Use of Dilatometer in Unusual Difficult Soils – a Case Study

Mensur Mulabdić
University of Osijek, Faculty of Civil Engineering. E-mail: mulabdic@gfos.hr

Krunoslav Minažek
University of Osijek, Faculty of Civil Engineering. E-mail: krumin@gfos.hr

Keywords: loess soil, wetting, settlement, earth dam, in homogeneity, dilatometer test

ABSTRACT: Dilatometer tests were performed on two construction sites in eastern Croatia in unusual soils. First site was the building on a hard loess soil that suffered from settlements caused by soil wetting. It was necessary to find out about soil stiffness in order to design soil improvement by use of jet grouting. The second site was an earth dam that had to be checked for in homogeneity in clay fill mechanical properties, in connection with rehabilitation of the dam. In both cases knowledge of soil stiffness was important, and dilatometer tests were performed in addition to other test methods (in situ and laboratory), so that comparison of evaluated value of soil modulus of vertical deformation was possible. Also, hard loess soil required dilatometer blade to be hammered in order to penetrate at certain intervals of depth, which in turn required careful and repeated reparation of the instrument. Despite these difficulties instrument worked well. Comparison of soil parameters evaluated from dilatometer measurements with parameters obtained by other in situ and laboratory tests showed that dilatometer is useful and reliable tool but needs to be checked in unusual soil conditions. Correction coefficients for evaluated soil parameters from dilatometer testing are obtained on some points and were used for improving evaluation of soil parameters on other places.

1 INTRODUCTION

Marchetti dilatometer is very useful tool in determination of soil stiffness, and together with piezocone test is very often part of in situ testing program. Usually dilatometer penetration is achieved by pushing force of a drilling rig, with or without pre-boring. But, sometimes it is necessary to hummer the blade (via the drilling rods) to certain depth, either because of insufficient drilling force or due to high soil stiffness. Such operation can damage blade electric connections and requires blade control and reparation. This paper describes use of dilatometer in two projects in Croatia, in different soil conditions, were standard procedure of test performance or test interpretation was not possible. First project is related to high school in Vukovar (eastern part of Croatia), founded on loess soil. Loess material changes its stiffness with water content dramatically - when dry it is very stiff, but when subjected to wetting collapse of its structure occurs. The second project described in this paper was related to the earth dam, were dilatometer tests were conducted in order to get insight in mechanical properties of compacted clay necessary for planning of remediation work for the dam. Both projects were unusual, in terms of performance of test and in terms of test results interpretation.

2 VUKOVAR HIGH SCHOOL BUILDING

2.1 *Description of foundation problems*

A high school building in Vukovar, reconstructed after the 1990's war destruction, situated on the elevated loess terrain near the Danube river, was suffering from the decline of the bearing capacity of the foundation soil and excessive settlements followed by the formation of cracks within the structure and at its facade.

Few years after the war reconstruction (1998), some cracks had been noticed on the building. In the period between 2002-2006 the cracking progressed, regarding both the number and width of cracks throughout the object. The structure was built of massive masonry and was sensitive to settlement. In the early phase of cracking, the settlements of the object were recognized as a main cause for crack formations. The extensive exploratory works, observations and geotechnical measurements on the object and its surroundings were conducted. It turned out that poorly reconstructed rainfall collecting system caused the wetting of the foundation soil composed mostly of loess (Civil Engineering Faculty in Osijek 1998. and 2007.).

2.2 *Exploration works*

The purpose of the exploration works was to identify the regions affected by yielding and to determine soil properties of the foundation soil to direct the remediation measures. After exploration works were completed, a remediation by jet-grouting method followed.

Exploratory borings, dilatometer testing and laboratory investigation works were conducted. Disposition of boreholes, inclinometers and deformeter holes are presented in the Fig. 1. The foundation soil is composed of clay layers in the upper part and loess layers beneath them (the soil profile is shown in the Fig. 6.). Special consideration was given to loess wetting (caused by precipitation water due to a poor rainfall collecting system around the object). The soil profile with the moisture change, observed in the period between the first noticed cracks and time of remediation, has been made. Also the modulus of vertical deformation change with depth has been obtained and then used as the basis for the analysis and modelling of the remediation works.

