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Some Innovative Technologies and Techniques in Geotechnical Engineering

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Abstract

Several emerging technologies and techniques have been in focus of geotechnical community during the past few decades. This paper presents some of them, such as non-destructive testing methods and utilization of industrial waste in sustainable soil improvement. These elements represent a step forward from the classical concept of geotechnical engineering which is mostly based on destructive investigation works and application of standard engineering cement-based materials. Further, perspectives faced by geotechnical engineering in the use of the shallow geothermal energy will also be presented due to more and more prominent needs for the utilization of this valuable renewable energy source. Finally, during the last few years risk management has been implemented in geotechnical engineering, especially when there is a need for a rational decision-making process conducted by the infrastructure managers/owners.

1. Introduction

Geotechnical engineering connects civil engineering and geo – sciences and as such it comprises a wide range of activities which are necessary in order to secure a safe, functional and economical structure. Investigation works in geotechnical engineering, including the ones for the assessment of the condition of existing structures, are still predominantly conducted using destructive methods. Classical soil and rock investigations primarily include borehole drilling, which is the basic geotechnical test that provides an insight into the geological structure of the foundation soil. By carrying out the SPT tests during the drilling, as well as taking samples and their testing in the laboratory, an insight into physical and mechanical properties of the foundation soil is obtained. However, this traditional method has certain limitations in terms of time and finances, and these limitations were the main motive for the development of the non-destructive methods that would, besides saving these resources, encompass larger volumes being investigated. Of course, these non-destructive methods are still burdened with certain disadvantages, which partially restrict their use, but an increasing trend of their application is evident. Advantages of non-destructive testing come to the fore in the assessment of the condition of strategic infrastructure line structures such as railway lines, road and motorway network, embankments for flood protection, etc. In order to evaluate a method as acceptable and successful, there must be a change in the physical properties of soil and rock to which the method is sensitive. Therefore, the choice of geophysical methods suitable for the observed problem is of crucial importance. The type of physical properties clearly determines the scope of application of non-destructive methods [1]. Knowledge and experience is needed to interpret the data collected through non-destructive methods, because the set of data obtained from tests does not have to indicate a specific condition in the soil or rock, which may result in unsatisfactory results. The paper will demonstrate several applications of non-destructive testing examples in the field of geotechnical engineering.

The urbanization process has several negative effects on the environment and on social life [2]. One of the most prominent negative effects is the production of industrial waste materials, where huge amounts of thermal power plant byproducts, as well as steelworks byproducts, need to be disposed in a proper manner. In the same time, rapid urbanization leads to lack of suitable construction surfaces for further development activities caused by progressive city development. Two solutions are possible to overcome the problem of construction site deficiency. The first one is expansion of cities in underground where an increasing number of underground structures gives rise to the complexity of underground building systems. The second solution is to ‘stay on surface’ and to utilize the ground which is, from the geotechnical aspect, originally unsuitable for construction.

The later one is still more often applied. These mentioned problems of non-satisfactory ground characteristics and accumulation of industrial waste materials on deposits can be simultaneously dealt with a ground improvement as one of the disciplines which tend to reuse waste materials. In second part of 20th century, a series of techniques for engineering treatment of ground were developed in order to enhance its geotechnical characteristics and this paper also discusses potential of using industrial byproducts for different ground treatment technologies.

Geothermal energy is thermal energy generated and stored within the Earth. The exploitation of geothermal resources is divided into deep and shallow resources, where the ‘separation line’ is roughly determined by a depth of 400 m [3]. Geothermal energy is a very attractive energy source that has many advantages over conventional energy sources (coal, natural gas and oil). The most significant advantage is in the fact that it is a renewable and clean energy source with no negative environmental impact. Croatian experience in the exploitation of geothermal energy was historically mainly based on the possibilities of exploitation of deep geothermal resources. In particular, this form of exploitation is attractive in the Pannonian basin where the geothermal gradient exceeds the world average. However, during the last few years systems for exploiting shallow geothermal resources have been developed at a high rate. Based on the principle that soil/rock and groundwater temperatures at a specific depth are constant throughout the year, numerous scientific studies and subsequent implementation in practice are based on applying underground structural elements in the process of exploitation of shallow geothermal energy, as presented in the paper.

