EXPERIENCES OF USING SASW IN THE QUALITY CONTROL OF SOIL IMPROVEMENT BY DEEP VIBRO COMPACTION IN CROATIA

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ABSTRACT - The paper describes experiences of using SASW in quality control of soil improvement by deep vibro compaction and vibro replacement in Croatia. The method belongs to the group of non-destructive testing, it is carried out from the terrain surface and does not demand expensive borings. The procedure if quick and enables a large number of measurements to be carried out by only one field operation.

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1. Introduction

In modern construction, the need for foundation of heavy structures and building infrastructure on weak soils, those with inadequate bearing capacity, has become increasingly common. The decision as to which foundation methodology is suitable for such situations depends on the systematic examination of a range of influencing factors; the adequacy and quality of information, the number of alternatives available to choose from, as well as the use of appropriate models and techniques towards the selection of the optimal, most favourable, alternative.

The decision making process takes place under conditions of certainty, risk or uncertainty. Certainty presents a situation in which all of the influencing factors are quantifiable. Hence, with the application of the appropriate methods, in the decision making process the outcome can be accurately predicted. A decision brought under certainty is a simple replacement of the existing soil with new stiffer and more stable soil. This represents a practical way of avoiding the "geotechnical" solution to the problem as it is founded on a new "produced" soil of conditioned stiffness and bearing capacity. Expenses are high, however, the uncertainty and risk of excessive settlement, namely, loss of bearing capacity, are brought to a minimum and under control. Another such decision would be relocating to a different site with higher soil stiffness and bearing capacity. The most extreme scenario would involve abandoning the project.

If there are two or more options at our disposal where not all influencing factors are quantifiable, then decision making is conducted under uncertainty or risk. The decision is made under risk if the individual making the decision can, with a certain degree of assurance, rationally and intuitively, estimate the likelihood of a specific event taking place on the basis of available information on similar events that have taken place in the past, or on personal experience. An example would be estimating foundation costs prior to investigation works being conducted and foundation load being defined. Such an estimate, with a certain degree of assurance, namely with a certain degree of risk, can be made on the basis of existing information on previously realised structures with similar ground conditions on the basis of personal experience belonging to the individual making the expense estimate. If such information does not exist, and the individual has no experience with similar structures and soil...
conditions, then the decision making takes place under uncertainty. Risk becomes uncertainty when there is insufficient information or experience at disposal to be able to set a mathematical model and forecast the most probable outcome.

Decision making under uncertainty represents a standard geotechnical approach which manifests itself in the planning of foundation constructions with respect to the soil's low stiffness and insufficient load bearing capacity. The geotechnician sets up a foundation structure capable of accepting a set load. In such situations, foundation expenses are generally lower than soil replacement; however, as such they are inversely proportional to risk, Uncertainty very rarely transforms into risk.

The third solution presented in this paper is ground improvement. It represents decision making under risk. Using a range of compaction and mixing technologies of the existing and new soil, the natural soil transforms into a new material. Using ground improvement methods it is possible to increase soil load bearing capacity, reduce or keep under control total and differential settlements, reduce the necessary deformation times, reduce the permeability of the soil, completely remove water from the soil by creating internal drainage systems as well as increasing stability for erosion.

Ground improvement can be performed with the use of a range of different technologies. A rapid development in improvement technologies, and techniques, has occurred because of an increased need for foundations in extremely difficult conditions.

In the selection of a suitable soil improvement technology a number of factors must be taken into account, of which the following are most significant: ground improvement goal, namely the degree of increase in stiffness, load bearing capacity or permeability, surface, depth and total volume of the soil being improved, soil type and its mechanical characteristics, availability of materials for the improvement (sand, gravel, mix), ecological factors and local experience, turnaround time and, of course, expenses.

2. Soil improvement using deep vibro compaction

In recent years, in collaboration with the Geotechnical department of the Faculty of Civil Engineering in Zagreb, GeoTechnik (a member of the Keller group), a Croatian company from Varazdin, has been employing and developing soil improvement technologies with the use of deep vibro compaction. Depending on soil particle size, two types of deep vibratory compaction technologies can be distinguished.

The Vibro Compaction method was developed specifically for non-cohesive soils while the Vibro Replacement method is used for cohesive and mixed soils. The Vibro Compaction method uses vibrations to reduce the pore volume of soil, thus soil compaction and stiffness. In the Vibro Replacement method, often referred to as Vibro Stone Columns, "stone" or compacted granular columns are inserted into the ground which, proportional to their stiffness and volume, bear a significant part of the construction structural load.

