Advanced design of friction piles for operation in complicated soil conditions

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Abstract. Development of advanced designs for friction piles is a problem solution to reduce material costs at the stage of a pile foundation construction in complicated soil conditions. The constructive approach aimed to a rational use of construction materials in production of piles is proposed in this paper. The idea of technical proposal is to change a shape of a pile cross-section to increase the length of a perimeter limiting the area, invariable in a size. An equilateral triangle cross-section meets fully these requirements. Results of theoretical studies and the analysis of existing calculation method of bearing capacity of a friction pile in a foundation soil showed a possibility of practical implementation of this engineering approach. The utilization of a pile with a cross-section in a shape of equilateral triangle increases bearing capacity of a pile in a foundation soil up to 28.6 % in comparison with a round cross-section and up to 14 % compared to a square cross-section. Conducted laboratory studies confirmed the correctness of theoretical calculations. The application of obtained results of theoretical and laboratory studies in the construction of pile foundations in complicated soil conditions will not only reduce material costs for the foundation production, but will also decrease transportation costs which are rather high under development of new fields.

1. Introduction

Further prospects of oil and gas industry development in Russia are closely connected with the development of new oil-and-gas areas in the Far North. One of the factors significantly complicating the industrial infrastructure development in addition to weather and climatic conditions is the existence of extensive territories with complicated soil conditions. The existing normative documents regulate the project implementation process on the construction of pile foundations at every stage. This includes not only geological engineering surveys at the site of a prospective construction, but also the design phase involving the selection of principle for using the overlying soils. This relates to construction stages of the facility and its subsequent technical maintenance during all its life cycle up to the final dismantling stage [1]. Moreover, revised editions of the existing regulations impose additional restrictions related to problems of environmental safety and protection on the developed design solutions. Obviously, all these factors can not but affect the growth of material and time expenditure at all stages of project implementation in complicated soil conditions, thereby reducing the investment attractiveness of projects, and in the long term increasing payback periods and decreasing competitiveness of extracted natural resources.

Application of new materials with improved consumer and operational properties can be a problem solution to reduce costs, including those arising in construction of soil foundations and in erection of buildings and structures for a technological infrastructure of transportation, storage and processing of hydrocarbons in the Far North conditions. The example of this approach is the technology using materials with improved heat-insulating characteristics at the stage of zero cycle that can reduce thermal losses during transport and storage of liquid hydrocarbons, but at the same time can provide required bearing properties [2]. The usage of advanced technology on a construction site, such as, a designed change of physical and mechanical soil foundation properties is another prospective engineering solution [3,4]. Such technology allow local mineral resources to be used more efficiently for the construction of soil foundations of buildings and facilities elevated far from sources of materials with required construction properties and supply bases [5].

The potential of constructive approach in a solution of material costs reduction for the construction of bases and foundations is not fully exhausted [6.7]. This very approach, as a rule, is more adopted to existing technology, construction machinery and mechanisms and does not require big additional capital investments for its realization [8]. Thus, for example, the shape change of a pile cross-section affects its bearing capacity in a foundation soil, and the form change of loading on foundation soils can have a crucial effect on the stability of buildings and facilities [9,10]. This engineering approach is proposed to solve a complex problem of the most complete utilization of construction materials and simultaneously transportation costs reduction in the construction of pile foundations in complicated soil conditions.

2. Problem statement

The problem solution of rational construction materials utilization in construction of pile foundations for oil and gas facilities in complicated soil conditions can be implemented through the search of new pile structures, which provide a higher bearing capacity without additional material costs and simultaneously providing technological requirements in manufacturing.

3. Theoretical studies

In accordance with current regulations bearing capacity F_u of a vertically loaded friction pile while using for example permafrost soils according to Principle I is determined by formula [1]:

$$F_u = \gamma_t \gamma_c \left(RA + \sum_{i=1}^{n} R_{af,i} A_{af,i} \right) \tag{1}$$

where γ_t is a temperature coefficient considering changes of temperature in foundation soils due to random changes of ambient air temperature; γ_c is a condition load effect factor of a foundation. R is a design resistance of a frozen soil under a pile foot (kPa); A is an area of pile bearing on a soil (m^2); $R_{af,i}$ is a design resistance of a frozen soil or a soil solution to a shift on a side surface of a pile regelation within the i-th soil layer (kPa). $A_{af,i}$ is an area of surface regelation of the i-th soil layer with a side pile surface (m^2); n is a number of permafrost soil layers defined in calculating.

