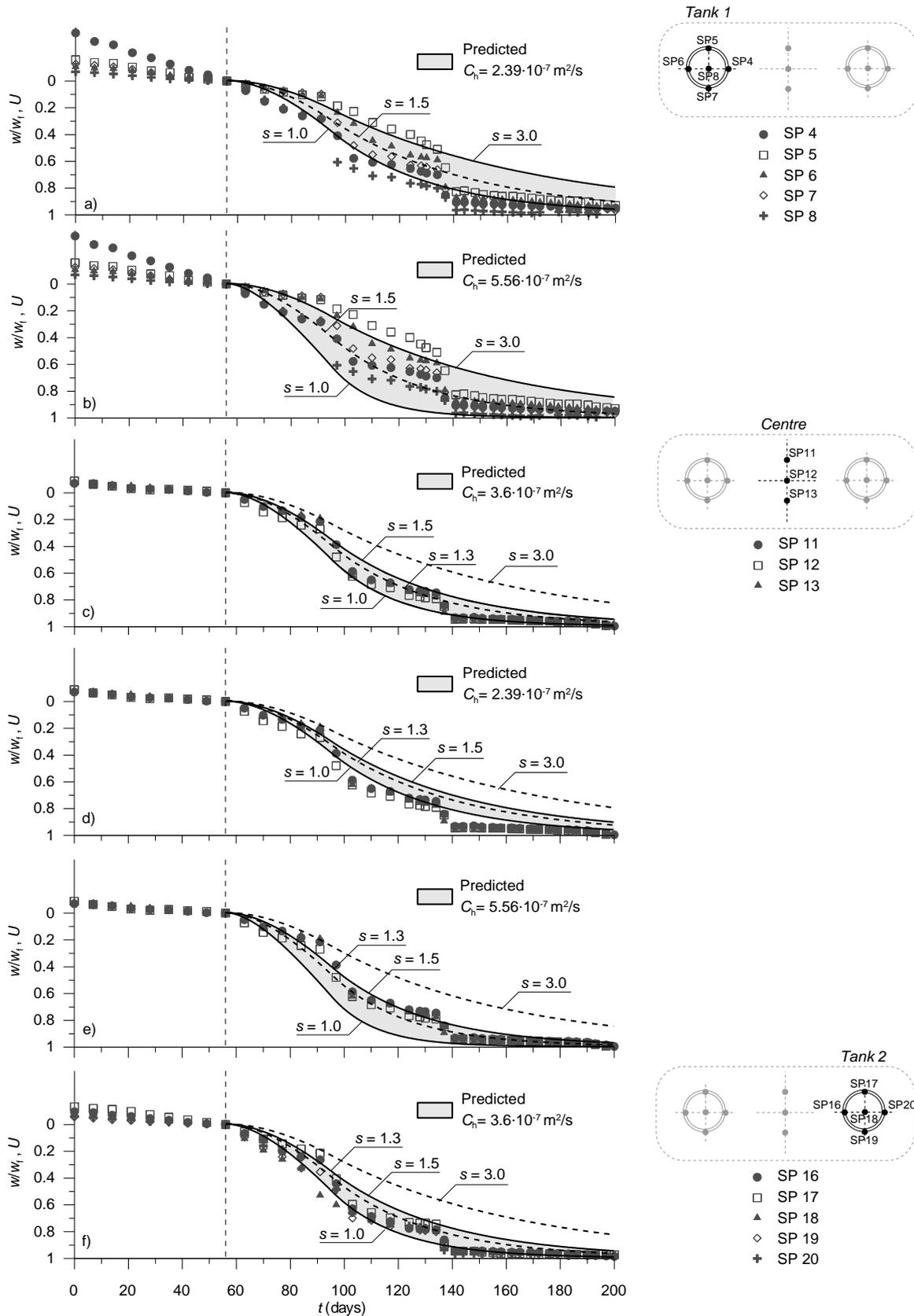


Fig. 3. Normalized settlements time-histories and comparison with the predicted average degree of consolidation.

