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ARTICLE

Determination of Optimal Designs for Geothermal Energy Piles in the Soil Supporting a Multi-storey Building

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Abstract: The article presents the optimal design of geothermal energy piles supporting a multi-story building at different pile spacing. The optimization model OPTPILE, based on the construction cost of the single pile, was used for this purpose. It was provided with geotechnical and structural design constraints that satisfy the requirements of building codes. The optimal design of a geothermal energy pile was studied for a 10-storey building with different pile spacing. So far, only a single energy pile has been optimized and therefore the spacing between the piles has not yet been considered in the design. However, in this work, pile spacing is taken into account by considering the entire load distribution of the multi-story building. A 3D beam-slab frame was created to determine the pile loads. The recommendation for the optimal design of geothermal energy pile spacing for a 10-storey building was developed. The results show that the optimal pile spacing (square distribution) for a 10-storey building is about 7 m. The construction cost for all thermal pile foundations and concrete structural components for a 10-storey building is estimated to be 101.1 €/m^2. The optimal architecturally reasonable spacing of piles with a square distribution for a 10-storey building is 8.5 m. In this case, the cost of the concrete structural elements of the building and the piles increases by 1% to 102.1 €/m^2. The cost of installing the heating pipes in the pile is about 1 €/m^2.

Keywords: Geothermal energy piles, Structural design, Optimization, Multi-storey building

1. Introduction

In 2019, a project COST ACTION TU1405 GABI was completed. The project deals with geothermal applications for buildings and infrastructures (GABI). It addresses the use of shallow geothermal energy for heating/cooling. Shallow geothermal energy is energy stored in the form of heat directly below the earth's surface. There are two types of near-surface geothermal energy use: open-loop shallow geothermal energy systems (well systems, surface water systems) and closed-loop shallow geothermal energy systems (horizontal systems, vertical systems, and geostructures). The geothermal energy piles are typical geostructures used for heating/cooling buildings [1-4]. Ge-

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othermal energy piles have two basic functions, one is to transfer loads to the ground with higher bearing capacity and the other is to transfer excess heat from the multi-storey building to the cooler ground in summer and extract heat from the ground in winter [5]. The influence of pile geometry on bearing capacity of pile has been already extensively researched, however recently the effect of pile geometry on heat exchange between pile and soil was also discussed [6]. To evaluate the effects of thermal cycling on the shear strength of the soil-pile interface, a laboratory test was also conducted [7].

The ultimate and serviceability limits of the pile should be checked according to the standard methods [8,9]. When designing reinforced concrete piles, longitudinal and transverse steel reinforcement should be provided in accordance with Eurocode specifications [10] and recommendations [11]. However, the effects of thermal loading are much more significant when the pile is designed for serviceability limit state, while thermal loading can be neglected when designing for ultimate limit state [12].

This paper deals with the use of shallow geothermal energy for heating/cooling of multi-storey buildings. The design of geothermal energy piles is based on several analytical, numerical and experimental studies [13-16]. Some empirical equations for geothermal pile design have been proposed [17,18]. A useful design chart for additional settlement of pile heads in clay due to thermal effects was provided by the Ground Source Heat Pump Association (GSHP) [19]. In this paper, optimization was performed to design economic competitive piles. A direct comparison is possible when geotechnical and structural conditions are fully utilised (without resistance reserves). So far, only a single energy pile has been optimized and therefore the spacing between the piles has not yet been considered in the design. However, in this work, pile spacing is taken into account by considering the entire load distribution of the multi-story building.

2. Optimal Design of Conventional and Geothermal Pile

The model contains an accurate objective function for the material and labour costs of the structure subject to the (in) equality constraints to satisfy the requirements of the Eurocode specifications and the GSHP recommendations. The objective of the optimizations is to determine the minimum construction cost of a single pile for selected design parameters and to obtain the optimal design, which includes the diameter of the pile, the pile length, the diameter and number of main reinforcing bars, and the diameter and spacing of the bars. For this reason, the DIscrete and Continuous OPTimizer (DICOPT) program was used to solve mixed integer nonlinear programming (MINLP) problems [20]. Also, the MINLP optimization model OPT-PILE (Optimal PILE) proposed by Jelušič and Žlender [21] was used to solve the optimization problem.

