Improving Rigidity of Clay by Using Explosives and Proofing by Multichannel Analysis of Surface Waves (MASW)

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Abstract. The construction foundation problem in complex conditions with specific types of soils (peat and organic sediment, sludge, soft clay, etc.) is relevant at the present time. Excessive moisture, low bearing capacity, high compressibility, and other negative qualities of these soils make the process of foundation more expensive and complicated. To improve the properties of granular soil can be applied explosive compaction (EC) technology, which has been used for more than 80 years, but mostly for the compaction of gravels, sands and silts. This paper documents the successful application of EC for the compaction of clay soils. To cause compaction, the sequential detonations were performed using explosives placed in boreholes. To investigate the efficiency of explosive compaction on cohesive clay soil, geophysical testing was performed. Applied geophysical testing methods were a Multichannel analysis of surface waves (MASW) and seismic down-hole, whose test results are shear wave velocities (V_s) in depth. The shear modulus (G_o) at small deformation, which is directly related to the V_s, were used to determine the degree of soil improvement. From a comparing of results of pre- and post-blast testing, the positive effects are evident.

1. Introduction

Explosive Compaction (EC) is a soil modification technique which involves placing an explosive charge underground in a borehole and then detonating the charge. During this process the natural structure of the soil is destroyed, near the explosive charge cavities are created, and soft soil layers are compacted. Compaction increases ground stiffness and strength, and EC has wide application for general ground improvement [1].

The EC's effectiveness depends mostly on the soil profile, grain size distribution, initial status, and the intensity of energy applied to the soil [2]. Some researchers [1, 2 and 3] has shown that EC is most effective in fine-to-medium sands with a fine content less than 5% and hydraulically deposited with an initial relative density ranging from 30% to 60%, coarse cobbly sands and gravels.

Research from this study shows that EC is effective in clay soils. In situ geotechnical investigations via boreholes drilling, explosive charges placing in boreholes, and charges detonating were carried out on exploitation field of brick clay Cukavec II, near City of Varaždin [4], figure 1. To investigate the efficiency of explosive compaction on the rigidity of cohesive clay soil, geophysical pre- and post-blast testing was performed. The primary investigation method was MASW, which many authors have already used to control ground improvement [5, 6, 7 and 8]. To control results of MASW method afterwards was preformed seismic down-hole investigations.

Figure 1. The geographical position of the Cukavec II

The results of geophysical investigations were shear wave velocities *(V_s)* in depth, which are directly related to the shear modulus *(G_o)* at small deformation, via equation 1, where G_o is the shear modulus in kilopascals, V_s is the shear wave velocity in meters per second, and ρ is the density of soil in kilograms per cubic meter. The ground improvement coefficient *(K)* was obtained by the relationship between post-blast G_o and pre-blast G_o, via equation 2.

$$G_0 = \rho \cdot V_s^2 \tag{1}$$

$$K = \frac{G_{0,post-blast}}{G_{0,pre-blast}} \tag{2}$$

2. Research methods and field works

In situ investigations was taken on exploitation field of brick clay Cukavec II, during 2015. Cukavec II is located close to the city Varaždin, the northwestern part of the Republic of Croatia as shown in Figure 1. Contemporary and high-quality equipment and software were used for the investigations and result analysis. Figure 2 shows the results of geodetic measurements, which were carried out as part of the research by using RTK GNSS method. Online transformation parameters via CROPOS (CROatian POsitioning System) was used to define coordinates and elevations of boreholes.

2.1. Drilling, blasting and laboratory testing

Drilling of 131 mm diameter investigation boreholes was made with motor rotary drilling set, with continuous coring, up to a depth of 2 m. The groundwater level is recorded at a depth of 2.5 m. Representative samples of drilled cores were prepared and transported in the geotechnical laboratory to perform the test soil density *(ρ)*. Laboratory soil tests were conducted by a laboratory of the Faculty of Geotechnical Engineering, accredited according to HRN EN ISO/IEC 17025:2007. Explosive charges of 1 kg Permonex V19 were determined for blasting every borehole, because by blasting the trial boreholes that amount proved to be the most appropriate. The explosive charges were connected by the NONEL system with a delay of 250 ms between each bore, and the blastfield is activated over electrical detonators. During trial blasting, the 0.5 m fine sand stemming, 0-2 mm granulation, was ideal.