Both processes involve the lowering, pressing, of the vibrator to a certain depth and, depending on the process, soil compaction or the installation of stone columns is performed. Soil improvement technologies using deep vibro compaction are more cost efficient than traditional foundation methods. Turn around time is relatively short, and the process is adaptable to site conditions. The foundations of future structures can proceed immediately once the soil improvement is completed. Only natural materials are used, and as such, this process is ecologically acceptable.

2.1. Vibro Compaction

In nature, non-cohesive of small granular portions generally tend to have a density less than maximum. Employing deep oscillations and vibrations, it is possible to "rearrange" soil particles thereby increasing soil density, the interior angle of friction, and the soil stiffness modulus.

The process is shown in Figure 1. The vibrator head vibrates and, aided by water pressure
irrigating the granules, penetrates the soil to the design depth. Once at the required depth, the flow of water is reduced and compaction begins. Performed in stages, bottom-up, it includes the rollerder around the vibrator, radius of up to 5m. The compaction effect is registered by the consumption of electricity of the vibrator's motor. Around the vibrator, on the surface of the site, a funnel is formed which is then filled with backfill. Following the completion of deep vibro compaction, the surface layer is removed, and the surface of the base soil is compacted by the roller.

The limitation of this process lies in the fact that cohesive and mixed soils with a fine content greater than 20% cannot be effectively compacted using deep vibro.

![Figure 1. Deep Vibro Compaction - Construction sequence](image)

2.2. Vibro Replacement

In cohesive and mixed soils with a silt or clay content greater than 20%, densification and vibration are used to insert stone columns which then take on additional loads. Together with the surrounding soil, this granular material, implanted with the use of a vibrator, has a higher stiffness thus creating greater shear resistance. The bearing capacity of the base soil is increased, and settlement decreased. Consolidation time is accelerated considerably because of the stone columns' significant watertightness. And as such, the consecutive increase in shear strength of the natural soil is greater. The danger of liquefaction is also reduced.

The process is shown in Figure 2. Equipped with a batching device and forced guidance, the vibrator is positioned about the marked spot. The vibratory probe is stabilised on hydraulic outriggers. A single loader charges the skip with stone. The skip travels up to the leaders and automatically discharges stone into the reception chamber at the top of the vibrator. Once the chamber is closed, pressurised air presses hard inert material towards the opening of the conical nose of the vibrator. Assisted by water pressure or pressurised air from the outriggers, the vibrator then displaces surrounding soils penetrating the ground to design depth. Once full depth is reached, the vibrator is raised 30-50cm, creating a cavity in its path, which is then filled with backfill under pressure. Lowered again, the vibrator compacts the material and laterally densifies the surrounding soils. In such a way, using the bottom feed method, the densely compacted stone column is constructed, up to the site surface or a particular required depth.

The limitations of this method are, first and foremost, manifested in the loss of lateral resistance in very soft clay, silt or loose sand and in the inability to achieve the desired column shape and volume due to ground cavities, tree roots and such.
3. Use of SASW for the quality control of soil improvement

Significant attention, when performing soil improvement, is given to the quality control of the achieved improvement.

Typically, for the quality control of soil improvement by deep vibro compaction technique a some of the penetration tests (Standard Penetration Test, Cone Penetration Test, Dilatometer Test) are used. These tests are a good method of representing the degree of ground improvement achieved using Deep Vibro Compaction.

The process of Vibro Replacement allows for the reliable assessment of soil stiffness and bearing capacity of the stone column or surrounding soil. However, the results of this experiment are not a reliable means of determining the degree of improvement in average stiffness properties of the newly created soil, and as such, cannot be compared with the design hypothesis.

The complex state of stress and interaction between the stone columns and surrounding soil prevents local testing of components from determining the stiffness of the composites. In order to determine the degree of ground improvement, it is necessary to conduct tests which will include a higher volume of improved soil and determine its average newly created stiffness properties.

The average increase in soil stiffness using Vibro Replacement can be successfully and reliably carried out using the nondestructive process of Spectral Analysis of Surface Waves (SASW). By way of this process, the shear modulus profiles (G) of the soil can be measured versus depth, at very low deformations prior to, and after soil improvement. The ratio of shear modulus, post- and pre- improvement, represents the degree of soil improvement which is then used as a measure as to the success of the performed process.