The importance of risk management in geotechnical engineering was recognised in the second half of the 20th century. In Croatia, systematic research on the identification, analysis and response to risks in geotechnical interventions has been conducted during the past 15 years. The primary objective of managing each project, including those of a geotechnical nature, is to implement a project for a predetermined period of time with planned costs and with satisfactory quality. Contrary to this is the fact that due to insufficient knowledge of soil and rock conditions, the implementation of a geotechnical project takes place in conditions of uncertainty, meaning that the outcomes of all envisaged events cannot be predicted with certainty. Every geotechnical project goes through several phases in its evolution and in each phase, the number of potential risks or adverse events with an unfavourable outcome that may negatively impact the success of the project can be determined. Virtually every activity carried out in implementing a project is burdened by the possibility that something might go wrong, so the implementation of the risk-based management plays an important role in geotechnical engineering.

2. Application of non-destructive testing tools

One of the first major applications of non-destructive testing in Croatian geotechnical practice was the dynamic testing of pile capacity and testing of the pile columns integrity. Dynamic testing of the capacity is based on the measurement of deformation and acceleration of the pile induced by a shock impact using relatively heavy loads. The weight of the load is 1-2% of the expected static capacity of the pile [4]. The height from which the load falls is 0.5-3 m. At a depth of at least two pile diameters, two or four deformation gauges or two or four accelerometers are placed at the shaft area of the pile. Based on measurements of deformation and the presumed elastic modulus, the dynamic force in the pile is calculated. Integrating the acceleration provides the velocity. Using numerical analysis based on a one-dimensional wave equation, the capacity of the pile is determined from the measured force and velocity. The dynamic process is much faster with a considerable lower cost compared to the static test. Testing of the pile column integrity is based on measuring acceleration or velocity of the column head caused by mechanical impact shocks. A low-deformation impact generates a pressure wave that travels toward the bottom of the column. Due to changes in its cross-section or in the quality of concrete, the wave is reflected and the tension wave travels toward the top of the column. By making an assumption of the wave propagation velocity in the column, defects in the columns can be located, as well as changes in the cross-section or cracks. The test is quick, cost-effective and allows testing of tens of pilots in a single day.

Figure 1 shows examples of dynamic testing of pile capacity and the integrity of a column for the requirements of foundations at the Drežnik viaduct on the Zagreb-Split-Dubrovnik motorway. A total of 69 dynamic tests and 358 integrity tests were performed.

One of the most widely used non-destructive geophysical method in Croatian geotechnical engineering is the Spectral Analyses of Surface Waves (SASW). It is used

Fig. 1. Dynamic testing of the pile capacity and integrity of pile columns

to determine the stiffness of soil at various depths, the compaction quality of road fills and fills made of reinforced soil, the thickness of transportation structures, the thickness of the concrete lining in road and hydropower tunnels and the quality control of soil improvement.

The measuring process is reliable since it avoids disturbances in the soil due to drilling, extracting samples and inserting samples in laboratory equipment. The method solves some of the fundamental problems of surface refraction, since it can reveal a softer layer that lies beneath a stiffer layer. The SASW method measures the layer stiffness and thickness with an expected accuracy of 5% and it is based on the dispersion characteristics of Rayleigh waves. It takes into account the fact that Rayleigh surface waves of different wavelengths or frequencies disperse to different depths [5]. Surface waves are generated mechanically by vertical impact at the ground surface. Vertical sensors, geophones and accelerometers are placed at predefined intervals and measure the velocity and acceleration of a passing wave. Fourier analysis transforms the received signal from the time to frequency domain and the transformed signal is subjected to further spectral analysis. Spectral functions of the phase (cross power spectrum, coherence) assist in determining dispersion characteristics of the wave. Back-analysis utilises the dispersion characteristics of the surface wave and result in stiffness values of horizontally layered soil.

Figure 2 shows an example of the test implementation and its results for the quality control of soil improvement with stone columns technique at seven sections of the Zagreb-Macelj motorway. A total of 13,090 stone columns were constructed (approximately 104,780 m’). A total of 856 tests were conducted before and after the improvements.