2.2. Geophysical investigations

In this paper, the Multichannel Analysis of Surface Waves (MASW) geophysical method is used as the primary method for monitoring soil rigidity improvement at a site on Cukavec II. This surface wave method was introduced by the Kansas Geological Survey [9]. Surface wave geophysical techniques are rapid, non-intrusive and results may be produced in the field for immediate assessment. The MASW

method uses multichannel recording and processing techniques that are similar to those used in conventional seismic reflection surveys.

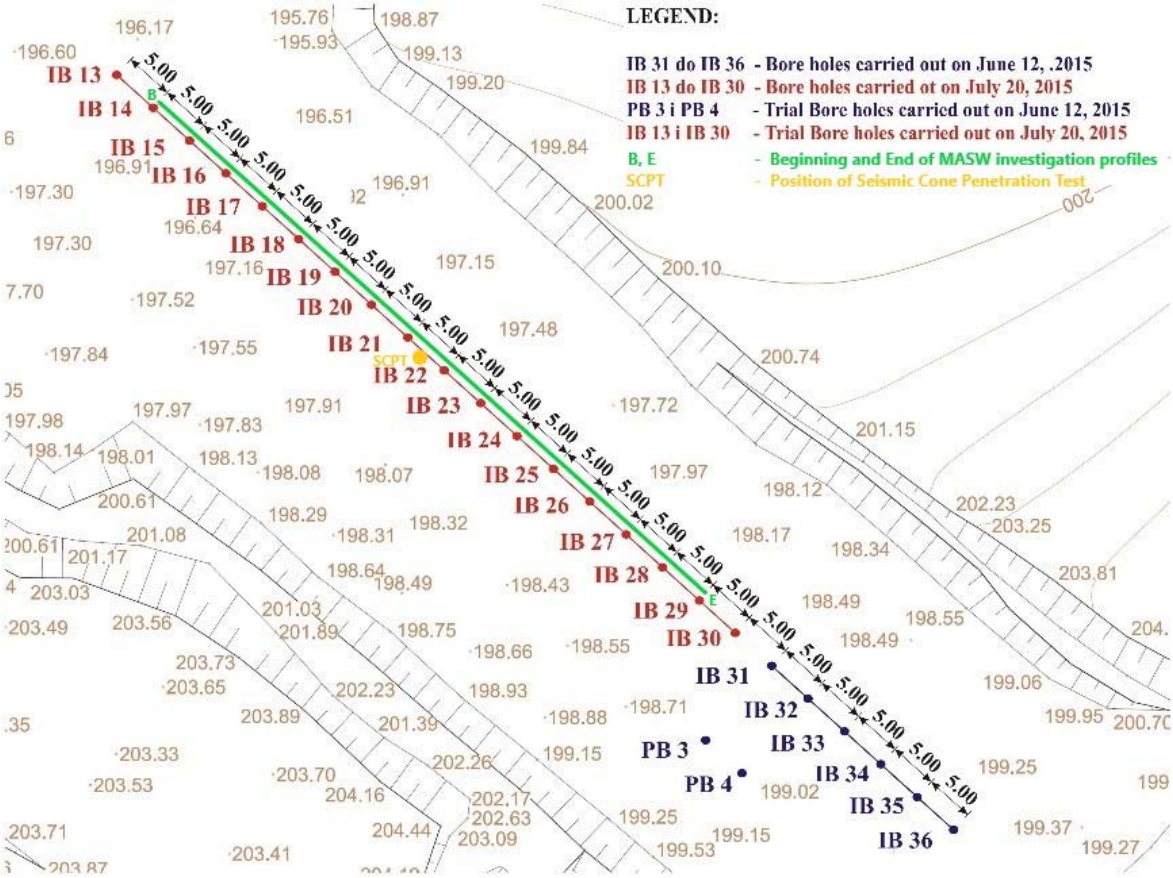

Figure 2. The geodetic determined position of the represented boreholes and geophysical investigations

