July 2014, Volume 8, No. 7 (Serial No. 80), pp. 824-832
Journal of Civil Engineering and Architecture, ISSN 1934-7359, USA

In Situ Tests—Predicted vs. Observed Settlements: A Comparative Case Study

Neritan Shkodrani[1], Ergys Anamali[1], Luisa Dhimitri[2] and Shpresa Gashi[1]

1. Department of Civil Engineering, Faculty of Civil Engineering, Polytechnic University of Tirana, Tirane 1001, Albania

2. Unit of Geotechnical Engineering, T.T. Soil & Earthquake Consulting, Tirane 1001, Albania

Abstract: This paper aims to deal with the comparison of the estimated settlements derived by in situ tests with the observed settlements in site, in order to evaluate the accuracy of settlement prediction by in situ tests, in comparison not only with site observation by topographic means, but also with the values of settlements derived by numerical analysis by means of PLAXIS 2D and 3D. The site where are carried out the tests and periodically are observed the settlements since the beginning of construction process, is located in the Oil Product Terminal, at the industrial park of Porto Romano, Durres, Albania. The main purpose of this project was the ground improvement by using preloading method in order to prevent liquefaction process and settlements. The data used to conduct this study are taken by the site investigation done after inserting into the soil vertical drains made of columns of free—draining gravel (gravel pile drains) until 14 m depth and center-to-center spacing of 2 m, and wick drains (premanufactured) until 25 m depth and center-to-center spacing of 1.8 m. The observed settlements are periodically measured by topographic equipments. This paper will present the conclusions derived by settlement analyzes from in situ tests and site observations.

Key words: Settlements, cone penetration test, dilatometer test, constrained modulus.

1. Introduction

Predicting settlements is one of the biggest advantages of in situ tests (CPT (cone penetration test) and DMT (dilatometer Marchetti test)), especially in cases, where it is difficult to carry out laboratory tests. Each of the tests predicts the settlements by using the value of constrained modulus "M", evaluated by different methods. In this case, particular attention is paid to the correlation methods and the way of determining the constrained modulus from in situ tests.

The more accurate determination of soils properties that cannot be easily sampled in the undisturbed state and the ability of testing a larger volume of soil are the main reasons for the growing interest in the use of in situ testing techniques. These tests are very reliable methods for predicting the rate and the magnitude of settlements, especially in cases of embankment constructions in soft and sensitive soils. One of these case studies is presented in this paper. The aim of this study is to evaluate the settlement by using the data obtained by a series of piezocone tests and seismic dilatometer tests (hereafter mentioned as CPT and DMT), including also the comparison of CPT and DMT—calculated vs. observed settlements, in order to evaluate the accuracy of settlement predictions based on these tests.

2. Project Overview

The oil product storage in Porto Romano is located 10 km far from Durresi city, on a flat construction site, with an area equal to 67,000 m^2, at an average present level of -0.42 m, below the sea level. Thirteen oil product storages vertical tankers (deposits) of different capacities, one LPG (liquefied petroleum gas) tanker, one water storage tanker, pipelines, office building, roads and railway were foreseen to be part of this project. In this study, only four tankers for oil products (T-02, T-03, T-06, T-07) are considered. The area

Corresponding author: Neritan Shkodrani, Ph.D., research fields: soil mechanics and foundation engineering. E-mail: neritans@yahoo.com.

where are located these tankers, is the one where there are sufficient data from in situ tests and observed settlements in site, to conduct this study. The complete view of this area of the construction site, including also some of the oil product vertical storages (T-01, T-02, T-03, T-04, T-05, T-06, T-07, T-12, T-13) and the LGP is given in Fig. 1. Meanwhile, a list of the oil product storages vertical tankers and the dimensions of the oil product vertical storages and LPG are given in Table 1, where are bold face the oil product storages vertical tankers which are considered in this study.

