Automated construction process for foundation engineering

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Abstract –

The purpose of this manuscript is to outline a scientific task aimed at improving the technological and organizational methods for pressing piles into the ground. The study proposes the development of conceptual piling equipment and construction methods for various structural and technological solutions for pile fields, especially under complicated conditions. The efficiency indicators are confirmed experimentally on real sites. The ratio of the specific weight of the load moved by a service crane to the total number of project piles and the number of modules used, as well as the organizational and technological schemes for their use, are determined. Additionally, mathematical models are used to estimate the efficiency of various methods and options of pile work. A three-stage algorithm is proposed for the variant design of complex technological processes. Overall, this manuscript presents a comprehensive approach to solving the task of automating the construction of pile foundations, providing valuable insights for engineers and researchers in the field.

Keywords –

Construction automation; Technological process modeling; Foundation engineering; Piling machine

1 Introduction

Construction automation strategy, through the integration of cyber-physical systems into construction processes, aims to improve industry efficiency by overcoming the nonconformity between the pace of urbanization and the limitations of conventional technologies. For this purpose, equipment that combines conceptual design with automated processes, such as large-scale Printing Systems [1], is being developed worldwide. However, the problem of the disparity between the pace of erecting the overground parts of the building and the installation of the underground parts remains unsolved. The underground parts require significant labor costs and can account for up to 50% of total construction, and remains slow, one of the most hazardous and expensive [2].

Analysis of information sources [9] shows that pile foundations can be made reliable by using prefabricated building elements that are pressed into the ground, resulting in minimal environmental impact. Research has demonstrated that conventional piling techniques do not provide sufficient labor productivity in constrained working environments. Inefficient auxiliary processes used by machinery in such conditions can consume more than 75% of the machining time, resulting in decreased productivity and increased, labor and operating costs.

The relevance of the topic is determined by the lack of research on aggregate-modular type piling systems when they are used in foundation engineering.

2 Automated Construction Equipment

The development of automated construction process for pressing precast pile elements into the ground begins with the creation of the Modular Aggregative Piling System (MAPS). Developed by EC "Transzvuk" in Ukraine, this system is used for the construction of pile foundations and sheet pile structures for civil and industrial buildings [7]. The MAPS, shown in Figure 1, consists of the original piling machine of pressing type and a modular skidding system.

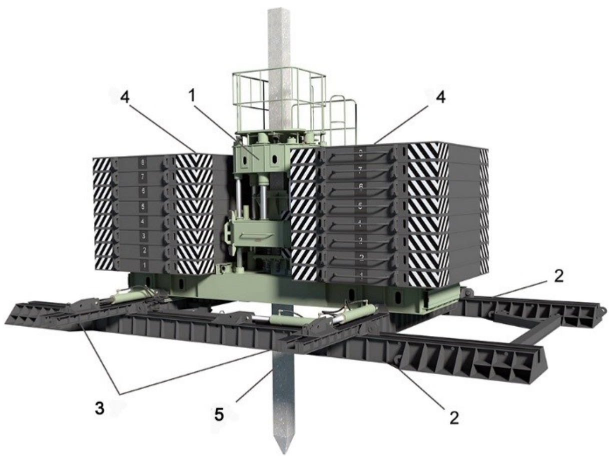

Figure 1. Modular Aggregative Piling System:
1 – piling machine, 2 – basic module, 3 – cross carriage, 4 – anchor loads, 5 – concrete pile

The concept of using MAPS provides precise, two-axis (X-Y) controlled repositioning of the Piling Machine, without remounting and re-anchoring operations and without the interruption of the main technological processes: pile installation – machine displacement.

Specifications of the MAPS are given in Table 1.

Table 1. Technical Specifications

Indicator	Value
Nom. pressing force	2000 kN
Pile pressing speed	1.5 ÷ 3 m/min
Displacement speed	2.1 m/min
Positional precision	± 10 mm

2.1 Hydraulic Piling Machine

The Piling Machine (PM) CO-450 is intended for pressing into the ground precast elements: concrete piles with cross-sections up to 450×450 mm, sheet piles not more than 500 mm width, and metal pipes. The pressing force of PM is up to 2300 kN. It works on the principle of self-centering the pile utilizing a side wedge-operated clamping system and cyclically pressing a pile into the ground in manual or automatic mode.

