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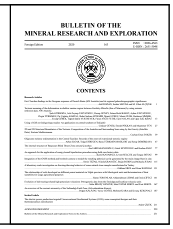

Integration of the GNSS method and borehole camera to model the resulting spherical cavity generated by the main charge blast in clay

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ABSTRACT

A depth camera was used to record the spherical cavity which occurred during blasting in clay soil. For this purpose, the integration of the Global Navigation Satellite System (GNSS) method was applied in addition to the depth camera and the laser, to determine the resulting spherical cavity. The expanded spherical cavity, formed after the blasting of the explosive charge in the bottom of the borehole, was measured by a depth camera-laser system. The GNSS measurement method was instrumental for obtaining the coordinates of the borehole. The Multichannel Analysis of Surface Waves (MASW) measurement method was also used during the study. Shear wave velocities (V_S) were calculated using MASW method to evaluate the dynamic properties of the clay soil along the in-situ profiles. The results obtained in this way, showed that there was an increase in the stiffness of the surrounding clay soil after blasting. The main objective of the study was to determine the resulting shapes and volume of the occurred cavities. For a more detailed graphical interpretation, an application was developed, which calculates the coordinates, shape and volumes of the formed spherical cavity.

1. Introduction

Expansions that occur when explosive charge is detonated, have not been sufficiently investigated in the view of the positive effects that its application can produce. This applies to blasting done in soft rocks at different depths below the soil surface to form a spherical cavity and at the same time activating a specific type and mass of the explosive charge. These cavities are most commonly used to install structural members for anchoring foundation and supporting walls and for anchoring underground structures in less solid and soft rocks (Težak, 2018; Težak et al., 2018; 2019).

A detonation of concentrated explosive charge in the clay soil, generates a shock wave supported by the expanding explosion product which creates intense strong pore excess pressure and oscillations in the surrounding area of the explosive charge (Qingwen et al., 2015; Težak et al., 2019). In that case, the natural structure of the clay soil is destroyed, a significant increase in the borehole volume is achieved, generating the spherical cavity and in the adjacent area, the clay soil is significantly compressed and has its density increased (Figure 1) (Zhongqi and Yong, 2003; Težak et al., 2019).

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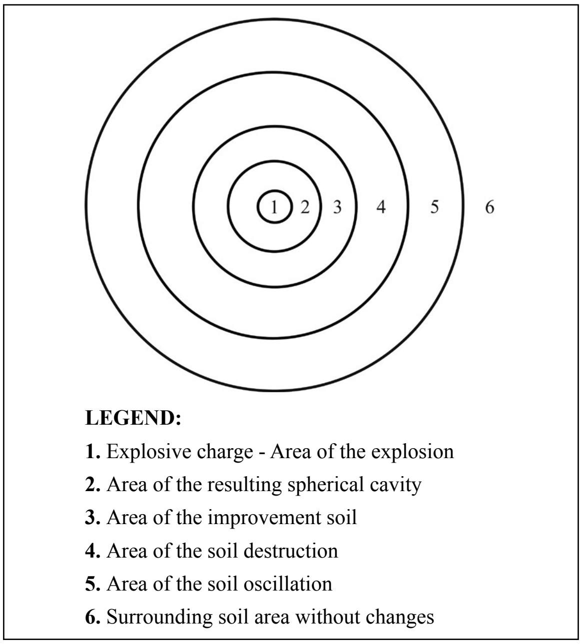

Figure 1- Performance of explosion in soft rock (Težak et al., 2019).

The cavities generated by the explosive charge are used to incorporate the grout and geotechnical anchor, with the purpose of creating mechanical and adhesion bonds of the surrounding clay soil and grout. The efficiency rate of conducted blasting is measured by volume of the resulting expansion. The use of the standard field and laboratory methods can determine the expansion volume and the compaction of the clay soil, along with changes in the compressive strength, shear strength, density and elasticity modulus in the clay soil after blasting. This research will enable the determination of the improvement of the soil properties depending on the detonation parameters, quantity, and type of explosives. Accordingly, with the determination of the influence of the above-mentioned blasting parameters on the shape and volume of the implemented extension, suggestions will be proposed for recording and measuring the resulting expansion. (Težak, 2018).

Cavities resulting from blasting in clay soil were different in shape and size. In the case of homogeneous clay soils, it is basically a sphere-shaped extension (Araya et al., 1993). The spherical cavities for the given diameter and depth of the boreholes were a result of detonating of Permonex V19 and Pakaex explosives (Ester, 2005). During the research, it was necessary to determine the shape and calculate the volume of the formed cavity after activating the explosive charge at a certain depth of a 131 mm diameter borehole (Mesec et al., 2015; Težak, 2018; Težak et al., 2018).

The Multichannel Analysis of Surface Waves (MASW) is a seismic geophysical method which results allow the estimation of soil stiffness directly related to the shear modulus, which is one of the most important engineering parameters. This method was introduced into geophysical research in the late 1990s (Park et al., 1999) and became the subject of many researches and found application in many branches of science. Depending on the problem we need to solve, the MASW method is used in one dimension (1D) or sounding, two dimensions (2D) or tomography and in three dimensions (3D). The MASW method employs low-frequency (1-30 Hz) surface waves that have a dispersion property, and the depth of the survey ranges from several meters to several tens of meters. It is basically an engineering seismic method whose operating frequency range is from several Hz up to tens of Hz (3-30 Hz). Recording is done by multiple channels (24 or more), and the geophone layout can be set so that the distance between them is between several meters to several hundred meters (2-200 m). Passive and active MASW method can be distinguished. The passive MASW research method provides more depth of testing, while active method research is a more common type that gives 2D V_s profiles and is more prevalent in engineering projects than the passive method. The active MASW method adopts the conventional method of exploration with the use of an active seismic source (i.e. a hand hammer or a guide hammer) and fields of linear receivers (geophones), thus collecting data in a roll-along mode. It uses surface waves that propagate horizontally across the measurement surface, directly from the source to the receiver. Also, it provides V_s velocity information in 1D (depth) or 2D (depth and surface) formats in a cost-effective and time-efficient manner. The maximum depth of the survey is generally in the range of 10 to 30 m, but this may vary depending on the type of active seismic source used (Akgün et al. 2013; Pamuk et al. 2018). In this article, the MASW method was used to evaluate the dynamic properties of clay soil according to the depth of the profile before and after blasting.

For this purpose, a system for observation, measuring and calculating the shape and volume of the resulting cavities was designed and developed. The system includes an instrumental and programming part, where a designed application enables detailed graphical interpretation of the cavity in 2D and 3D views, along with the borehole coordinates and resulting cavity volume calculations (Težak, 2018; Težak et al., 2018; 2019). The system also represents the integration of the GNSS measurement method (Official Gazette, 110/2004, 114/2004), a depth borehole camera (http://www.geovision.org/) and laser (EDS-C) (https://dimetix.com/en/?product=eds-c).

2. Previous Research

In the late 1980s, some research was carried out to determine the possibility of applying anchoring and anchoring extensions to structures built in soft soil (Hudec et al., 1989). Excavation through soft rock is one of the most complex tasks in the construction of underground structures and tunnels. Attempts have been made to develop procedures that can facilitate the fabrication of underground structures in rocks that, by their geotechnical characteristics, are soil. Almost all prior anchoring methods used reinforcing steel bars, pipes or prestressing cables, with the use of cement or plastics for injection and have not been sufficiently successful at anchoring to be made in clay, loam or similar soft or earthy materials. The anchors are made in the form of rigid profiles, or in the form of steel cables (Muhovec, 1987). The aforementioned procedure is protected by a patent, based on the fact that the explosion of a certain mass of explosives, located in a borehole of coherent soil, results in a limited expansion of the most commonly shaped sphere. Its volume depends on the mass and type of explosive used and of course on the geotechnical characteristics of the soil (Frgić et al., 1988; Bakr, 2019; Soltani et al., 2019).

