# Evaluation of piezocone characterization in deltaic deposits

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ABSTRACT: At the Port of Ploce, situated in the river Neretva delta at south Adriatic coast of Croatia, intensive building activities are undertaken. Comprehensive and massive geotechnical investigations are needed for different structures, including drilling, laboratory testing on samples, and in situ penetration testing. Soft soil prevails in first 40 m of foundation soils. Since the quality of undisturbed samples was not satisfactory, in situ tests were used as a source for parameters for geotechnical design. CPTU, DMT, SDMT and VT tests were performed over the area. It was necessary to correlate shear strength and moduli obtained by different tests, in order to complete data for specific locations where only some testing was conducted. Useful correlations and good agreement in predicting undrained strength and moduli are shown in this paper, confirming the power of in situ tests in characterizing geotechnical properties of soft soils.

## 1 INTRODUCTION

Comprehensive geotechnical investigations have been carried out in deltaic deposits at the Port of Ploce in order to enable design and construction of the new bulk cargo (BCT), container (CNT) and liquid cargo (LCT) terminals. The Port of Ploce is located in the Neretva River mouth on the South Adriatic coast in Croatia.

The soils in the area of the Port of Ploce are formed of Quaternary deposits. The deltaic formations were formed through the Neretva River depositions, but also through marine influences, due to the changes in sea level that occurred in course of the Quaternary. The sediments of the delta appear in the form of thick formations (more than 100 m) accumulated through the clayey Paleozoic relief. The accumulation of a complex series of marine, fresh water-brackish, and laguna deposits started as early as in the Pleistocene and is still continuing today. The composition of formations varies from clay and sand to gravel, but the consistency and density generally increase with the depth. Groundwater is influenced by the sea and occurs mainly as brackish or fresh water, which depends on periodical oscillations of fresh water inflow from the river or sources at the rock and soil contact, and may be upward in character.

The investigation was focused on the soil layers reaching down to about 40-50 m in depth, where the dense and thick gravel deposit, forming reliable bearing base for most of the planned construction work, is situated. The typical soil formation of the investigated area is presented in Figure 1. The subsoil profile within the top 50 to 55 m can be roughly divided into three distinguished layers. Starting from the top, the profile includes: 1) loose sand and silty sand of variable thickness reaching down to approximately 12-15 m below the sea level; 2) normally consolidated clay layers down to 33 m below the sea level and 3) dense silty gravel layer. The top loose sand and silty sand layer in the area of CNT is thinner than in areas of BCT and LCT.

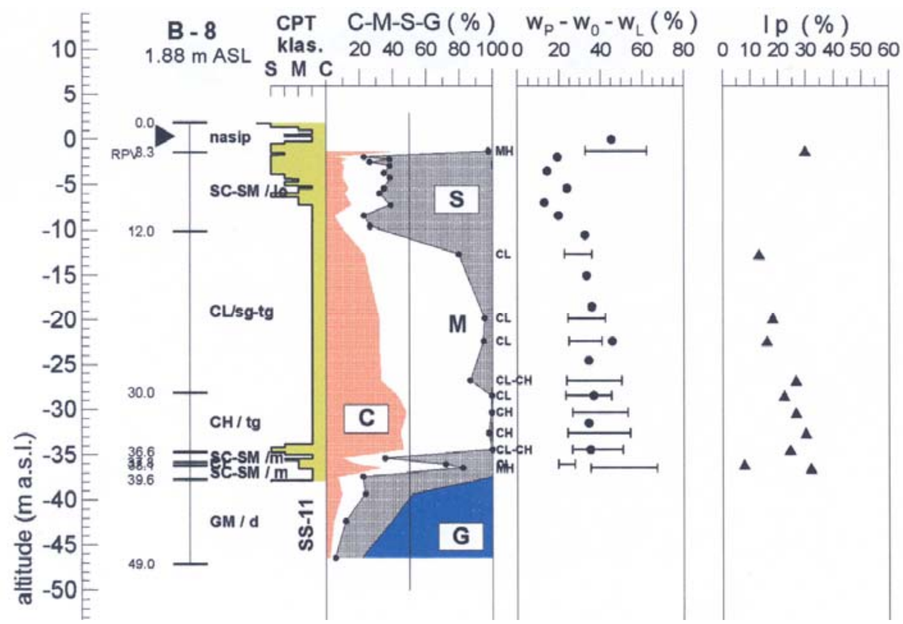


Figure 1. Typical soil profile at the BCT Ploce in Croatia.