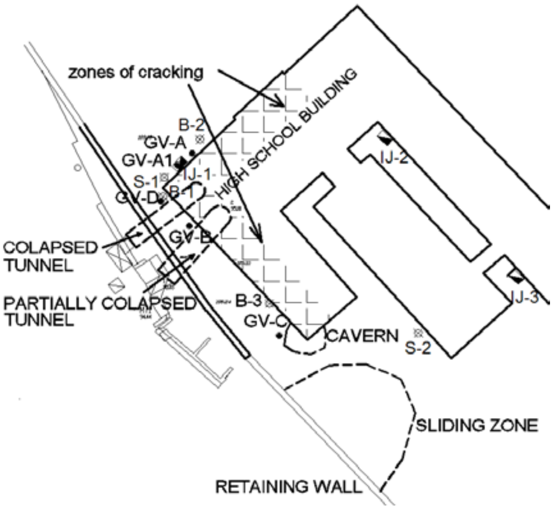

Fig. 1. Disposition of boreholes, inclinometer and deformeter holes, along the area of the building (boreholes: B-1, B-2, B-3, S-1, S-2, IJ-1, IJ-2, IJ-3, deformeters: GV-A, GV-B, GV-D, inclinometers: GV-C, GV-D).

The exploration works have revealed the zone of increased moisture content in the soil right beneath the foundation, to the depth between 9 – 11 meters. This fact provoked collapse of the loess structure, which has been confirmed by the oedometer tests. Wetting and softening of the foundation soil did not affect the whole object equally, and the most affected area was the south-eastern part of the object under which several tunnels were positioned (Fig. 1. and Fig. 2.).

The tunnel vaults under the building (see the cross-section presented in the Fig. 2.) made of loess became wet because the tunnel served as a drain for the excess water in the soil. Gradually they started to collapse causing the additional soil settlement under the structure. It was therefore decided to fill the tunnels with concrete.

In one exploration borehole (named GV-B, Fig. 1.) dilatometer test was employed. Pre-boring was made to the depth of 4 m to get under the foundation base level. Dilatometer measurements were made from the 4,5 m to 13,5 m depth in intervals of 0,5m. The interval of 0,5 m was chosen for practical reasons. The pushing machine didn't have large pushing power (less than 2 t) and pre-boring to clean the borehole above test depth at several intervals was necessary. Three consecutive measurements were made by pushing dilatometer blade (in total depth interval of 1,5 m), then the borehole needed to be cleaned. Dilatometer blade was hammered by vibration of drilling machine rotary head into the soil for the last measurement before cleaning the borehole. After several intervals of hammering, the dilatometer probe needed to be repaired, because electrical contact cable inside the blade detached from its position and needed to be soldered back. The preparation of dilatometer borehole GV-B is shown in Fig. 3. and the dilatometer blade after retrieval from the borehole after measurement is shown at Fig. 4. Dilatometer test results are presented in Table 1 (material index with soil description, dilatometer and constrained modulus, and the friction angle) and in Fig. 5. (material index and constrained modulus).

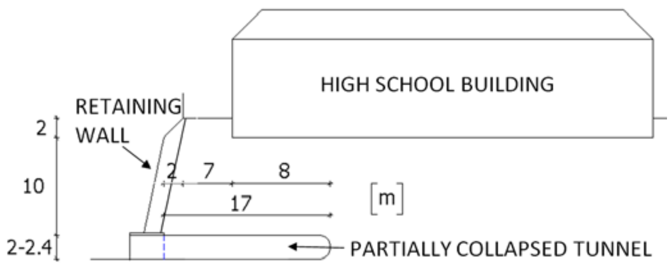

Fig. 2. Schematic cross-section of high school building with position of collapsed tunnels.

Fig. 3. Preparation of DMT test near high school building.

Fig. 4. Dilatometer blade after retrieval from borehole of stiff loess.