The MASW method is based on the dispersion properties of Rayleigh surface waves, which are the most widely used in geotechnical engineering from the early 2000s. Most important properties of R waves are a wave velocity frequency dispersion. Wave propagation velocity at each particular frequency is called phase velocity, whereas curve representing phase velocity in dependence of frequency is called phase velocity curve or dispersion curve [10]. The dispersion curve is then necessary to invert to produce shear wave velocity – depth profiles, and V_s is ideally suited for monitoring ground improvement. From an elastic theory viewpoint, shear wave velocity V_s is the most powerful indicator of a material's stiffness [11].

The MASW investigation is performed on site before EC clay soil improvement, which provided a baseline stiffness profile. Further stiffness profile is acquired rapidly after the improvement process and compared to the baseline profile. Investigation profiles were placed directly next to the line that connects the boreholes (Figure 2). Receiver spread for the MASW profile consisted of 24 vertical 4,5 Hz geophones, with receiver spaced out 3,0 m. The depth of penetration for the surface wave, MASW method for this particular survey was 30 m. For the interpretation purpose, fundamental mode and first higher mode of the dispersion curve are used, M0 and M1. Experimental dispersion curve measured on the field was interpreted using SeisIMAGER 4.0.1.6. OYO Corporation 2004-2009 computer software.

The downhole seismic investigation is performed only after blasting by a seismic cone penetration test (SCPT) with an accelerometer located within the penetrometer. The seismic cone is a particularly versatile tool as it is a hybrid of geotechnical penetration coupled with downhole geophysical measurements [12]. For SCPT is not required cased borehole, what is the advantage. Shear wave and compression wave trains obtained at each 1 m intervals during downhole testing by SCPT. The results from the SCPT are compared with MASW results.

3. Results and discussions

After data acquisition through field investigations, follows the stage of field records processing to reach the result. The first step of processing multichannel records is dispersion analysis, followed by the inversion of surface waves. Shear wave velocity variations below the surveyed area are the final result. In this paper final V_s information is provided in 1D and 2D formats. The results from the SCPT are given in 1D formats, like profiles of the V_s and V_p waves in depth, and they are compared with MASW results. By measured velocities of shear waves and soil density (geotechnical laboratory) the small strain shear modulus (G_o) is evaluated, according to equation 1, and the ground improvement coefficient (K) was calculated using equation 2. Finally, the effective depth of the improvement is determined.