Five different conditions are considered in the OPT-PILE optimization model as structural analysis and design conditions: Condition 1 - the bearing capacity pile, Condition 2 - the settlement of the pile must be within a limited value, Condition 3 - the required main steel reinforcement area must not exceed the designed steel reinforcement area in the pile, Condition 4 - the minimum area of steel reinforcement must be checked, and Condition 5 - the minimum area of shear reinforcement (links) must be checked.

The repeated occurrence of thermal effects leads to a deterioration of shaft friction along the pile with an accumulation of settlement. This accumulated settlement was considered in the design conditions for geothermal energy piles.

3. Multistorey Building

The Geological-geotechnical circumstances and geotechnical conditions for construction of multi-storey building are given in this chapter. The description of proposed multi-storey building is also provided.

3.1 Ground Conditions

The geological composition of the region under consideration is summarized from the geological base map of the Celje region and data from six (6) research boreholes drilled at the site of the foreseen construction project. Boreholes were also used to determine the water table and to perform standard penetration tests. Soil samples were recorded in the field according to soil classification and collected for laboratory testing. Based on the stratification, the laboratory tests and the SPT blows mechanical properties of the soils were estimated (Table 1).

The considered region is located on the northern edge of the Celje depression. The ground is tectonic dismembered with joints and folded. The soil in the region of the proposed structure is even and stable. The region consists of alluvial sediments represented by clay and clayed sandy soils. The soil material originates from the rocks of the near and distant surroundings and forms heterogeneous layers. The groundwater of the considered region is located at a depth of about 2 m below the soil level.

In general, the stratification of ground layers has an influence on the seismic degree of the considered region. The influence of local ground conditions on earthquake effects is considered according to EN 1998-1:2005 [22], which considers a period of 475 years and places the considered region in the 8th degree of EMS. According to the design ground acceleration map that is comparable with map of earthquake intensity, the regions of small and high earthquake risks coincide very well in average. For considered region design ground acceleration is $Q_g = 0.2 \cdot g$.

Table 1. Recommended soil parameters for analyses, based on laboratory and field tests.

Depth (m)	Undrained shear strength cu (kPa)	Compressibility modulus Eoed (MPa)
1	50	15.0
5	82	24.6
10	122	36.6
15	162	48.6
20	202	60.6
25	242	72.6
30	282	84.6

3.2 Structural Elements of Building

The building is a ten-storey concrete building with flat concrete slabs and concrete beams supported by concrete columns. Four different spacing of piles are considered in this paper. A smaller spacing of the piles results in a smaller load applied on the pile, however than a larger number of piles are required. If the spacing of the piles is increased, more piles are required, but the load on the piles is then greater. The dimensions of the building with column beams and slabs are given in Table 2.

Table 2. Specifications of different types of multistorey buildings

Alternative	Type 1	Type 2	Type 3	Type 4
Number of Stories (-)	10	10	10	10
Storey Height (m)	3	3	3	3
Number of Bays, (X and Y direction)	7	6	5	4
Bay Width (m), (X and Y direction)	5	6	7	9

The section properties provided in Table 3, apply to the entire length of the beams and columns and all the slabs.

Table 3. Section properties of beams, columns and slabs

Section	Width (m)	Depth (m)	Concrete Material	Concrete reinforcement
Column	0.5	0.5	C30/37	S500
Beam	0.3	0.6	C30/37	S500
Slab	-	0.3	C30/37	S500

The Figure 1 shows the ten-storey building modelled in computer program SAP2000 [23] in order to obtain the reaction forces. Those reaction forces are than used as a load on the pile foundation.

