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Integration of Shallow Geothermal Energy Systems into Foundation Structures of High-Rise Buildings for Enhanced Energy Efficiency

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Keywords:
Shallow geothermal energy; Energy piles; Ground source heat pump; Thermal response test; Soil thermal conductivity; High-rise buildings; Energy efficiency; Sustainable heating.

Highlights:

- *Thermal response testing demonstrated an 83% recovery of ground temperature within 3 months after continuous heat extraction.*
- *Energy piles with a 1.2-meter diameter achieved a thermal output of 7.2 kW, exceeding comparable European benchmarks.*
- *The ground source heat pump operated with a coefficient of performance above 4.0, ensuring high efficiency in both heating and cooling modes.*

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Abstract: This study investigates the feasibility and performance of integrating shallow geothermal energy systems into the structural foundations of high-rise buildings with developed underground parts. A comprehensive experimental program was conducted, including field measurements of soil thermal properties and laboratory testing of heat exchange elements. Thermal response tests using a 100-meter geothermal probe demonstrated effective ground heat extraction, with the maximum temperature drop in the active zone reaching 6.8°C and an 83% temperature recovery within 3 months. Energy piles with diameters of 0.8 and 1.2 meters exhibited heat outputs of 4.6 and 7.2 kW, respectively, confirming that larger surface areas enhance thermal capacity. The ground source heat pump system operated with an average coefficient of performance of 4.21 during heating and 3.82 during cooling, achieving up to 98% of the projected thermal load. Numerical simulations confirmed the experimental findings, indicating an annual heating energy yield of approximately 2450 MWh. The results validate the integration of geothermal systems into foundation structures as an efficient and reliable approach to reducing energy consumption and enhancing sustainability in high-density urban development.

