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In this study three already finished projects in Lithuania were investigated, the problems faced in the projects were examined, and the main advantages and drawbacks of the chosen geopile installation technology were identified. Three alternative solutions for geopile installation were selected for the investigation: driving a hollow steel pipe into the ground using a deep vibrator and using geosynthetic material to reinforce soils (A_1); driving a closed-ended hollow steel pipe into the ground and using geosynthetic material to reinforce soils (A_2); driving an open-ended hollow steel pipe into the ground and using geosynthetic material to reinforce soils (A_3). Those alternatives were evaluated according to the following criteria: geopile installation cost (K_1), level of mechanization (K_2), load bearing capacity (K_3), installation options (K_4), impact on the environment (K_5), duration of the installation of geopiles (K_6). In order to find out the significance of the evaluation criteria a survey questionnaire and a ranking procedure were used. The same order of criteria importance, namely K_1>K_3> K_2>K_4>K_6>K_5 was obtained using the selected rank-order weighting method. Basing on the selected criteria, a rational option for geopile foundations was identified using the multi-criteria assessment method TOPSIS. The results show that driving an open-ended hollow steel pipe into the ground and using geosynthetic material to reinforce soils (A_3) is the most rational option for the installation of geopiles in the investigated finished projects in Lithuania. This article is based on Master thesis topic "*Research on installation technology of geopiles*".

Keywords: ground properties, floating stone columns, geopiles, geopile installation technology.

Introduction

With the rapid development of urbanization level and changing climatic conditions, Lithuania is increasingly facing negative water effect on roads, street sites and city infrastructure. Construction starts in places where people would never have thought about them before. Increasingly, structures are being erected in peat-lands or flooded areas. As cities grow and expand, the infrastructure they need is growing and expanding too. In 2018 alone, the Lithuanian government allocated almost half a billion euros for the development of road infrastructure. The infrastructure construction industry often usually faces peaty or flooded areas and related problems. All over the world, including Lithuania, the aim is to build roads, railways or footpaths so that they can be used as long as possible. There are several ways to deal with the construction of new roads or buildings in the face of unfavourable building conditions.

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In literature, geopiles are called differently: geosynthetic piles, ground piles, stone columns, etc. Geopiles are a type of piles. Their main distinguishing feature is that the geopiles aggregate is an impermeable, draining, mostly mineral material. Construction waste ground to a medium fraction may also be used as aggregate.

Since geopiles can only take on very small transverse loads, they are most often used in places where such loads are virtually non-existent, underneath bollards, roads or railways, transport infrastructure structures, building floors or storage sites (Pivarč 2011, Tandel 2013, Ng 2014, Das 2014, Ng 2015, Ng 2016).

There are various technologies for laying geopile foundations in the world, but only the most popular and the most widespread technologies are analysed in this article. At present only two technologies are used in Lithuania: geopile installation driving a forged pipe and geopile installation driving a close-ended hollow steel tube. In order to ensure the bearing capacity of geopiles, it is the most appropriate to use an open-ended hollow steel pipe using geosynthetic material as driving an open-ended hollow steel tube pushes the tube until a response is achieved, and the response can be achieved for a variety of reasons (weak soil compression, suction, a stronger soil interlayer or larger stone). The use of an open-ended hollow steel pipe technology ensures the load-bearing capacity of the geopiles, thus protecting the structure from collapse.

Installation of geopiles using a deep vibrator is the most common method in South America, Africa and southern Europe due to the prevalence of water-saturated thick layers of fluid clay. Geopiles installed using a deep vibrator are often referred to as crushed stone pillars. Crushed stone pillars are installed from the bottom up. During vibration, reversible movement (two steps up, one down) is used to press the column aggregate (crushed stone, gravel or gravel sand) from the cavity in the upper part of the vibrator into the clutch soil. This allows to compact the poured aggregate and increase the diameter of the column (Sližytė 2012).

The installation of such columns using vibration in clay soil is sometimes referred to as vibrational soil replacement, although this term is not precise - local soil is not replaced but pushed aside, filling the cavity formed by the vibrator with coarse aggregate.