In turn, bearing capacity F_d of driven piles of friction, carrying a pressure load when using permafrost soils according to Principle II is calculated by formula [11]:

$$F_d = \gamma_c \left(\gamma_{cR} RA + u \sum \gamma_{cf} f_i h_i \right), \tag{2}$$

where γ_c is a condition load effect factor of a pile in a soil; γ_{cR} is a condition load effect factor of soil under a pile foot. R is a design resistance of soil under a pile foot (kPa). A is an area of pile bearing (m^2); u is an outside perimeter of a pile shaft cross-section (m); γ_{cf} is a condition load effect factor on a side pile surface. f_i is a design resistance of the i-th soil layer on a side surface of a pile shaft (kPa); h_i is a thickness of the i-th soil layer contacting with a side surface of a pile (m).

Bearing capacity F_d of a filling pile of friction, carrying a pressure load under using permafrost soils on Principle II is calculated by the formula [11]:

$$F_d = \gamma_c \left(\gamma_{cR} RA + \gamma_{cf} u \sum f_i h_i \right) \tag{3}$$

The analysis of dependences 1 - 3 defines promising trends to increase a bearing capacity of friction piles, operating in permafrost soils while using those piles both on Principles I and II. One of these directions can be an area increase of a pile side surface, contacting with a soil, without enlargement of its cross-section area. This provides the same consumption of constructional materials for pile manufacturing with the same pile length. Obviously the increase of a contact area «pile side surface – soil» in its turn is provided by the increase of a cross-section perimeter length. In formula 1 unlike in formulas 2 and 3 explicitly there is no perimeter value. However, it is possible to calculate this parameter knowing the surface area of soil regelation with a pile side surface and the depth of a pile penetration into a permafrost soil.

A comparative calculation was performed to prove an assumption, that a cross-section shape affect a bearing capacity of a friction pile operating in permafrost soils. Geometrical sizes of S100.35-A800 pile were used as initial data to calculate the bearing capacity of a vertically loaded friction pile [12]. Geometrical sizes of round and triangular sections were calculated taking into account equal areas of a cross-section of the piles under study.

The following initial conditions and assumptions were accepted by formula 1 in a comparative calculation of bearing capacity of foundation Fu for vertically loaded friction piles, used in permafrost soils on Principle I:

- the piles under study have the same length and the same cross-section areas that with a reasonable reliability provides approximately equal material consumption for manufacturing of piles.
- permafrost soils of a foundation are homogeneous in composition and consist of nonsaline loams and clays, with the ice content i_i<0,2, the soil temperature does not change with the depth and equals T_0=−1ºC.
- calculated values of strength characteristics for frozen soils are accepted according to reference tables [1];
- in calculations the dimensionless temperature coefficient γ_t, considering temperature changes of foundation soils due to random changes of ambient air temperature is taken as γ_t =1.

Figure 1 shows the calculation results.