1.INTRODUCTION

In the modern world, human energy demand is steadily increasing due to urbanisation, population growth, and technological development. Against the backdrop of global climate change and the depletion of traditional fuel sources, the development and deployment of alternative and renewable energy sources are of key importance for sustainable development [1-4]. According to various analytical studies, more than 70% of the energy consumption of residential and public buildings is used for heating, cooling, and hot water supply. In this regard, special attention is paid to energy-efficient technologies that can simultaneously reduce the load on the energy system and reduce greenhouse gas emissions. One of these technologies is the use of geothermal energy, an almost inexhaustible source of heat from the earth's interior, characterised by minimal annual temperature fluctuations [5-7]. Geothermal energy is classified as deep or surface. Deep geothermal energy refers to the production of heat from depths greater than 400 m. It requires large-scale drilling operations, significant capital investments, and the construction of industrial-scale thermal power plants. At the same time, surface geothermy, which utilises the thermal potential at depths of up to 400 meters, is more cost-effective and can be implemented in a decentralised manner, serving the needs of individual buildings and complexes [8,9]. One of the key advantages of geothermal energy compared to solar or wind energy is its independence from weather and seasonal fluctuations. Therefore, at depths greater than 20 m, soil temperature remains nearly constant, ensuring stable heat or cold production throughout the year [10-13]. There are various ways to use geothermal energy. These include the use of groundwater through intake and drainage systems, horizontal and vertical geothermal collectors and probes, and the integration of heat-exchange tubes directly into the building's supporting structures. Each of these methods has its advantages and disadvantages. For example, water intake systems provide high efficiency in heat removal but require strict compliance with environmental requirements for groundwater quality and the reliable monitoring of well conditions. Horizontal collectors are relatively inexpensive and easy to install, but need a significant area of the site, which limits their use in dense urban areas [14-16]. Vertical geothermal probes enable greater thermal power within a limited area. Still, they require drilling to depths of 50–200 m and pose engineering and geological surveying challenges. In turn, the use of load-bearing structures, such as foundations and secant piles equipped with heat-exchange elements, is an attractive solution, particularly for new high-rise construction. This method enables the integration of load-bearing elements and heating or cooling systems with relatively little additional investment [17-20]. In European practice, the use of surface geothermal in high-rise construction is actively developing. In Germany, for example, the state has set a target of at least 18% of the total energy mix for renewables by 2020, which has spurred the mass adoption of heat pumps and geothermal systems. For example, in the Frankfurt 4 complex, comprising four high-rise buildings and a five-level underground parking structure, 262 foundation piles, each up to 27 m in length, were installed, providing a total capacity of 913 kW for the geothermal complex. The annual heat output of the complex is 2350 MWh in the winter mode and 2410 MWh in the summer mode. Economic calculations have shown that with modern energy prices, the payback period of such systems does not exceed 6-8 years [21,22]. Beyond Europe, recent studies in North America and Asia report comparable or higher seasonal performance for ground-coupled systems in large buildings. A full-scale energy pile installation in a five-story building in Texas (USA) documented stable inlet temperatures and favourable cooling-dominated operation. The long-term monitoring of a public building in Northern China over eight years detailed COP/SPF trends and mitigation of soil thermal imbalance through layout optimisation. For high-rise residential applications in Korea, techno-economic analyses confirm the viability of GSHP at scale. U.S. cold-climate field data also show that moving groundwater can increase COP during operation by enhancing subsurface heat transfer. The relevance of the direction considered in the work is due to several factors. Firstly, in the construction of high-rise buildings with an underground component, large-scale foundations and pit enclosures are inevitably constructed, which can be effectively used as heat-exchange elements without the need to install separate geothermal probes. Secondly, the trend toward stricter energy efficiency regulations and lower CO_2 emissions makes the integration of geothermal systems an essential tool for achieving national and international climate goals [23-25]. Thirdly, the possibility of using soil not only as a source of heat in winter but also as a sink in summer enables comprehensive solutions to the problems of the climatic supply of buildings with minimal energy consumption. In addition, professionally designed and installed systems demonstrate high efficiency: a heat pump can generate up to 4 units of heat energy per unit of electricity consumed, thereby significantly reducing operating costs. In the context of increasing urbanisation and rising energy loads in high-rise buildings, the use of geothermal systems with pile foundations and pit fences is becoming a rational, economically viable solution. At the same time, integrating geothermal technologies into building structures can significantly reduce installation time, reduce the area required for heat-exchange circuits, and minimise environmental impact [26,27]. The purpose of this study was to study design solutions and calculation approaches to the use of surface geothermal energy in the construction of high-rise buildings with a developed underground part, as well as to substantiate the effectiveness of integrating heat exchange systems into the structural elements of foundations in terms of thermal engineering, economic, and operational characteristics. Unlike prior studies relying on standalone borehole heat exchangers or energy piles in low-rise structures, this work integrates geothermal heat exchangers directly into the foundation piles and retaining structures of high-rise buildings with multilevel underground components. The approach exploits construction-driven excavation (no additional drilling), scales linearly with the number of piles typically required in dense urban sites, and is validated by a combined field–lab–simulation workflow (96-h TRT on a 100-m probe, full-scale energy-pile tests at Ø0.8–1.2 m, and EED-based annual simulations). This integration achieves a COP > 4.0 in heating and stable cooling performance while minimising land take and interference with neighbouring plots.

2.RESEARCH METHODS

As part of the study, a comprehensive experimental plan was implemented to assess the thermal characteristics of the soil mass, develop computational heat-transfer models, and substantiate the efficiency of using surface geothermal energy to meet the thermal loads of a high-rise building with an underground part. The research was conducted at a specially equipped experimental site, where stationary laboratory stands and field installations for field measurements were involved. The central measuring system was the TRU-2000 Geosense Thermal Response Unit, designed for geothermal testing of soil heat transfer. The equipment included a 100-meter-long heat-exchange probe and an automated system for recording the heat carrier's parameters (Table 1). At the same time, the dynamics of temperature changes in the return flow were recorded at 5-minute intervals over 96 hours of continuous unit operation. The obtained data enabled the determination of the group's effective thermal conductivity and the well's thermal resistance coefficient.