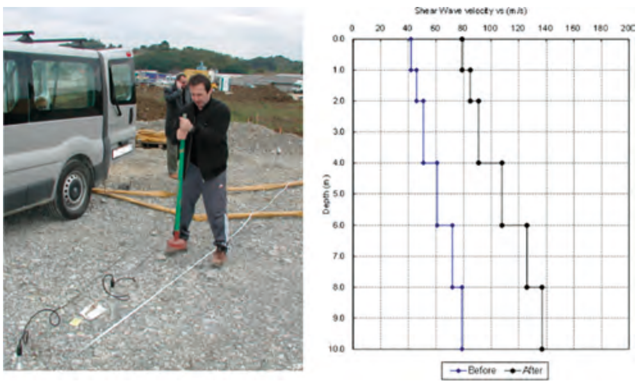


Fig. 2. The SASW method on the Zagreb-Macelj motorway

Further, very common is the use of seismic non-destructive geophysical methods, which are based on the determination of longitudinal wave velocities. Methods of seismic refraction and reflection, and their combination called the hybrid method, have important application in Croatian geotechnical engineering practice. The refraction and reflection methods define the velocity profile of longitudinal waves based on depth. The propagation velocities of the waves depend on the stiffness properties of the material through which they pass after generation of impulse or controlled vibrations at the ground surface. At the boundaries between the layers the waves are reflected or refracted, and then travel back to the surface. The arrival of a wave at the surface is detected by measuring sensors – geophones, which are placed at predefined positions. The time it takes for the waves to reach the geophones is measured. The seismic refraction method which analyses the refracted waves and reflection method which analyses reflected waves, have their advantages and disadvantages. The zone of weathering, typical for karst, is successfully registered using refraction, and provides significantly better results at lower depths. However, reflection has an advantage of being a test for identification of faults, fissures, cracks or caverns at greater depths. The hybrid seismic method combines independently obtained results of refraction and reflection into a single profile, providing geologists and geotechnicians a better insight into the engineering-geological profile being investigated [6].

Figure 3 shows implementation and test results of hybrid seismic method conducted for the requirements of the foundation project for column S17 at Pelješac Bridge [7]. Testing was conducted along two profiles, 09PELJ-1 with a length of 60 m and 09PELJ-2 with a length 80 m. Testing conducted on profile 09PELJ-1 gave possible positions of faults in a north-east direction, which is associated with a mass of debris and loose material, clearly recognisable. Profile 09PELJ-2 runs along the fault, which is seen as a zone of non-compacted material. Zones containing this kind of material are registered due to a reduction in the velocity of seismic waves in that particular area.

When appropriate, the refraction method is used in combination with Ground penetrating radar (GPR) as an electromagnetic geophysical method which provides a high-resolution image of dielectric characteristics of investigated media. The depth of testing varies considerably, and generally depends on the frequency of the antenna used [8]. Ground penetrating radar surveying is based on the principle of transmitting electromagnetic signals of different frequencies into the ground, rock or structure by using an appropriate antenna. The emitted

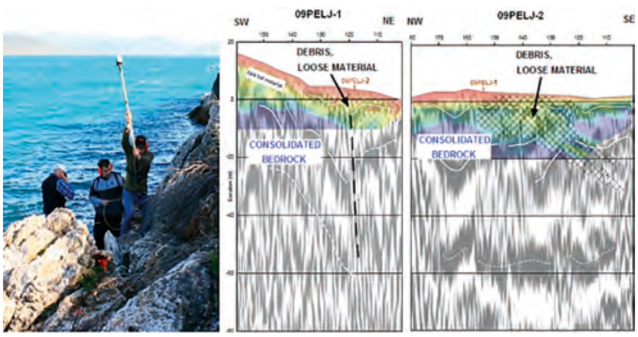


Fig. 3. The hybrid seismic method applied at the Pelješac Bridge

waves may attenuate, reflect or refract. When a wave encounters an obstacle, part of the energy is reflected back to the receiver, and the reflection is processed by forming a continuous profile of the material's electrical properties. The frequency of the antenna determines two key test parameters – the test depth and the resolution. At higher frequencies, a lower investigation depth can be achieved, but image has higher resolution. The use of lower frequencies results in lower resolution images, but a greater investigation depth can be achieved.