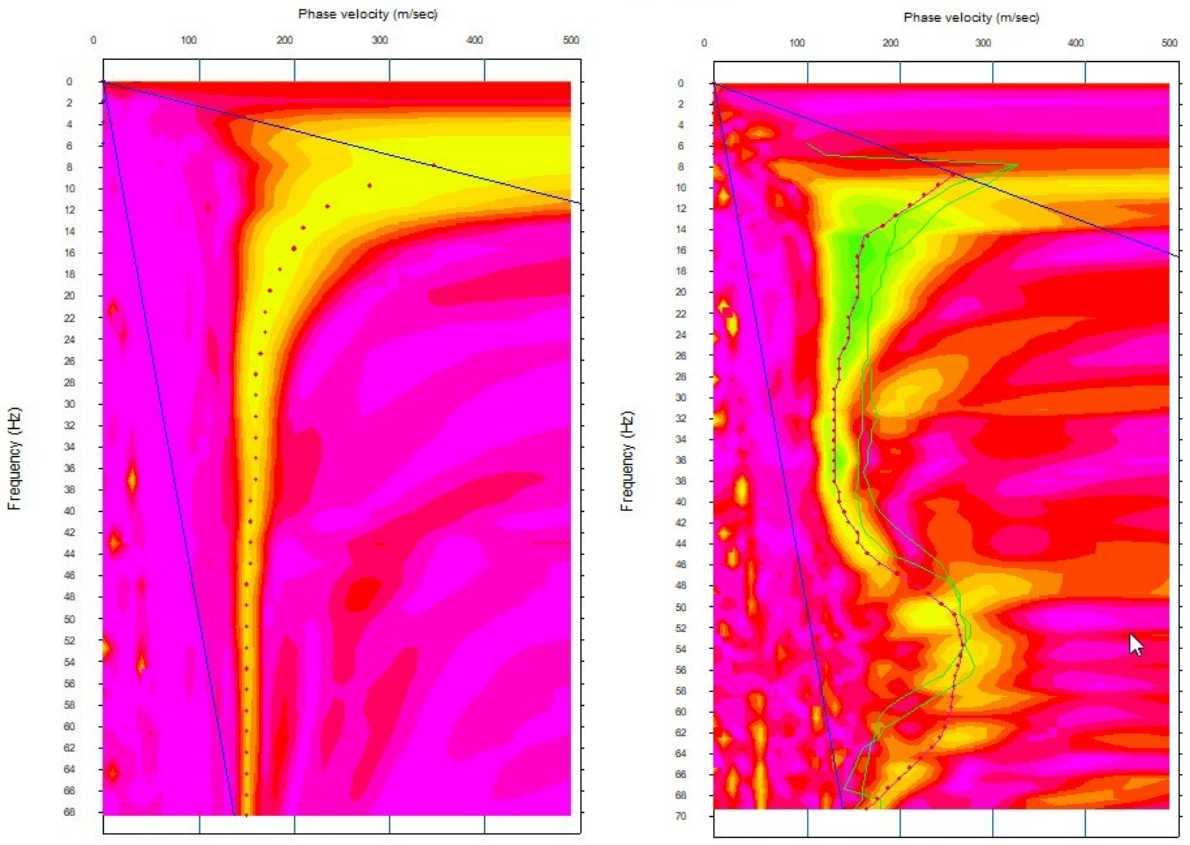

Figure 3. Dispersion curves from MASW measurements at Cukavec II: before EC soil improvement on the left side and after improvement on the right side

3.1. MASW dispersion analysis

The goal of the dispersion analysis is to estimate dispersion curve. On the left side of figure 3 can be seen dispersion curve obtained by processing pre-blast multichannel records, where only the fundamental mode was used for interpretation. On the right side of figure 3 can be seen dispersion curve

obtained by processing post-blast multichannel records, where the first higher mod was used for the interpretation.

3.2. MASW inversion analysis

The next step of processing multichannel records is inversion process, which tries to find a proper layer (shear velocity, V_s) model whose theoretical dispersion curve match the measured one as closely as possible. Such they the 1D (depth) variations of V_s can be seen in figure 4. By comparing two profiles in figure 4, the V_s increase is visible in the depth interval of 2 to 3 m on the right side (post-blast V_s 1D profile). These 1D V_s profiles are assigned to the centre location of the receiver spread.

With accumulation of multiple number of this 1D V_s profiles assigned with a unique surface coordinate, a 2D V_s maps are constructed (Figure 5). On the upper part of figure 5 can be seen pre-blast V_s 2D map and on the lower part post-blast V_s 2D map, where is visible the V_s increase in the depth interval of 2 to 3 m.