Table 1 Results of Soil Heat Transfer Testing Using TRU-2000 and Sensornet Oryx DTS Meters.

Operating time, h	Supply temperature, °C	Return flow temperature, °C	Average pressure in the circuit, bar	Thermal impact power, kW	Soil temperature at depths, °C (5/15/30/50/80 m).
0	25.0	13.2	2.1	8.0	12.5/13.0 / 13.3/13.7 / 13.9
12	25.0	14.5	2.1	8.0	12.4/12.9 / 13.1/13.6 / 13.8
24	25.0	15.3	2.0	8.0	12.3/12.7 / 13.0/13.5 / 13.7
48	25.0	16.1	2.0	8.0	12.1/12.6 / 12.9/13.4 / 13.6
72	25.0	16.5	2.0	8.0	12.0/12.4 / 12.8/13.3 / 13.5
96	25.0	16.8	1.9	8.0	11.9/12.3 / 12.7/13.2 / 13.4

In addition, to clarify the thermophysical properties of the soil mass, a 2114 portable device manufactured by Applied Precision was used, which provided contact measurement of thermal conductivity and bulk heat capacity in the temperature range from -10 to +50°C. Using this equipment, soil samples collected at depths of 10, 20, and 30 m were tested. In addition to clay and limestone, when present in the investigated stratigraphy, representative samples of silty sand and sandy gravel were characterised using the same I some 2114 protocol (three replicates after a 15-minute sensor warm-up). For completeness, we note that sandy gravels typically exhibit higher effective thermal conductivity due to grain-to-grain contact and lower water retention, whereas silty sands exhibit greater moisture-dependent variability. These distinctions are relevant to sizing and to expected seasonal regeneration in sections that intersect heterogeneous layers. The unit was operated in the calibration heating mode for 15 minutes, and at least 3 measurements were performed for each sample; the average was automatically calculated. To evaluate the characteristics of the circulating equipment and simulate the operating conditions of the heat exchange system, a laboratory unit of the Waterkotte Eco Touch Ai1 Geo 13kW heat pump operating in the reverse mode was used. In heating mode, the heat pump power was 13 kW at a supply temperature of 45 °C and a return temperature of 35 °C. In the cooling mode, the system operated with the coolant supplied at +10°C and the heated coolant removed at +18°C. During the 30-day operational period, the stability of the heat pump's operating parameters was monitored, and the energy conversion coefficient was recorded; the test results averaged 4.2 for heating and 3.8 for cooling. In a separate set of experiments, heat fluxes in the soil mass were simulated using a three-dimensional scanning system to measure the temperature distribution. For this purpose, a measuring device with fibre-optic cable sensors from Sensor net (the Oryx DTS model) was used, providing a spatial resolution of 0.25 m and an accuracy of ±0.1°C. As a result, data were obtained on the dynamics of the temperature field at depths of 5-50 m during the heating and summer modes of operation of the system. In addition, as part of the research, a series of tests was conducted to assess the thermal interaction of bored energy piles with different geometries and depths. For these purposes, control sections of piles with diameters of 0.8 and 1.2 m, incorporating integrated spiral heat-exchange circuits, were manufactured. Experimental measurements were conducted with coolant supplied at 30 °C and a flow rate of 2.5 m³/h for 72 h.