Using generally known construction methods, it is possible to effectively improve the geotechnical characteristics of soft soils. Explosive Compaction (EC) is a soil modification technique where, in a borehole, energy released by detonation is used to compress soft soil. The effectiveness of EC depends on the type and size of soft soil grain and the type of explosive charge. The studies were conducted at thirteen work sites in the world where the EC method was successfully applied. It was concluded that the density, stability and strength of soft soil can be improved with the help of EC. Processing the field data obtained, EC efficiency was observed for unstable and liquefiable deposits with particle sizes ranging from gravel to dry sand with less than 10% clay (Shakeran et al., 2016; Težak et al., 2019).

However, EC is still less commonly used to improve the geotechnical features of soft soil than conventional construction methods, such as vibro methods, Deep Soil Mixing (DSM), Deep Dynamic Compaction (DDC) or jet grouting (Težak, 2018; Težak et al., 2019).

A review of the available literature has not documented systematic studies that define the impact of technical characteristics of explosives on the formation of spherical cavity at a certain depth of clay soil after blasting of explosive charge. No research has been found to define a method for determining the shape and volume of the resulting spherical cavity.

However, a new and 3D visualization in exploration borehole, to record natural discontinuities in rock, has been developed. The method is 3-D visualization of fracture distributions in volumes close to boreholes for well planning, reservoir-scale fracture model building, reservoir flow simulation, and hydraulic fracture control discontinuities (Wu and Pollard, 2002).

Also, Schepers et al. (2001) investigated characteristics of the rock structure, and defined the common meaning of core images and images of acoustic borehole wall.

The developed BoreIS application was studied and introduced. This software was developed as an extension to ESRI's ArcScene three-dimensional (3D) GIS environment. BoreIS interactive manipulation of terms in complex queries, simple addition of contoured surfaces, and masking by lithology or formation helps geologists find spatial patterns in their data, beyond the limits of data tables and flat maps (McCarthy and Graniero, 2006; Težak, 2018).

Based on available literature, it was imperative to develop an application and a unique method for computing the volume and 3D representation of the resulting spherical cavity. The described method demonstrates the integration of GNSS measurement data and data obtained by measuring with a borehole camera and laser (Težak, 2018; Težak et al., 2019).

3. Field Survey and Geotechnical Research

Survey and geotechnical field research were carried out on exploitation field Cukavec II during 2014, 2015 and 2016. The exploitation field Cukavec II is located in the vicinity of Varaždin (Figure 2). During the field research, the polygon in question was recorded and boreholes were staked out by the GNSS method. The modern blasting technique and technology was also used, and the newly developed application and AutoCad Civil 3D were used to processing the obtained data (Težak, 2018; Težak et al., 2019).

The importance and contribution of the application are reflected in the use of open source technology, and in compatibility with commercial tools and the ability to connect to other systems through a variety of interfaces. Additionally, the application involves using web technology that enables secure login to the system from any computer, tablet, cell phone, or other similar device connected to the internet. All the data that users collect and enter into the system are immediately available to all remaining process participants. The concept and possibilities of the application in the technical field are innovative. The application calculates and draws 2D and 3D models of the resulting cavity. The compatibility of the application with other CAD tools gives a more detailed 3D cavity expansion model. The presented method and application, measure and calculate the volume of the resulting cavity expansion, which helps engineers and geotechnicians to build and run overhead and underground structures in clay much more economically (Težak, 2018).

3.1. Survey Field Research

In order to define 3D coordinates of boreholes (MB1 to MB8, MB13 to MB45 and PMB1 to PMB6), a RTK GNSS method based on CROPOS (CROatian POsitioning System) was used. The positioned boreholes are shown in figure 3 (Težak, 2018; Težak et al., 2018; 2019).

Real-Time Kinematic (RTK) is a method where relative coordinates of an unknown point, in respect to the known one, are determined a moment after placing the rover on that point. The only limitation of the method is the distance range of radio connection which is resolved by implementing VRS (virtual reference stations) in CROPOS (Figure 4) (Pribičević and Medak, 2003; Težak et al., 2018).

The position of the boreholes is defined with the GNSS receiver TOPCON HiPer+ (Figure 5), with main technical features of the accuracy of RTK horizontal measurement H= 10mm+1ppm and accuracy of RTK vertical measurement V= 15mm+1ppm. The horizontal position of the surveying profile of boreholes is staked out in official reference coordinate system HTRS96/TM.

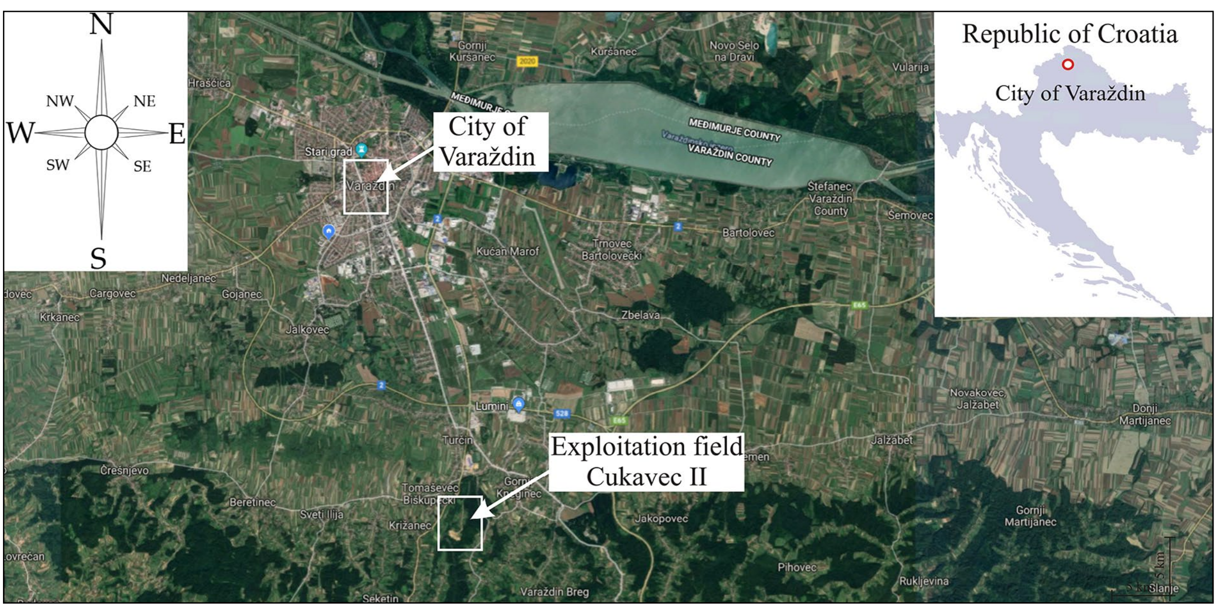

Figure 2- Location of exploitation field Cukavec II.