At the end of the preliminary geotechnical investigation, when it carried out twelve boreholes, the site was reported to be in unfavorable geotechnical

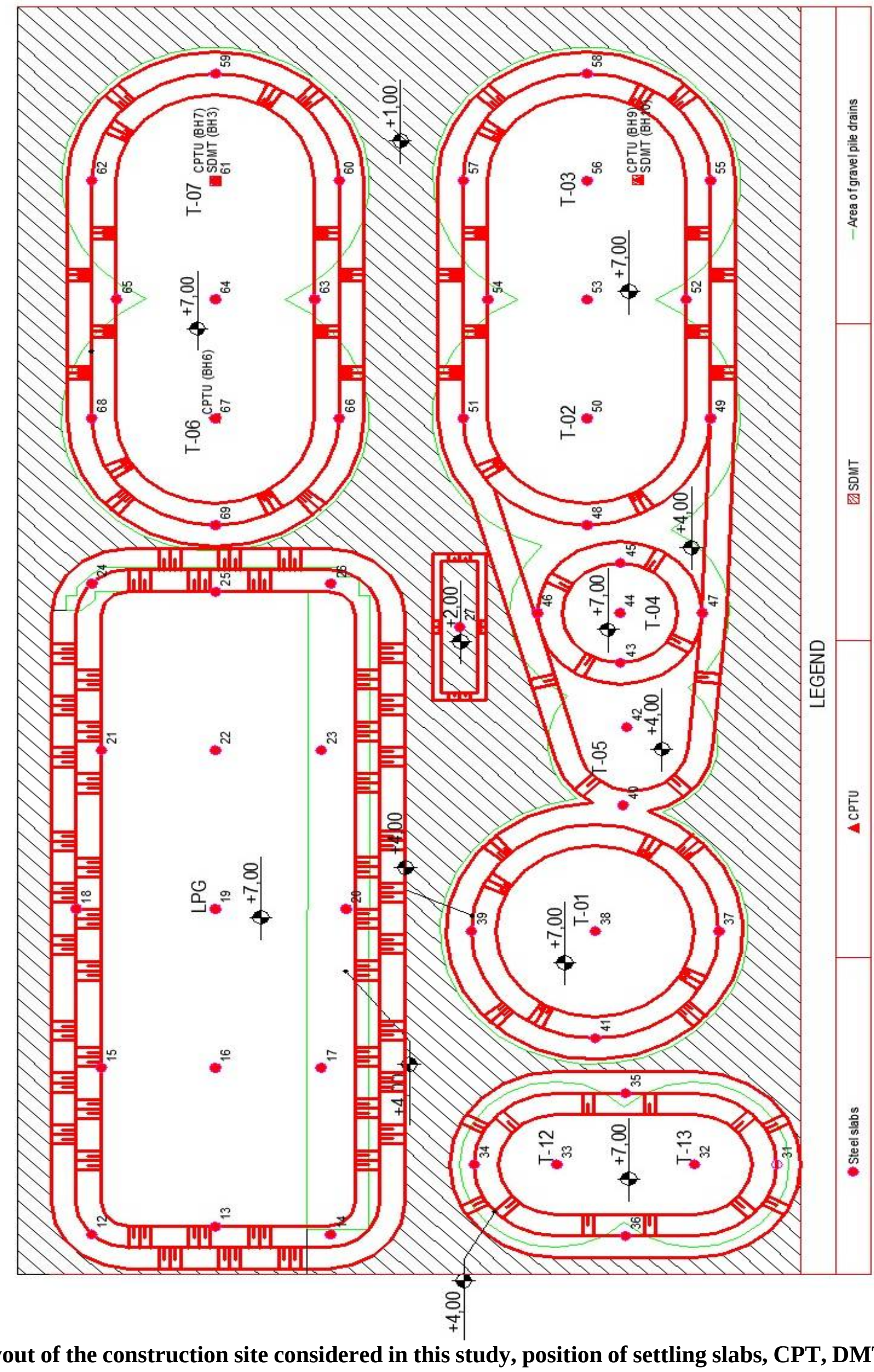

Fig. 1 General layout of the construction site considered in this study, position of settling slabs, CPT, DMT and area of gravel pile drains.

Table 1 List of deposits and their dimensions.