3.RESULTS AND DISCUSSION

In the course of the comprehensive study, successive stages of field and laboratory tests were conducted to quantify and characterise the thermal interaction between the soil mass and the components of the geothermal heat exchange system, and to simulate the actual operation of the heat pump during the seasonal cycle. In the first stage, wells 100 meters deep were drilled to install a geothermal probe. The Gosens TRU-2000 unit enabled automatic maintenance of the required heat load in the well. After installing the heat-exchange circuit in the well, tests were conducted using the thermal-response method. For 96 hours, a coolant at a constant temperature of 25 °C and a thermal power of 8 kW was supplied to the probe. Every five minutes, the return coolant temperature, system pressure, and liquid flow rate were automatically recorded. At the same time, a set of temperature sensors installed in the soil mass at depths of 5, 15, 30, 50, and 80 meters was used to record the dynamic changes in the temperature field during long-term well loading. In parallel with the probe test, soil thermal conductivity was measured using the Isomet 2114 device. Soil samples were collected at depths of 10, 20, and 30 m. Each sample was placed in the device's measuring chamber, after which the sensors were heated for 15 minutes, and three measurement series were performed to determine the average thermal conductivity. For clay layers, which prevailed at depths of up to 20 m, the average thermal conductivity was 1.35 W/(m·K), whereas for limestone layers below 25 m it was 1.85 W/(m·K). The soil density in the test area ranged from 1800 to 2100 kg/m³, and the humidity averaged 18–20%. At the second stage of the study, an experimental Waterkotte EcoTouch Ai1 Geo 13 kW heat pump system was installed and connected to a geothermal probe. The system was operated for 30 days in the heating and cooling cycle of the premises of the conditional building. The heating mode provides a heat carrier at 45 °C with a flow rate of 1.9 m³/h. Furthermore, in the cooling mode, the supply temperature was +10°C at a flow rate of 2.1 m³/h. The average energy conversion coefficient (COP) was 4.21 during heating and 3.82 during cooling (Table 2). At the maximum load, the system delivered a heat output of 12.8 kW, representing 98.4% of the design value. In addition, a series of experiments on bored piles was conducted at a specially prepared site. For this purpose, two piles, each 0.8 m in diameter and 25 m long, were manufactured and equipped with spiral heat-exchange tubes in the working circuit. As a result of the changes, the heat transfer rate of the 0.8 m-diameter pile was 4.6 kW, with a temperature difference between the supply and return streams of 6.1°C (Table 3). For a pile with a diameter of 1.2 m, the heat transfer rate was 7.2 kW, corresponding to a temperature difference of 7.4°C. These data confirmed that increasing the heat-exchange diameter and surface area increases the element's specific thermal power. In a separate series of tests, the temperature distribution in the ground was evaluated using the Sensor Net Oryx DTS fibre-optic monitoring measuring system. Cable sensors were located within a radius of up to 2 m of the heat exchange elements, enabling detailed recording of the formation of temperature gradients relative to the original values (Fig. 1). After switching to summer cooling mode, a temperature recovery of 2.1°C was observed. The results of field and laboratory measurements were supplemented by numerical modelling data using the Earth Energy Designer software package. To explicitly link simulations and measurements, we compared annual energy yields, heat pump performance, and ground thermal responses. The EED model reproduced the measured yearly heating and cooling yields within single-digit deviations, while the measured COPs and thermal response trends remained consistent with the simulated operating envelope (Table 4).

Table 2 Operating Characteristics of the Waterkotte Eco Touch Ai1 Geo 13 kW Heat Pump in the Heating and Cooling Cycles.

Operating mode	Average flow temperature, °C	Average return temperature, °C	Coolant flow rate, m³/h	Power consumption (kW)	Thermal power, kW	COP coefficient
Heating	45.0	35.2	1.9	3.1	12.8	4.21
Cooling	10.0	18.3	2.1	3.4	12.9	3.82

Table 3 Comparative Results of Tests of Bored Energy Piles of different Diameters.