It is desirable to use crushed stone or gravel as an aggregate, although in exceptional cases sand could be used if it were too difficult and expensive to bring coarse aggregate. Using this technology, the installation of columns next to each other can create a reinforced base pillow. However, this technology is not widespread in Lithuania, and even little known. This is due to the technological difficulty of installing long piles when using a deep vibrator. Usually the length of the piles using this technology is 6-7 meters. However, in Lithuania, where soil reinforcement is required, strong soil is found in deeper layers.

Crushed stone columns are installed at the locations provided in the project. Inventory steel pipe 30-50 cm in diameter with a special closing and opening spike is plunged into the soil through the entire depth of the substrate deformation zone or to a strong soil where the weak soil layer is thinner than the deformation zone. By dredging the inventory pipe, the soil is compacted, as in the case of a pile, in a zone of approximately 3 d (where d is the diameter of the pipe). Water from the soil is squeezed through adjacent previously made rubble columns, resulting in a significant compaction of soil. Deep soil vibrator is a device for spreading and compacting coarse soil in weak soils. This device is mounted on a pile-driver. There are different types and capacities of deep soil vibrators.

Geopile installation technology driving an open-ended hollow steel pipe using geosynthetic material can only be used in low adhesion soils. Soil adhesion C_u <15 kPa (peat, soft clay). The strength of these geopiles is higher due to the use of the geosynthetic material. As geotextile takes over tensile stresses, small transverse stresses can also be transmitted to the pile. As the aggregate is poured into the geosynthetic material, it does not mix with the weak soil, forming a round cross-sectional pile (Sližytė 2012).

This technology is the fastest for geopile installation, but its use is limited due to the high vibration pressure in the pipe. The minimum distance from existing structures must be at least 25m. The aggreagte in the geotextile is compacted by pulling the forged pipe. After installation, the pile-driver moves to the design position of the next pile. Often, several inventory pipes with special heads are used so that the pile-driver does not have to wait for the geotextile bag to be filled.

Geopile installation technology driving an open-ended hollow steel pipe using geosynthetic material can be used in low adhesion or medium-strength soils (Sarvaiya 2017). Soil adhesion C_u <30 kPa (peat, soft clay, loose soils, construction waste). The strength of these geopiles is higher due to the use of the geotextile shell. As geotextile takes over tensile stresses, small transverse stresses can also be transmitted to the pile. As the aggregate is poured into the geosynthetic material, it does not mix with the weak soil, forming a round cross-sectional pile (Sližytė 2012).

With this technology, geopiles are installed at a slightly slower rate than with a forged pipe, but due to the minimal vibrations generated during installation, these piles can be installed close to existing structures, it is only necessary to provide a protective distance for the drilling head. The minimum distance from existing structures must be at least 0.8 m (Sližytė 2012).

The aim of this work is to investigate three finished projects in Lithuania, to examine the problems faced in the projects, and to identify the main advantages and drawbacks of the chosen geopile installation technology.

Methods

For the analysis of geopile foundation installation three finished projects in Lithuania were chosen for the research. Information about the chosen projects is provided in Table 1.

Three alternative solutions for geopile installation in this research were selected for the analysis:

- driving a hollow steel pipe into the ground using a deep vibrator and using geosynthetic material to reinforce soils (A_1);
- driving a close-ended hollow steel pipe into the ground and using geosynthetic material to reinforce soils (A_2);
- driving an open-ended hollow steel pipe into the ground and using geosynthetic material to reinforce soils (A_3).

The geopile foundation alternatives chosen in the article will be evaluated according to the following criteria:

K_1 - pile installation cost (EUR) is a quantitative, economic indicator that measures the cost of installing one meter of pile. The cost is calculated based on the analysis of the completed projects.

K_2 - the level of mechanization is a qualitative indicator expressed in terms of the degree of mechanics involved. This indicator is determined by an expert method.

K_3 - load-bearing capacity is a qualitative score-based indicator that measures the ability of geopiles to withstand loads transmitted by structures. The bearing capacity of geopiles depends on the ground conditions, the dimensions of the pile, the method of installation, etc. The indicator is determined by an expert method.