The terrain of the investigated area is generally flat with altitude ranging from about +1.5 to +4 m above sea level (ASL). Centres of terminal areas (BCT-CNT-LCT) form approximately equilateral triangle, with site length of about 1 km.

The investigation program in areas of the bulk cargo (IGH, 2007) and container (IGH, 2006) terminals included 19 piezocone tests (CPTU) in total, among which 13 were deep tests down to the top of the silty gravel layer (about 40 m below ground level). The program further included drilling of 8 onshore and 2 offshore boreholes from which numerous samples were taken. In addition, 51 field vane (VT) and 102 standard penetration tests (SPT) were carried out within the boreholes as well. One borehole was drilled down to the bedrock (-98 m below ground level) while others were finished in the gravel layer. The “undisturbed” samples were taken by means of a fixed piston tube sampler technique. Unfortunately, during the laboratory testing it became evident that most of samples taken in soft clay formations were disturbed and therefore the laboratory results were considered unreliable. This fact promoted significance of in situ penetration tests for geotechnical design. The investigation program in the area of the liquid cargo terminal (Leta, 2009) included 6 deep piezocone tests, one standard (DMT) and one seismic (SDMT) dilatometer test down to 38.5 m depth.

In this paper stress history, strength and deformation characteristics of normally consolidated clay layers found in the studied area are analysed based on in situ test results. Comparisons between CPTU, DMT/SDMT and VT results are made and discussed.

In addition, measured ground movements are compared to calculated ground movements based on in situ test results, in the area were crushed rock embankment was used for preloading as a part of ground improvement measures.

## 2 COMPARISONS OF TEST RESULTS

Representative CPTU, VT, DMT and SDMT profiles obtained in the studied area are presented in Figure 2. The results of investigations, and piezocone results in particular, show that the bedding of the soil profile is primarily horizontal. The clayey formation and its boundary horizons are characterized by similar values of the cone resistance in the whole area under study. The depth interval were soft clay was detected was between 8-10 m and 33-35 m below the sea level. All test results presented here are related to the altitude, so as to compare the same soil stratigraphy at different locations.