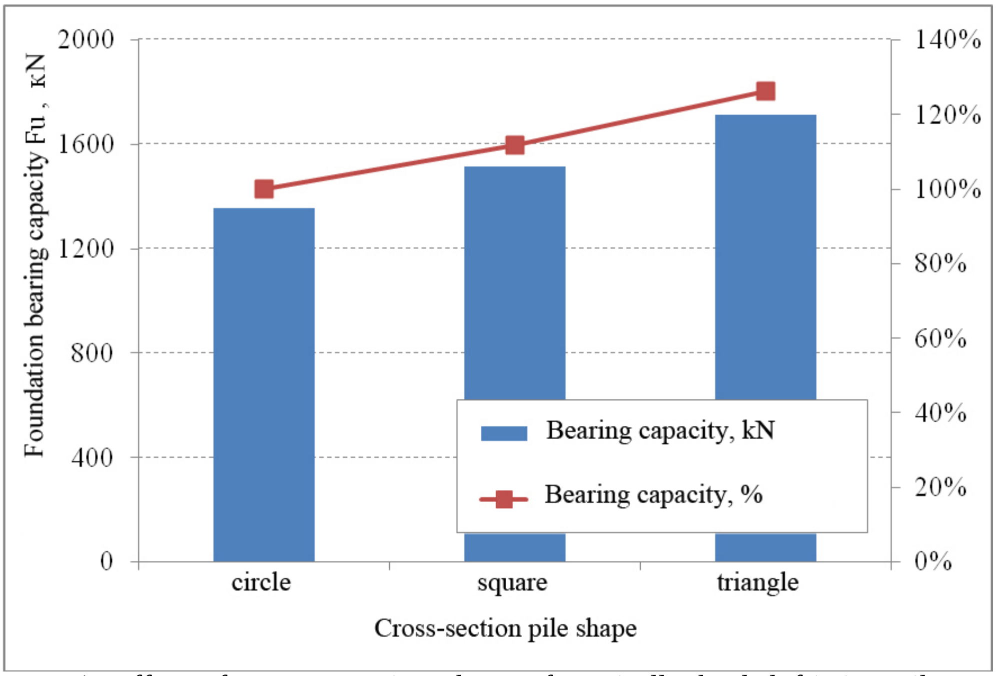

Figure 1. Effect of a cross-section shape of vertically loaded friction piles used in permafrost soils according to Principle I on piles' bearing capacity in a foundation soil.

The following initial conditions and assumptions were accepted by formulas 2 and 3 in a comparative calculation of bearing capacity F_d for driven piles of friction and filling piles of friction carrying the pressure load and used according to Principle II [11]:

- the piles under consideration have the same length and equal cross-section areas that provides with a reasonable reliability approximately the equal material consumption for manufacturing of piles.
- foundations are homogeneous in composition and consist of clay soils with the index of liquidity I_L=0,3
- the design resistance of a soil under a pile foot and on the side surface are taken according to reference tables [11].

Calculation results of bearing capacity F_d for driven piles of friction are shown in figure 2, for filling piles of friction the results are in figure 3.