An example for the combined use of seismic refraction and GPR method is the location of an opening with a depth of approximately 3 m and aperture area of 10 m^2, appeared between the two lanes on Croatian highway. Figure 4. Detailed geological mapping indicated that the reason for this is due to the so-called 'reverse' karstification where the rock mass dissolves from bottom layers to top layers [9].

Fig. 4. The opening between two highway lanes

In order to determine the size and dispersion of the cavernous system, geological and geophysical investigations were carried out. Geophysical surveys included ground penetrating radar (GPR) profiling whose main task was to identify potentially 'karstification – caused' anomalies beneath the highway which could endanger its functionality and safety, while seismic refraction geophysical surveys were carried out in the area between the lanes and it was used to determine the volume and position of the cavern.

One of GPR profiles, Figure 5, located in the vicinity of surface opening, suggests that karst-linked features are presented. Therefore, GPR investigation has fulfilled its main task and also provided a useful information on where the optimal position to conduct seismic refraction investigations is.

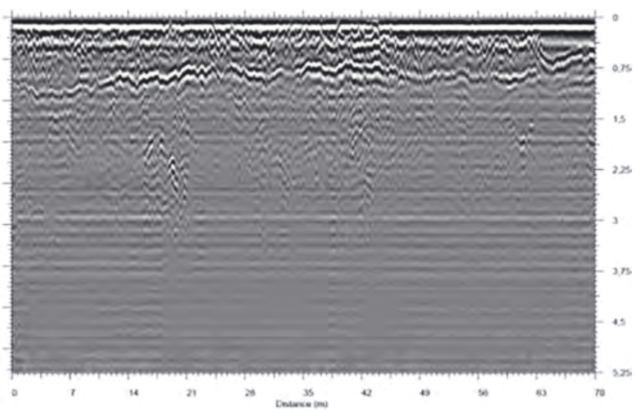


Fig. 5. One of the investigated GPR profiles on the location of an opening between two highway lanes

After the interpretation of refraction data, a longitudinal velocity profile was obtained and it is shown in Figure 6. A feature which can be easily seen is an area of the reduced velocity of seismic waves assigned to cavern which caused material collapse on the surface.

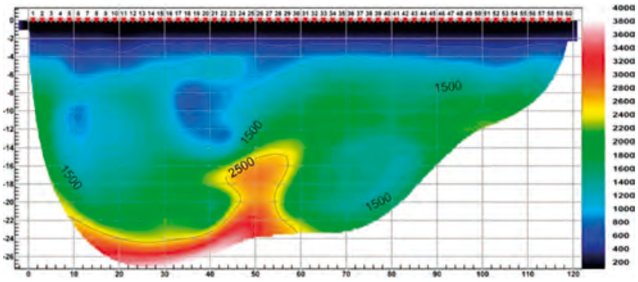


Fig. 6. A refraction profile with evident position and extent of zone with lower velocities [16]

Another example of the combined application of geophysical methods is the condition assessment of the 70 years old tramway embankment in Zagreb, located on line 2.7 km long line between Mihaljevac and Dolje stations [10]. In order to assess the condition of embankment, which will serve as a basis for remediation works, a non-destructive geophysical methods of Continuous Generation of Surface Waves (CSWS) and Ground Penetrating Radar (GPR) were implemented. The Continuous Generation of Surface Waves (CSWS) is a seismic geophysical method which represents a modification of Spectral Analysis of Surface Waves (SASW) method which uses a vibrator as an energy generator. This provides generation of controlled frequencies, overcoming the issues of the lack of certain frequencies from the source spectrum evident from SASW method. The GPR method, Figure 7, was used for the detection of geometrical features such as layer bound-

Fig. 7. Conduction of GPR investigations for the tram embankment condition assessment [10]

aries and man-made or natural anomalies, while the seismic CSWS method was used for the determination of small strain stiffness of the embankment.