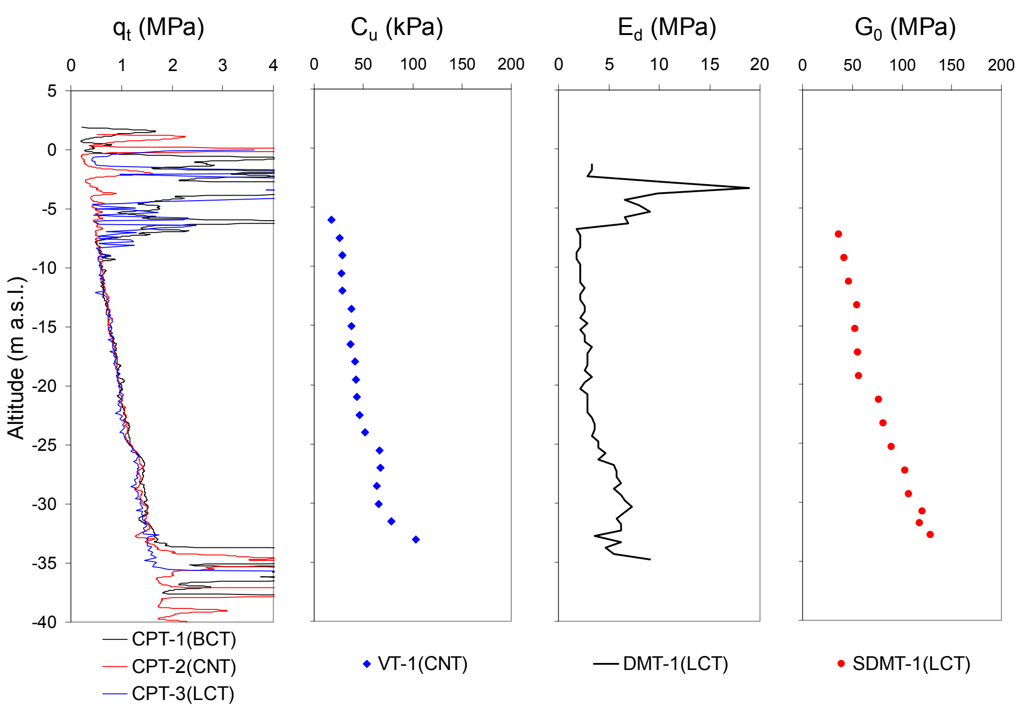


Figure 2. Representative CPTU, VT, DMT/SDMT profiles in Ploce, Croatia.

A piezocone profile designated as CPT-2(CNT), a dilatometer test DMT/SDMT-1(LCT) (only one test run), and vane test VT-1(CNT), all presented in Figure 2, are chosen for further comparisons of derived geotechnical parameters for the normally consolidated (NC) clay layer. Parameters to be presented here through different correlations are required for geotechnical design in the area. Due to fact that limited tests in type and quantity were available at different micro-locations in the area, it was useful to offer reliable correlations for particular soil parameter (*OCR*, $C_u$, oedometer modulus, shear modulus) interpreted using results from different test types.

The overconsolidation ratio, *OCR*, shown in Figure 3a, is estimated based on the corrected total cone tip resistance ($q_t$), using the following correlation:

$$OCR = k\frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \quad (1)$$

where the coefficient $k$ value is 0.25 (Kavur et al. 2008). The *OCR* estimated based on dilatometer test results (Marchetti, 1980) is also shown in Figure 3a. It is evident that clay is normally consolidated.

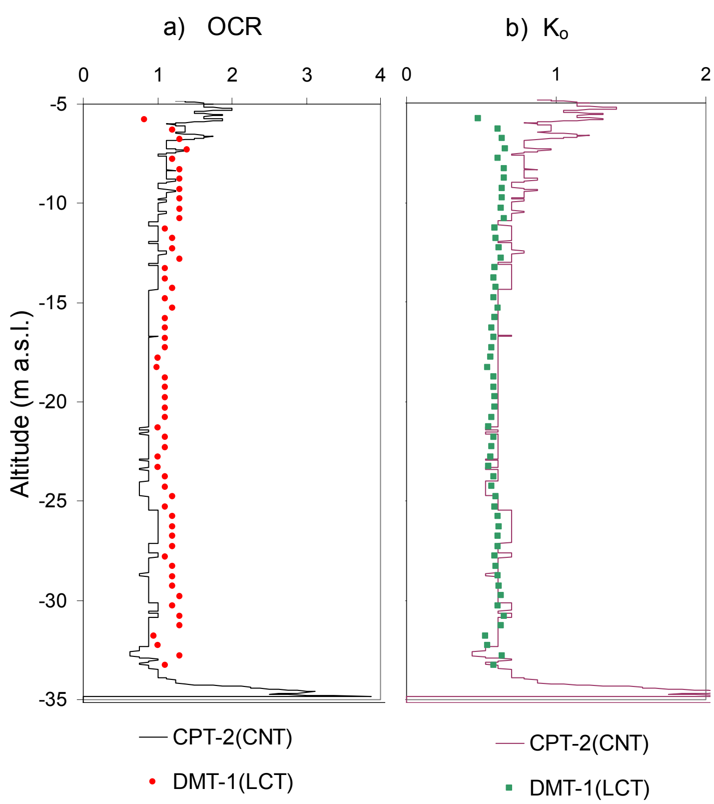


Figure 3. CPTU vs. DMT estimates of: a) OCR and b) $K_0$, in NC Neretva River clay, Croatia.