Figure 2. Piling Machine CO-450

The pile pressing force (soil resistance) is controlled by the hydraulic system of the PM. The PM is a gravity type and is anchored with metal loads by a service crane.

Total weight is up to 200 tonnes and is defined by ground resisting forces. Self-weight of the PM is 14.3 tons. It is the best performance for existing equipment in relation: to the pressing force of the machine to its weight. This property is important for limited space conditions.

The pile to be installed is fed into the PM by a crane. When installing piles below the ground level (up to 12 m), a metal inventory tool is used. The team consists of an operator, a crane operator, and two slingers.

2.2 Modular Skidding System

Modular Coordinating Skidding System (MCSS) is a hydraulic push-pull system of the ground type consisting of the main (aggregative), auxiliary longitudinal module (fixed), and a cross carriage (movable). It was designed according to the general principles of the international standard for building engineering [6]. This ISO specifies the aims of modular coordination and defines the dimensions of buildings, foundations, and the positioning of their components, piles, equipment, and assemblies.

The modules used are identical and interchangeable, allowing them to be connected in various combinations.

The system utilizes four hydraulic drive cylinders of 500 kN to achieve synchronized skid motion controlled along two axes. MCSS could also be used to move heavy equipment or structures (up to 350 t) on it in both longitudinal and transverse directions [8]. Specific pressure on the ground when using 1 (2) module: 15,7 (8,3) tons per square meter. That allows working on slopes and sites with weak or water-saturated soils.

3 Construction Methods

To unify and typify the technological solutions, the authors proposed to classify the existing methods of pile work, by the technological sequence of pile installation and positional displacements of the equipment. It refers to the ability of the equipment used in piling work to complete the installation process without requiring any readjustments or interruptions to the main technological process. The classification distinguishes:

1) Point; 2) Lineal (X); 3) Coordinate (X, Y) methods. Based on this classification, three piling methods have been developed, with each method utilizing an automated Piling Machine CO-450. When developing the piling methods, the geometric parameters of pile foundations for civil buildings [6] were taken into account in order to ensure maximum architectural flexibility.

3.1 Point Method

The point (P) method is based on PM repositioning by a service crane. It is used for the installation of single piles, including the piles of increased liability in a case when the safety of nearby buildings is the determining factor. This method remains indispensable in conducting pile works under conditions of maximum proximity to existing buildings (1m for piles and 0.5m for sheet piles). Unfortunately, the productivity of the P-method is low [10]. It is one pile per hour, with 25% of the time spent pressing a 16m pile into the ground and the remaining 75% of the time spent on inefficient auxiliary processes such as mounting, anchoring, disassembly, and repositioning of the Piling Machine CO-450 by service crane.

3.2 Lineal Method

The lineal (L) method is based on the PM one-coordinated positional movement along the longitudinal X coordinate, along the axis of the pile row, using fixed longitudinal skid guides 2, as exemplified in Figure 3.

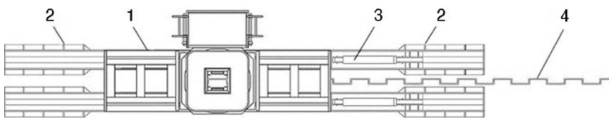

Figure 3. Sheet piling by the lineal method: 1 – piling machine, 2 – longitudinal guides, 3 – drive cylinders, 4 – sheet pile wall

This method is used for the single-row arrangement of building elements: concrete piles, tubes, sheet piles, etc. The advantages of the L-method are obvious for all types of linear works, be it cutoff or retaining walls of a sheet pile type or anti-landslide structures.

The labor productivity is significantly increased in comparison with the P-method, but it is still insufficient for multi-row pile structures, because of the frequent need for equipment readjustments.