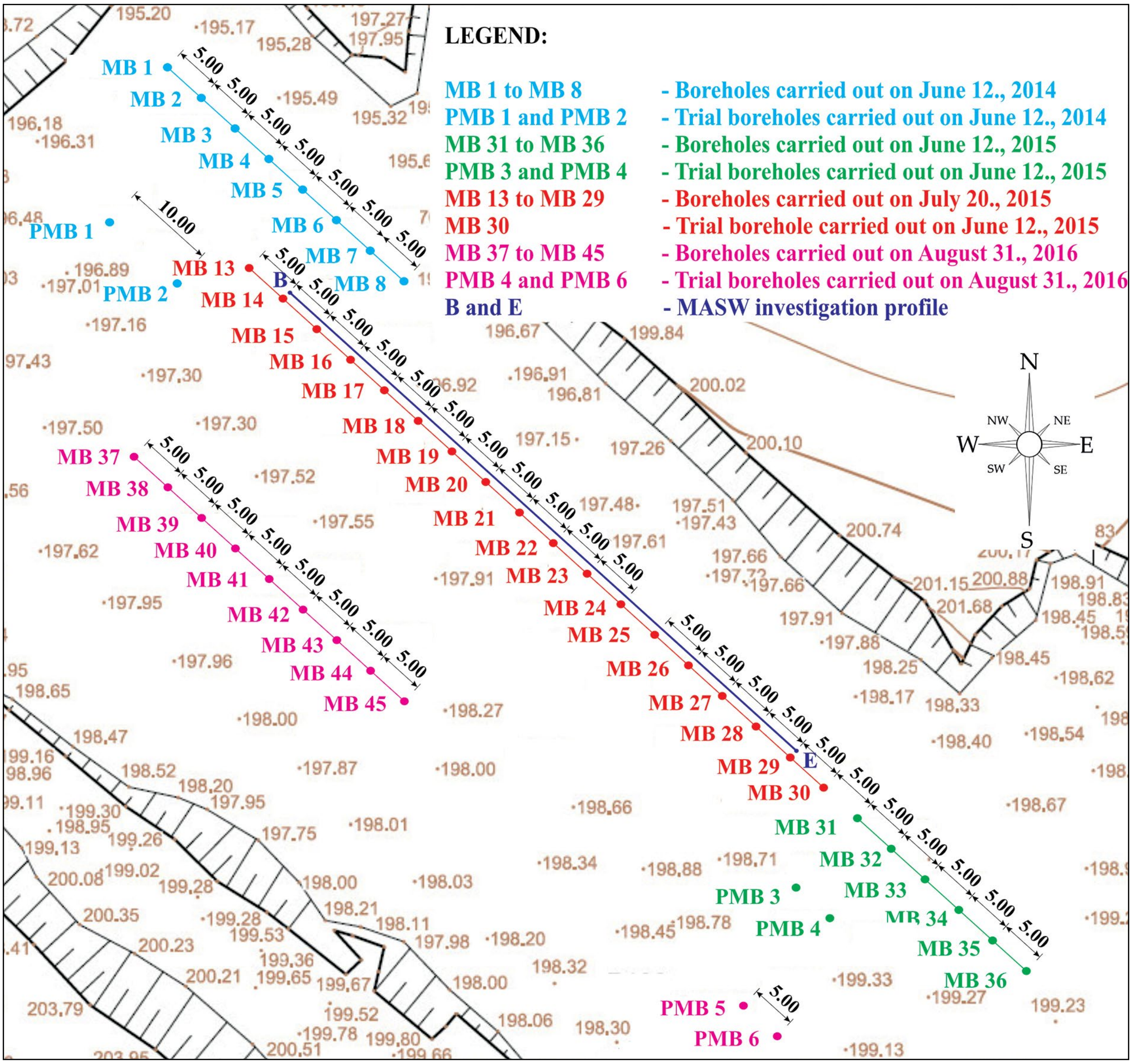

Figure 3- Exploitation field Cukavec II and positioned boreholes (Težak, 2018; Težak et al., 2019).

Preceding to blasting was the measurements of characteristic field points to make up a geodetic map. In order to stake out mine boreholes, they need to be defined on a surveying map. Boreholes are defined 5 meters apart and each has its own unique name. That way every borehole a has name, E and N coordinate. All boreholes are transferred to specific file in the format: NAME, E coordinate, N coordinate, h coordinate where the h coordinate is equal to zero for all entries.

Next step before blasting is staking out boreholes and evaluating the results of staking out. The processing of staked out data was done in TopoSURV v.8.2. Results are shown in table 1. From table 1 one can see that stake out points are almost the same as projected values. A conclusion based on the results from table 1 is that stake out points have great accuracy for blasting.

3.2. Geotechnical Field Research

Geotechnical field research has gathered useful data on soil layers at depth using geophysical seismic methods and in-situ testing of the dynamic properties of clay soil. Presented methods were implemented for better insight into the clay soil.

Before carrying out the investigations made at in the exploitation field Cukavec II, laboratory tests

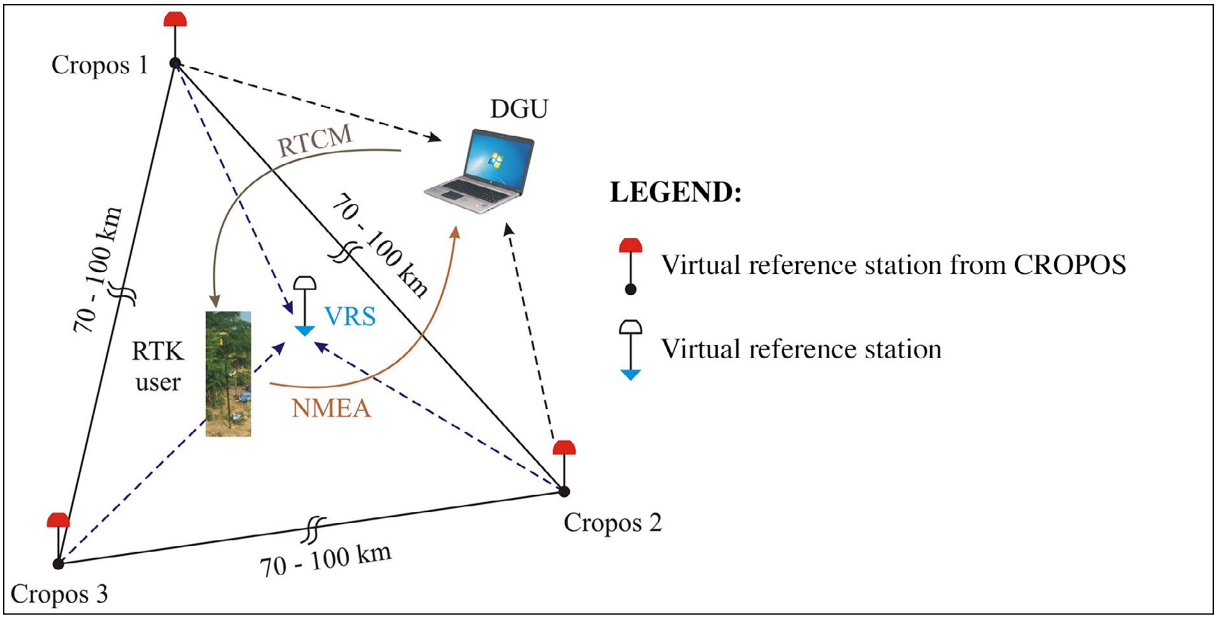

Figure 4- Principle of the virtual reference stations (Težak et al., 2018).

Figure 5- GNSS receiver-Topcon HiPer+.

were carried out on clay soil. Based on laboratory tests, a shear modulus G was obtained which, in small deformations, is directly related to the shear wave velocity V_s.

3.2.1. Geophysical Field Research

Shear wave velocity (V_s) was measured to estimate the dynamic properties of the soil by profile depth with Multichannel Analysis of Surface Waves (MASW) method (Gabriels et al., 1987; Park et al., 1999).

In refraction analysis, the travel times of the first arrival on each geophone was used. The geophones were arranged in a row along the profile (Figure 3 and 6). The record length and sample interval are the most sensitive parts of the measurement interpretation.

Investigation profiles were placed directly next to the line that connects the boreholes (Figure 6). Receiver spread for the MASW profile consisted of 24 vertical 4.5 Hz geophones, with the receiver spaced out 3.0 m. The depth of penetration for the surface wave for this particular survey was 30 m. For this purpose, fundamental mode and first higher mode of the dispersion curve are used. Experimental dispersion curve measured on the site was interpreted using SeisIMAGER 4.0.1.6. OYO Corporation 2004-2009 computer software (Strelec et al., 2019).

As typical seismic profiles shown are those which were performed in 2015. During field seismic surveys, a total of 2 seismic profiles were performed in 2015 using the MASW method. The profiles were placed in a line across the center of the borehole, and each profile included 15 boreholes with an average depth of 2.5 meters, and at a distance of 5 meters. MASW method was carried out before and after the activation of the explosive charge.

The MASW method gathered data, among other things, about the S wave velocities of the profiles. For the purpose of this article, changes in the velocity of S waves in profile 2 are presented. Figures 7 and 8 show 2D V_s - Depth graph on profile 2, before and after blasting.

Table 1- The comparison of projected and stake out values.