Figure 7 shows a section of the investigated line, where the GPR profile is the upper one, and CSWS results are shown through the developed classification system based on obtained stiffness values. A cca 85 m zone of extremely small values of small strain stiffness to greater depths (lowest stiffness near the surface) can be seen. The GPR results also point to certain anomalies in this section. In this part of section, anomalies of tram tracks along with tilting of tram poles was noticed through the visual inspection. This demonstrates the advantages of using non-destructive methods for the condition assessment, since the destructive methods would yield much larger time and financial resources to obtain an insight into embankment condition.

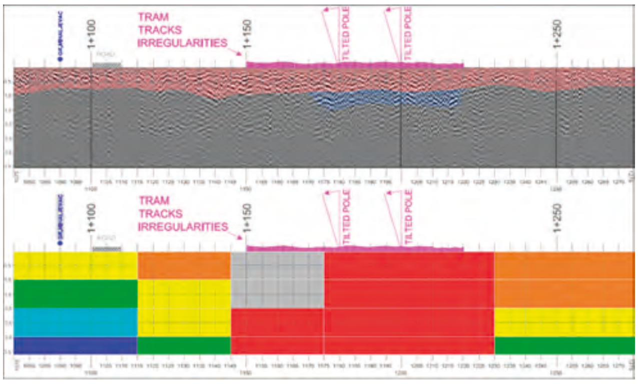


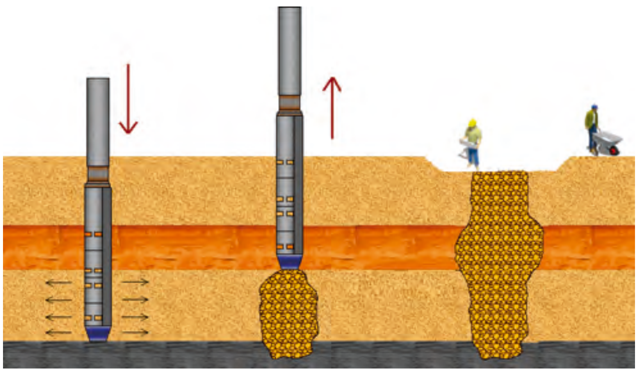
Fig. 8.. GPR and CSWS results for one section of tram line [10]

3. Use of industrial waste materials in sustainable ground improvement

In today's construction industry, there is an increasing need for the foundation of residential, commercial and infrastructure structures on ground possessing low stiffness characteristic or insufficient load-bearing capacity. Improving soil mechanics is a technological process that increases the load-bearing capacity of soil, reduces or maintains under control total and differential settlements, reduces the time for deformations to occur, reduces soil permeability, completely removes water from the ground by creating internal drainage systems, increases erosion stability of the soil and reduces the danger of liquefaction. This involves a controlled change in state, nature and behaviour of the soil in order to achieve planned and satisfactory results for existing or future engineering activities. The use of various technological processes transforms natural soil into a new material that provides better physical and mechanical characteristics. A great potential in using industrial waste materials for sustainable soil improvement have applications of the slag in stone columns technique and use of fly ash in deep soil mixing technique, Figure 9.

Fig. 9. Industrial waste materials: fly ash (left) and slag (right) [2]

The technology used in stone columns is based on the implementation of columns of gravel or crushed stone into the ground by pressing in or through vibration. In combination with the surrounding soil, this kind of granular material inserted using a vibrator has a higher stiffness and provides greater resistance to shear forces. It increases the load-bearing capacity of the foundation, while reducing settlement. Due to the high permeability of stone columns, the consolidation time is significantly decreased, consequently leading to a successive increase in the shear strength of natural soils [11]. The danger of the onset of liquefaction is also reduced (Figure 10).