K_4 - installation options - a qualitative, score-based indicator that assesses the complexity of geopile installation, site conditions, and access. The indicator depends on the power and quantity of machinery used, materials needed for installation, etc. This indicator is determined by an expert method.

K_5 - impact on the environment - a qualitative indicator of the environmental damage caused by the installation of geopiles (noise, vibration, earthworks, etc.). The indicator depends on the pile-driving technique, the method of pile-driving, the materials used for piles, etc. This indicator is determined by an expert method.

K_6 - duration of the installation of geopiles is a score-based quantitative indicator that measures the duration of pile installation. This indicator is determined by an expert method.

Table 1

Information about the chosen projects

Investigation object	Advantage of used technology	Disadvantage of used technology
Object No 1: Construction work for the modernization of Rambynas border checkpoint. **Problem:** Geological surveys have shown that 5-6 m thick peat and silt layers are found throughout the area. Because the area is very large and the layer of weak soil is thick, replacing a weak soil with a strong one would be very expensive, so it was decided to look for alternative ways to reinforce the foundation. **Solution:** To transfer the loads acting on the area into strong soils that lie deeper beneath the whole area, geopiles have been designed. The geopiles are arranged in a 2.6 × 2.6 m grid, with a pile diameter of 0.8 m and a pile length ranging from 6 to 7 m. By using prefabricated reinforced concrete slabs to increase the footprint of the 1.2 × 1.2 × 0.15 m piles, this solution saves even more time on contract work. The geo-grid structure is equipped with a geo-grid-reinforced soil dam. In total, more than 5.600 geopiles have been installed. The piles are installed driving an open-ended hollow steel pipe using geosynthetic material.	Ensures that the pile is installed to the required depth. No high vibrations. Can be installed with lower efficiency machinery.	A large amount of fossil soil is generated, which is unsuitable for further work and needs to be removed from the construction site, resulting in additional transport costs for soil.
Object No. 2: Installation of Vaižganto street in Utena between J.Basanavičiaus and Pievu streets. **Problem:** Geological surveys have revealed that there is peat under a large part of the newly designed street. Because of the high thickness of the peat layer, replacing a weak soil with a strong one would be very costly, so it was decided to look for alternative ways to reinforce the foundation. **Solution:** It was decided to install the street structure on the platform of geopiles and geogrids. The geopiles are arranged in a 2.2 × 2.2 m grid, with a pile diameter of 0.8 m and a pile length of about 11 m. To increase the footprint of the 1.2 × 1.2 × 0.15 m piles, pre-fabricated reinforced concrete slabs further save time on contract work. The geo-grid structure is equipped with a geo-grid-backed platform. In total 840 geopiles are installed. The piles are installed driving an open-ended hollow steel pipe using geosynthetic material.	Ensures that the pile is installed to the required depth. No high vibrations. Can be installed with lower efficiency machinery.	A large amount of fossil soil is generated, which is unsuitable for further work and needs to be removed from the construction site, resulting in additional transport costs for soil.
Object No. 3: Reconstruction of state road No.144 Jonava - Kėdainiai - Šeduva from 76.4 to 90.508 km. **Problem:** Geological surveys have shown that under the reconstructed road there are layers of weak gray soil with a thickness of up to 12 m. Replacing a weak soil with a strong one would be very expensive, so it was decided to look for alternative ways to reinforce the foundation. **Solution:** It was decided to install the road structure on the platform of geopiles and geogrids. The geopiles are arranged in a grid of 1.5 × 1.5 m, a pile diameter of 0.6 m and a pile length of up to 13.5 m. A 22000 m geotextile shell was used. The geo-grid structure is equipped with a geo-grid-backed platform. The piles are installed driving an open-ended hollow steel pipe using geosynthetic material.	Piles are installed faster. There is no additional soil to be removed from the construction site.	It is difficult to ensure that the piles are sufficiently deepened into the supporting soil. Due to the high vibration, the surrounding soil is liquefied, making it difficult for construction machinery and workers to move. High-capacity construction machinery is required to forge the pipe.