3.3 Coordinate Method

The coordinate (C) method is based on PM two-coordinated positional movement along the longitudinal axis, using the cross carriage 3, as shown in Figure 4, option C. It is used for a cluster and multi-row disposition of piles. The technological process for C-method using two modules with sequential reconnection was presented in the paper [8]. It was displayed, that the implementation of the C-method together with the accuracy of the pile installation (position and inclination control) cuts down the production time providing higher productivity.

However, in a restricted workspace, the sequential reconnection of modules is difficult due to the limitations of the service crane operation area [4]. There is a need for additional operations that rising the machining time, such as the equipment being repositioned by crane into a new working space, MCSS re-mount, and PM re-anchor.

When the pile row on the X axis is over, again there is a need to readjust the main process: pile installation – machine displacement, together with the positioning control interruption. The parallel mounting of modules when PM moves in the transverse direction Y does not ensure the continuity of the modular grid system, and as a consequence, the impossibility of complex automation.

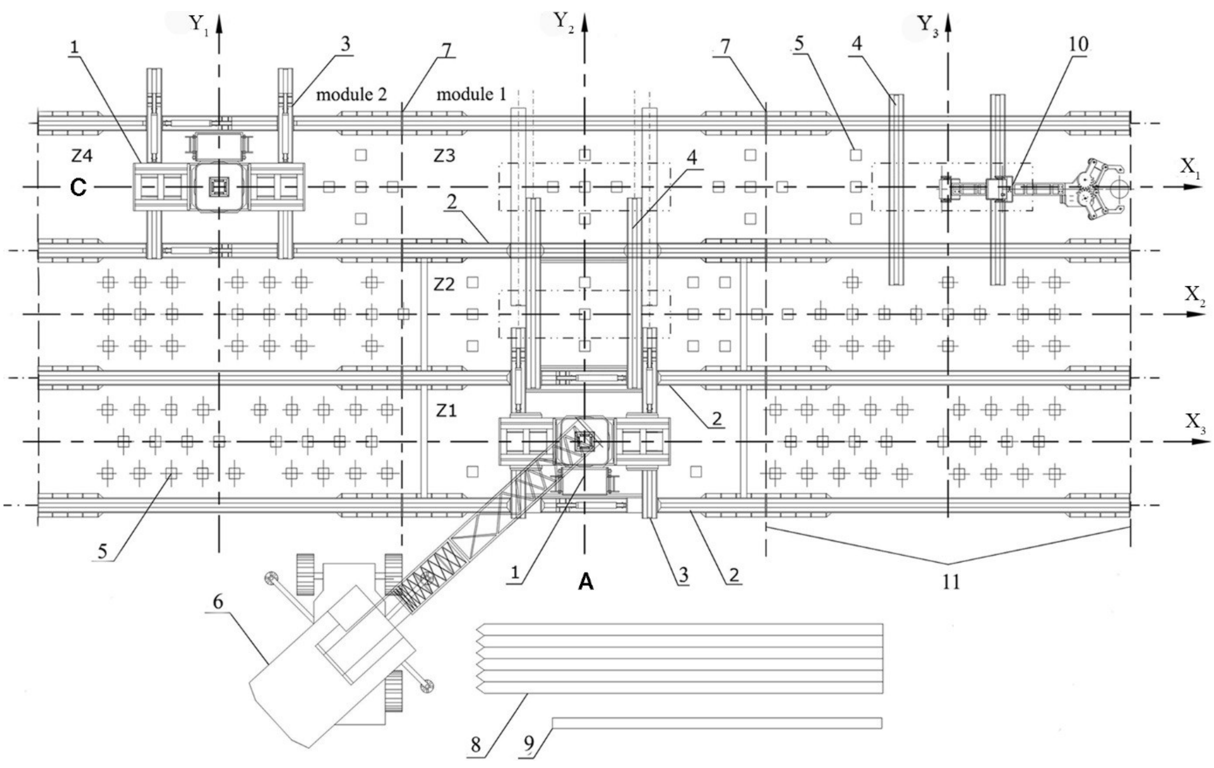

Figure 4. The layout of the coordinate method: 1 – piling machine, 2 – longitudinal guides, 3 – cross carriage (transverse), 4 – auxiliary carriage, 5 – pile point, 6 – service crane, 7 – modules connection unit, 8 – concrete piles, 9 – metal inventory tool, 10 – additional equipment, 11 – a coordinating grid system

3.3.1 Flow-production method

The use of MAPS has been proposed as a new flow-production method for pressing piles into the ground [7].