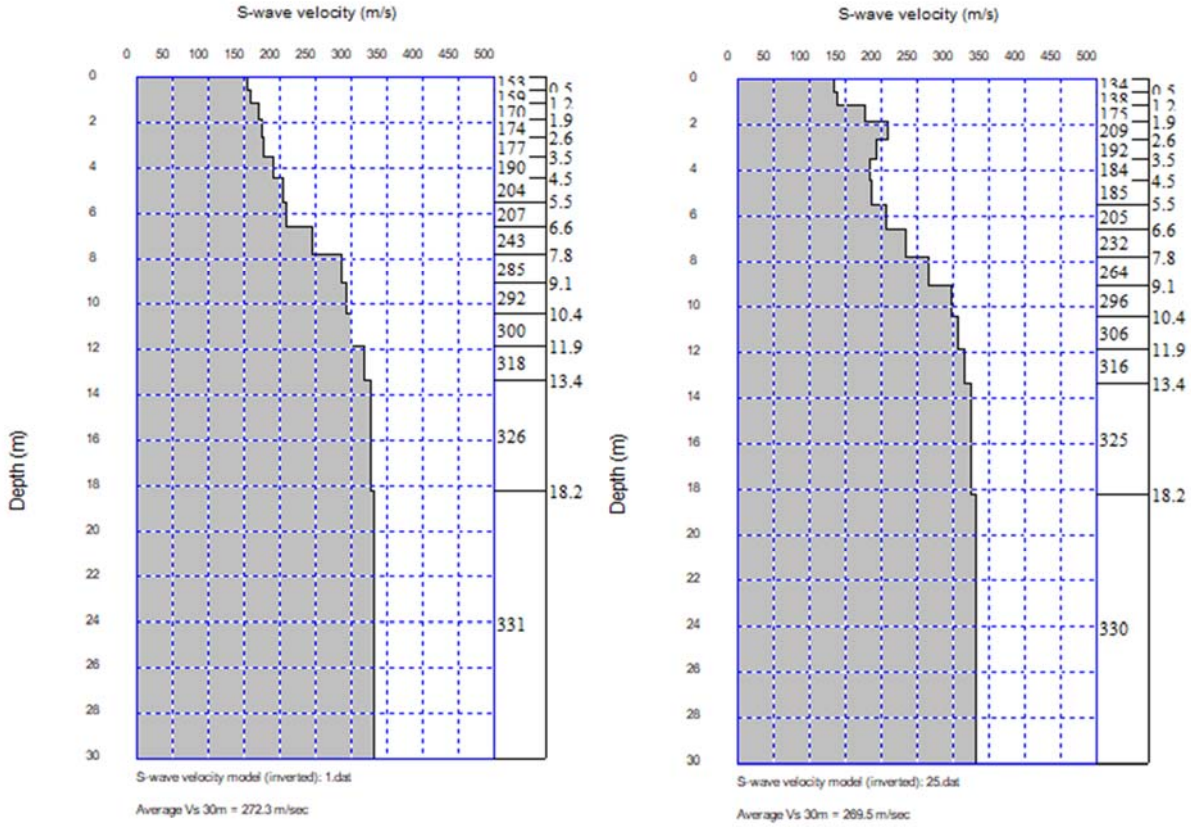

Figure 4. 1D V_s profiles from MASW measurements at Cukavec II: before EC soil improvement on the left side and after improvement on the right side.

3.3. SCPT results analysis

Figure 6 shows the SCPT (seismic downhole) results. 1D profile velocities of S-waves from figure 6 can be compared with first 9 meters depth 1D profile velocities of S-waves from right side of figure 5. Based on the comparison it can be concluded that the matching of results is very good. By analyzing the 1D profile of P-waves in Figure 6, it can be seen that the velocity of the P-waves increases rapidly by coming to the groundwater level (depth of 3 m). That confirms the known fact that compression waves are affected by water [13 and 14]. Therefore, P-waves are not suitable for monitoring soil improvement at locations where groundwater is present. On the other hand, the compression wave propagation is an

extremely sensitive tool to distinguish fully from near to saturated soils. So, the V_p have capability to map the saturation surface position in the subsoil [13].