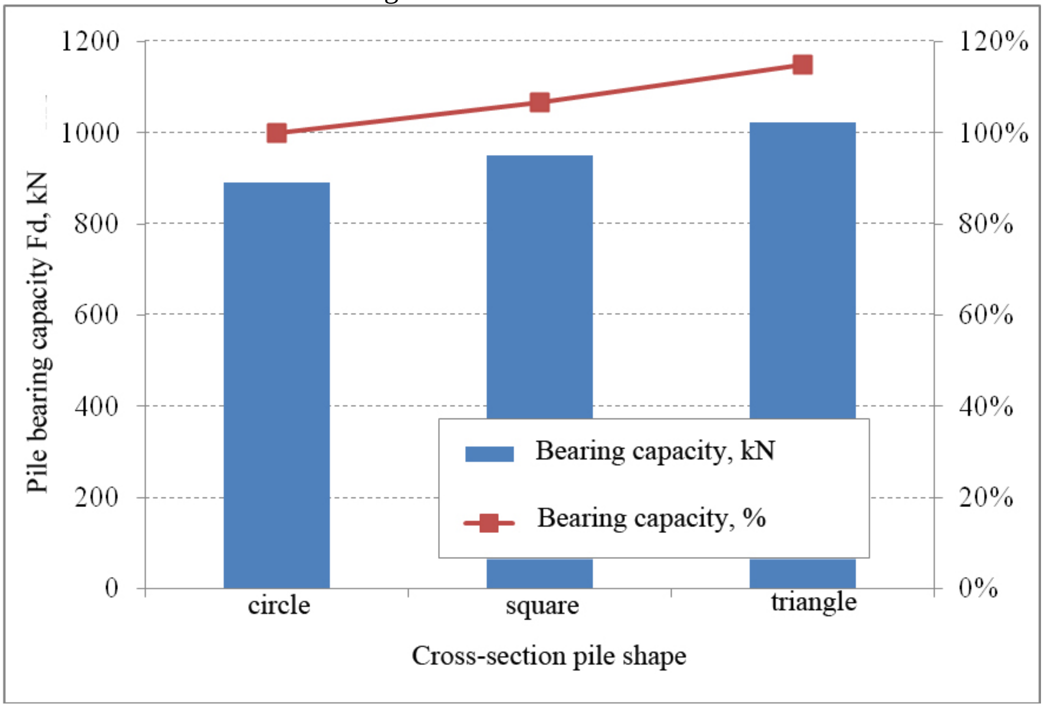

Figure 2. Effect of a cross-section shape of vertically loaded driven piles of friction used according to Principle II on piles' bearing capacity in a foundation soil.

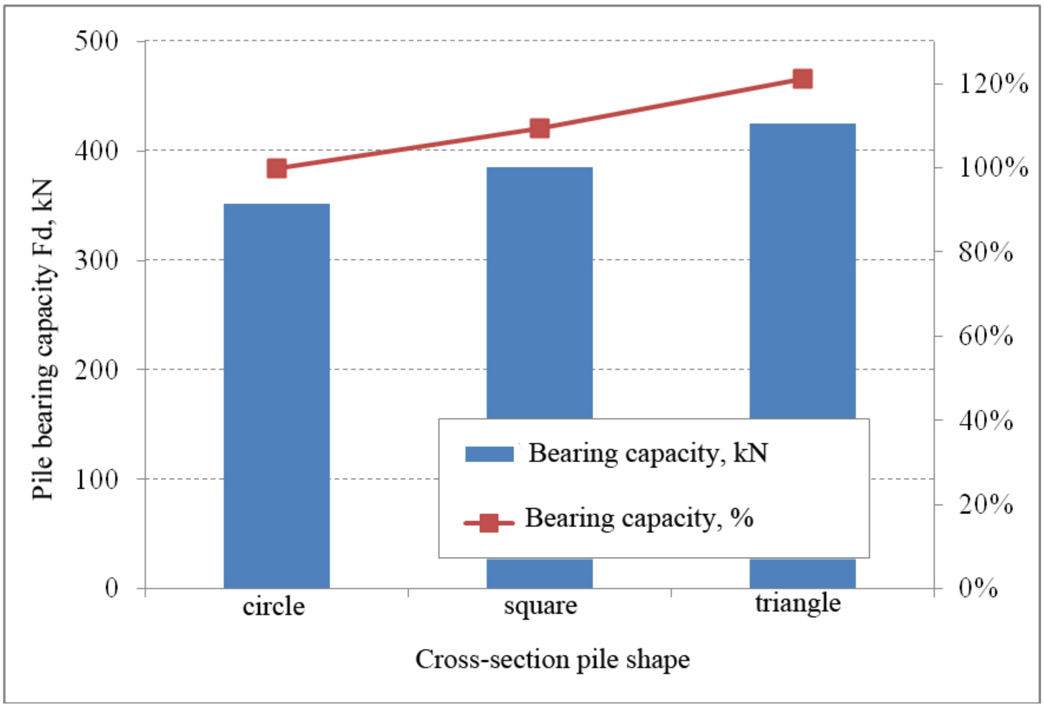

Figure 3. Effect of a cross-section shape of vertically loaded filling piles of friction used according to Principle II on their bearing capacity in a foundation soil.

4. Laboratory research

Bench tests of piles models were conducted in the research laboratory Bases and Foundations of Oil and Gas Facilities of Oil and Gas Engineering, Standardization and Metrology department in Omsk State Technical University (see figure 4). A circle, a square and an equilateral triangle were used as a cross section shape of models. The models made of concrete and wood were used in laboratory studies (see figure 5). The equality of cross-sectional areas and lengths of the models was a mandatory requirement for models manufactured of a selected material:

$$\begin{cases} A_{circle} = A_{square} = A_{triangle} \\ L_{circle} = L_{square} = L_{triangle} \end{cases}, \quad (4)$$

where A is a cross-sectional area of the corresponding model shape (m^2); L is a model length (m). Both for the models made of concrete and for the models made of wood, the cross-sectional area A equaled 0.001024 m^2, and models' length L was 0.240 m.