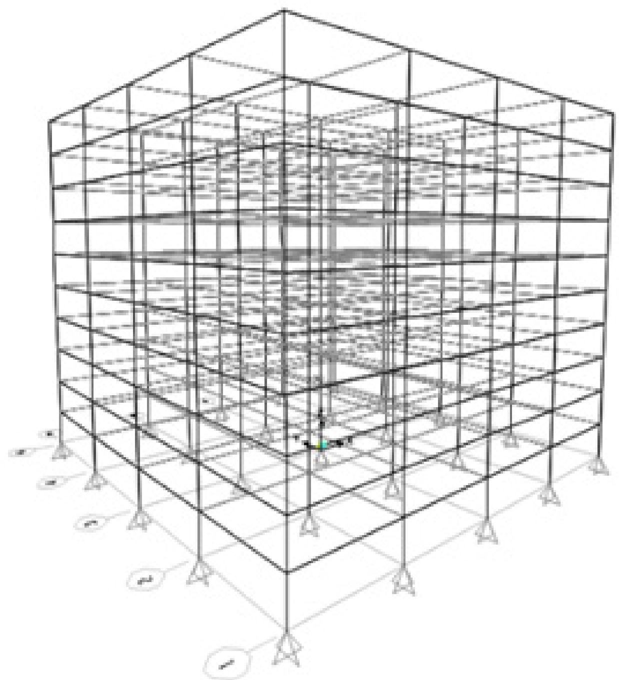

Figure 1. Ten-storey concrete building - Type 4.

3.3 Numerical Analysis

The reaction forces at each column were obtained as presented in Figure 2. The maximum vertical forces calculated for each of four building types are given in Figure 3. The figure presents the influence of spacing between the piles on the increment of vertical force on the pile.

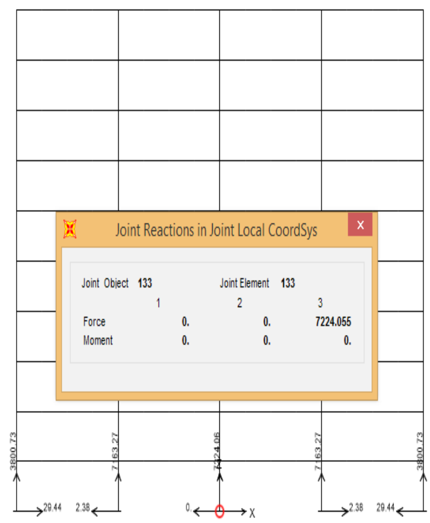

Figure 2. The vertical force on the support

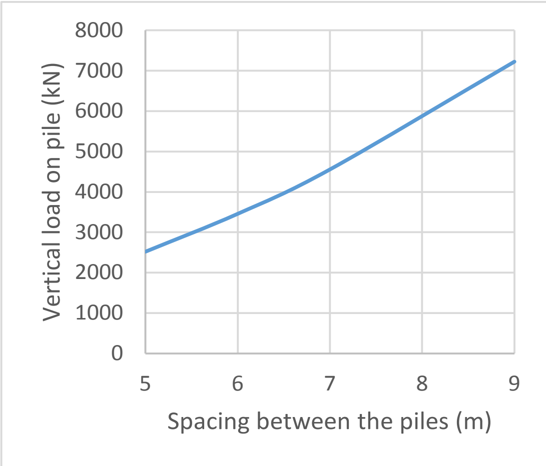

Figure 3. The increase of vertical force on support due to increase of the pile spacing

3.4 Optimization Model for the Design of Conventional and Geothermal Energy Pile

The optimization model for the design of conventional and geothermal energy piles was created. The model contains input data (in-variables), variables, and the cost objective function of a pile structure subject to geotechnical analysis, dimensioning and discrete (binary) constraints. The input data are composed of the cost and design data (in-variables) for optimization [24-26].

The objective function for the construction cost of a conventional and a geothermal energy pile (€), see Equation (1), was created:

$$\min COST = C_{drill} + C_{conc} + C_{rein,main} + C_{rein,shear} + C_{thermal} \quad (1)$$

where:

COST - the self-manufacturing costs of the geothermal energy pile;

C_{drill} - cost of ground drilling;

C_{conc} - cost of concrete;

$C_{rein,main}$ - cost of main reinforcing steel;

$C_{rein,shear}$ - cost of shear reinforcing steel;

$C_{thermal}$ - cost of installation of heating pipes in the pile.

Five different conditions were defined in accordance with Eurocode standards and recommendations in the form of five inequality constraints, which were entered into the OPTPILE optimization model as structural analysis and dimensioning constraints [21], see Figure 4:

1) the bearing capacity of the pile (Condition 1),

2) the settlement of the pile must be below an acceptable value (Condition 2),

3) the required main steel reinforcement area must not exceed the provided steel reinforcement area of the pile (Condition 3),

4) the minimum area of main reinforcement shall be provided (Condition 4) and

5) the minimum area of shear reinforcement (links) shall be provided (Condition 5).