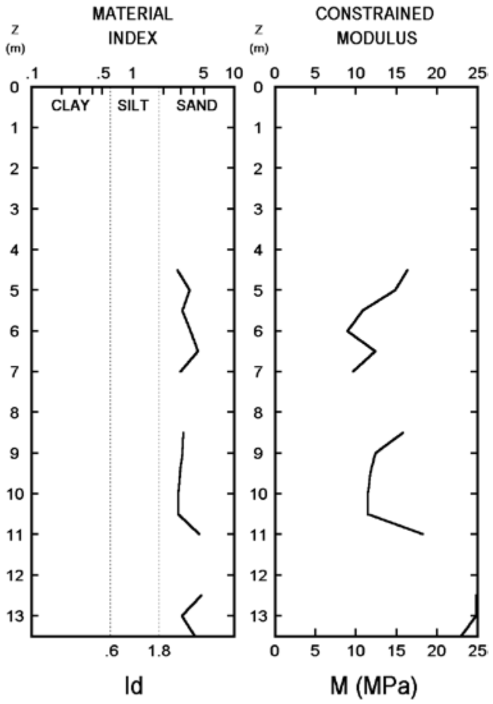

Fig. 5. Dilatometer test results: distribution of material index and constrained modulus with depth.

In the same borehole, after reaching depth of 12 m, standard penetration test was made, and also at depths of 16 and 18m. The results from these tests are presented in Table 2.

Table 1. Results of Dilatometer tests in borehole GV-B.

Depth (m)	Soil description	Ed (MPa)	M (MPa)	Phi (Deg)
4.5	silty sand	14.9	16.3	32
5.0	sand	16.8	14.8	31
5.5	silty sand	12.8	10.8	29
6.0	sand	10.6	9.0	26
6.5	sand	14.6	12.4	27
7.0	silty sand	11.3	9.6	27
8.5	silty sand	18.6	15.8	29
9.0	silty sand	14.6	12.4	27
9.5	silty sand	13.8	11.8	27
10.0	silty sand	13.5	11.5	27
10.5	silty sand	13.5	11.5	26
11.0	sand	21.5	18.3	26
12.5	sand	29.1	24.8	27
13.0	silty sand	29.1	24.8	29
13.5	sand	27.0	22.9	27

Table 2. Standard penetration test results for borehole GV-B.

Depth (m)	N(SPT) - uncorrected
12,00	10
16,00	12
18,00	9

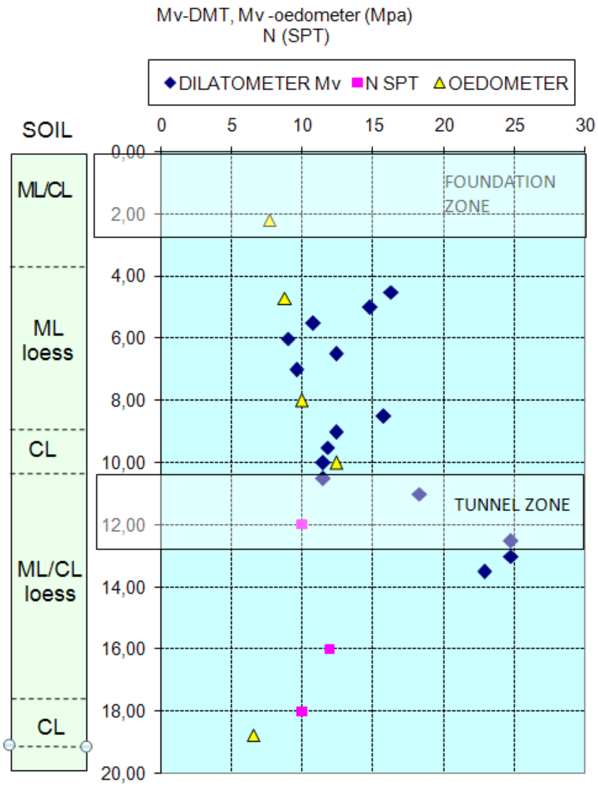

Fig. 6. Soil profile and modulus of vertical deformation.

Dilatometer data, although available from just one borehole, enabled interpretation of soil stiffness at 0,5 m intervals. Very few undisturbed samples from loess soil were taken and tested in oedometer.

Comparison of values of the constrained modulus obtained by dilatometer test with oedometer modulus values from other nearby boreholes is presented on Fig. 6. Reasonably good fit of data can be noticed. In terms of soil type identification (Table 1) it can be seen that dilatometer recognized coherent material (ML/CL, Fig. 6.) as sandy or silty - sandy soil.

If only this description would have been used in designing jet grouting work it would have led to the wrong grouting set up. Therefore, check of dilatometer interpretation with findings from classical drilling records is highly recommended in non-standard soils.