A questionnaire was prepared based on the analysis of literature sources and selected geopile technology assessment criteria. This questionnaire was sent to companies operating in Lithuania, which specialize in geopile installation or have facilities to install it. Survey participants were able to rank the criteria in the questionnaire to find out the significance of the criteria. Respondents were asked to record scores from 1 to 10 for each criterion, which would indicate the importance of the criteria.

The evaluation is carried out in the following way: first, the most important evaluation criterion is selected, the significance of which is equal to 10 scores (there may be several criteria). The remaining criteria are then compared to the most important criterion.

The purpose of quantitative Multiple Criteria Decision Making (MCDM) methods is to determine the best of the alternatives to be compared or to rank them in relation to the purpose of the assessment. One of the most important components of these methods is the weighting of the criteria used in the research. The importance of individual criteria describing the influence of the research object on the examined aim is different, therefore it is important to determine the significance of the criteria, i. y. their weights (Podvezko 2013, Simanavičienė 2015).

Most of the currently known and applied multi-criteria weighting methods are based on expert assessment. The subjective basis for determining criteria weights is based on expert assessment. The opinions of individual experts are often contradictory and sometimes may be contradictory; therefore, the importance and priority of the individual expert evaluation criteria will vary. Assessment depends on the qualifications of the experts, the specifics of the job, the interest in obtaining certain assessment results, seniority and so on. Criteria weights as summarized averages of expert opinions can be used in a multi-criteria assessment if consistency in the expert assessments has been identified, i. y. opinions have been shown to be statistically consistent. The Kendall's coefficient of concordance can be used to determine the consistency of assessment (Herve 2007). Whatever the subjective method of weighting, the assessment process should start with the ranking of the criteria.

Ranking is the procedure when the most important criterion is given the highest rank – rank one, the second most important - rank two and so on, i.e., the last criterion is given the rank m, where m is the number of criteria to be compared. Equivalent criteria are given the same value - the arithmetic mean of ordinary ranks. The method is easy to apply in practice, but it should be emphasized that the method has low accuracy. Regardless of the assessment methods used, expert assessments are marked as c_{ik} (i = 1,..., m; k = 1,..., r), where m is the number of criteria used, r is the number of experts (Ginevičius. 2004).

Assessment results are placed in the matrix C = || c_{ik} ||. A number of criteria weighting algorithms can be introduced where criteria weighting rankings are used. The purpose of conversion is to assign weights in descending order of rank. Thus the top rank (first) is given the highest value. The most accurate result is provided by the linear transformation of assessment. In this case, the values of the criteria weights can be calculated according to (1) equation:

$$\omega_i = \frac{\sum_{k=1}^{r}(m+1-c_{ik})}{\sum_{i=1}^{m}\sum_{k=1}^{r}(m+1-c_{ik})} \tag{1}$$

here: m is the number of criteria to be compared; r - number of experts

Determination of criterion weights using direct and indirect assessments. These methods have a higher accuracy compared to the ranking method. Applying the direct criterion weighting method, the sum of all assessment weightings c_{ik} must be equal to 1 (or 100%). The method of indirect criteria weighting uses the selected scoring system (5, 10, 20, etc.) (Ginevičius, 2004). Assessments can be repeated. The criteria weights are calculated on the basis of direct and indirect assessment according to (2) equation:

$$\omega_i = \frac{\sum_{k=1}^{r} c_{ik}}{\sum_{i=1}^{m} \sum_{k=1}^{r} c_{ik}} \quad (2)$$

The Topsis method was chosen for the multi-criteria assessment. The essence of the method is to determine which solution is the closest or the farthest to the ideal point. This means that the best solution will be the closest to the ideal and the worst will be the farthest.

Assume that the values of each indicator are constantly increasing or decreasing. It is then possible to determine the "ideal" solution that consists of the best indicator values and the "negatively ideal" solution that consists of the worst indicator values. To apply the proximity to the ideal point method, it is necessary to construct a solution matrix or provide data on alternative solutions (Simanavičienė, 2015).