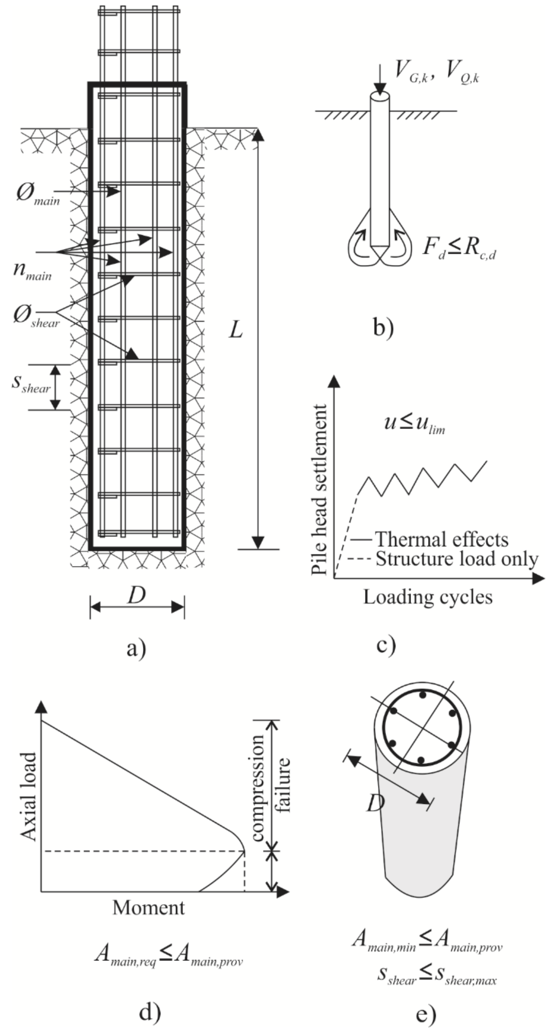

Figure 4. Geothermal energy pile: Cross-section of pile (a), pile design resistance (b), pile settlement under thermal effects (c), interaction diagrams (d) and steel reinforcement design (e) [21].

4. Results and Discussion

The results of the optimization are shown in Table 4. For each construction alternative (spacing of piles), the optimal solution was determined. A total settlement at the applied load that does not exceed 20 mm is acceptable for this multi-storey building.

The result in Table 4 is represented by the *COST* (€), where the thermal cost includes the cost of installing the heating pipes in the pile. The diameter of the pile *D* (mm), the length of the pile *L* (m), the diameter of the main reinforcement with bars $Ø_{main}$ (mm), the number of main reinforcement bars n_{main} (-), the diameter of the links $Ø_{shear}$

(mm), the spacing of the links shear (mm), and the production costs of the structure COST (€) were determined. The calculated cost COST (€) - conventional, refers to the construction cost of the pile without the cost of laying the heating pipes in the pile. The cost of the geothermal energy pile design for a pile spacing of 9 m (Type 4) is €9213.88, while the geothermal energy pile design for a pile spacing of 5 m costs 3346.40 €.

Table 4. Specifications of different types of multi-storey buildings

Alternative	Type 1	Type 2	Type 3	Type 4
Load (kN)	2519.13	3456.69	4555.32	7224.06
D (mm)	900	1100	1200	1400
L (m)	18	18	18	20
Ømain (mm)	16	16	18	28
nmain (-)	8	8	8	8
Øshear (mm)	200	200	200	225
sshear (mm)	18	19	22	26
COST - conventional (€)	2986.40	4041.12	5342.28	8693.88
COST - thermal (€)	3346.40	4421.12	5782.28	9213.88

As the spacing for each type of building is different the number of piles is also different. The number of piles of each type of building is given in the Table 5 along with the total construction cost of piles. Even though a larger pile spacing (Type 4) means a smaller number of piles for a fixed area, the total cost for all piles is slightly higher than for a smaller pile spacing (Type 1) because the cost for a single pile is higher.

Table 5. Number of piles and the construction cost of piles for different spacing of piles

Alternative	Type 1	Type 2	Type 3	Type 4
Number of piles (-)	64	49	36	25
COST - conventional (k€)	191.1	198.0	192.3	217.3
COST - thermal (k€)	214.2	216.6	208.2	230.4

The cost of concrete structural elements is different for each type of building. The weight and volume of each structural element are given in Table 6, along with the total cost. The term total cost represents the cost of the structural elements and the cost of the pile foundations. It should be noted that the cost of the concrete structural elements per volume is assumed to be 300 €/m^3. The unit weight of reinforced concrete was determined to be 25 kN/m^3. The total area of the 10-storey building is 16000 m^2.