Borehole	Projected values		Stake out values		Distinction between projected and stake out values	
	E coordinate (HTRS96/TM) (m)	N coordinate (HTRS96/TM) (m)	E coordinate (HTRS96/TM) (m)	N coordinate (HTRS96/TM) (m)	ΔE (cm)	ΔN (cm)
MB1	489450.00	5122751.77	489449.97	5122751.77	-3	0
MB2	489453.79	5122748.40	489453.83	5122748.38	4	-2
MB3	489457.47	5122745.07	489457.46	5122745.05	-1	-2
MB4	489461.22	5122741.75	489461.23	5122741.75	1	0
MB5	489464.88	5122738.43	489464.84	5122738.44	-4	1
MB6	489468.61	5122735.08	489468.57	5122735.08	-4	0
MB7	489472.40	5122731.76	489472.41	5122731.77	1	1
MB8	489476.12	5122728.26	489476.14	5122728.24	2	-2
MB13	489075.02	5122634.35	489075.01	5122634.34	-1	-1
MB14	489078.74	5122631.02	489078.74	5122631.02	0	0
MB15	489082.47	5122627.68	489082.45	5122627.68	-2	0
MB16	489086.20	5122624.35	489086.21	5122624.35	1	0
MB17	489089.92	5122621.01	489089.93	5122621.01	1	0
MB18	489093.65	5122617.68	489093.64	5122617.65	-1	-3
MB19	489097.37	5122614.35	489097.39	5122614.36	2	1
MB20	489101.10	5122611.01	489101.10	5122611.00	0	-1
MB21	489104.83	5122607.68	489104.82	5122607.66	-1	-2
MB22	489108.55	5122604.34	489108.54	5122604.32	-1	-2
MB23	489112.28	5122601.01	489112.28	5122601.01	0	0
MB24	489116.00	5122597.68	489116.00	5122597.67	0	-1
MB25	489119.73	5122594.34	489119.76	5122594.34	3	0
MB26	489123.46	5122591.01	489123.46	5122590.98	0	-3
MB27	489127.18	5122587.67	489127.18	5122587.67	0	0
MB28	489130.91	5122584.34	489130.90	5122584.32	-1	-2
MB29	489134.63	5122581.00	489134.66	5122580.99	3	-1
MB30	489138.36	5122577.67	489138.35	5122577.65	-1	-2
MB31	489142.09	5122574.34	489142.09	5122574.35	0	1
MB32	489145.81	5122571.00	489145.81	5122570.99	0	-1
MB33	489149.54	5122567.67	489149.53	5122567.63	-1	-4
MB34	489153.26	5122564.33	489153.27	5122564.36	1	3
MB35	489156.99	5122561.00	489156.98	5122560.99	-1	-1
MB36	489160.72	5122557.67	489160.70	5122557.69	-2	2
MB37	489059.52	5122615.00	489059.48	5122615.04	-4	4
MB38	489063.24	5122611.74	489063.20	5122611.77	-4	3
MB39	489066.97	5122608.38	489066.96	5122608.40	-1	2
MB40	489070.71	5122605.03	489070.67	5122605.06	-4	3
MB41	489074.43	5122601.75	489074.40	5122601.77	-3	2
MB42	489078.13	5122598.39	489078.13	5122598.41	0	2
MB43	489081.86	5122595.05	489081.84	5122595.04	-2	-1
MB44	489085.61	5122591.71	489085.60	5122591.75	-1	3
MB45	489089.30	5122588.35	489089.26	5122588.39	-4	4
PMB1	489445.79	5122735.66	489445.79	5122735.62	0	-4
PMB2	489453.24	5122729.03	489453.24	5122729.04	0	1
PMB3	489127.98	5122573.54	489127.98	5122573.54	0	0
PMB4	489133.55	5122568.55	489133.55	5122568.55	0	0
PMB5	489126.59	5122555.03	489126.55	5122555.03	-4	0
PMB6	489130.32	5122551.69	489130.32	5122551.70	0	1

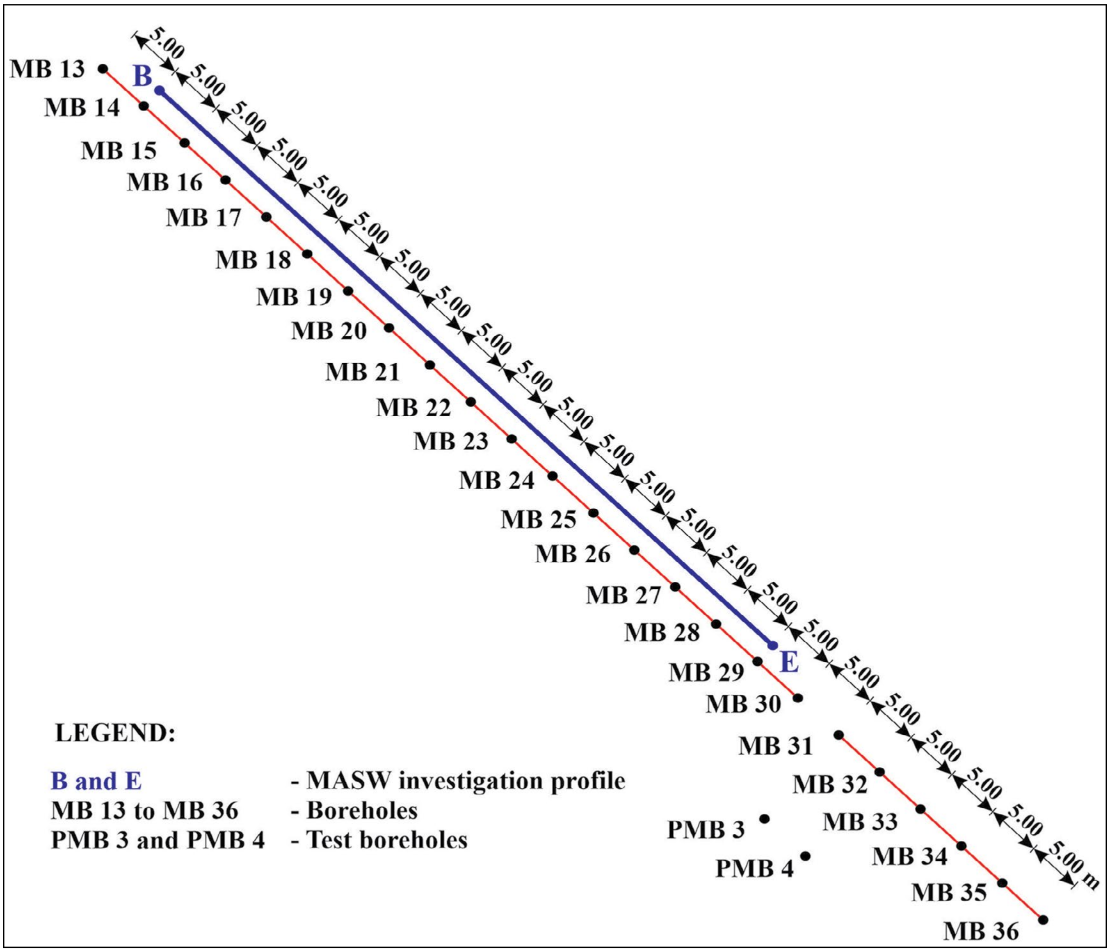

Figure 6- Geodetically determined MASW profile on the exploitation field Cukavec II in 2015.