It is, however, valuable to point out that dilatometer blade worked very well, despite hammering. There are two ways to perform dilatometer tests with drilling rig of limited pushing force: (1) it is possible to work with pre-drilling for some depth intervals (say 1-1,5 m) and then perform consecutive dilatometer tests over the limited depth interval (say 1-1,2 m), or (2) one can force blade by hammering as long as it progresses. In this latter case one should be aware of need for the blade reparation. Therefore, two blades should be at the site, in order to keep the work going well in time (the authors experienced this at some other projects too, like in the case of testing sand deposits under one embankment in Eastern Croatia). When undisturbed samples are unavailable, and/or when rig doesn't have enough pushing power, hammering of the dilatometer blade can be performed, under the condition that constant control of blade functionality and integrity of electronics in it is checked.

2.3 *Remediation works*

Based on the analysis of foundation soil and detected damages to the structure it was concluded that remediation of the foundation soil and improvement of the foundation was necessary. That required transmission of the loads form the structure to greater depth to the zone of improved soil. It was achieved by jet-grouting technology, producing firm columns under the foundation in the appropriate disposition.

The zone of improvement realised by jet-grouting produced columns of 60 cm in diameter, extended to the depth of 6 or 9 meters under the foundation. The plan view arrangement of jet-grouting columns can be seen in the Fig. 7. The typical jet-grouted column cross-section for foundation underpinning is shown in the Fig. 8. (Mulabdić & Minažek 2009).

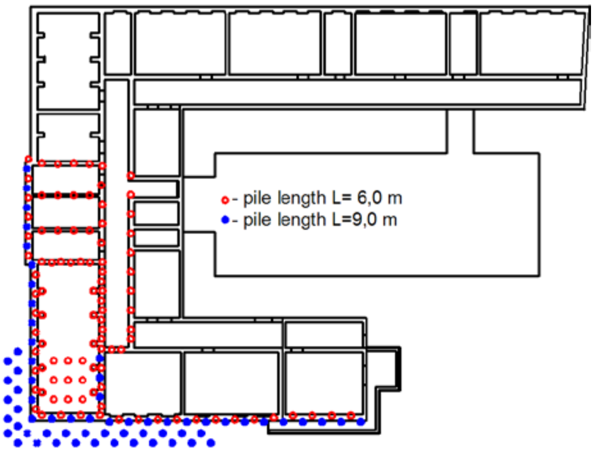

Fig. 7. Disposition of jet-grouting piles under footings.

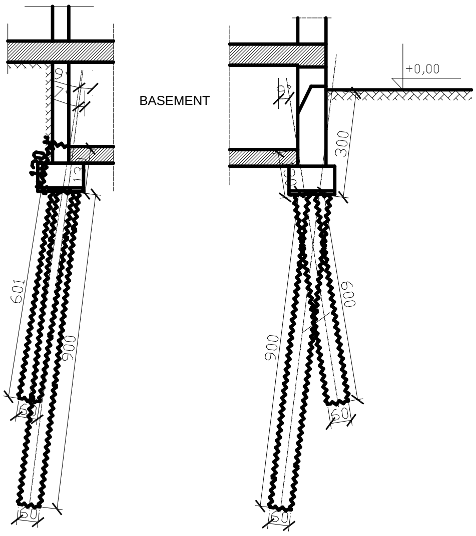

Fig. 8. Typical cross sections of foundation with pile positioning and dimensions.

3 SMALL EARTH DAM EMBANKMENT-THE SECOND CASE

3.1 *Description of foundation problems*

A small earth dam was built as a part of a future irrigation system. The dam was about 10-meter high at the deepest point in a depression, and was constructed of the clay from its vicinity. During the construction of the dam it was noticed that the construction company didn't fully follow the design requirements and criteria related to zoned construction, replacement of foundation soil and degree of compaction of the lifts of clay. During the filling of the lake, when only few meters of dam slopes were covered with water, problems with bottom discharge were observed and filling of water had to be stopped. It was decided that the dam should be checked for safety against sliding and deformability, for which geotechnical properties of compacted clay in the dam should have been checked in detail (Mulabdić 2013).