The system consists of three longitudinal guides and two cross carriages that enable the PM to move along two axes, X and Y, as shown in Figure 4, option A.

When assembling the MAPS, the main axes (X, Y) of the modules are controlled concerning the modular coordinating grid system of the building. This approach ensures proper alignment and integration of the MAPS with the building structure. The preparatory process involves mounting the longitudinal guides 2. The main carriage 3 is then mounted on the longitudinal guides, followed by mounting machine 1 on carriage 3. The hydraulic system of the modules is then connected to the PM and the anchor weights are installed using a crane.

Once the anchors have been secured, the horizontal position of the PM is checked to complete the process.

The main technological process, pile installation - machine displacement, is carried out inside working space Z1. Additional longitudinal guide 2 and auxiliary carriage 4 are mounted by the crane, without interrupting the main process. Coordinating axis distance (X–Y) to the modular grid system is permanently under control.

After all the piles are installed in Z1, PM moves to the next workspace Z2. The main process is performed.

At the same time, the modular system is reassembled. The PM moves from the auxiliary carriage 4 to the main cross carriage 3 by driving cylinders. The main process is carried out inside workspace Z3. After installing all piles inside Z3, the PM shifts to the next workspace, depending on the desired direction. Parallel to this, module 2 can be attached by crane to the extension of module 1, as shown in Figure 4, option C.

When piling is completed within the working space of module 1 (Z3), the PM moves to module 2 (Z4). The movement along the X-axis is carried out by a method of sequentially re-connecting the modules. At the same time, the auxiliary carriage 4 can be used to mount additional equipment 10 on it: a boring machine, crane manipulator, mechanisms for stone columns, vertical energy wells, etc.

This method offers modularity and flexibility for configuring different pile foundations and is suitable for use in large-scale and mass construction for multi-row and continuous pile fields. It is also most suitable for complex automation.

4 Construction Process Parameters

The study of developed piling methods using MAPS was carried out from 2014 to 2022 in Ukraine during the construction of pile foundations for civil buildings [10].

Full-scale experiments under production conditions were conducted to gather reliable data on piling processes using specified technological schemes at real sites.

The initial construction parameters can be illustrated in the example of a multistory residential complex with its underground space 'Park Fontanov', Odesa, 2018.

- Land plot size: 12.8 hectares
- Number of buildings: 10
- Height of buildings: 9 floors
- Car parking: Underground

Foundation: more than 1800 piles, 180 per building.

Pile type: reinforced C140.35 and C120.35 with a cross-section of 350×350 mm and length of 14 m and 12 m, multi-row arrangement, with a step of 1.05 m (3d).

Site conditions: clay loam with limestone layers, soil subsidence properties category – II. The category of soils is II, according to seismic properties.

Groundwater depth: 3.5 m and 10.5 m.

Equipment: Piling Machine CO-450 and MCSS.

The standard architectural and planning solutions of these buildings allowed for the implementation of a combination of options considered earlier. For example, the C-method uses two modules, as shown in Figure 5.

Figure 5. Coordinate piling method by using two modules with their sequential reconnection

Piling data: the pressing force was from 1600 kN to 2000 kN, respectively, for the pile length 12 m and 14 m. The pressing speed was from 1.5 m/min (automate) to 2.5 m/min (manual). The speed of PM displacement (manual) was 2.1 m/min. Productivity: from 20 to 30 piles per shift.

According to the project, full-scale physical modeling [3], and pile testing were made without any additional equipment, essentially requiring no temporary work.

The research methodology involved determining the duration, labor input, and the total weight of the movable load during the implementation of the complex technological process on allocated sections of 126 and 396 piles. During the study, the focus was on the main and auxiliary processes and their readjustment. The study of auxiliary processes allowed for the determination of efficiency indicators for single piles and multi-row pile fields. The comparison of these indicators, as a result of the preliminary processing of the construction datasets, is presented in the following section.

