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Measurements and predictions of settlements induced by preloading and vertical drains on a heterogeneous soil deposit

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ABSTRACT

The paper describes a comparison between in situ measurements and theoretical predictions of the ground settlements induced by preloading and vertical drains on a heterogeneous soil deposit.

Settlement measurements, normalized with respect to the final value of the consolidation settlements computed using the hyperbolic approach, were compared with an average degree of consolidation predicted by a rigorous theoretical solution accounting for radial and vertical consolidation induced by a time-dependent loading history and including the smear effect. The comparison allowed estimating proper values of the diameter describing the smeared zone and revealed the remarkable influence of the lithological and mechanical heterogeneity of the soil deposit.

1. Introduction

A reliable prediction of the ground settlements induced by preloading with vertical drains is a crucial aspect in the design procedures required for the engineering projects involving this well-established soil improvement technique. In fact, the results of the ground settlements prediction are decisive in the selection of the appropriate time for removing the preloading embankment, when the desired average degree of consolidation has been achieved in the soil deposit.

However, either using simplified theoretical solutions or advanced numerical approaches, unsuccessful predictions of the induced consolidation settlement are frequent, especially in the case of thick and/or heterogeneous soil deposits (e.g. [1–3]). This is mainly due to the use of values of parameters not effectively representative of the horizontal and vertical permeability of the soil deposit and to an improper selection of the input variables describing the smear effect.

Actually, most of natural clay deposits are not uniform, usually have a crust at surface and, sometimes, sandwiched thin sand layers (e.g. [4]); thus, the selection of appropriate input parameters, as well as the definition of the drainage contours, represent an extremely complex matter. Moreover, the boundary between smeared and undisturbed zones around the drains, as well as the permeability of the smeared zone, are key input parameters for the settlement prediction but, in practice, it is extremely difficult and to specify their values (e.g. [5,6]).

The use of observational procedures during the construction of the preloading embankment and during the overall preloading period, permits to adjust the prediction of the time-settlement relationship, leading to a reliable estimation of the final ground settlement, and, thus, allows savings in cost or time on geotechnical engineering projects (e.g. [7,8,2]).

Different observational procedures are available to monitor the induced consolidation process into the soil

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deposit; these range from the monitoring of excess pore water pressure dissipation to the estimation of the increase in undrained shear strength of cohesive soils. However, the analysis of the average degree of consolidation, evaluated from in-situ settlement measurements, is the most widely adopted and accepted criterion. In this context the estimation of the ultimate primary consolidation settlement (final settlement) of the soil deposit and the prediction of operative values of the horizontal consolidation coefficient represent more critical issues rather than fitting the measured time-settlement curve.

Among the methods developed to estimate the final settlement, the hyperbolic approach [9,10] and the method by Asaoka [8] are the most widely used.

The hyperbolic approach, as well as other derived methods based on a hyperbolic time-settlement relationship (e.g. [11–13]), provides a reliable prediction of the final settlement only when a large amount of the consolidation process (generally more than 60%) has already occurred; conversely, this approach leads to an overestimation of the final settlement if applied using the measurements carried out in the early stages of the preloading period.

Moreover, all the methods based on a hyperbolic time-settlements relationship are based on the assumption that external loads are applied suddenly.

Actually, the preloading embankment is gradually built-up, stage-by-stage, and a single ramp or multi-ramp loading history should be accounted for in the prediction of consolidation settlements (e.g. [14,15]). In presence of prefabricated vertical drains, which speed up the consolidation process, the loading history becomes an important issue especially when the construction of the preloading embankment takes a time interval which is a relevant portion of the overall preloading period. In these cases, the hypothesis of instantaneous loading may lead to a considerable overestimation of the consolidation settlements in the early stage of the preloading process (e.g. [14,16]); accordingly, the corresponding prediction of the final settlement obtained assuming a hyperbolic time-settlement relationship could be unsafe.

Asaoka's [8] method is probably the most widely adopted procedure to estimate the final settlement induced by the preloading process. However, this method does not allow predicting the time-settlement relationship and may underestimate the ultimate settlement of the soil deposit, depending on the time interval selected for the back-analysis (e.g. [17,2]). Finally, like in the hyperbolic approaches, a reliable estimation of the settlement time-history requires: (*i*) a long period of settlement measurements (for which a large amount of the consolidation process has already developed) and (*ii*), in order to make effective the hypothesis of instantaneous loading, a ramp loading stage of negligible duration in comparison with the overall preloading period.

The methods to estimate a field-value of the coefficient of horizontal consolidation C_h through a back-analysis of the settlement measurements are mainly based on the Asaoka's (e.g. [18–20]) or the hyperbolic methods (e.g. [19,12,13]). As a consequence, the above mentioned uncertainties in the prediction of the ground settlements may be reflected in the predicted values of C_h.

Based on these assumptions the paper describes a comparison between in situ measurements and theoretical predictions of the ground settlements 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.

In situ settlement measurements derive from an almost one-year long topographic monitoring period. Uncertainties on the topographic survey data were evaluated following the recommendations of the GUM [21], assessing the combined standard uncertainty, as it is usual also in geotechnical problems in which an indirect evaluation of displacements is involved (e.g. [22]). Measured settlements were used to estimate the final value of the consolidation settlements using the hyperbolic approach.

These estimates were then combined with an average degree of consolidation, provided by a theoretical solution for the consolidation process, to obtain a prediction of the settlement-time relationships. The theoretical solution is rigorous and refers to the combined radial and vertical consolidation process induced by a time-dependent loading in presence of vertical drains. The solution encompasses the possible occurrence of the smear effect, due to the drain installation, and was applied using values of the horizontal consolidation coefficient evaluated analyzing the rate of dissipation during *CPTU* tests carried out at the site.

The comparison between measurements and predictions are presented and discussed in the paper focusing on the important role of soil heterogeneity.

2. Work description and site geotechnical characterization

Two cylindrical steel tanks (diameter of 19 m and height of 15.6 m), namely *Tank*1 and 2, had to be built in a site characterized by compressible alluvial soils up to a depth of about 80 m, which resulted heterogeneous both in vertical and horizontal direction.

In order to keep tank foundation settlements within allowable limits ([23]), a preloading and vertical drains system was designed and installed at the site to induce a rapid soil consolidation process. The ground settlements induced by the embankment were monitored for almost one year.

A detailed description of the work sequence and of site geotechnical characterization can be found in [24].

Herein, a summary of the work sequence is provided together with the main aspects of site investigation and geotechnical characterization, focusing on the data and parameters relevant for the prediction of the ground settlement induced by the consolidation process during the monitoring period.

In the area where the tanks had to be constructed the ground surface was excavated to a depth of about 0.7 m and 20-m-long prefabricated vertical drains (*PVDs*) were installed in a triangular pattern, with a spacing of s_d = 1.5 m. *PVDs* were 97-mm-wide and 3-mm-thick wick