Fig, 10. Stone columns technology [2]

Slag is a waste product generated from the purification and alloying of metals. Large amounts of the material can be found on the territory of the Republic of Croatia, totalling about 1.8 million tonnes. The material is easily accessible from steelworks in Sisak and Split. Results acquired from slag samples at the Faculty of Civil Engineering in Zagreb [12], where they were for tested for the usability of slag as an aggregate in concrete, includes particular tests implemented to evaluate the quality of the slag used in stone columns all in compliance to British standards. These results showed that the available slag in Croatia does meet the criteria for use in stone columns. The impact of slag on the environment has also been confirmed as non-hazardous and easily controllable. Although the idea of using slag in stone columns is not new, it has not been accompanied by adequate research or construction techniques. In Croatia, not a single stone column has been constructed using slag as substitute for gravel or pulverised stone.

By using mechanisation, deep mixing technology breaks down the soil structure and afterwards a binder is mixed

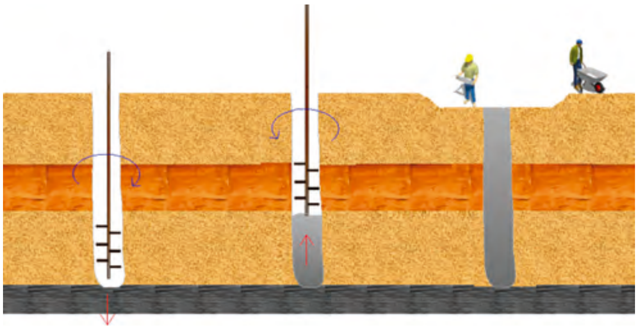


Fig. 11. Deep mixing technology [2]

into the soil resulting in elements of various shapes and configurations [11]. Ground columns, when distributed in a dense grid, improve strength and stiffness of otherwise soft soils (Figure 11).

The concentration of cement and lime in a soil improvement process is usually 2-5 %. A reduction in the quantity of used cement and lime reduces consumption of natural raw materials and fossil fuels as well as CO_2 emissions. For instance, to improve one ton of soil, at least 20 kg of cement and 30 kg of natural raw materials are required including 96 MJ of fossil fuel energy. Furthermore, 18 kg of CO_2 [13] are emitted into the atmosphere. The introduction of synthetic binders such as fly ash reduces the concentration of cement and lime in the soil improvement process.

In Croatia, the only coal combustion thermal power plant, Plomin, is located on the east coast of the Istrian peninsula. It is the only thermal power plant due to the fact that energy sources in Croatia are mostly focused on hydropower. At present, there is no deposited fly ash in Croatia due to a small generated amount which is mostly used in concrete industry. The same as in Croatia, where deposition of fly ash is managed properly due to small deposits, neighbouring Slovenia has also 'settled problem' with fly ash. With total three thermal power plants in operation, Slovenia annually produces around 970,000 tons of fly ash of which most is used as fill material in construction and mining operations, while only a small portion is deposited. On the other hand, neighbouring countries as Bosnia and Herzegovina and Serbia still have huge deposits of fly ash due to large quantities of fly ash produced on the annual basis (Bosnia and Herzegovina produces annually around 2 million tons of industrial ashes, while in Serbia, five thermal power plants produce close to 7 million tons of industrial by-products annually).

4. The prospects of utilising geothermal energy in geotechnical engineering

Foundation structures, retaining structures, tunnel support systems, anchors and geosynthetics are used as parts of geothermal system for transferring heat from soil and rocks to the surface or vice-versa during the summer [14].

Referring to the above mentioned items, foundation structures are the most frequently encountered underground energy structures. Even though their primary role is to fulfil all safety and functional requirements of a particular structure, the piles can be a part of the geothermal system (they are referred to as energy piles). In case of prefabricated driven piles, the geothermal pipes are installed in the factory, while in case of piles constructed on construction site, the pipes are attached to reinforcement cages. The piles are installed to the depth defined by the design and, at the bottom of they are rotated for 180°, so that they assume the shape of the letter U. In this way a pile is used as the vertical heat exchanger, Figure 12.