4.1 Efficiency Indicators comparison

Full-scale experiments made it possible to obtain actual data on main and auxiliary technological processes for different foundation designs, organizational and technological schemes for pile work, as well as the various site conditions and scale of construction.

The study of the main process – pile pressing into the ground, performed in automatic mode, determined that the speed of pile pressing remains unchanged (1.5 m/min) for different soil conditions if the force of soil resistance does not exceed 1600 kN at a nominal pressing force of the machine is up to 2000 kN.

To compare the efficiency indicators of the specified methods, a technological model of an anti-slide structure of 126 piles (C100.35) in a three-row arrangement on a site with a total length of 50 meters, was chosen.

The selected technological scheme is easily scalable, and its decomposition makes it possible to analyze single-row and double-row structures, as well as various pile arrangements. The following efficiency indicators have been determined for the three methods: duration, productivity, labor input, and machining time to the entire scope of piling work and per unit of output. Unit of output: 1 concrete pile with section 350×350 mm, length 10 m, pressed into a depth of 12 m.

4.1.1 **Process Duration and Labor Input**

The duration of separate technological processes and operations was determined in hours by timing at construction sites. Process duration is given in Table 2.

Table 2. Processes Duration

Indicator (hour)	P	L	C
Preparatory work	0.3	0.7	1.1
Assembly, anchoring	116	3.7	1.4
Piles pressing (automated)	31.5	31.5	31.5
Modules reconnection	–	2.0	0.6
Unloading, disassembling	52.5	1.8	1.2
Summary	200.3	39.7	35.8

The duration of the main automated process remains unchanged for the three piling methods.

Labor input for the entire scope of work was determined by multiplying the duration of processes by the team composition. Labor inputs are given in Table 3

Table 3. Labor Input

Indicator (man–hour)	P	L	C
Preparatory work	1.2	2.8	4.9
Assembly, anchoring	537	16.5	6.7
Piles pressing (automated)	54.5	58.7	58.7
Modules reconnection	–	6	2
Unloading, disassembling	263	7.8	4.4
Summary	856	92	77

There was a significant decrease in labor input for the identified most labor-intensive process – PM re-anchor by service crane. It is more than twice for C-method, in comparison with the L-method, and more than thirty times compared to the P-method. The process of modules sequential reconnection was decreased three times from 6 man–hours (L) to 2 man–hours (C), with constant characteristics for the basic automated process.

4.1.2 **Labor Productivity**

Based on the data on labor input and the total duration of the processes for the entire scope of work of 126 piles, presented in Tables 2 and 3, the following specific (unit) productivity indicators have been calculated.

Overall productivity (pile/hour) is the ratio of the entire scope of work to the total duration of its implementation. Hourly output is the number of installed piles per hour. Work output per man (man–hours, number of piles) is the ratio of the amount of work to the total labor input. Output per pile (man–hour) is the ratio of total labor input to the entire scope of work. Data given in Table 4 display the labor productivity indicators for three methods on a section of 126 piles.

Table 4. Labor Productivity

Unit Indicator	P	L	C
Overall productivity	0.63	3.17	3.52
Hourly output	1	3	4
Work output per man	0.15	1.37	1.64
Output per 1 pile	6.8	0.7	0.6

The labor productivity for C-method is increased, up to 4 piles in 1 hour, due to the non-interrupted process: pile installation – machine displacement. This is the main distinguishing feature of the automated process.

4.1.3 **Machining Time**

Machining time is the time taken by machines and mechanisms to install one pile. Data given in Table 5 display the machining time for tree piling methods.

Table 5. Machining Time

Unit Indicator (mach.–hour)	P	L	C
Service Crane KS-5363	1.39	0.19	0.16
Piling Machine CO-450	0.17	0.17	0.17
Modular Skidding System	–	0.03	0.03

The data in Table 5 shows that the machine time for PM and MCSS remain unchanged for the three methods.

At the same time, the most time-consuming and labor-intensive processes are provided by a service crane.