Deposit	*V* (volume) (m^3)	D_R (m)	D_{OD} (m)	*H* (hight) (m)
T-01	20,000	36	42	20
T-02	**20,000**	**36**	**42**	**20**
T-03	**20,000**	**36**	**42**	**20**
T-04	5,000	21	26	14.5
T-05	1,000	12	17	10
T-06	**20,000**	**36**	**42**	**20**
T-07	**20,000**	**36**	**42**	**20**
T-12	5,000	21	-	14.5
T-13	5,000	21	-	14.5
LPG	550 × 21	-	-	-

Table 2 Soil layers and properties.

Soil	Thickness *z* (m)	Unit w height γ (kN/m^3)	Cohesion *c* (kPa)	Friction angle φ (°)	Oedometer modulus E_{OED} (kPa)
Fill	3.25	22	1	40	40,000
Silty clay	2.00	19	5	18	3,000
Silty sand	10.00	18.5	1	33	25,000
Silty clay	6.00	18.5	1	20	1,500
Silty clay	8.00	18.5	1	20	1,500
Sand	16.00	20	1	38	30,000

conditions due to the high presence of organic material and sensitive formation until 2 m of depth. The underground water level, measured in site varies from 0.5 m until 0.8 m under the ground surface. Shallow foundations were foreseen to be used in this project, embedded in a small depth from the ground surface. In order to improve the ground conditions, it was decided to use the preloading method by constructing an embankment [1].

The embankment was foreseen to be constructed in two different phases due to sensitive soils met under the ground surface and the low bearing capacity, and its final height was foreseen to be equal to +7.00 m.

The geotechnical design was conducted by TOP Project d. o. o. from Zagreb, Croatia and all the results were given in the report No. E-28-09. As part of this report, recommendations concerning the fill of the site and the method of embankment's construction were given. As part of the geotechnical study, it is also reported the settlement analysis by means of PLAXIS 2D and 3D. During these analyses, it is taken into consideration, only a part of the construction site, where are located four oil product vertical storages (T-02, T-03, T-06, T-07). These are the same tankers, we considered in this study. The soils properties considered for PLAXIS 2D analysis are determined by the laboratory tests carried out into five samples taken in site during the preliminary geological study, which are given in Table 2 [2].

In PLAXIS 2D, the general fill until +3.25 m was considered for creating the numerical model. The bulk density of the fill material is given in Table 2. While, the preloading (from the general fill up to the level of +7.00 m) was modeled as a surcharge equal to 80 kPa, only within the tanker area of 42 m diameter.

Initially the range of the settlement was calculated by means of PLAXIS 2D, and then for more accurate conclusions it was calculated with PLAXIS 3D. The considered reported case is the one that matches with the case in which this study is dealing with and it is given in Table 3.

On further to these calculations, the load during the settlement calculations is considered to be equal to 130 kPa, considering both the effect of general fill up to the level of +1.00 m and the preloading up to the level of

Table 3 Calculated settlements at the oil terminal by means of PLAXIS 2D and 3D.

Case	Calculated settlements
Settlement under preloading for 42 m diameter tank (+7.00 m)—PLAXIS 2D	76 cm
Settlement under preloading for 42 m diameter tank (+7.00 m), full consolidation—PLAXIS 2D	67 cm
Settlement after 3.25 m of general fill—Phase 1, PLAXIS 3D (analysis withthout vertical drains)	36 cm
Settlement after 80 kPa preloading including settlements from Phase 1 to Phase 2, PLAXIS 3D (analysis without vertical drains)	69 cm
Settlement after 80 kPa preloading including settlements from Phase 1 to Phase 2, PLAXIS 3D (analysis with vertical drains)	92 cm

+7.00 m. It acts on the ground surface (level ±0.00) and represent the total load only within the area of oil product vertical storages with a diameter of 42 m.

The construction of the embankment was executed into two phases, reaching first the level of +3.25 m and after, the embankment was finalized at the level of +7.00. But, before starting construction of the embankment, it was necessary to install the drainage system. For this purpose, on the ground surface, it was laid a layer of geosynthetic material. It covered all the area, except the area where were foreseen to be constructed the free—draining gravel piles. In the area of gravel pile drains was placed a layer of 20-30 cm of fine sand. Before executing the first phase of embankment construction, the gravel pile drains and premanufactured wick drains were installed, in order to accelerate the consolidation process. The diameter of gravel pile drains was equal to 80.0 cm and the total depth was 14.0 m, measured at the ending level the general fill. Meanwhile, the wick drains reached the depth of 25.0 m from the same level. In order to collect the water coming from vertical system of drains, a system of horizontal drains was installed. The cross section of the vertical drainage system is shown in Fig. 2.