Figure 4. Laboratory bench to study forces arising in the course of installation/extraction of pile models of various design.

Loading conditions of models imitated pile pressing into a dispersed noncohesive soil (Principle II). An air-dry medium sandy soil was used as a dispersed noncohesive soil. The sinking rate was constant for all models and equaled $1.25 \cdot 10^{-3}$ m/s.

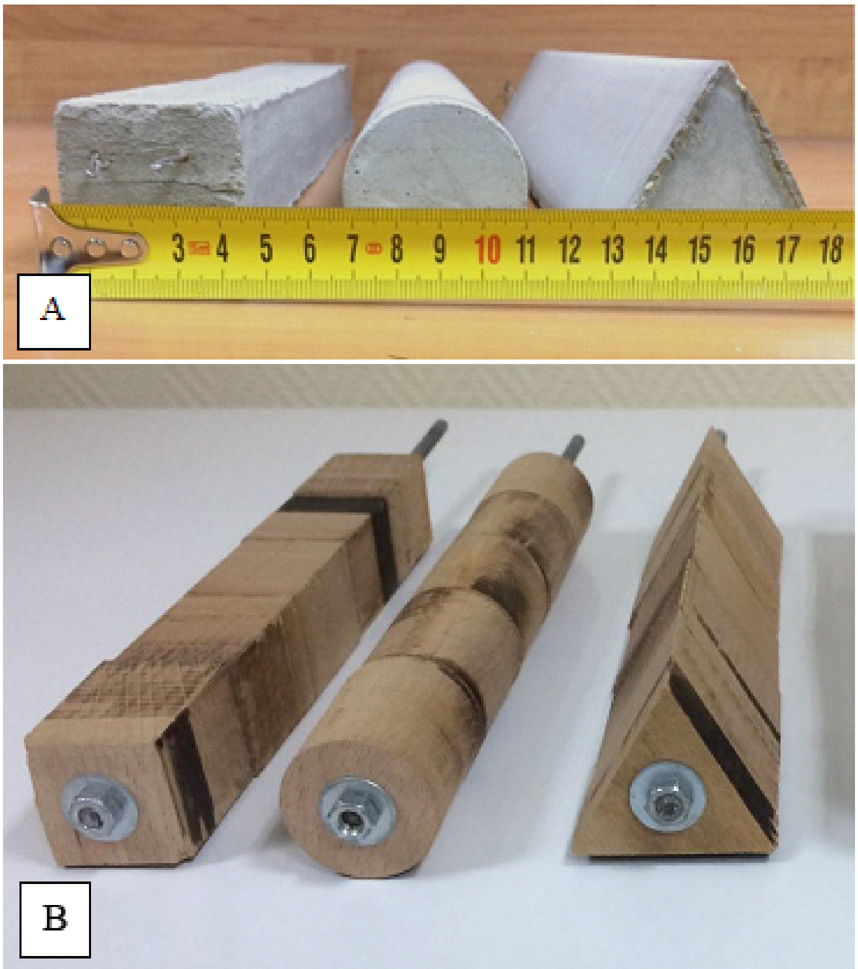

Figure 5. Pile models made of concrete (A) and pile models made of wood (B).

During the laboratory research the change of penetration force was registered under the penetration of models in a sandy soil (see figure 6).