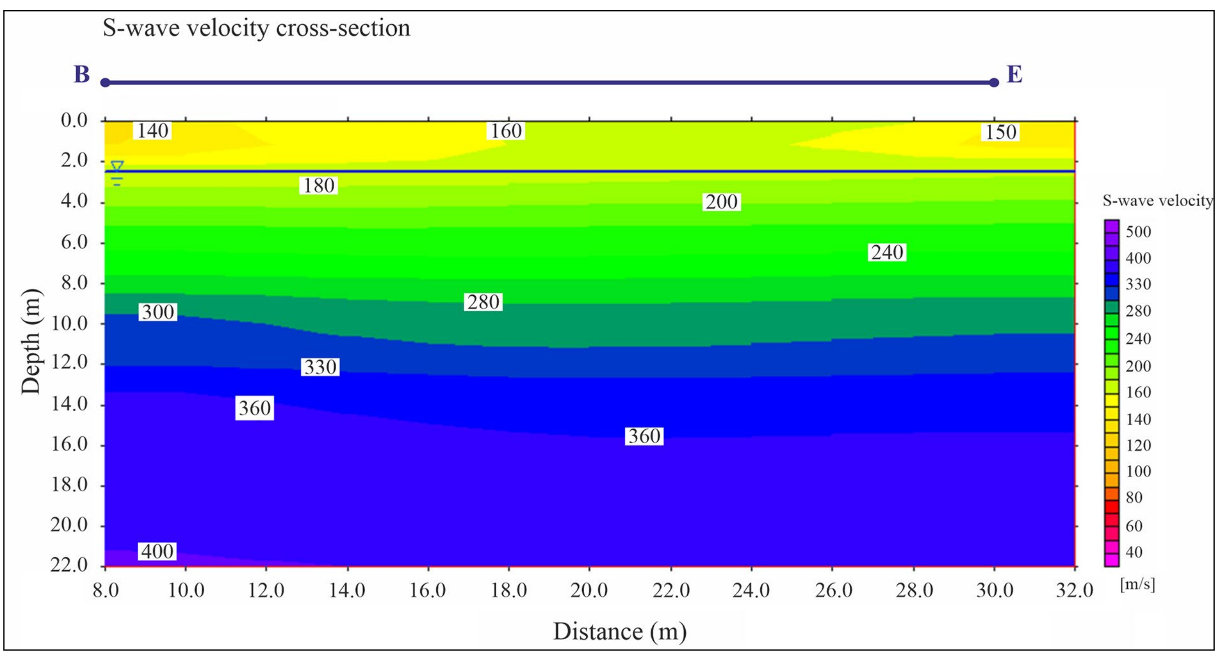

Figure 7- 2D V_s - Depth graph on profile 2 before blasting.

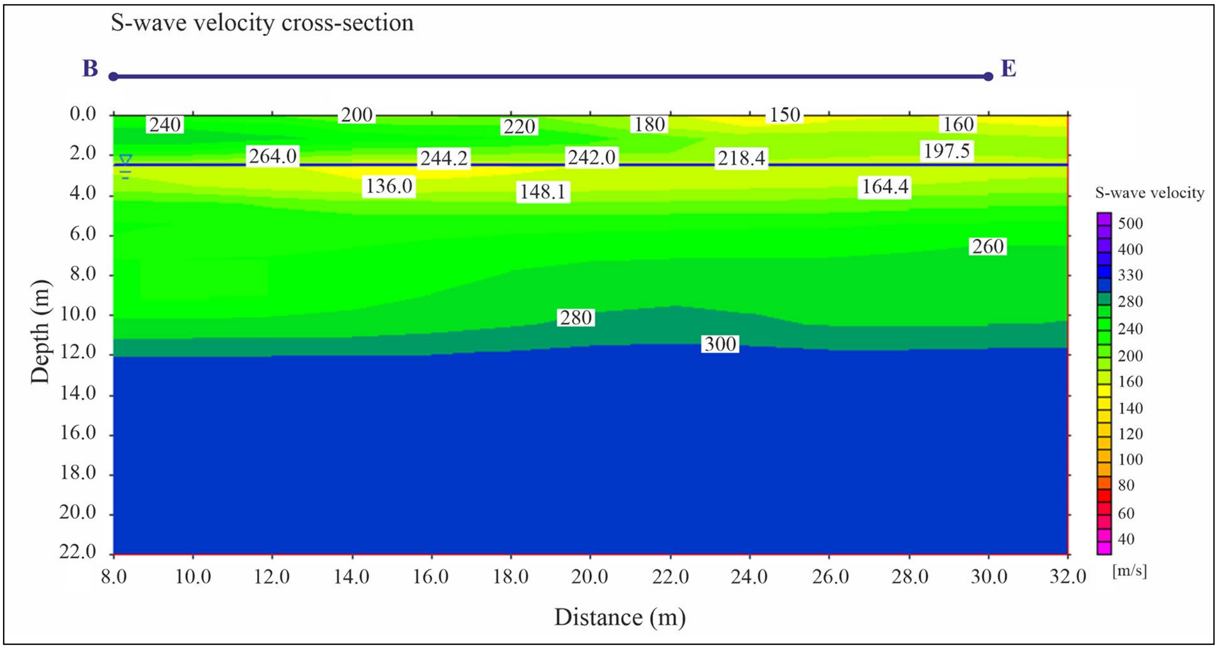

Figure 8 - 2D V_s - Depth graph on profile 2 after blasting.

Based on the above 2D V_s - Depth graph, figures 7 and 8, by comparison of the S wave velocities are shown before and after blasting. It shows that the activation of explosive charges resulted in an increase in S wave velocities at an average depth of 2.0 m to 3.0 m, which leads to a conclusion that there is an increase in the stiffness of the surrounding clay soil after blasting. A detailed MASW analysis is presented in the PhD thesis, Težak, 2018 and in a published article by Strelec et al., 2019.

3.2.2. Trial Blasting to Determine the Optimum Quantity of Explosive Charges Used to Produce Spherical Cavities in Clay Soil

During the trial blasting, effective quantities were determined for the used explosive charges, which produced spherical cavities in the clay soil. For a given borehole diameter of 131 mm and a depth of 2.00 - 3.00 m, a spherical cavity can be made with explosive charges Pakaex and Permonex V19 (Figure 9), ranging in mass from 0.2 to 1.6 kg. Detonation velocity for

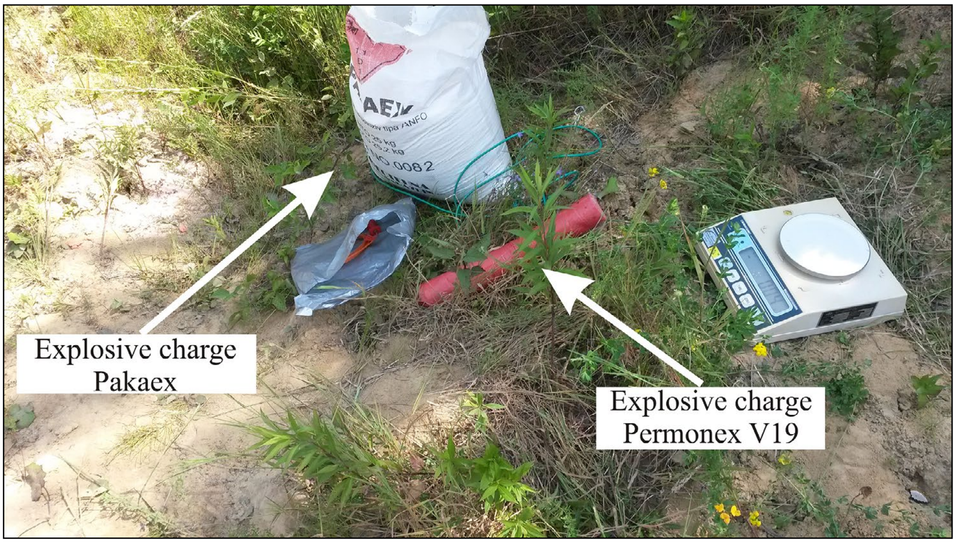

Figure 9- Explosive charge, Permonex V19 and Pakaex (Težak, 2018).

the Permonex V19 was determined in the accredited Explosive Materials Laboratory at the Faculty of Mining, Geology and Petroleum Engineering. The detonation velocity of Permonex V19 is 4500 m/s and that of Pakaex 2950 m/s (Ester, 2005). Activation of the blast field was performed by the NONEL system via instantaneous electric detonators (IED). The ideal size of the sand stem was 0.5 m, and made of stone material grain size of 0/4 mm. The construction of the borehole explosive loading is shown in figure 10a. Figure 10b shows the moment of activation of the explosive charge, and figure 10c shows a schematic representation of the resulting spherical cavity (Težak, 2018; Težak et al., 2018; 2019).