Normalization of matrix B to matrix $\overline{B}$. Because the B measurement criteria in the matrix are different units of measurement, we cannot compare alternative engineering solutions. For this reason, it is necessary to normalize the matrix B, i. y. resized to dimensionless dimensions. Matrix B normalization is performed using the vector normalization method (Simanavičienė, 2015) according to **(3) equation**:

$$\overline{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^{2}}} \quad (3)$$

here: x_{ij} – i – line and j – column of Matrix

Table 1

Initial Matrix A of alternative solutions

Criterions / Alternative solutions	K_1, pile installation cost	K_2, the level of mechanization	K_3, load-bearing capacity	K_4, installation options	K_5, impact on the environment	K_6, duration of the installation
A_1	...	...	...	...	...	...
A_2	...	...	...	...	...	...
A_3	...	...	...	...	...	...
$\sqrt{\sum_{i=1}^{m} x_{ij}^{2}}$	...	...	...	...	...	...
Optimality	min	max	max	max	min	min
Theoretical significance, %	...	...	...	...	...	...

Following the normalization of Matrix B, a weighted normalized Matrix B*of alternative solutions is created. To this end the normalized Matrix B is multiplied by the vector of criteria weight using **(4) equation** (Simanavičienė 2015):

$$B^* = [B] \cdot [q], \quad (4)$$

The ideal best condition a+ (the best value) variant is adjustable by (5) equation (Simanavičienė 2015):

$$a^{+} = \left\{ \left[\left(\max_{i} x_{ij} \,/\, j \in J \right), \left(\min_{j} x_{ij} \,/\, j \in J^{'} \right) \right] / \, i = \overline{1,m} \right\} = \left\{ a_1^{+}; a_2^{+}; a_3^{+} \right\}; \quad (5)$$

And the ideal worst condition a- (the worst value) are found by (6) equation (Zavadskas, E. K. 2001):

$$a^{-} = \left\{ \left[\left(\min_{i} x_{ij} \,/\, j \in J \right), \left(\max_{j} x_{ij} \,/\, j \in J^{'} \right) \right] / \, i = \overline{1,m} \right\} = \left\{ a_1^{-}; a_2^{-}; a_3^{-} \right\}; \quad (6)$$

Distances between the real option a_i and the ideal best condition a+, as well as between the real option a_i and the ideal worst condition a- are computed according to (7,8) equations (Simanavičienė 2015):

$$S^{+}{}_{i} = \sum_{j=1}^{n} \left| a_{ij} - a_{j}{}^{+} \right| \ , \ \ (i = \overline{1,m}) \quad (7)$$

$$S^{-}{}_{i} = \sum_{j=1}^{n} \left| a_{ij} - a_{j}{}^{-} \right| \ , \ \ (i = \overline{1,m}) \quad (8)$$

The relative proximity of compared options to the ideal option is found, i.e. criterion C_i is calculated using (9) equation (Simanavičienė, 2015):

$$C_i = \frac{S_i^{-}}{S_i^{+} + S_i^{-}} \ , \ \ i = \overline{1,m} \, ; \ when \ \ C_i \in [0{,}1] \quad (9)$$

Having the criterion C_i value calculated, the priority rank of compared options is made. In our case, the best option is the one that has the highest value of criterion C_i. In the last stage the degree of utility N_l of compared options is calculated using (10) equation:

$$N_l = \frac{C_{i,l}}{C_{i,\max}} \cdot 100\% \quad (10)$$

The most rational engineering option is the one with the highest value (Simanavičienė 2015). Then the degree of utility's calculated according to equation 10 to compare the value of the analysed option with the value of the ideal option.

Results

As the technology of geopile foundation installation is specific in Lithuania and all over the world, only 18 respondents were able to answer the questionnaire.

The distribution of respondents who participated in the survey according to their current position is presented in Fig. 1.

The first survey questionnaire was answered mainly by company managers and salespeople, the number of respondents - 8, which made up 44%. In the second place - design engineers, 7 respondents, which made 39%, and in the third place according to the number of answers were work supervisors, 3 respondents, which made up 17%. The answers to the survey were distributed according to the occupations of the respondents. For design engineers the most important assessment criterion was bearing capacity, while managers ranked the installation price as the most important.