3.2 *Testing program*

The site testing program consisted of drilling of boreholes to get samples for a laboratory testing of the clay, cone penetration testing (CPT) and a dilatometer testing (DMT). The results of analysis of clay properties in the dam based on CPT, DMT and laboratory testing are presented in this section. Boreholes were positioned over the dam body and penetration tests were performed in the crest, see Fig. 9. (Elektroprojekt Zagreb 2010).

Four CPT test boreholes and three DMT test boreholes were made. All empirical and theoretical expressions for the interpretation of test results of these two tests are based on natural soils (Larsson & Mulabdic 1991, Lunne et. al. 1996, Marchetti 1980). Therefore it was necessary to check the applicability of standard interpretation methods to compacted clay, for both tests. It should be noted that there is not much experience presented in literature covering CPT and DMT testing in compacted clay.

Both tests were conducted according to relevant standards (EN 1997 – Part 2:2006). Glycerine was used as fluid in porous stone in CPT cone.

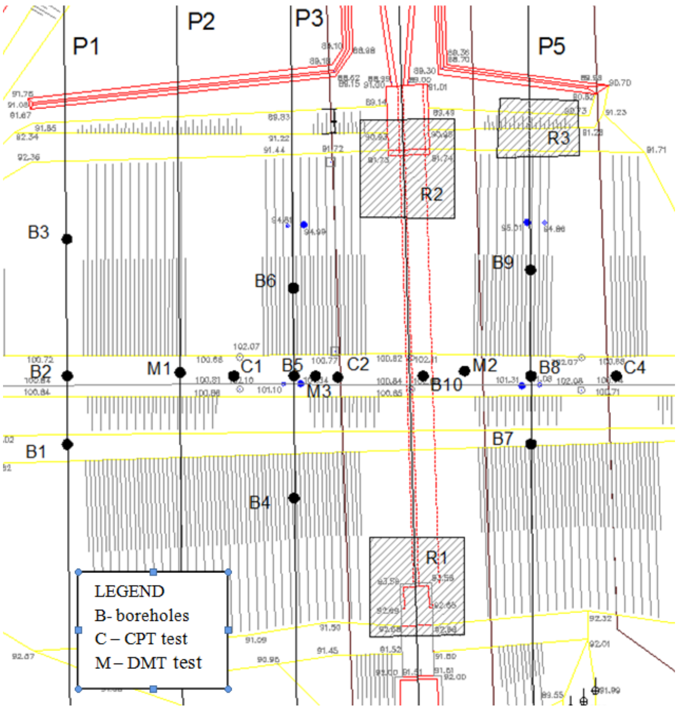

Fig. 9. Position of in situ tests and boreholes on the dam; most important work was done on the crest (line B2-C4).

3.3 *Soil identification*

Clay in the embankment was never submerged, except for the part deeper than 9 m measured from the crest. CPT soil type identification was done according to a widely used chart (Robertson, 1990), and in doing so clay of low plasticity was identified in most cases, with some thin layers of silty clay. Pore pressures measured behind the cone (u_2) were almost zero, or slightly negative, at all depths.

In terms of soil type interpretation, DMT test interpreted clay soil as sandy-silty to silty-sandy soil type, with very rare clayey-silty thin layers as it can be seen in Fig. 10. Therefore there were almost no data for undrained strength in DMT interpretation. According to Marchetti (1980), in DMT test for clay soil material index Id it should be $0.1 < Id < 0.6$. Since the value of Id in compacted clay of the dam was found to be about or higher than 2 (suggesting a sandy or sandy-silty soil type) and there was no in situ pore pressure in soil, it could be concluded that p_0 was too small, due to structure of compacted soil and absence of in situ pore pressures.

Fig. 11 shows values of modulus of vertical deformation as interpreted from DMT tests compared to design required values, and undrained shear strength as interpreted from CPT test compared to design required values. Both, CPT and DMT tests detected very pronounced inhomogenity in the clay embankment – it seems that almost every lift of compacted clay can be distinguished from the penetration test results.