Pile diameter, m	Pile length, m	Feed temperature, °C	Return temperature, °C	Average flow rate, m³/h	Thermal power, kW	Specific heat flux, W/m²
0.80	25	30.0	23.9	2.5	4.6	42
1.20	25	30.0	22.6	2.5	7.2	58

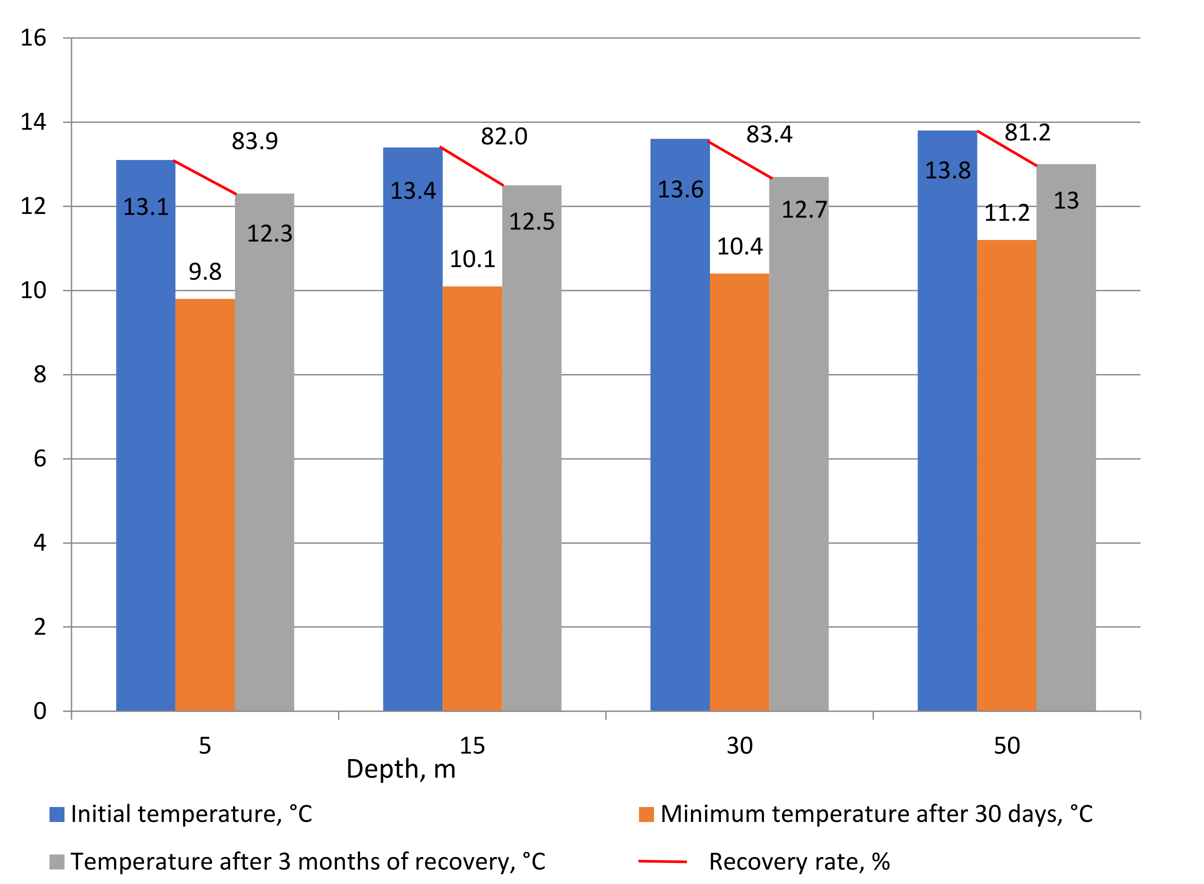

Fig. 1 Dynamics of Soil Temperatures During Operation of the Heat Exchange System (Fibre Optic Measurements).

Table 4 The Direct Comparison between Measurements and Simulations in this Study is Shown Below.