After the construction of the general fill and drainage system, it was necessary to perform another site investigation in order to have information about their effect on the ground conditions. 4 CPTs and 2 DMTs were carried out. The locations of in situ tests are also shown in Fig. 1 [2].

The results of these tests are used in this study to estimate the settlements by each in situ testing method and then comparing the results of in situ predicted settlements with observed settlements in site. The observed settlements in site were estimated by topographic means, installed in site before starting the preloading process. At the area of the site taken into consideration, where are located tankers T-02, T-03, T-06 and T-07, 22 circular steel plates with diameter equal to 500 mm and ruler steel rods installed in the flat plates, were placed at the level of +1.00 m from the ground surface. The location of the steel plates and the rods in the considered area is shown in Fig. 1.

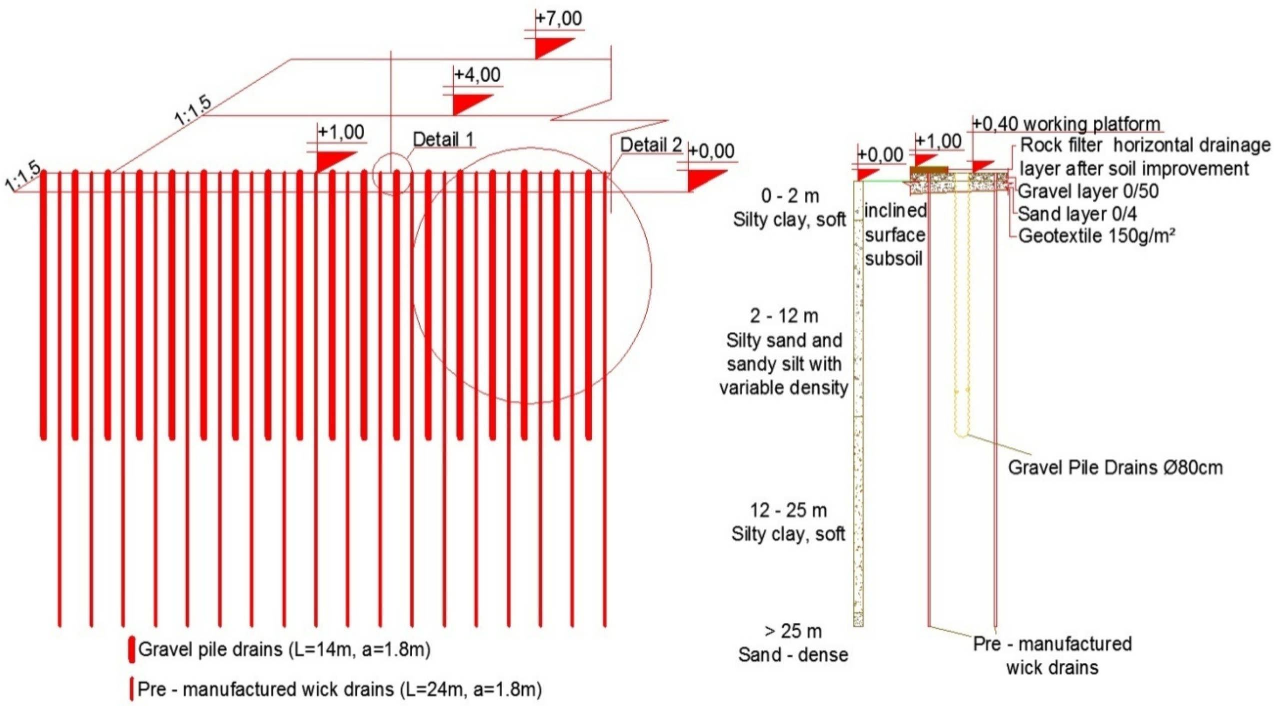

Fig. 2 Cross section of drainage system installed in site and the detailed drawing of gravel pile drains.