After ranking the criteria, it was found that the most important criterion when choosing geopile installation technology is installation price (Eur/m), the second place – load-bearing capacity (in scores), the third place - installation technology mechanization level (in scores), the fourth place – pile installation possibilities (in scores), the fifth place - the duration of pile installation (in scores), and the sixth place – the impact of pile installation technology on the environment (in scores).

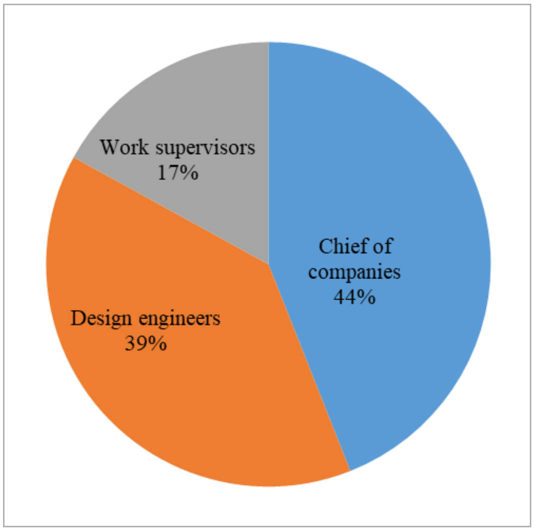


Fig. 1

Distribution of respondents by position

Criteria are ranked applying the direct ranking method (selected score scale 6 ... 1), which means that the highest scoring criterion will receive the highest rank score, i.e. 6; the second will receive 5 and so on.