Values of the coefficient of lateral earth pressure at rest, $K_0$, required for design of supporting structures, shown in Figure 3b, are estimated from DMT (Marchetti, 1980) and $q_t$. For the latter one, the correlation developed to fit DMT prognoses was

$$K_0 = 0.175 \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \quad (2)$$

Kulhawy and Mayne (1990) recommend a coefficient value of 0.1 (instead of 0.175) to be used in correlation (2) for $K_0$ estimates.

The most interesting parameter for geotechnical design was the undrained shear strength, $C_u$. The value obtained by VT was taken as a reference value. Values of $C_u$ are also interpreted from DMT and CPT results and are shown together with reference values on Figure 4a. A piezocone estimated curve is calculated by the correlation:

$$C_u = \frac{q_t - \sigma_{vo}}{N_{kt}} \quad (3)$$

with $N_{kt}$ = 14. Values of $C_u$ from DMT results were derived using Marchetti (1980) suggested interpretation. All three tests show extremely good agreement in defining undrained shear strengths.

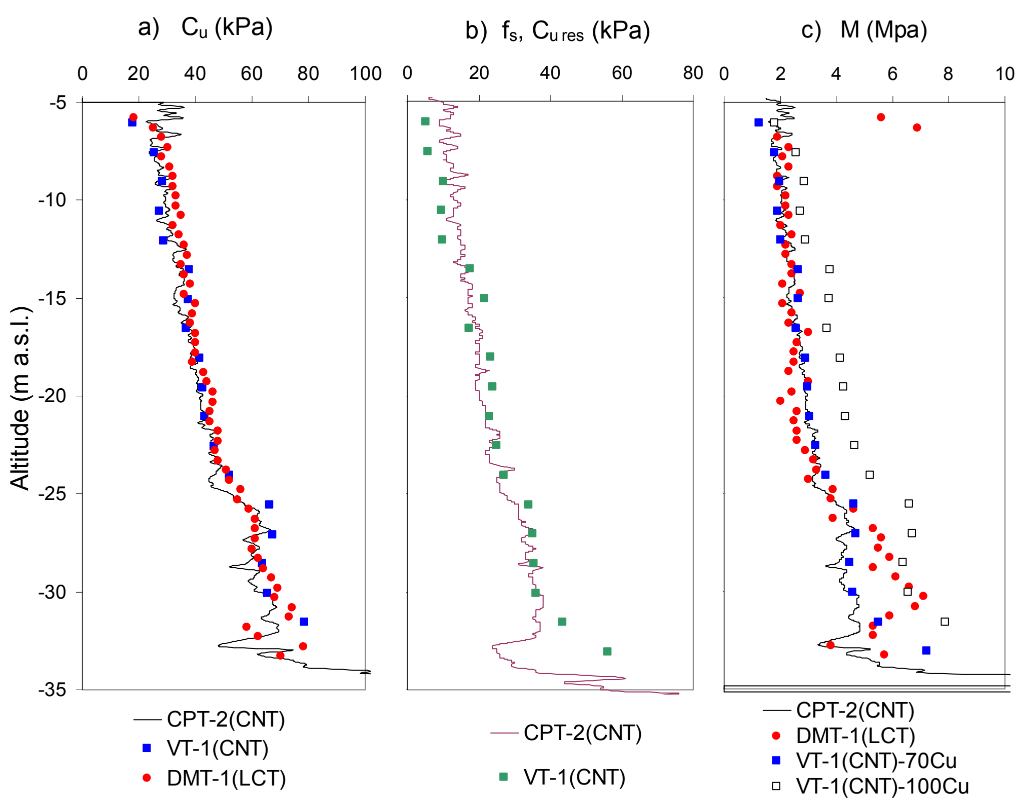


Figure 4. Strength and deformation characteristics of NC Neretva River clay based on CPTU, DMT and VT results: a) peak undrained shear strength; b) CPT friction sleeve vs. VT residual shear strength; c) modulus of compressibility.