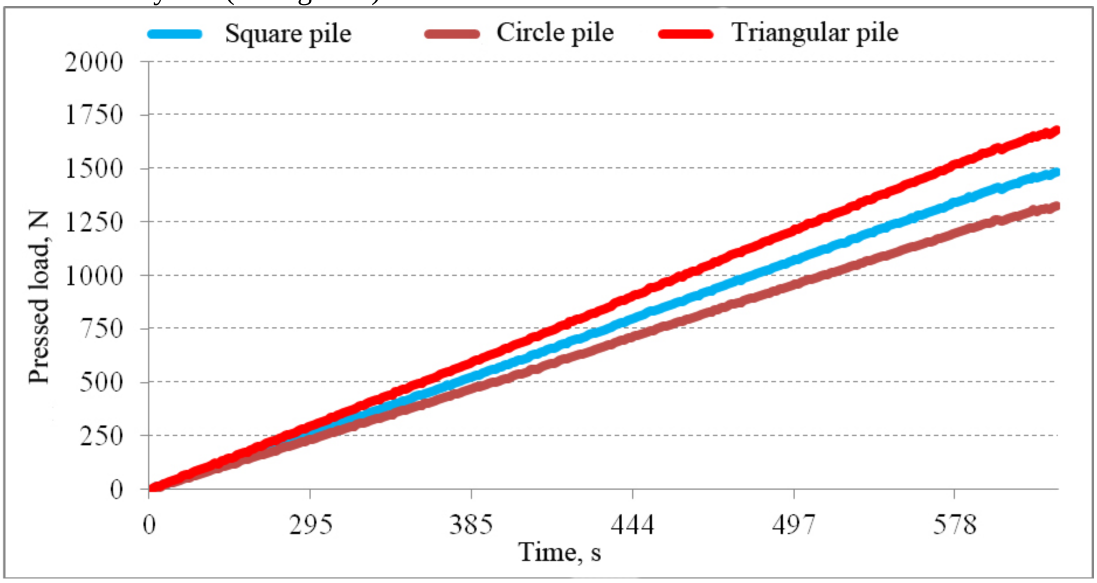

Figure 6. The change of penetration force in the course of time for pile models made of wood with a various cross section shape.

5. Discussion

The research carried out before showed a principle possibility to increase the bearing capacity of friction piles in a foundation soil. To analyze prospects of using piles' cross sections different from traditional shapes, such as circular and square, it is proposed to use the numerical parameter characterizing the relation of perimeter to the area, limited by the perimeter – u/A (see figure 7). Obviously the more its size, the bigger the design resistance of a soil on a pile side surface will be achieved.