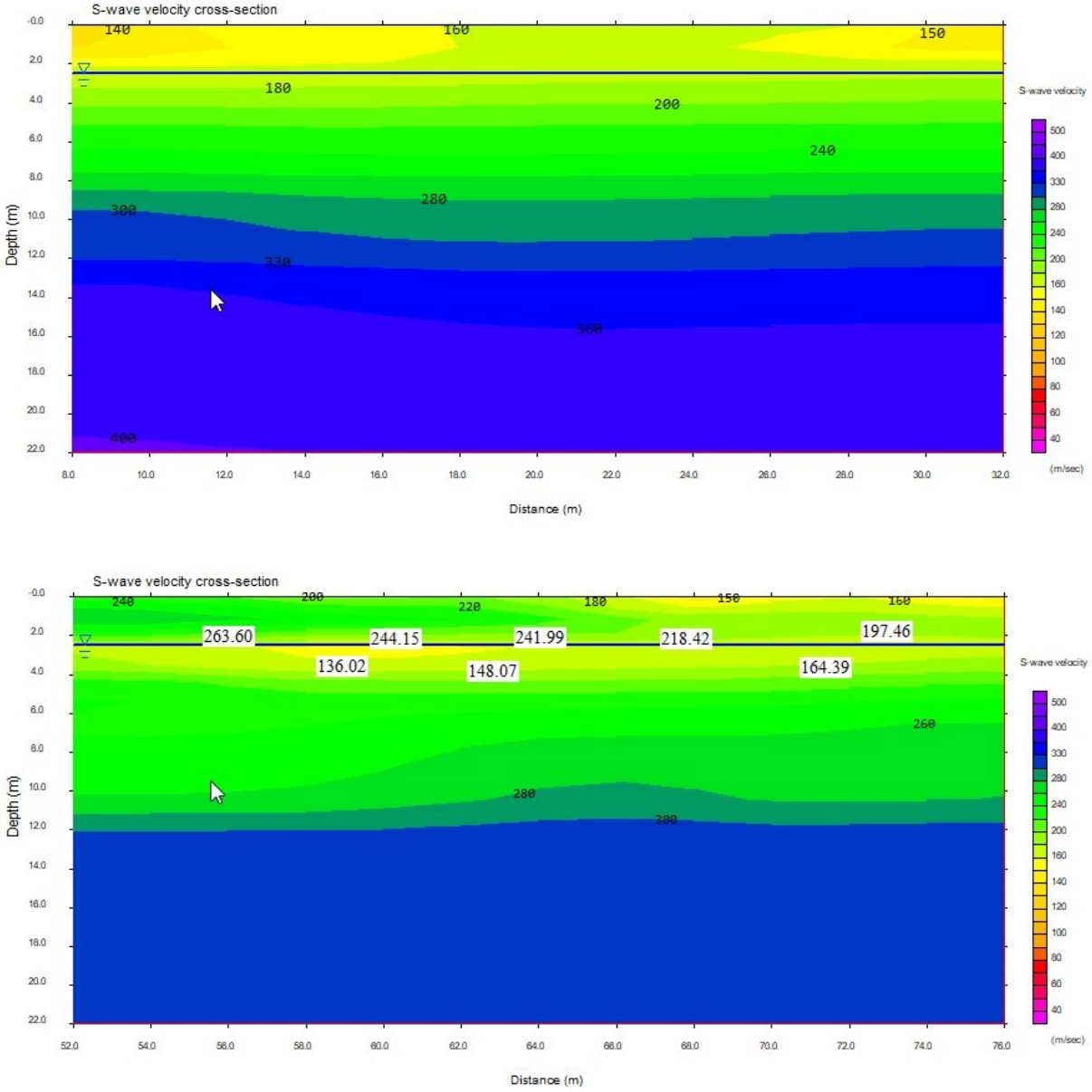

Figure 5. 2D V_s maps from MASW measurements at Cukavec II: before EC soil improvement on the upper part and after improvement on the lower part.

3.4. G_0 and K from MASW and SCPT results

According to the results of laboratory testing of soil samples, natural soil density *(ρ)* increases with depth from 1.84 t/m^3 at 1 m depth, up to 1.90 t/m^3 at the depth of 5 m. For depths greater than 5 m the analysis of G_0 and K was not done, since the geophysical investigation results show that EC does not have any influence on this depths. Table 1 shows the calculated values of the shear modulus *(G_o)* and ground improvement coefficient *(K)* from MASW results. Ground improvement coefficient the highest value (K = 1.466) have at a depth of 3 m (Table 1), which means that there was a significant improvement in soil rigidity (stiffness) at a depth of 2 to 3 meters.