The residual shear strength, $C_{u\ res}$, expected to be used in design of driven piles, was obtained by vane test. That value is compared with a sleeve friction, $f_s$, from a piezocone test, in Figure 4b. A very good agreement between these two curves is obtained. The clay sensitivity, $S_t$, based on peak and residual vane shear test values, ranges from 2 to 4.

Settlement calculations were required for embankments constructed for different purposes, and good prognoses of compressibility in terms of the constrained modulus ($M$) was of special interest (Figure 4c).

The CPT estimated curve of the modulus of compressibility, $M$, is determined by the correlation (4) for stresses below the preconsolidation pressure:

$$M = m_i\, q_{net} = m_i\,(q_t - \sigma_{vo}) \tag{4}$$

where $m_i$ = 5 was used. According to Senneset et al. (1989), $m_i$ ranges between 4 and 8 in NC clays. In geotechnical practice many times engineers use undrained shear strengths in predicting soil modulus. Here, values of $C_u$ obtained by VT were used to estimate values of $M$, using two multiplication factors: $70\times C_u$ and $100\times C_u$. Relatively good agreement between CPT, VT ($70\times C_u$), and DMT estimated values (Marchetti, 1980) was obtained in the upper low plasticity (CL) clay layer, found between -7 and -27 m a.s.l. In the lower high plasticity (CH) clay layer, DMT estimates of $M$ are higher than both the CPT and VT ($70\times C_u$) interpreted values.

The SDMT test, run as one single test to 35 m depth, enabled $G_0$ interpretation by depth, which was proven to give reliable results in these soils (Cavallaro et al. 2006).

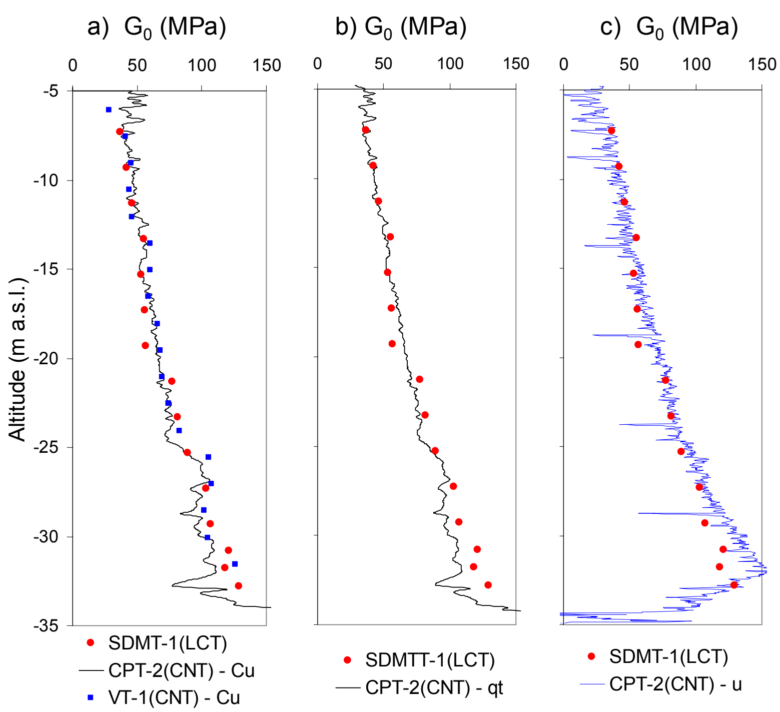


Figure 5. SDMT measured vs. estimated small strain shear modulus ($G_0$) based on: a) undrained shear strength ($C_u$); b) corrected total cone tip resistance ($q_t$); c) excess pore pressure ($\Delta u = u_2 - u_0$).