A satisfactory prediction of most of the data concerning the *central area* and the area of *Tank2* can be obtained assuming $C_h = 3.6 \cdot 10^{-7} \text{ m}^2/\text{s}$ along with $s = 1.3$ which can be assumed as the best estimate of the smear ratio. Despite the heterogeneity of the soil deposits, which is more remarkable in the area of *Tank1*, a pair $C_h = 3.6 \cdot 10^{-7} \text{ m}^2/\text{s}$ and $s = 1.3$ can be considered as approximately representative for the whole site.

V. CONCLUDING REMARKS

The paper describes the results of a back-analysis a large set of in situ settlement measurements carried out during the preloading period of a heterogeneous cohesive soil deposit where 20 m long prefabricated vertical drains were installed to accelerate the consolidation process.

Measured settlements were normalized with respect to the final values of the consolidation settlements, computed using the hyperbolic approximation, and were compared with theoretical values of an average degree of consolidation obtained through a rigorous solution accounting for the combined radial and vertical consolidation process induced by a time-dependent loading history and including the smear effect and the effect of the drain hydraulic resistance.

Values of the horizontal consolidation coefficient were evaluated from *CPTU* dissipation test results, whereas the variables describing the smear effect were selected according to the literature or varied, parametrically, in narrow range.

The comparison between in situ measurements and theoretical predictions shows the effectiveness of the adopted theoretical solution and the accuracy of its predictions if a proper selection of the model parameters is performed.

For the considered case the values of the smear ratio that allowed matching the normalized field data vary in the range $s = 1 \div 1.5$ as a consequence of the significant fractions of silty and sandy soils in the soil deposit which was revealed by the geotechnical investigations at the site.

Conversely small variations of the horizontal consolidation coefficient C_h significantly influenced the match between measurements and predictions.

The remarkable lithological and mechanical heterogeneity of the considered soil deposit, reflected in the spatial distribution of settlements measurement and of the final values of predicted consolidation settlements, did not permit a reliable back-analysis of the parameters describing the smear effect.

However, using the selected theoretical solution, a pair (C_h, s) approximately representative for the whole site was nonetheless detected.

REFERENCES

- [1] E. Cascone, V. Bandini, A. Galletta, G. Biondi, "Acceleration of the consolidation process of a clay soil by preloading and vertical drains: field measurements and numerical predictions", *Geotechnics of Soft Soils - Focus on Ground Improvement - Proceedings of the 2nd Int. Workshop on Geotechnics of Soft Soils*, 2009, CRC Press/Balkema, Glasgow, pp. 379-385.
- [2] G. Di Filippo, G. Biondi, E. Cascone, "Measurements and predictions of settlements induced by preloading and vertical drains on a heterogeneous soil deposit", *Journal of the International Measurement*, Elsevier, under review.
- [3] E. Cascone, G. Biondi, "A case study on soil settlements induced by preloading and vertical drains", *Geotextiles and Geomembranes*, vol. 38, 2013, pp. 51-67.
- [4] T. S. Tan, T. Inoue, S. L. Lee, "Hyperbolic method for consolidation analysis", *Journal of Geotechnical Engineering*, vol. 117, No. 2, 1991, pp. 1723-1737.
- [5] S. A. Tan, "Validation of hyperbolic method for settlement in clays with vertical drains", *Soils and Foundations*, vol. 35, No 1, 1995, pp. 101-113.
- [6] D. T. Bergado, H. Asakami, M. C. Alfaro, A. S. Balasubramaniam, "Smear effects of vertical drains on soft Bangkok clay", *Journal of Geotechnical Engineering*, ASCE, vol. 117, No. 10, 1991, pp. 1509-1530.
- [7] B. Indraratna, I.W. Redana, "Numerical modeling of vertical drains with smear and well resistance installed in soft clay", *Canadian Geotechnical Journal*, vol 37, No. 1, 2000, pp. 133-145.
- [8] S. Hansbo, "Consolidation of fine-grained soils by prefabricated drains", In: *Proc. 10th Int. Conf. on Soil Mechanics and Foundation Engineering*, Stockholm, 1981, 3, pp. 677-682.
- [9] C.C. Hird, V.J. Moseley, "Modeling study of seepage in smear zones around vertical drains in layered soil", *Géotechnique*, vol. 5, No. 1, 2000, pp. 89-97.