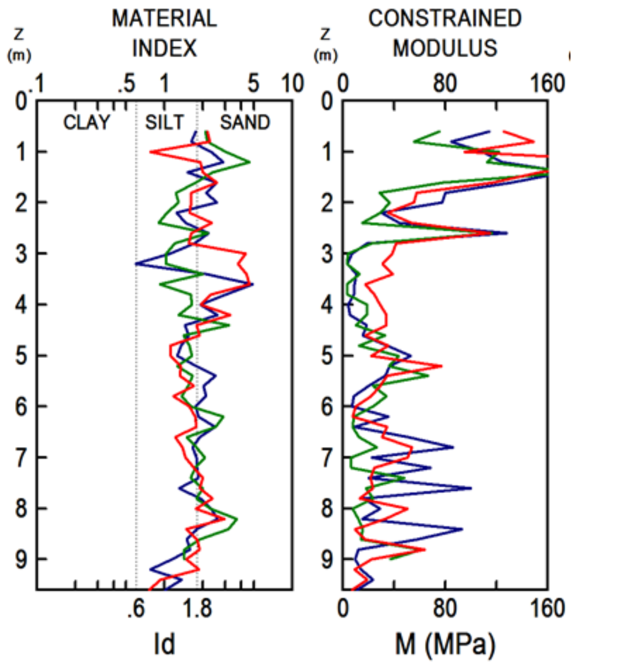

Fig. 10. Distribution of DMT material index and constrained modulus with depth for positions M1 (blue), M2 (green) and M3 (red).

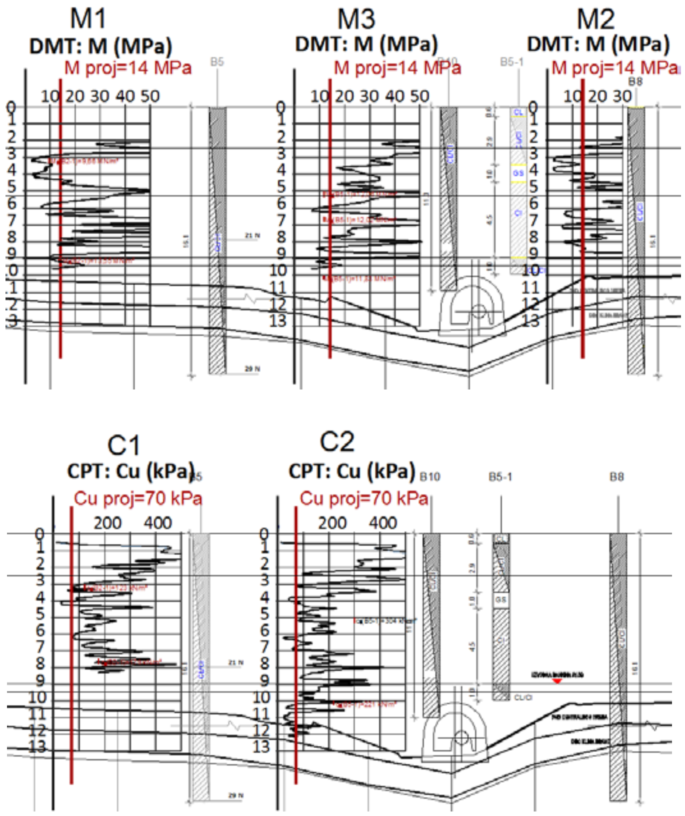

Fig. 11. DMT (M1, M2, M3) and CPT tests (C1, C2), over the dam height (cross-section along the crest).

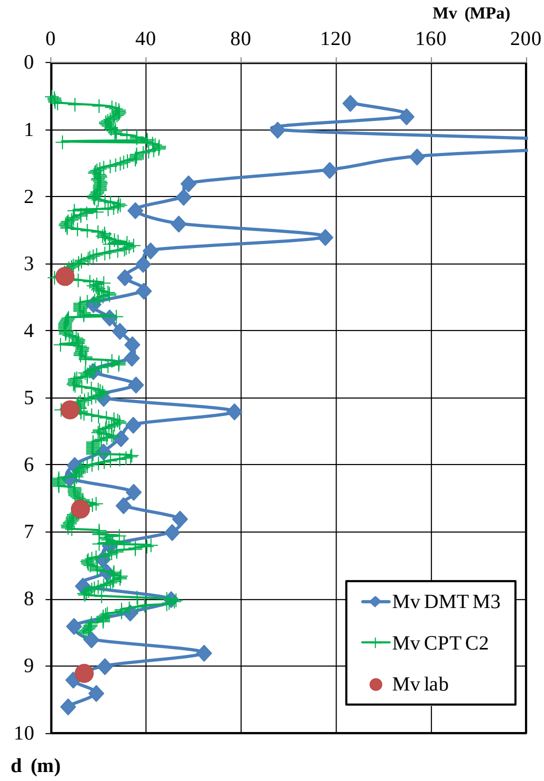

Fig. 12. Modulus of vertical deformation from oedometer (on submerged specimens), CPT interpretation, compared to DMT standard interpretation values (performed on clay layers that were not submerged).