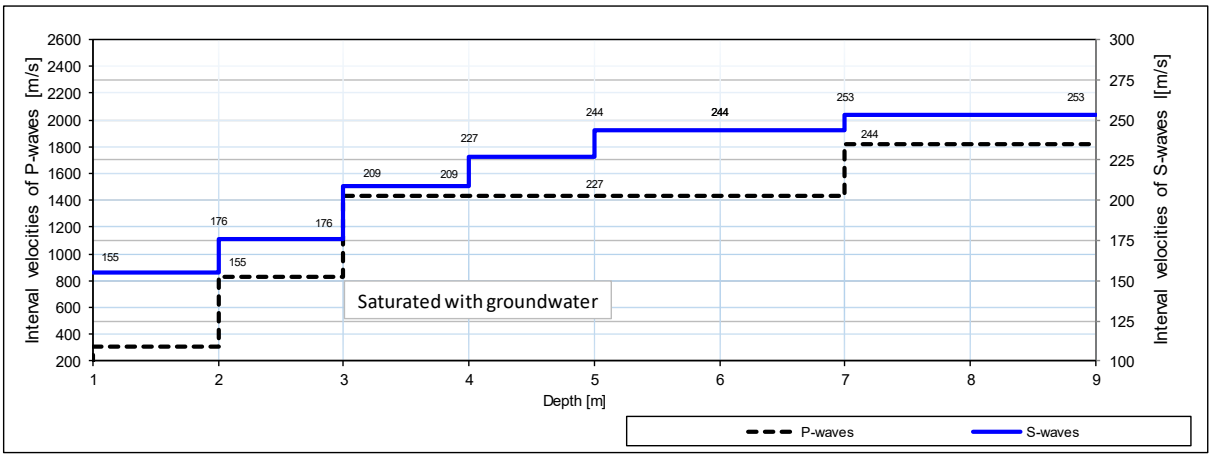

Figure 6. 1D V_s and V_p profiles from SCPT measurements at Cukavec II

Table 1. The values of the shear modulus *(G_o)* and ground improvement coefficient *(K)* from MASW results.

	Natural soil parameters, before ground improvement			Improved soil parameters, after applying EC technique			The ground improvement coefficient
Depth (m)	ρ (t/m^3)	V_s (m/s)	G_0 (kPa)	ρ (t/m^3)	V_s (m/s)	G_0 (kPa)	$K = G_{0,\text{pre-blast}}/G_{0,\text{post-blast}}$
1	1.84	159	46517	1.86	138	35422	0.761
2	1.86	170	53754	1.92	175	58800	1.094
3	1.87	175	57268	1.96	207	83984	1.466
4	1.88	186	65040	1.94	186	67116	1.032
5	1.90	199	75242	1.92	198	75271	1.001

Table 2 shows the calculated values of the shear modulus *(G_o)* of improved soil from SCPT results. At depths 2 and 3 m, the calculated values of G_o and measured values of V_s are approximately equal to the values obtained by MASW measurement (Table 1, improved soil parameters), thus proving the accuracy of the measurement by the MASW method.

Table 2. The values of the shear modulus *(G_o)* of improved soil from SCPT results.

	Improved soil parameters, after applying EC technique			
Depth (m)	ρ (t/m^3)	V_s (m/s)	V_p (m/s)	G_0 (kPa)
1	1.86	155	303	44686
2	1.92	176	833	59474
3	1.96	209	1429	85615
4	1.94	227	1429	99966
5	1.92	244	1429	114309

4. Conclusions

In this paper explosive compaction has been successfully applied for modifying clay soil. To monitor the improvement of the soil, the geophysical seismic MASW method was used. The results of MASW investigations are shear wave velocity – depth profiles, and V_s is shown as ideally suited for monitoring ground improvement. By calculating shear modulus G_o, which is directly related to the V_s, and ground

improvement coefficient *K*, an increase of soil rigidity (stiffness) at the level of set explosive charges have been demonstrated.

To control results of MASW method, seismic down-hole investigations were performed, by a seismic cone penetration test (SCPT). The results of SCPT investigation shows that compression waves are not a good parameter for the control of soil improvement, as P-waves are very sensitive to soil saturation with groundwater. The velocities in the clay underwater are not precisely determined. The reason for this is increased velocity to more than 1500 m/s due to the presence of groundwater (Figure 6). Due to the influence of water and the increase in P wave velocity, it is not possible to determine the parameters of dynamic elasticity well. Finally, it is concluded that the multichannel analysis of surface waves (MASW) is a high-quality tool for field-testing of ground improvement. They are rapid, non-intrusive and results may be produced in the field for immediate assessment.

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