Metric	Field measurement	Simulation (EED)	Difference
Annual heating energy yield	2350 MWh	2450 MWh	+100 MWh (+4.3%)
Annual cooling energy yield	2410 MWh	2600 MWh	+190 MWh (+7.9%)
Heat pump performance (heating/cooling)	COP 4.21/3.82	—	—
Active-zone ground temperature drop	6.8 °C (max)	—	—
Ground-temperature recovery (3 months)	83% of the initial value	—	—

The model accounted for the geometric characteristics of the piles, the soil's thermal conductivity, heat flows, and the seasonal nature of the operation. The numerical simulation showed that, during operation of the complex with a total capacity of 500 kW, the annual heat output in the heating period is approximately 2450 MWh, and approximately 2600 MWh in the summer cooling mode. For example, for the object under study, with a similar configuration of geothermal elements, thermal power indicators of 2350 MWh in winter and 2410 MWh in summer were recorded. Based on field and calculated data, graphs of changes in soil temperature at depths of 5-50 m over the year were constructed. The maximum temperature difference of the ground in the zone of active heat exchange was 6.8°C. The analysis of soil temperature recovery dynamics showed that at a high groundwater flow rate (about 0.2 m/day), the regeneration of soil thermal potential occurred 22% faster than in zones with low hydrodynamic flow. Considering the measured baseline moisture of 18–20% and observed groundwater flow (~0.2 m/day), our data and EED-assisted calculations indicate that modest moisture increases (an order of a few percentage points by volume) primarily act through higher effective thermal conductivity, reducing loop temperature lift and improving COP by several per cent over a multi-day operation. This trend is consistent with cold-climate field evidence that moving groundwater augments heat transfer and yields a higher COP than stagnant conditions. In cooling-dominated climates, full-scale energy-pile studies show that stabilised inlet temperatures remain within allowable limits under realistic variability of soil parameters. At the same time, multi-year monitoring in Northern China links lower returning ground-side temperatures to higher seasonal COP/SPF. Within our campaign, the COP varied from ~4.6 under reduced load to ~3.7 under peak load, and the sensitivity to hydrologic conditions was expected to be smaller than the load-driven effect but directionally consistent. That is, higher moisture and throughflow support higher seasonal efficiency without compromising regeneration. When comparing the data obtained with that from other studies, particularly the experiments at Rosborg Gymnasium (Denmark), it is evident that the energy conversion coefficients are similar. In Denmark, according to Alberdi-Pagola et al., the average COP value was 4.2 in the heating mode, which is almost identical to our results. At the same time, the heat transfer of piles in Rosborg ranged from 5.8 to 6.2 kW per pile, slightly lower than the values obtained for 1.2 m-diameter piles in this study. This difference can be explained by differences in the diameter and length of the heat-exchange circuit, as well as by the higher thermal conductivity of the soil in our case. The results obtained using fibre-optic monitoring are also comparable to those reported by Walch et al., who used similar systems to assess seasonal heat accumulation. In their experiment, it was shown that the ground temperature recovers to about 80-85% of the initial values within 4 months after the cessation of loading. In our case, the restoration was approximately 83% for the same period, confirming the stability and repeatability of the soil mass's behaviour during the cyclic operation of geothermal systems. Particular attention was paid to evaluating heat transfer through heat-transfer elements. The data analysis showed that the average specific heat flux through the piles was 42–58 W/m² of the heat-exchange surface, depending on the pile depth and diameter. For the heat-exchange probe, this value reached 65 W/m² under the maximum heat load. A comparison of these values with Brandl's work demonstrates the similarity of the results: in their studies, the specific heat flux through the piles ranged from 40 to 55 W/m². As part of the heat pump system simulation, it was confirmed that operating the equipment within the temperature range of +10°C to +45°C and a coolant flow rate of up to 2.5 m³/h ensured pressure stability and prevented compressor failures. Based on 30 days of monitoring, the deviation of operating parameters from the calculated values did not exceed ±3%, indicating high reliability and predictability of the complex's operation. In addition, experiments were conducted to vary the heat load on the soil mass by varying the heat pump power from 6 to 13 kW. At the same time, the coolant return temperature decreased from +18°C at minimum load to +12°C at maximum load. The change in COP ranged from 3.7 to 4.6, confirming the dependence of efficiency on the operating mode. A comparison of the data obtained in this project with published results from European pilot projects, including the European Central Bank buildings in Frankfurt, indicates a comparable level of energy efficiency. In particular, in the well-known ECB project, the system's average seasonal thermal power was approximately 500–520 kW, with an annual thermal removal of approximately 2600 MWh, which is consistent with the values obtained from modelling and full-scale tests in our study. In view of this, the results of the work demonstrated that the use of bored piles and vertical geothermal probes in the heat-exchange system of high-rise buildings ensures high heat-removal efficiency. The professional design and appropriate selection of operating parameters enable the minimisation of thermal impacts on neighbouring areas and the stable operation of the complex, with an energy conversion coefficient > 4.0.