3.4 *Modulus of vertical deformation*

Comparison of modulus of vertical deformation was made for relevant results for oedometer, CPT and DMT test. For CPT it seems that the value of modulus is two times greater than the oedometer modulus, and the values of Mv from DMT test were the highest of these three (Fig. 12.). This might be due to the fact that oedometer tests were performed on submerged specimens, and CPT and DMT tests were performed on clay fill in the embankment that was not submerged.

The influence of presence of water on interpretation of DMT test results in terms of modulus Mv was discussed in Mulabdic and Bruncic (2000), for natural soils. They concluded that error in water depth assumption had limited influence on interpreted Mv values. Compacted clay of which the dam was made obviously would be softer if it was submerged. It is difficult to predict soil modulus Mv of a submerged embankment fill from an in situ test performed on a non-submerged embankment fill.

Fig. 13. shows that CPT and DMT tests on different locations gave similar mechanical properties of the compacted clay with depth.

The comparison as shown in Fig. 12 can only be used as a guide for correcting in situ evaluated parameters to laboratory values, but even then correction would not be constant with depth.

Tests marked as M1, M2 and M3 (DMT-tests) were performed in one run as standard tests and seismic tests (SDMT), using a seismic probe as described in Cavallaro et al. (2006). Fig. 14. shows shear wave velocities measured in 0,5-meter depth intervals. Since a shear wave velocity is a „measure“ of soil structure and its rigidity, variability of those two parameters should be regarded as a basic indication of the variability of soil mechanical properties. These variabilities are less pronounced in wave velocity diagrams than in CPT and DMT standard diagrams, probably due to difference in depth interval of interpretation: 0,5 m for seismic test compared to depth interval of 0,2 m for static DMT. Although velocities generally increase with depth, there are weaker and stronger intervals at certain depths in M2 and M1 boreholes. The M3 location shows constant increase in shear wave velocity by depth.

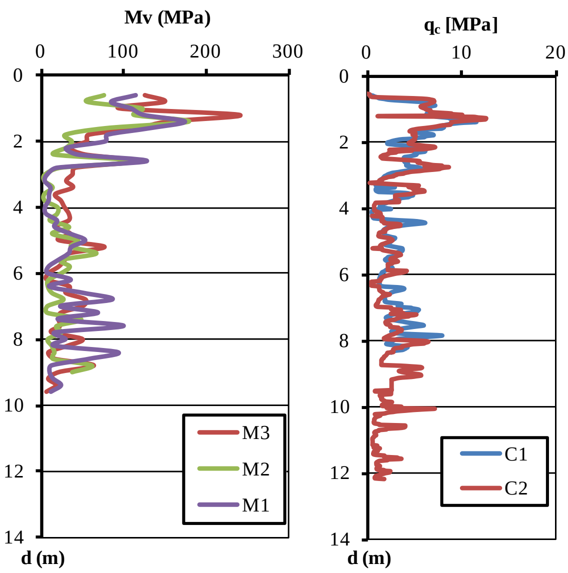

Fig. 13. CPT and DMT tests in cumulative presentation.

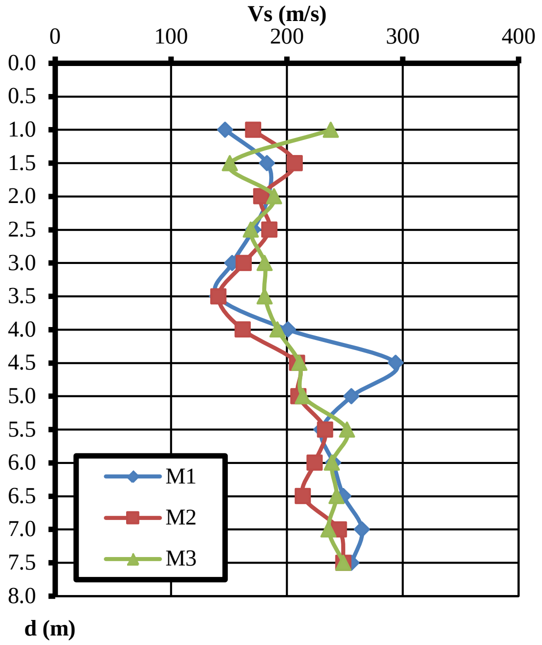

Fig. 14. Measured shear wave velocity at different SDMT locations, depth intervals 0,5 m.