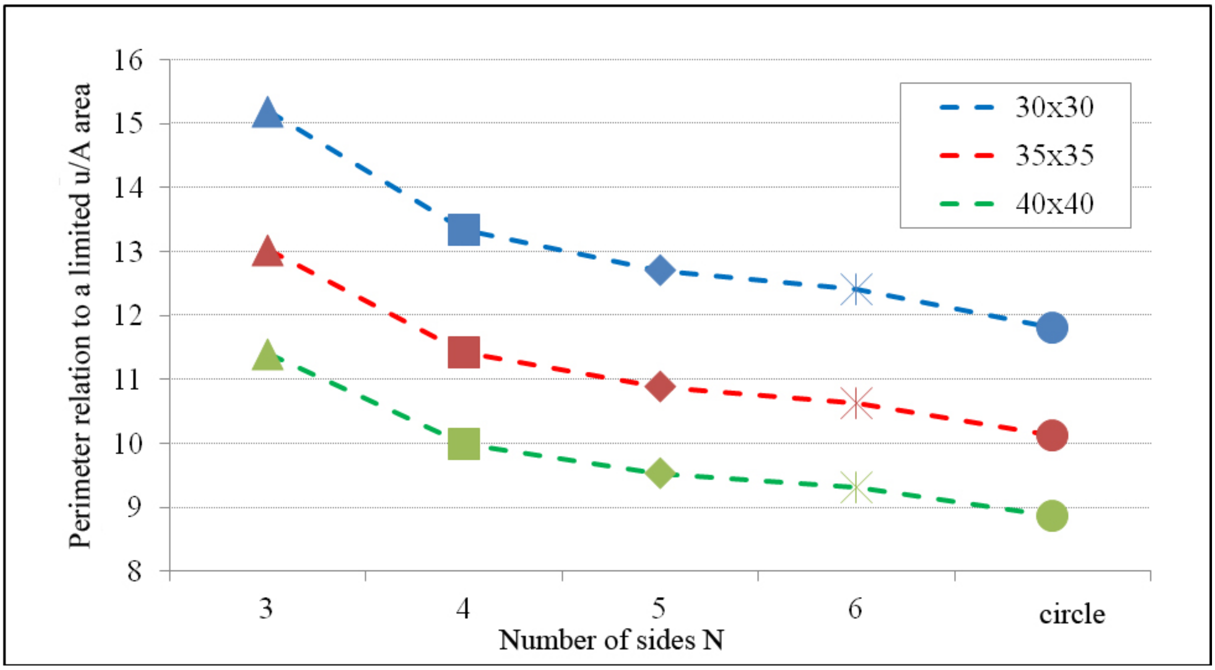

Figure 7. The influence of number N sides of equilateral N-gon on u/A relation for various cross-section areas of piles (according to the State Standard (GOST) 19804-2012).

The diagrams above show that the highest effect in a pile bearing capacity due to a pile side surface will be achieved if an equilateral triangle cross section is used. The diagrams above show that the highest effect in a pile bearing capacity due to a pile side surface will be achieved if an equilateral triangle cross section is used. The value increase of u/A parameter for a triangle compared to a square is 14%, in comparison with a circle it is 28.6%. At the same time, the value increase of u/A parameter for a square compared to a circle is only 12.8%. It is evident that the obtained numerical data characterize maximum, achievable only in theory value of a possible increase in a bearing capacity of a friction pile.

The effect of a cross section pile shape on its bearing capacity was specified, based on existing engineering techniques 1-3 and according to performed calculations, regardless of the principle of using permafrost soil (see table 1).

Table 1. Bearing capacity of friction piles in a foundation soil.

Principle of permafrost soil usage		Shape of a pile cross section		
		Circle	Square	Triangle
Principle I		1357 kPa	1516 kPa (+11.7%)	1712 kPa (+26.2%)
Principle II	Driven pile	890 kPa	950 kPa (+6.7%)	1022 kPa (+14.8%)
	Filling pile	352 kPa	385 kPa (+9.4%)	426 kPa (+21.0%)

The analysis of obtained data confirms a significant increase in a bearing capacity of a friction pile and prospects in using an equilateral triangle as a pile cross-section in comparison with round and square sections. A spread of obtained values in increase of a pile bearing capacity is caused not only by the principle of a permafrost soil usage, it depends on the soils themselves (their composition and properties) as well as geometrical parameters of a pile, kind of technology applied to the construction of pile foundations and some other factors.

Obtained theoretical data were confirmed during laboratory studies of pile models having various cross-section shapes (see table 2).

Table 2. Maximum penetration force of pile models in a sandy soil.

Model's cross-section shape	Circle	Square	Triangle
Maximum penetration force	1325 N	1484 N (+12.0%)	1679 N (+26.7%)

As can be seen from the data provided, the greatest growth by 26.7% of a maximum penetration force compared to a cylindrical model was observed under testing a model with a triangular cross-section. A model with a square cross section had only 12% growth. The observed increase of a maximum penetration force for a model with a triangular section compared to a model with a square section was 13.1%.

6. Conclusion

The problem solution to reduce capital costs at the construction stage of buildings and facilities for a technological infrastructure of oil and gas industry is possible due to introduction of advanced designs of pile foundations [13, 14]. The results of performed studies allow drawing a conclusion about prospects of using advanced designs of friction piles with a cross-section in a shape of equilateral triangle in permafrost soil conditions. The proposed structural solution allows construction materials to be rationally used providing a weight reduction of a product without deterioration of its operational properties. The weight reduction of a product, in turn, will lead to a decrease in transportation costs which share in the development of new fields is traditionally large. Moreover, an important quality of the proposed solution should be noted that is the simplicity of manufacturing techniques of triangular cross section piles that should obviously enable the fast and seamless implementation of new products.

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