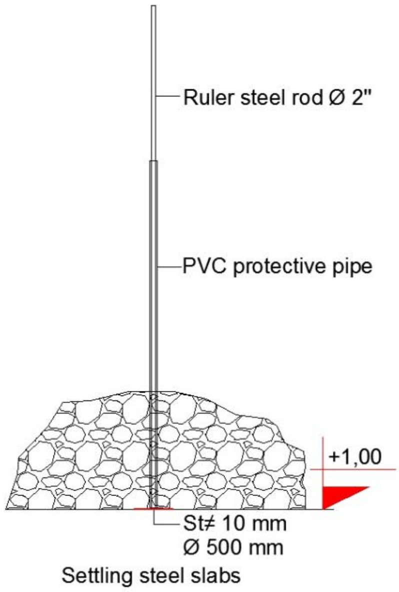

Fig. 3 Settling slab and ruler steel rod to observe the settlements in site.

Table 4 Average values of settlements observed in site.

Tanker name	Load (kPa)	Steel slab No.	Settlements sum, ΣS (cm)	Average settlement, $S_{average}$ (cm)
T-02 T-03	130	R 48	7.76	9.2401
		R 49	11.62	
		R 50	3.86	
		R 51	12.73	
		R 52	9.74	
		R 53	14.39	
		R 54	9.56	
		R 55	12.25	
		R 56	12.21	
		R 57	4.25	
		R 58	3.28	
T-06 T-07	130	R 59	8.25	13.69
		R 60	2.74	
		R 61	17.85	
		R 62	5.61	
		R 63	21.73	
		R 64	23.18	
		R 65	16.87	
		R 66	11.19	
		R 67	22.43	
		R 68	2.23	
		R 69	13.57	

Meanwhile, the detailed drawing of the settlement observation system in site is shown in Fig. 3. The height of each ruler steel rod is more than 7.0 m, in order to exceed the final total height of the embankment. The results of the observed settlements in site are given in Table 4.

3. Calculation Methods for Prediction of Settlement by Using in Situ Tests

In order to calculate the settlements, the methods which use theory of elasticity to estimate the distribution of the stress increase and modulus are applicable in all types of soils. The modulus may be estimated empirically or semi-empirically by in situ tests. The methods used to evaluate the settlements by means of in situ tests, are described as follows.

3.1 Settlement Calculations Using the CPT

The good estimations of soil modulus over a wide range of uncemented soils, from soft clay to dense sands, by using CPT, are based on linear elasticity theory and provide settlement values proportional to the loads [3].

Consolidation settlements can be estimated using 1D constrained modulus, M_{CPT} (CPT constrained modulus), which is calculated by the formula given the following [1]:

$$M = \frac{1}{m_v} \tag{1}$$

where, m_v → equivalent oedometer coefficient of compressibility.

The one dimensional constrained modulus, M_{CPT} can be estimated from the CPT using the Eq. (2) [1]:

$$M_{CPT} = \alpha_M (q_t - \sigma_{v0}) \tag{2}$$

where,

α_m → a coefficient, which varies with soil plasticity and natural water content;

q_t → cone resistance corrected for pore pressure effects;

σ_{v0} → in situ total vertical stress [4].

The value of settlements is calculated by the formula given below:

$$S = \sum \frac{\Delta\sigma_v}{M_{CPT}} \cdot \Delta z \tag{3}$$

where,

$\Delta\sigma_v$ → the change in vertical stress due to the loading, generally calculated according to Boussinesq;

M_{CPT} → constrained modulus that can be estimated from CPT tests;

Δz → the interval between readings.

3.2 Settlement Calculations Using the DMT

One of the most widely applications of DMT test results to engineering problems is the prediction of the settlements. They are generally calculated by means of 1D Eq. (5), which being based on linear elasticity provides a settlement proportional to the load, and is unable to provide non linear prediction [4].