4 CONCLUSIONS

The paper presented application of dilatometer testing in difficult / non-standard soils, for two buildings: at one site dilatometer test was a part of investigation program for foundation improvement, and at the other site dilatometer test was used to investigate poor construction quality of an earth dam embankment. Test results from dilatometer testing were compared with test results from laboratory and other in-situ tests (SPT and CPT).

For a high school foundation improvement, were loess was a foundation soil, insertion of dilatometer blade was difficult because of small pushing power of available boring rig. DMT testing was performed by cleaning the borehole after several measurements and by hammering the dilatometer blade. The blade was repeatedly repaired and used with great confidence.

In a case of an earth dam embankment of a poor construction quality, in order to characterize clay fill in the embankment in terms of its physical and mechanical properties, CPT and DMT tests were performed in addition to borings and laboratory testing. The purpose of these two in situ tests was to determine variation of clay properties by depth and at different positions on a dam crest. Based on analyses of in situ and laboratory test results following conclusions can be made: (a) CPT and DMT detected inhomogeneous clay conditions very clearly along the depth, both in static testing and in DMT seismic testing (SDMT), (b) common interpretation of CPT and DMT test results should be used with caution, allowing for appropriate corrections when tests are performed in compacted clays, since they are developed for natural clays, and not for the compacted – man made soil; (c) it is of importance for the analysis and characterisation of clay properties whether the embankment is dry or submerged at the time of performing in situ tests; (d) CPT and DMT tests showed remarkable repeatability and proved to be valuable aid in characterizing embankment quality, both in terms of inhomogeinity and physical and mechanical properties; SDMT results also proved to be particularly useful; (e) local correlations between laboratory and in situ test results should always be used, in order to properly account for effects of the presence of water (submerged or non-submerged), specific structure of compacted soil, specific stress distribution and limited experience in using in situ tests for the characterization of compacted soils.

5 REFERENCES

Mulabdić, M. and Minažek, K. (2009). “Foundation improvement for a building on loess soil.” *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering*, Egypt, 2362-2365

Civil Engineering Faculty in Osijek. (1998). “High school in Vukovar -Site investigation report.”

Civil Engineering Faculty in Osijek. (2007). “Geotehnical project of remediation of foundation for the building in Vukovar.”

Mulabdić, M. (2013). “Use of penetration testing for determination of soil properties in earth dam.”

Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, 595-600.

Elektroprojekt Zagreb (2006). “Design solution documentation for Opatovac dam.”

EN 1997-2:2006. Eurocode 7: Geotechnical design - Part 2- Ground investigation and testing.

Larsson, R. and Mulabdić, M. (1991). “Piezocone tests in clay.” *Swedish Geotechnical Institute*, Report No. 42, Linköping, 240.

Lunne, T., Robertson, P.K. and Powell, J.J.M. (1997). “Cone Penetration Testing in Geotechnical Practice.” *E & FN Spon*, 312.

Marchetti S. (1980), "In Situ Tests by Flat Dilatometer." *ASCE Journal GE*, Vol. 106, No. 3, March 1980, 299-321.

Mulabdić, M. and Brunčić, A. (2000). “Prilog analizi primjene dilatometra Marchetti.” *Građevinar*, Vol 52, No. 1, 9-17 (in Croatian).

Robertson,P.K. (1990). “Soil classification using the cone penetration test.” *Canadian Geotechnical Journal*, 27 (1), 151-158.

Cavallaro, A., Grasso, S. and Maugeri, M. (2006). “Clay Soil Characterization by the New Seismic Dilatometer Marchetti Test (SDMT).” *Proc. 2nd international flat dilatometer conference.*, Washington, 261-267