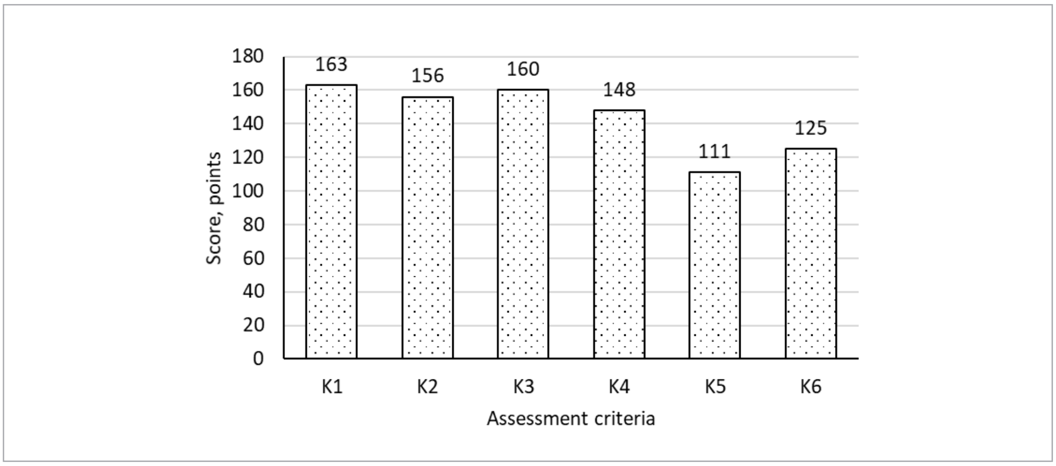


Fig. 2

The scores obtained by the criteria in the survey of respondents

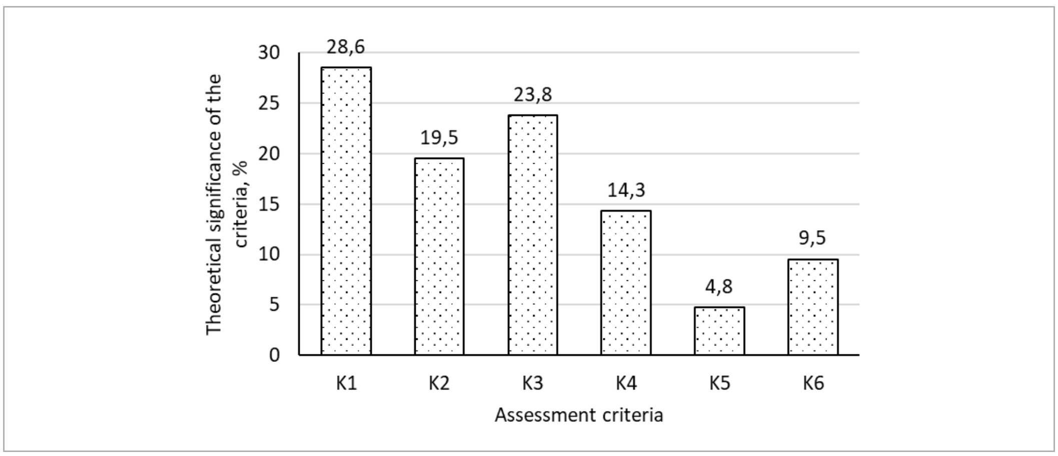


Fig. 3

Criteria weight distribution by theoretical significance

In order to determine a rational geopile installation solution, a multi-criteria task is solved, i.e. three alternatives are compared by assessing them according to 6 criteria, and the initial matrix is presented in Table 2.

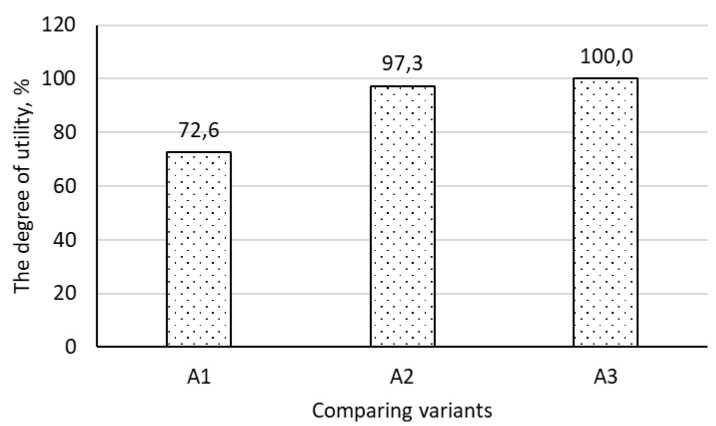
Table 2

Initial Matrix A of alternative solutions

Criterion / Alternative solutions	K_1	K_2	K_3	K_4	K_5	K_6
A_1	9.0	28	25	20	27	30
A_2	11.0	27	31	24	21	28
A_3	12.5	27	29	31	18	24
$\sqrt{\sum_{i=1}^{m} x_{ij}^2}$	18.9	47.3	49.3	44.0	38.7	47.5
Optimality	min	max	max	max	max	max
Theoretical significance, %	28.6	19.5	23.8	14.3	4.8	9.5

Fig. 4

Schedule of alternate utility degrees



A_1 – driving a hollow steel pipe into the ground using a deep vibrator and using geosynthetic material to reinforce soils;
A_2 – driving a closed end hollow steel pipe into the ground and using geosynthetic material to reinforce soils;
A_3 – driving an open-ended hollow steel pipe into the ground and using geosynthetic material to reinforce soils

A multi-criteria assessment was performed and it was found, that that a rational geopile installation technology is the use of an open-ended hollow steel pipe using geosynthetic material. This is not the cheapest way to install a pile, but it is in the most optimal of all criteria. This technology has a particularly wide range of installation options, good load-bearing capacity and assurance of load-bearing capacity.

Conclusions

1 According to the survey questionnaire data, the ranking order of the assessment criteria is as follows: installation cost (Eur), load-bearing capacity (in scores), mechanization level of the installation technology (in scores), pile installation possibilities (in scores), duration of pile installation (in scores), impact of pile installation technology on environment (in scores).

2 A multi-criteria assessment was performed and it was found that a rational geopile installation technology is the use of an open-ended hollow steel pipe using geosynthetic material. The use of this technology provides minimal restrictions to installation possibilities, and the installed piles have good filtration and mechanical properties.

3 The most economical way for installation of one meter geopile is the use of deep vibrator technology. However, this technology can rarely be applied in Lithuania and the installed piles eventually lose their filtering properties.

4 The highest load-bearing capacity is obtained in geopiles that are fitted with a closed-ended hollow steel pipe using geosynthetic material technology. However, this technology generates high vibrations that can spread very far through the fluid layers of the soil, thus undermining the foundations and stability of the surrounding structures.

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