3.2.3. Determination of the spherical cavity

- Heavy Duty GeoVision Borehole Camera was used to record spherical cavities after blasting,

- EDS-c laser was used to determine the distances of the resulting expansion,

- The volumes of spherical cavities obtained by the activation of individual blastholes were determined by an integrated system, a Heavy Duty GeoVision Borehole Camera to which the EDS-C laser was added (Figure 11).

4. Integration of RTK GNSS Methods with Borehole Camera and Laser System

Determining the shape and volume of the spherical cavity was the main reason for developing a unique method of observation.

The integration of the RTK GNSS measurement method, depth camera and laser is the basis of the unique method of the observation. The application was developed to calculate the coordinates of boreholes based on the known E and N coordinates (obtained by GPS device) and the height H obtained by using a depth camera. In order to be able to calculate all the coordinates of boreholes at a certain depth of shooting, a laser was also used to obtain distances between the depth camera and the walls of boreholes. In this way, input data was obtained for the application, which calculated the coordinates, plotted the characteristic cross sections, and finally calculated the volume of the resulting spherical cavities of each borehole (Figure 12).

4.1. The Records of the Depth Camera and Laser

Depth camera shooting is designed in such a way that the depth camera rotates 360° clockwise at a

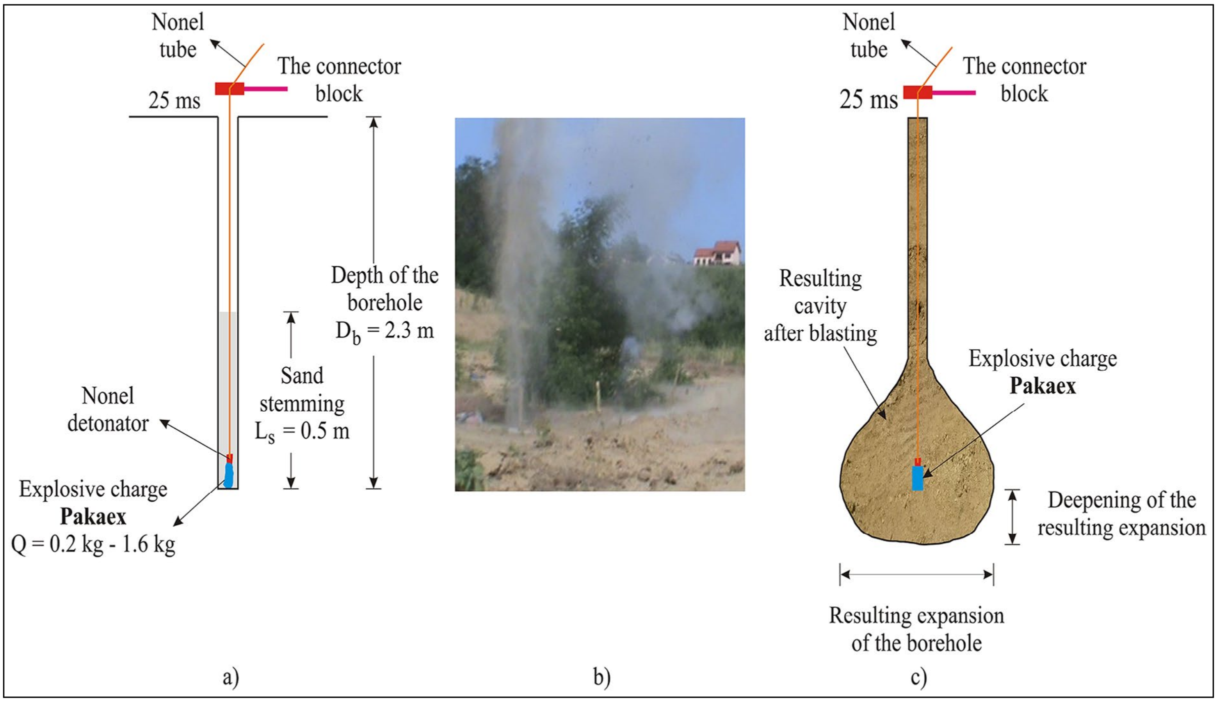

Figure 10- a) Shows the construction of the borehole, b) shows the moment of the activation of the explosive charge and c) shows the resulting spherical cavity after the explosive charge is activated (Težak et al., 2019).

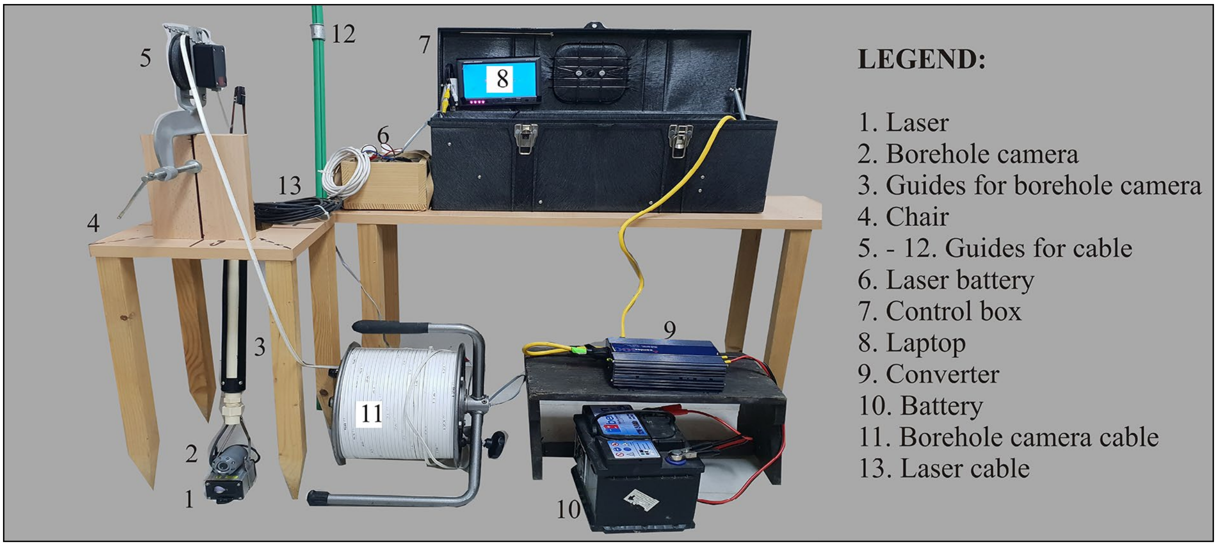

Figure 11- Spherical expansion measurement equipment (Težak, 2018).

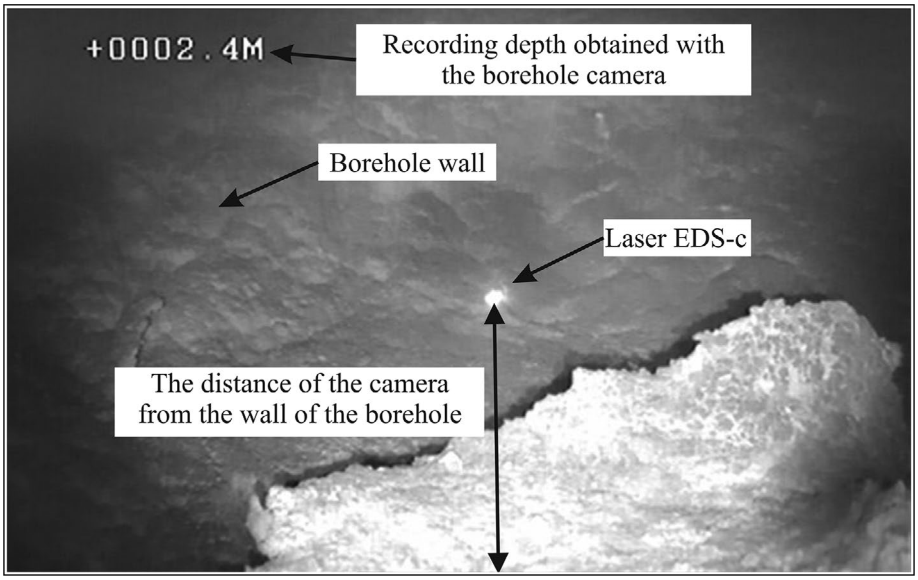

Figure 12- Depth camera snapshot of the spherical expansion (Težak et al., 2019).