Table 6. The weight and costs of the structural elements

Structural element	Type 1	Type 2	Type 3	Type 4
Beams (kN)	25192.6	22673.3	18894.4	16195.2
Columns (kN)	11996.5	9184.8	6748.0	4686.1
Slabs (kN)	91847.9	97171.3	91847.9	97171.3
∑ (kN)	129036.89	129029.39	117490.3	118052.6
Structural element	Type 1	Type 2	Type 3	Type 4
Structural costs (k€)	1548.4	1548.3	1409.9	1416.6
Total COST - conventional (€/m^2)	108.7	109.1	100.1	102.1
Total COST - thermal (€/m^2)	110.2	110.3	101.1	102.9

Figure 5 shows the influence of the pile spacing on the production cost of the geothermal energy pile per m^2. The reducing the structural elements such as beams and columns of multi-storey building when the pile spacing is increased, decrease the structural cost of building. In summary, as the pile spacing increases, the cost of the pile foundation increases and the structural cost of the building decreases. All this leads to an optimal pile spacing of 7 m for a 10-story building. Similarly, the Figure 6 presents the influence of spacing of piles on the total cost per m^2 of concrete structural elements and production costs of the geothermal energy pile.

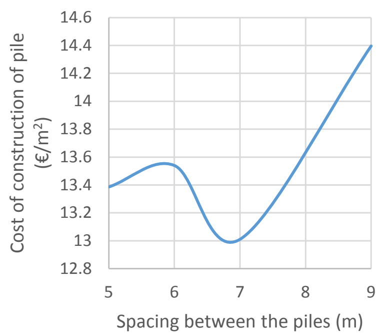

Figure 5. The production costs of the geothermal energy pile per m^2 of the 10-storey building.

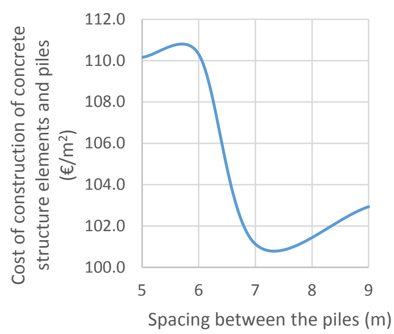

Figure 6. The total costs of concrete structural elements and geothermal energy pile production costs of the 10-storey building.

5. Conclusions

The paper deals with the cost optimization of conventional and geothermal energy pile and presents the effect of the pile spacing on the construction cost of the multi-storey concrete building. The optimization was performed using the OPTPILE optimization model. The results show that the optimum pile spacing (quadratic distribution) for a 10-storey building is approximately 7 m. The self-construction cost for a single geothermal energy pile is 5782.28 €. The construction cost for all pile foundations for a 10-storey building is estimated at 230.4 k€. If this cost is calculated per square meter of the building surface, this value is 13 €/m^2. The total cost, this the cost of the concrete structural elements of the building and the piles, is estimated at 1618 k€ or 101.1 €/m^2. On the other hand, the optimal architecturally reasonable spacing of the piles by square distribution for a 10-storey building is 8.5 m. In this case, the cost of the concrete structural elements of the building and the piles increases by 1% to 102.1 €/m^2. In this research the pile spacing was taken into account in terms of design of piles that supports the multi-storey building. However, further research is needed for the optimal design of pile rafts, which are often used as foundations for multi-story buildings. The optimal design of pile rafts should take into account not only pile spacing, but also the thickness of the rafts and the load carried by the piles compared to the load carried by the rafts.

Author Contributions

Conceptualization, P.J. and B.Ž.; methodology, P.J.; formal analysis, P.J. and B.Ž.; writing—original draft preparation, P.J. and B.Ž. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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Nomenclature

D - diameter of pile, mm
L - length of pile, m
$\emptyset_{main}$ - diameter of main reinforcement bars, mm
n_{main} - number of main reinforcements bars
$\emptyset_{shear}$ - diameter of links, mm
s_{shear} - spacing of links, mm

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