M_{DMT} is a "corrected" modulus and the deformation properties in general are derived from it. The DMT modulus is obtained by Eq. (4) [5]:

$$M_{DMT} = R_M \cdot E_D \tag{4}$$

where,

$R_M = f(I_D, K_D)$→ correction factor strongly related to K_D and varies in range of 1 to 3;

E_D → dilatometer modulus obtained as: E_D = 34.7 · (p_1 − p_0) and it is used only in combination with I_D and K_D.

The value of settlements is calculated by the formula given in Eq. (5):

$$S_{1-DMT} = \sum \frac{\Delta\sigma_v}{M_{DMT}} \cdot \Delta z \tag{5}$$

4. Results of in situ Predicted Modulus and Settlements

In this section, the values of constrained modulus M, derived by CPT and DMT, and also calculated settlements based on the data of in situ tests, are presented as follows.

4.1 Modulus Derived by in Situ Tests

The results of the derived modulus M, by CPT and DMT are given in Fig. 4. In the first graph, it is shown the variance of the constrained modulus measured in site by means of DMT and CPT, carried out at tankers area T-02 and T-03. The second graph in Fig. 4, shows the same variance of the data processed by the tests carried out at tankers area T-06 and T-07. The CPTs are carried out until 15.0 m of depth and the derived constrained modulus by the measured parameters is given continuously each 2 cm. Meanwhile the DMTs are carried out until 26.0 m of depth, and the constrained modulus measured in site is reported in a

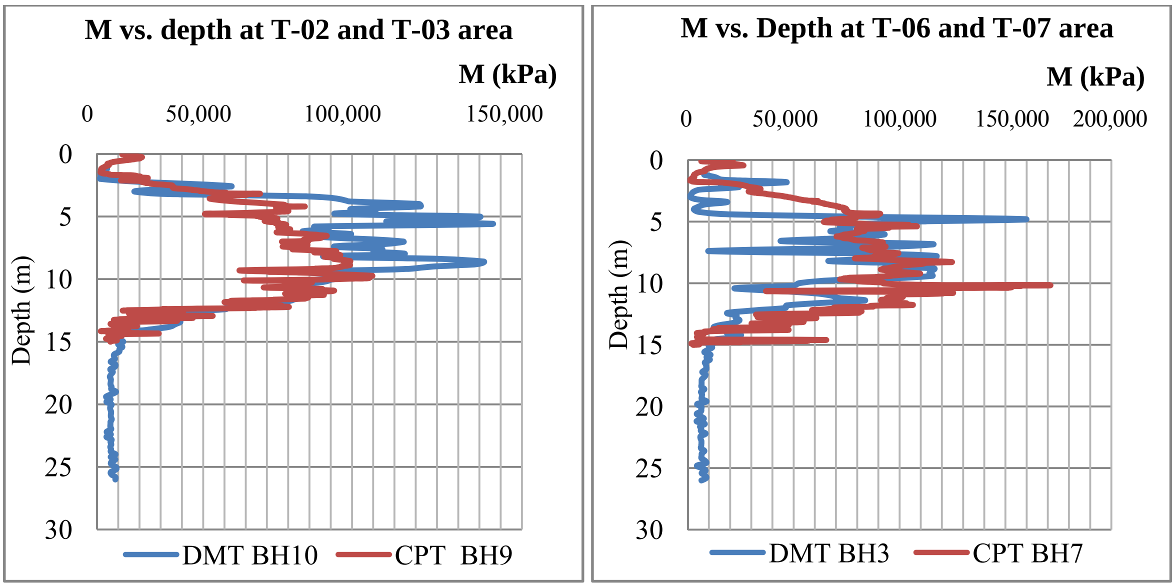

Fig. 4 M vs. Depth by CPT and DMT.

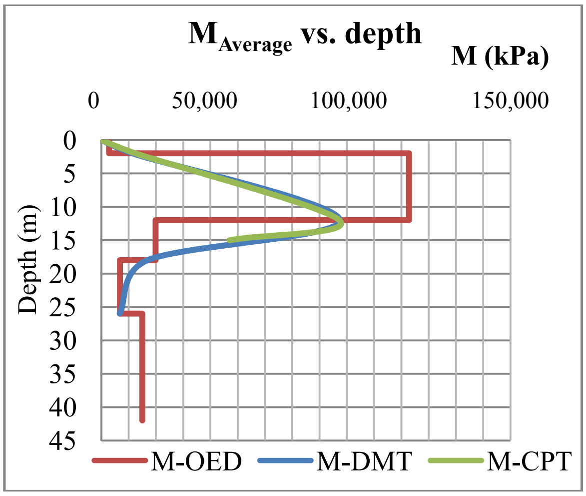

Fig. 5 $\mathbf{M_{Average}}$ vs. Depth by Oedometer, DMT and CPT.