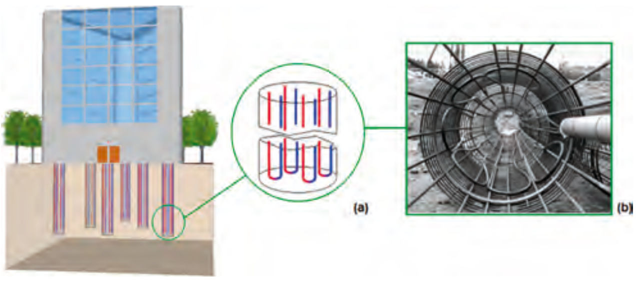


Fig. 12. Column used in energy facilities: a) pipe-positioning scheme in a column: b) geothermal pipes attached to a column reinforcement [14]

Retaining structures such as RC diaphragms, column retaining walls and even basement walls can be used effectively as part of a geothermal system, with the tubes tied to the rebars of supporting elements (Figure 13). In this case they are referred to as energy support structures.

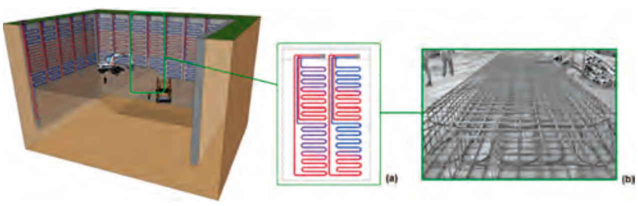


Fig. 13.. Retaining structure used in energy facilities: a) pipe-positioning scheme in a structure: b) geothermal pipes attached to a reinforcement [14]

Further, the use of TBM tunnels as parts of geothermal systems is based on utilization of prefabricated rings. After the excavation of tunnel segment, prefabricated concrete ring-shape segments are installed, containing geothermal pipes connected with the ring reinforcement, filled with working fluid and put into operation. In this way it becomes possible to use the heat of soil, or the heat generated by tunnel traffic, to heat buildings situated on the ground surface. Due to the fact that tunnels are linear structures that can measure several tens of kilometres in length, large volumes of soil or rock can be utilized in the geothermal energy exploitation process.

In Croatia, not a single underground structure has been constructed containing elements that have been used as heat exchangers in a geothermal system. Global knowledge and experience in the possibilities of using underground structures for exploiting geothermal potential has still not been implemented in Croatia. The first pilot project for the exploitation of geothermal energy using underground structures was stopped after the conceptual design phase [14]. The plans for the reconstruction of the Ksaver Sandor Gjalski Elementary School in Zagreb included a supporting structure approx. 150 m long which was designed as 20-metre high RC column wall, additionally secured using geotechnical anchors. In certain columns a heat exchangers would be located. The resulting energy would be used for heating the sports hall and associated locker rooms by using a conventional floor system.

5. Risk management in geotechnical engineering

The risk management process begins with the identification of the risk, and the objective is to form a list of key risks for each phase of a geotechnical project. In order to draw up such a list, the potential sources of risk, adverse events carrying such risks and adverse effects that occur if an expected adverse scenario occurs should be investigated. Each activity within a project can be identified as a risk or as a source of other risks, which then enters the list. A good example of this is geotechnical monitoring. Cerić et al. [15] identified the key risks involved in sustainable soil improvement, where unsatisfactory monitoring and quality control of soil improvement represented a risk on the ranked list of risks. Other identified risk factors are inadequate investigation works, selection of unsuitable soil improvement technologies, insufficiently worked out details in a soil improvement design and unsatisfactory performance of soil improvement works. Mihalinec et al. [16] characterised monitoring as a risk. They considered measurement purpose, measurement parameters, measurement equipment and measurement results as potential sources of risk in monitoring of landslides.

Risk assessment is carried out for each identified risk. The risk contains two independent components: the likelihood of risk (risk probability) and the impact of risk on the project (risk impact). Both of these components must be quantified in some way so as to analyse various risks, their mutual comparison and prioritisation. This is done by introducing the notion of risk exposure that represents the product of the risk probabilities and risk impact on the project: risk exposure risk = risk probability * impact risk [17]. Risk probability and risk impact for each identified risk can be determined using a quantitative or qualitative approach.