The SASW method is based on the dispersive characteristics of Rayleigh waves, taking into account the fact that surface Rayleigh waves of different wavelengths (frequencies) penetrate to various depths. In such a way, lower frequency waves, waves of a higher wavelength, penetrate deeper into the medium than high frequency waves, waves of smaller wavelength (Figure 3).
The process is divided into three parts:
1. On site data acquisition
2. Determining the dispersion curve
3. The inversion process of the determination of shear velocity profiles according to depth

3.1. On site data acquisition

The following measurement equipment is necessary for gathering data onsite: surface-wave generator, geophones, analogue-digital converter and computer.

The fundamental task of the surface-wave generator is, using a mechanical impact, to generate a wave with as great a frequency range and wave energy as possible. Different materials have different stiffness properties, so in order to cover as great a frequency range as possible, different generators are needed. In addition to this, a greater load is needed to move deeper layers, those requiring lower frequencies, than for layers closer to the surface which require higher frequencies.

Vertically polarised geophones are used to measure the velocity of a passing wave. The first requirement for the use of geophones is the frequency range it is capable of registering. When measuring various frequencies, the quality of the geophone is of great importance. And as such, it is important to use high quality geophones in this measurement. A facilitating circumstance is the fact that this method uses phase shift between two receivers as a measurement result, and not amplitude which is much more sensitive to errors in measurement. The second requirement for the use of geophones sensitivity. This is particularly important as sensitive geophones register higher wave energy. Across greater spacing, insensitive geophones completely lose the signal, meaning that what is registered turns out to be noise. When installing the geophone, it is important to pay attention to the surface positioning of the device. The entire surface area of the geophone must rest on the ground surface. This represents the slowest and most difficult part of the measurement process itself. Under no circumstance should the measurement process be hurried by setting up the geophone faster than necessary.

The analogue-digital converter is essential in order for the analogue signal to be received by the receivers, digitised and turned into a signal that the computer is capable of converting, storing and processing. The converter's most important property is its resolution. Resolution represents the number of bits the converter uses to interpret the incoming signal. A higher resolution means better data digitisation. These days 12 and 16-bit converters are used. They divided the incoming analogue range up to 65 536 (2 to the power of 16) times. Analogue-digital converters are available in an external design when they are equipped with their own power supply and connect to the computer. They are available in an internal design when they are
fitted inside the computer from which they source their power supply. The second important property is the conversion speed of the analogue-digital signal, namely, the sampling frequency. A 100 kHz converter is sufficient for SASW.

This method allows for any kind of personal portable computer to be used. However, it is desirable that it have a fast processor in order to be able to receive and process the signal in real time.

Surface waves propagating from the impact source towards the geophones are generated by mechanical impulses. From the geophone, the signal travels to the computer where it is store in digital form. The spacing between the impulse generator and the nearer geophone (S) is equal to the spacing between the geophones (X). In order to cover as great a frequency spread as possible, the geophones are moved to predetermined distances, the process is repeated and the data stored on the computer.

The process of measurement alone, the data acquisition, is basically conducted using two geophones. It is possible to speed up the entire process with the use of a larger number of geophones, but the principle remains unchanged.

Figure 4 shows a schematic representation of the measurement configuration of data acquisition. On site data acquisition is shown in Figure 5.

![Figure 4. Schematic representation of the measurement configuration of data acquisition](image)

Figure 5. On site data acquisition
3.2. Determining the dispersion curve

The dispersion curve represents the correlation between wave velocity on surface and wavelength. For every recorded receiver interval time, signals from both receivers $x(t)$ and $y(t)$ are transformed from a time into a frequency domain producing frequency signals, $X(f)$ and $Y(f)$. This is done using the Fast Fourier Transform (FFT). Further spectral analysis is performed on these transformed signals.

The key results of Spectral Analysis are Coherence function and Cross Power Spectrum Phase. Coherence function represents the relationship between the signal and noise, namely, the level of acceptability of the recorded signal. Coherence must be close to one in order for the data to be accepted for further examination. The Cross Power Spectrum Phase $\theta_{xy}(f)$ represents the phase shift of the receiver in motion.

For each frequency, the wave departure time between two receivers can be obtained from the formula, $t(f) = \theta_{xy}(f) / (2\pi f)$, in which the Cross Power Spectrum Phase is expressed in radians, and the frequency in Hz. The time is obtained in seconds.

The velocity of waves on surface is obtained by dividing the receiver intervals by the obtained time in the formula, $V_R(f) = X / t(f)$.

The corresponding wavelength is obtained by dividing the velocity of the passing wave by the frequency in the formula, $L_R(f) = V_R(f) / f$.