frequency of each 20 cm. Fig. 5 shows the differences between the modulus determined by laboratory tests (oedometer) and in situ tests (CPT and DMT). The oedometer tests are carried out into five samples of soils, one sample for each layer, taken in site during the preliminary geological study. The values of oedometer modulus are considered to be constant for the whole thickness of soil's layer and are presented in Table 2. The values of the modulus, derived by oedometric tests are calculated by Eq. (6):

$$M_{OED} = \frac{E_{OED}}{\beta} \tag{6}$$

where,

E_{OED} → modulus of soil total deformation obtained by oedometer test;

β → coefficient characterizing lateral expansion of soil, which has different values depending from the soil type [6].

The values of the constrained modulus by CPT and DMT are the averages for each layer of soil, considering all the data reported for each kind of test.

In this graph, it is noticed a very good accordance, between the constrained modulus derived by in situ tests. Meanwhile the values derived by oedometer tests have big differences with those derived by CPT and DMT.

4.2 Predicted Settlements from in Situ Tests

Settlements presented below are calculated by using the data of 4 CPT and 2 DMT tests. The settlements are computed according Eqs. (3) and (4) by dividing the soil beneath the embankment into layers of 2 cm for CPT and 20 cm for DMT, computing the settlement of each layer, and summing.

The summation must be extended up to a depth below which the deformations can be neglected. This depth, identified as active compression zone, must satisfy the requirement:

$$\Delta\sigma_z / \sigma'_{z0} < 0.1 \tag{7}$$

The settlements calculated considering all the layers up to the depth of investigation by CPTs and DMTs (15 m and 26 m, respectively) are reported in Table 5. Although, the total settlements predicted by in situ tests are expected to be higher, since the Eq. (7) is not satisfied. The ratio between induced stress ($\Delta\sigma_z$) and initial vertical effective stress (σ'_{z0}) is ≈ 0.8 and ≈ 0.3, at the depth of 15.0 m and 26.0 m, respectively. In order to predict the total settlement, the analysis must involve the entire active compression zone, which according to our calculations reaches the depth of 42.0 m, approximately.

Table 5 also reported the consolidation settlements calculated by using the modulus derived by oedometric

Table 5 Calculated settlements by CPT, DMT and OEDT (Oedmeter test).

Diameter of preloading (m)				42.0
Load (kPa)				130
Settlements (cm)	Case 1—Active zone 15.0 m	CPT	CPT BH6	7.58
			CPT BH7	10.08
			CPT BH9	9.58
		DMT	DMT BH3	12.82
			DMT BH10	8.50
		OED	Oedometer test	13.75
	Case 2—Active zone 26.0 m	DMT	DMT BH3	26.24
			DMT BH10	22.08
		OED	Oedometer test	56.1
	Case 3—Active zone 42.0 m	OED	Oedometer test	57.45

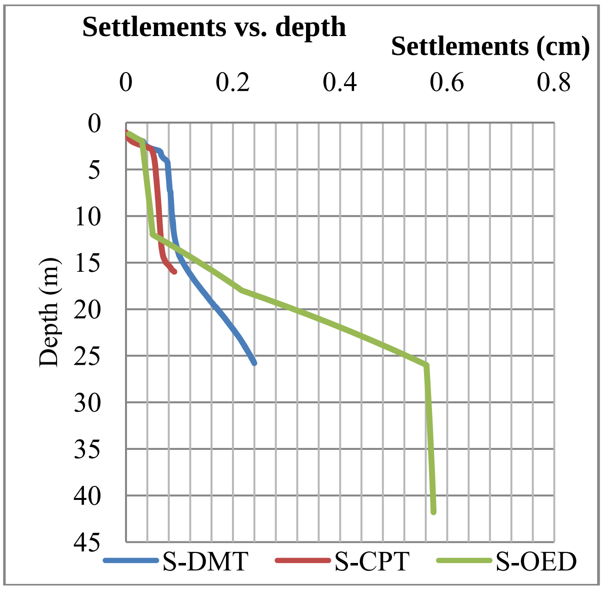

Fig. 6 Settlements vs. depth, by DMT, CPT and Oedometer.

tests. During the settlement analysis the depths of 15.0, 26.0 and 42.0 m are considered.