The quantitative approach implies that the probability of a certain risk can be calculated if there is a statistically relevant database of experiences related to similar events in the past. This creates the basis for forming the distribution function, for which the probability of occurrence, expectation, dispersion, confidence intervals and all other statistically significant parameters are calculated using statistical methods. The qualitative approach is applied when an appropriate database of previously implemented projects is unavailable. A qualitative approach to risk assessment for sustainable soil improvement by applying an analytic network process (ANP) was presented by Cerić et al. [15]. Based on the acquired risk exposure, a risk priority list is formed according to which responses to the risks are prepared as well as allocation of resources to respond to risks.

Each identified risk, depending on risk exposure value, is classified as unacceptable, undesirable, acceptable or negligible. Depending on this classification, a decision on response to each individual risk is made. If risk is classified as unacceptable, a response can be risk avoidance or risk transfer. If t risk is classified as undesirable, response can be risk avoidance, risk transfer, risk reduction or risk sharing accompanied by appropriate risk monitoring. If risk is classified as acceptable, response to risk can be risk retention accompanied by the appropriate risk monitoring. If risk is classified as negligible, it requires no response. Action taken as response to a risk may produce new risks that should be identified, analysed and, depending on risk acceptability, a response should be formulated. Thus, the risk management process becomes a cyclic process (Figure 14).

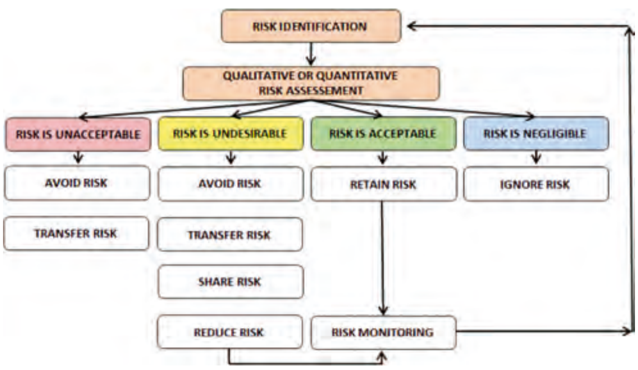


Fig. 14.. Cyclical risk management process [17]

In order to effectively manage risks in geotechnical projects, information systems for decision support should be developed. Holsapple and Whinston [18] define a decision support system as a computer system that supports the decision-making process by assisting the decision-maker in the organisation, identification, retrieval, analysis and transformation of information, selection and implementation of appropriate decision-making methods and assists also in the analysis of the acquired modelling results.

Cerić at al. [17] have developed a risk management methodology in tunnel construction using the PP-risk computer program that represents an independent and integrated information system satisfying all elements in a cyclic risk management process. PP-risk provides a basis for improving communication amongst all project participants and by using information technology it integrates all information relevant to project implementation. It was developed in a MS Visual Basic environment on the Microsoft Windows platform and consists of four mutually integrated modules: User interface, Database Management System, Method Management System and Document Management System. Data, methods and documents are accessed using the appropriate management systems, where a single user interface provides access to the entire system. From the main menu, the project list, user lists for a specific project and key risk (lists or the risks analysed at each stage) can be updated. Furthermore, risk probability and risk impact can be determined, which in turn identifies risk exposure. Finally, risk acceptability can also be directly determined once all necessary decisions are made and entered into the database (Figure 15).

Fig. 15. The PP -Risk user interface [17]

Conclusion

The technologies and techniques presented in paper are increasingly used in the field of geotechnical engineering. Their innovative aspects represent a step forward from the classical concept of geotechnical engineering. Non-destructive methods are used whenever it is appropriate since they provide savings in comparison to destructive of both time and financial resources, while at the same time offering possibility of much larger investigated soil and rock volume. The potential application of industrial by-products in ground improvement technologies could make a contribution to the reduction of their significant deposited amounts, while at the same time some amounts of standard (cement, lime) materials, usually used for ground improvement, could be reduced, leading to positive environmental footprint. Using geotechnical structures for the purpose of utilization of shallow geothermal energy is also an emerging field with numerous examples of the installed system throughout the world. However, Croatia is still waiting for its first implementation of structures as an integral part of geothermal systems. The techniques linked with risk management help effectively manage risks in geotechnical projects and for this purpose information systems for decision support should be developed. This has become more and more evident over the past years, especially when there is a need for a rational decision-making process conducted by the infrastructure managers/owners.

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