shooting interval of 45° (Figure 9). The characteristic recording depths for every borehole was determined by detailed analysis of in-situ measurements. The result (Figure 12) and the laser-obtained distance, at characteristic recording depths, are recorded in the measurement log. The obtained data from the field, were entered into application for detailed processing. The application calculates the volume of the resulting spherical cavities and provides the ability to draw the entire borehole as well as the resulting cavity in 2D and 3D views. The application was defined to calculate and export coordinates of the cross section of the borehole in AutoCad Civil 3D. In this way, the accuracy of the application can be tested with AutoCad Civil 3D tools. More accurate 3D representation of the resulting extensions was obtained, i.e. an entire mine borehole with integration of measurement data, AutoCad Civil 3D tools, and designed applications (Težak, 2018; Težak et al., 2018; 2019).

5. Measurement Results Obtained and Processed

During the course of the research, encouraging field and cabinet results were achieved (Table 2). Knowledge about the effects of explosive charge in

Table 2- Obtained and processed data for spherical cavity after blasting (Težak et al., 2019).

Pakaex					Permonex V19				
Borehole	Explosive charge mass	Volume of the resulting cavity	Resulting expansion of the borehole	Deepening of the resulting expansion	Borehole	Explosive charge mass	Volume of the resulting cavity	Resulting expansion of the borehole	Deepening of the resulting expansion
	Q (kg)	V_{rc} (m^3)	L_{re} (m)	D_{re} (m)		Q (kg)	V_{rc} (m^3)	L_{re} (m)	D_{re} (m)
MB20	1.00	0.7100	1.1570	0.5200	MB24	0.80	0.6184	1.1900	0.3100
MB41	1.00	0.8095	1.1110	0.6000	MB26	0.80	0.5690	1.1310	0.3600
MB34	0.80	0.3935	0.9530	0.3300	MB45	0.80	0.7405	1.0700	0.4000
MB18	0.80	0.3440	0.8770	0.4600	PMB5	0.80	0.7227	1.0710	0.4200
MB19	0.80	0.3626	0.8750	0.4800	MB23	0.60	0.5276	1.1040	0.3500
MB40	0.80	0.5190	1.0600	0.4000	MB25	0.60	0.6330	1.0850	0.2900
MB35	0.60	0.2555	0.7830	0.2500	PMB6	0.60	0.6151	1.1520	0.3500
MB17	0.60	0.6160	1.0430	0.3400	MB36	0.40	0.1135	0.6930	0.2300
MB39	0.60	0.3785	1.0880	0.4000	MB21	0.40	0.2925	0.9360	0.2600
MB15	0.40	0.2445	0.6980	0.3100	MB27	0.40	0.2160	0.5850	0.3200
MB16	0.40	0.1945	0.7870	0.3000	MB43	0.40	0.2815	0.8660	0.3000
MB38	0.40	0.2980	0.8480	0.4000	MB22	0.20	0.0825	0.5570	0.2600
MB13	0.20	0.1005	0.5760	0.1800	MB28	0.20	0.0700	0.5050	0.2200
MB14	0.20	0.0645	0.5770	0.2200	MB42	0.20	0.1480	0.6620	0.2000
MB29	0.20	0.0980	0.6870	0.2400					
MB37	0.20	0.1175	0.6010	0.2500					

clay soil and the possibility of using a particular type of explosive in geotechnical practice were expanded. In particular, this relates to blasting in soft rocks at different depths below the soil surface by activating a specific type and mass of explosives to form spherical cavities. The conducted field research and innovation in the field data processing has led to a sufficient amount of quality data, which enabled the development of the presented application (Težak, 2018).

The development of CROPOS systems in the Republic of Croatia has led to a strong development of applications that use GNSS data. Since then, the data is obtained in real-time. Comparing the projected values and the field measurements, we can conclude that GNSS data can be used for the purposes of determining the coordinates of blasting in clay soil. The Heavy Duty GeoVision Borehole Camera and EDS-c laser is a system that integrates well with the GNSS measurement data. Such a system, along with its associated application, is an advanced system for modeling blasting in clay soil and blasting in general.

5.1. Examples of Resulting Volume of Spherical Expansion

Thanks to a well-established research plan, encouraging results of the spherical expansion were obtained by field research, and after processing of the results, the volumes of spherical expansion were calculated more accurately. The knowledge about the effect of explosive charge in clay soil and the possibility of using a particular type of explosive in geotechnical practice have also been expanded (Težak, 2018; Težak et al., 2018; 2019).

The significance and contribution of the application is reflected in the use of Open Source Technologies, and on the other hand, in its compatibility with commercial tools and the ability to connect to other systems through a number of interfaces. It adds value to the use of web technologies to enable secure login to the system from any computer, tablet, mobile phone or other similar device connected to the Internet. All data that users collect and enter into the system is immediately accessible to all remaining process participants (Težak, 2018).

Also, the compatibility of the application with other CAD tools will greatly contribute to the verification and more detailed 3D model of the resulting expansion (Težak, 2018).

Listed below are examples of measured spherical cavities after activation of explosive charge in the Cukavec II exploitation field in 2014, 2015 and 2016, with the integration of RTK GNSS measurements, depth camera, and laser. Examples also show the accuracy of calculating the volume of a spherical cavity using an application and the AutoCad Civil 3D tool. In figures 13 and 14, an example from 2014 is given. Figures 15 and 16 show 2015 examples, and figures 17 and 18 show 2016 examples (Težak, 2018).

Example 1.

Borehole MB8 (*E 489476.12 N 5122728.26 H 196.24*). Explosive charge, Permonex *1.0 kg*, Stemming length *1.0 m* (*0.5 m* sand and *0.5 m* clay). Spherical cavity, AutoCad Civil $V_{ACAD} = 842.00\ dm^3$, Application $V_{application} = 828.95\ dm^3$. **Distinction** $V_{distinction} = V_{ACAD} - V_{application} = 13.05\ dm^3$.

Example 2.

Borehole MB31 (*E 489142.09 N 5122574.35 H 198.49*). Explosive charge, Permonex V19 *0.2 kg*, Stemming length *0.3 m* (sand). Spherical cavity, AutoCad Civil 3D $V_{ACAD} = 81.00\ dm^3$, Application $V_{application} = 77.00\ dm^3$. Distinction $V_{distinction} = V_{ACAD} - V_{application} = 4\ dm^3$.

Example 3.

Borehole MB38 (*E 489063.24 N 5122611.74 H 197,45*). Explosive charge, Pakaex *0.4 kg*, Stemming length 0.5 m (sand). Spherical cavity, AutoCad Civil 3D $V_{ACAD} = 304.00\ dm^3$, Application $V_{application} = 292.10\ dm^3$. Distinction $V_{distinction} = V_{ACAD} - V_{application} = 11.90\ dm^3$.

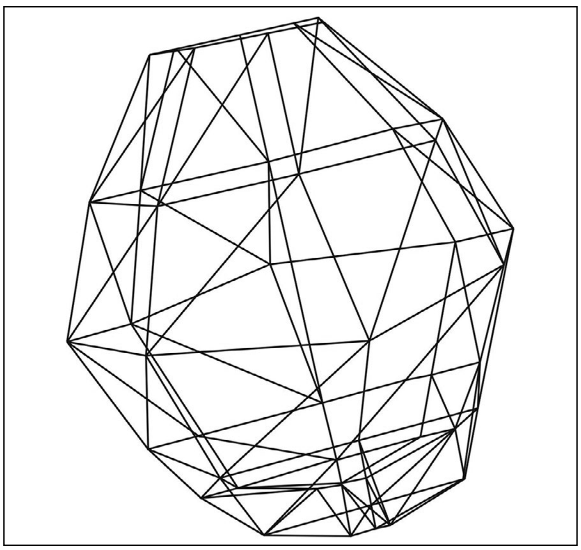

Figure 13- Linear 3D model of the resulting cavity, Borehole MB8, application.