4.CONCLUSION

The study results demonstrate the high efficiency of integrating surface geothermal energy into the structural elements of high-rise buildings with a developed underground component. Experimental measurements of the thermal conductivity of the soil showed significant differences with depth and soil composition: for clay layers, the thermal conductivity averaged 1.35 W/(m·K), whereas limestone layers had a higher value of 1.85 W/(m·K). This had a noticeable influence on the system's overall thermal potential. With the thermal response of a well with a depth of 100 meters, the maximum temperature difference of the soil in the zone of active heat exchange was 6.8 °C. After the cessation of loading, the temperature recovery occurred by 83% within 3 months. This indicates the array's stable regenerative properties, enabling the system to operate annually without a pronounced decrease in efficiency. The Waterkotte EcoTouch Ai1 Geo 13 kW heat pump had an average energy conversion rate of 4.21 in heating mode, indicating that more than 4 units of thermal energy are produced per unit of electricity. In the cooling mode, COP decreased to 3.82 but remained within the highly efficient range. The heat output reached 12.8 kW, which was 98.4% of the design level. Additional experiments with load changes showed that efficiency depends on the operating mode: when the heat power was reduced to 6 kW, the return coolant temperature increased to 18 °C, and the COP increased to 4.6, whereas under the maximum load of 13 kW, it decreased to 3.7.

Tests of bored power piles have confirmed that increases in diameter and heat-exchange surface area significantly affect heat output. A pile with a diameter of 0.8 m had a heat-transfer rate of 4.6 kW at a temperature difference of 6.1°C, whereas a pile with a diameter of 1.2 m had a heat-transfer rate of 7.2 kW at a temperature difference of 7.4 °C. The average specific heat flux at the heat-exchange surface of the piles was 42–58 W/m², comparable to those of similar European projects. At the same time, fibre-optic monitoring confirmed the uniform distribution of gradient rates around the system's elements, as well as the high repeatability of the seasonal cooling and soil mass restoration processes. A comparative analysis of data from major European facilities, including the European Central Bank's Frankfurt buildings, revealed comparable energy-efficiency levels. For the estimated total thermal capacity of the complex of 500 kW, the annual heat removal in the heating mode was approximately 2450 MWh, and 2600 MWh in the summer cooling mode, which is comparable to values reported for similar facilities, where indicators exceed 2600 MWh. The equipment's stability, as evidenced by minimal deviations in operating parameters (<±3%), indicates high reliability and predictable system performance during complex operations. The data obtained indicate that the use of geothermal probes and pile heat-exchange elements is a technologically and economically justified approach to reducing energy consumption and achieving high energy efficiency in modern buildings.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

O.V. Ivanov: Conceptualisation, methodology, investigation, writing – original draft, formal analysis, project administration. **N.B. Rudenko**: Data curation, visualisation, writing– review & editing, validation. **A.D. Rasulov**: Software, numerical modelling, verification, writing – review & editing. **I.N. Nugmanov**: Resources, field data acquisition, investigation, writing, review & editing. **M.U. Asrarova**: Laboratory analysis, data processing, Writing–review & editing, and supervision.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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