5. Conclusions

This study deals with the settlement analysis considering the data taken by laboratory tests and in situ tests and the comparison of the settlement results with the observed settlements by topographic means.

In order to accelerate the consolidation process, an embankment was constructed and the settlements of the site were periodically observed.

Based on the comparison of calculated settlements with the observed settlements in site, the following conclusions can be made.

The CPT and DMT methods estimate the settlement within the same range of accuracy. This is clearly shown in the Fig. 6 and from the numerical results given in Table 5. For example, at the locations of tankers T-07 and T-03, CPT/DMT gives almost the same settlement for the Case 1 (T-07: 10.08/12.82 cm and T-03: 9.58/8.50 cm, respectively).

The results also show that the CPT estimated M modulus is in a good agreement with the values of constrained modulus derived by DMT (Fig. 5). For this reason they predict similar settlement.

It is known that settlement is strongly affected by the depth of active compression zone, which in this case arrives until a depth of 42.0 m. Because of the limited depth of investigation by CPT and DMT it is not possible to estimate the value of total settlement, even in the case of DMT which reaches a larger investigation depth, up to 26.0 m. Calculations by oedometer methods show that the increase of the active compression zone below 26.0 m increases the value of settlement only by 1.35 cm. Since this increase in settlement value is not so high, most probably the total settlement predicted by DMT is not exceeding the value of 26.24 cm.

Total settlements derived by the data of oedometer test are clearly much larger then values predicted by CPT and DMT. The settlements calculated by the classical methods or PLAXIS 2D and 3D, both based on oedometer test data, are already 2 times higher than the settlements estimated by CPT and DMT methods. For example, until a depth of 26.0 m oedometer methods produce a settlement of 56.1 cm, while the DMT method gives a settlement of 22.08 to 26.24 cm. PLAXIS 2D and 3D produce values of settlements even larger than those of the classical methods. This is maybe due to the differences between the modulus estimated by these methods and because the oedometric modulus is kept constant for each layer, during the calculations. The in situ methods have the advantage of providing continuous profiles and soil properties with depth, as the values of modulus for example.

It is evident that all the settlements calculated by CPT and DMT methods or oedometer methods give values much larger than those observed in site. But, the difference is much smaller in the case of in situ tests.

In addition, performing in situ tests is much faster compared to the sampling and subsequent laboratory testing of soil samples. Hence the in situ methods settlement estimations can substitute the traditional settlement calculations based on laboratory tests that is time-consuming and cannot be run as cost—effective as in situ tests.

References

[1] P.K. Robertson, K.L. Cabal, Guide to Cone Penetration Testing, 5th ed., Greg Drilling & Testing, INC. Corporate Headquarters, Signal Hill, California, 2012.

[2] J. Logar, Geotechnical Design report E-28-09, Oil Product Terminal in Porto Romano, Durres, Albania, Top Project d.o.o., Zagreb, Croatia, 2009.

[3] T. Lunne, P.K. Robertson, J.M. Powell, Cone Penetration Testing in Geotechnical Practice, Spon Press Taylor & Francis Group, London & New York, 2009.

[4] On Ground Property Characterisation from in situ Testing, The Flat Dilatometer Test (DMT) in Soil Investigations, Report of the ISSMGE Technical Committee 16, 2001.

[5] P. Monaco, G. Totani, M. Calabrese, DMT—Predicted vs. observed settlements: A review of the available experience, in: Proceeding of the 2nd International Flat Dilatometer Conference, Washington D.C., Apr. 2-5, 2006.

[6] N. Tchytovich, Soil Mechanics, 2nd ed., Mir Publishers, Moscow, 1981.