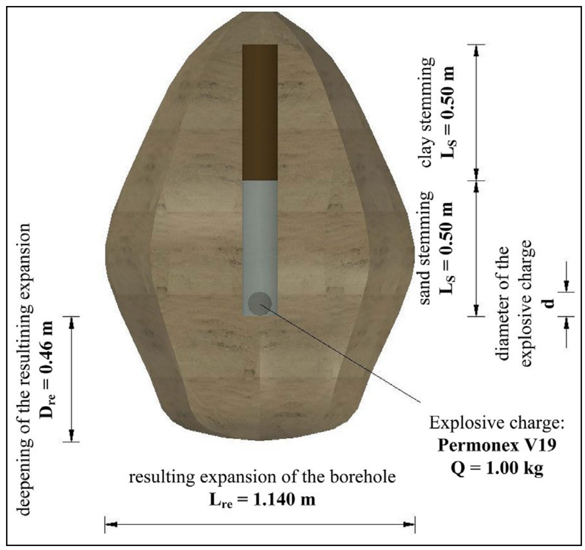

Figure 14- 3D model of the resulting cavity, Borehole MB8, AutoCad Civil 3D.

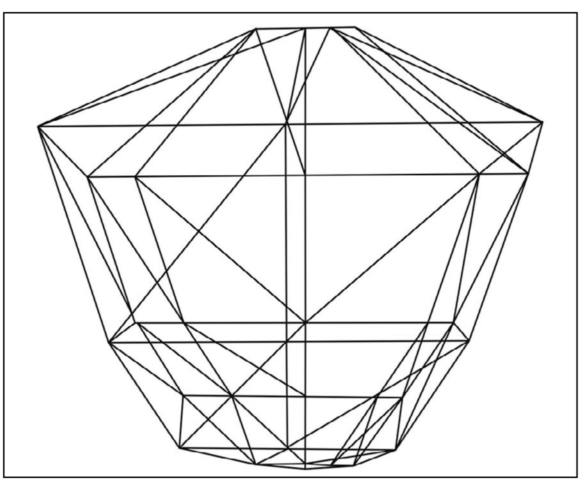

Figure 15- Linear 3D model of the resulting cavity, Borehole MB31, application.

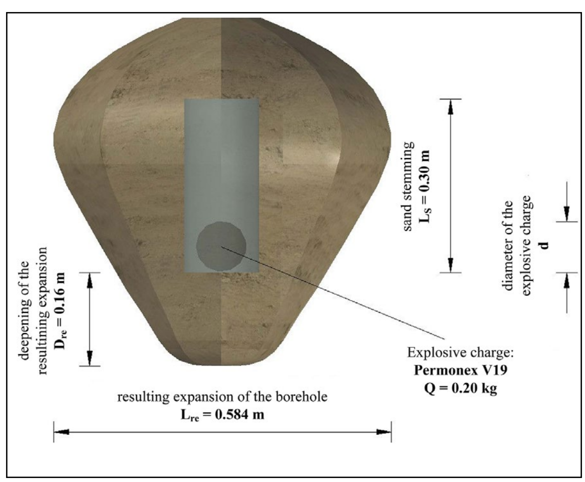

Figure 16- 3D model of the resulting cavity, Borehole MB31, AutoCad Civil 3D.

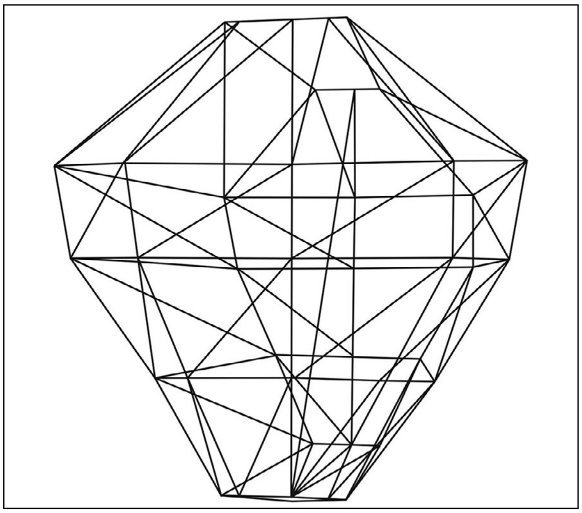

Figure 17- Linear 3D model of the resulting cavity, Borehole MB38, application.

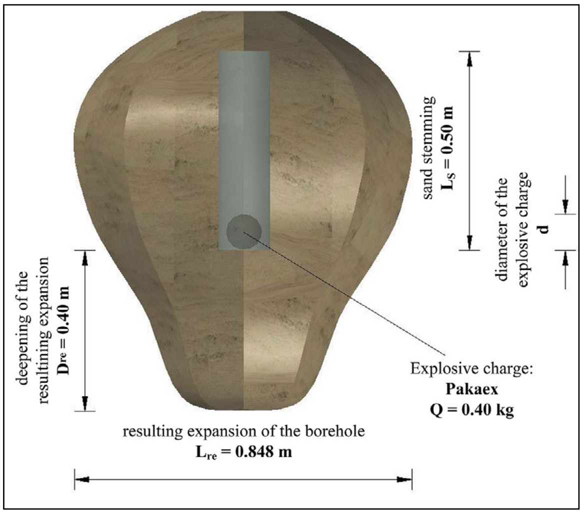

Figure 18- 3D model of the resulting cavity, Borehole MB38, AutoCad Civil 3D.

6. Conclusion

The paper presents an innovative method of measuring the resulting spherical cavities after the activation of an explosive charge, since spherical cavities in clay soil have not been studied widely.

The most significant results of the research presented in this paper are certainly the determination of the volume of cavities formed in the soft soil when blasting a series of boreholes set up on a certain profile. For this purpose, a unique system was designed and developed. The unique method of the observation is based on the integration of the RTK GNSS measurement method, depth camera and laser. An application is designed to calculate the resulting volume of the expansion. The concept and capabilities of the application in the technical field are innovative. In addition, the application draws 2D and 3D models of the resulting cavity. Also, the compatibility of the application with other CAD tools greatly contributes to the validation and more detailed 3D model of the resulting expansion.

The knowledge that it is possible to measure and calculate the volume of the resulting expansion will greatly help engineers to design and construct the overhead and underground structures more economically. The most important practical application of the research is in construction of structural elements for anchoring the foundation and retaining walls, the long-lasting slope stabilization in clay material and the stabilization of various structural objects. In conclusion, this paper clearly establishes the dependence of the volume of the formed spherical expansion on the mass of the explosive charge and the used explosive type and technical parameters. This way, the base for establishing the spherical formation model in different rocks and soil types has been laid, which is reflected in the application of the research results in the geotechnical practice of stabilizing and improving the properties of the working environment built of soil and rocks.

The aim of geophysical field research was to estimate the dynamic properties of the natural soil layers in depth, and to determine changes in the dynamic properties of the soil caused by the activation of explosive charges. To achieve this goal, the MASW method was implemented. It is a seismic geophysical method whose results allow estimation of soil stiffness. By comparing the 2D view of S wave velocities, before and after blasting, it was shown that activation of explosive charges led to an increase in S wave velocities at an average depth of 2.0 m to 3.0 m. It can also be concluded that at an average depth of 2.0 m to 3.0 m an increase in the stiffness of the surrounding clay soil after blasting occurs.

To improve this research, it is obligatory to perform supplementary researches that could bring new light to the technical characteristics of explosives and which type of soils have larger effect on the expansion diameter and volume. For this reason, it is also recommended taking the process of detonation into account, where the shock wave front seems to play the most significant role (Sućeska, 2001; Dobrilović, 2008; Dobrilović et al., 2010).

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