In order to be able to use other tests for estimation of $G_0$ at locations where SDMT was not performed, several existing correlations were checked using $G_0$ (SDMT) values as reference values. The VT test was used to check correlation (5) suggested by Larsson & Mulabdic (1991)

$$G_0 = \frac{k \times C_u}{w_L} \tag{5}$$

where the average liquid limit value of $w_L$ = 0.45 was used. Larsson and Mulabdic (1991) recommended a coefficient value $k$ = 500, but in our case value $k$ = 720 better fitted reference value. In Figure 5a this correlation is denoted as VT-1(CNT)-$C_u$ and CPT-2(CNT)-$C_u$.

For CPTU it was found that several parameters can be used in estimating $G_0$, as shown in Figure 5b. Fitting to $G_0$ (SDMT) values was achieved by correlations 70×$q_t$ and 200×$\Delta u$, where pore pressure is measured at the $u_2$ position (similar correlation to one developed by Mulabdic, 1994). It seems that these simple correlations, using parameters derived from ordinary piezocone and VT tests, can very well estimate $G_0$ values in this clay, which is very important to this location.

As an exercise, the ratio $G_0$ (SDMT) / $M$ (DMT) was investigated. In the NC Neretva River clay, this ratio was about 22.6, while the average DMT horizontal stress index equals to 2.2. Table 1. gives summary of correlations used in this study.

Table 1. Summary of correlations developed for NC Neretva River clay.

| $OCR$ | $K_0$ | $C_u$ | $M$ | | $G_0$ | | |
|---|---|---|---|---|---|---|---|
| 0.25×($q_{net}$/σ'$_{vo}$) | 0.175×($q_{net}$/σ'$_{vo}$) | $q_{net}$/14 | 5×$q_{net}$ | 70×$C_u$ | 720×($C_u$/$w_L$) | 200×$\Delta u$ | 70×$q_t$ |

At one location, a 5-m high embankment was used for prestressing foundation soil. Stone columns were installed down to the depth of about 20 m for improving soil below the embankment. Vertical deformations in ground at 1-m depth intervals were measured by means of a sliding deformeter probe in an instrumented borehole. Also, vertical deformations of improved soil were calculated, using $M$ (DMT) as a modulus of vertical deformation.

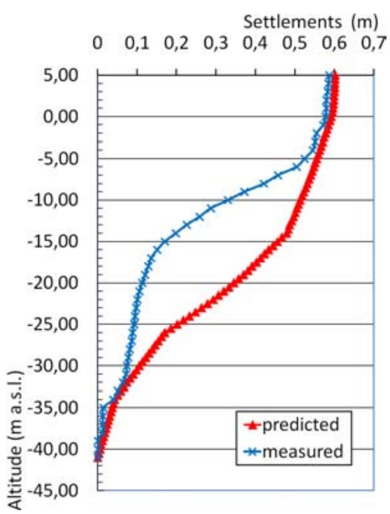


Figure 6. Comparison between measured and predicted settlement profiles.

Calculated settlements at surface agreed well with measured values (Figure 6), while at the toe and below stone columns there were notable differences (probably due to unknown stress distribution).

## 3 CONCLUSIONS

Intensive building activities have been undertaken in the Port of Ploce, in deltaic soil of the river Neretva at the South Adriatic coast in Croatia. They will involve many demanding structures. Significant geotechnical investigations were realised in the underlying soft foundation soils. With the lack of good quality undisturbed samples, in situ penetration tests became an important source of geotechnical parameters to be used in design. Large numbers of penetration tests were performed at different locations inside the whole construction area. Based on these results, it was shown that soil profile is relatively constant over the area, with soft clay as a dominant soil type. Existing recommendations for correlations between soil geotechnical parameters were checked and some local coefficients were adopted. It was shown that CPTU, DMT and VT tests can be used for evaluation of important soil parameters, based on interpreted undrained shear strength and/or measured pore pressure (CPTU). In situ tests were proven as powerful tools in estimating geotechnical parameters in soft soil, if recommended test procedures and relevant norms were followed.

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