There is now a corresponding wavelength for every frequency defining the dispersion curve.

3.3. The inversion process

In a layered medium where stiffness varies with depth, the inversion process is necessary in order to derive the depth-based shear wave velocity profile from the field measured dispersion curve (Figure 6).

![Figure 6. The Inversion Process](image)

The process is conducted so that, firstly, a theoretical dispersion curve is calculated for the assumed velocity profiles. The theoretical curve is then compared to the measured dispersion curve. As the curves do not overlap, the process is repeated with changes being made to the width, as well as the velocities, of the assumed profile. When the theoretical and measured dispersion curves overlap with a satisfactory engineering precision, the assumed profile is considered as a result. The theoretical dispersion curve represents the result of propagating Rayleigh waves based on the Haskell-Thompson matrix formulation of wave propagation in layered media (Thompson, 1950; Haskel, 1953). In this formulation, the dispersion curve represents its eigen values of the transer matrix of the layered medium. A typical result of inversion process is shown in Figure 7.
Apart from quality control of the soil stiffness improvement by stone columns and jet injection techniques, this method is efficiently used for quality control of compaction of road embankment and reinforced concrete embankments, and for determining the thickness of the layers of pavement structure and concrete lining in road and water transfer tunnels.


Figure 7. Shear wave velocity, Shear Modulus and Modulus of Elasticity v Depth before and after soil improvement.
4. The Croatian Experience

In recent years, a number of structures have been constructed on which Geotechnik from Varazdin has performed work and the Geotechnical Department at the Faculty of Civil Engineering in Zagreb has conducted control of improvement in soil stiffness properties. Each of the structures showed higher degrees of improvement than predicted by the design. Table 1 shows average degrees of improvement in Modulus of Elasticity of the soil performed by Deep Vibro Compaction.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Year of construction</th>
<th>Degree of improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>The port of Ploče, Ploče</td>
<td>1998</td>
<td>3.12</td>
</tr>
<tr>
<td>Potable water treatment plant, Slavonski Brod</td>
<td>1999</td>
<td>3.82</td>
</tr>
<tr>
<td>Housing and hotel complex HIT Marina, Novi Vinodolski</td>
<td>2001</td>
<td>3.47</td>
</tr>
<tr>
<td>Overpass on the Zagreb-Goričan Motorway</td>
<td>2002</td>
<td>3.11</td>
</tr>
<tr>
<td>Kaufland Shopping centre in Zagreb,</td>
<td>2003</td>
<td>4.14</td>
</tr>
<tr>
<td>Residential buildings, Government subsidized housing projects, Rijeka</td>
<td>2003</td>
<td>3.34</td>
</tr>
<tr>
<td>Welfare Centre Building, Ploče</td>
<td>2003</td>
<td>3.75</td>
</tr>
<tr>
<td>Warehouse and boiler room at the Uljanik Shipyard, Pula</td>
<td>2003</td>
<td>4.25</td>
</tr>
<tr>
<td>BOKŠIĆ Apartment Hotel, Makarska</td>
<td>2004</td>
<td>3.42</td>
</tr>
<tr>
<td>SRZIĆ Hospitality and Tourism Building, Makarska</td>
<td>2004</td>
<td>3.87</td>
</tr>
<tr>
<td>ZLOPAŠA Apartment Hotel, Makarska</td>
<td>2004</td>
<td>3.87</td>
</tr>
<tr>
<td>Residential and office building OMINING, Omiš</td>
<td>2004</td>
<td>4.11</td>
</tr>
<tr>
<td>Office Building PORR – ZAGREB TOWER, Zagreb</td>
<td>2005</td>
<td>3.61</td>
</tr>
<tr>
<td>Embankments on the Zagreb-Macelj Motorway</td>
<td>2005</td>
<td>3.56</td>
</tr>
</tbody>
</table>

5. Conclusion

The presented Deep Vibro Compaction processes represent a reliable way of carrying out significant improvement in soil stiffness and load bearing capacity of natural soil. Quality control of soil improvement can be successfully performed using Spectral Analysis of Surface Waves (SASW). This method belongs to a group of nondestructive tests and is performed on the surface of the site requiring no expensive drilling. Measurement is reliable as it avoids soil disturbance caused by drilling, mining for samples, or mounting samples onto laboratory devices. This method solves some of the fundamental problems of surface refraction as it is capable of detecting the softer layer located beneath the stiff layer. The process is fast, facilitating the execution of a large number of measurements in one site trip.

6. References


Thomson W. T., 1950, Transmission of elastic waves through a strati