To determine a crane operating input in large-scale production (Section 396 piles), the weight of a movable load: piles, inventory tools, and piling equipment was investigated, according to identified processes.

Data given in Table 6 display the total weight of the load by elements. There are PM, anchor loads, MCSS elements, and inventory tools we have to move by a crane to install 396 piles for identified piling methods.

Table 6. Load Weight

Indicator (ton)	P	L	C	A
Concrete piles	1228	1228	1228	1228
Inventory pile	594	594	594	594
Anchor loads, PM	164000	3857	1286	429
Longitudinal guides	–	435	160	72
Transverse guides	–	–	34	51
Summary	165822	6114	3302	2374

Specific (unit) weight was decreased from 419 tons per pile for P-method to 8.5 tons for C-method and almost two times, in comparison with the L-method (16 tons). If a flow method (A) is used, this indicator is 6 tons per pile, while the weight of the concrete pile (C100.35) fed by the crane, is more than 3 tons.

The ratio in Figure 6 shows the balance between the summary weight of the piles, inventory tool, and elements of the equipment, moved by the service crane, with a fixed output volume of 396 piles.

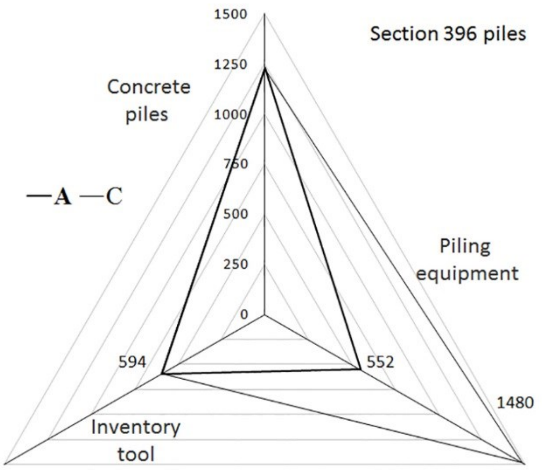

Figure 6. Summary weight by elements: A – flow-production method, C – coordinate method

The diagram illustrates the conditions under which the developed technology reaches its maximum performance at the lowest labor inputs, as well as the lowest operational cost of the equipment.

The use of an additional longitudinal guide and auxiliary cross carriage with a weight of up to 17 tons, makes mounting and anchoring processes achievable once. At the same time, the summary weight of movable equipment and inventory tool is less than the summary weight of the piles which have to be fed by a crane.

5 Technological Process Modeling

The different configuration and heterogeneity of construction objects, as well as the different number of piles and their mutual arrangement in foundation designs, necessitate the use of various methods and options for piling works. Technological modeling of construction processes was performed for three classified methods: Point (P), Lineal (L), and Coordinate (C).

Options are models of complex processes, developed according to standardized technological schemes:

1. Option C1 – one aggregate module with dimensions: 4.2×12 m, up to 24 piles in one grip;
2. Option C2 – two modules connected in series with dimensions: 4.2×24 m, up to 60 piles in one grip;
3. Option C3 – sequential reconnection of modules, which involves the flow method, more than 60 piles;
4. Option L1 – two longitudinal guides with a grip dimensions: 1.2×12 m, up to 8 piles in one grip;
5. Option L2 – four longitudinal guides connected in series, dimensions: 1.2 (4.2)×24 m, up to 20 piles;
6. Option L3 – sequential reconnection of four longitudinal guides, more than 20 piles;
7. Option P1 – single piles while conducting soils control tests with a piling machine: 1.6×6 m, 1 pile;
8. Option P2 – involves work in the construction flow, when the quantity of piles is more than one.

The most significant factors affecting all efficiency indicators are the total number of project piles (scale of production) and the weight of the load (piles, machines, modules, inventory tools, and anchor loads) moved by the service crane during the piling process.

The scale of production is the main design factor that affects all elements of the organizational and technological structure. With an increase in the number of piles, the number of processes for moving the specified loads by service crane increases.

The selected efficiency indicator (specific weight of the load) does not depend on the duration of processes and operations, soil conditions, and configuration of the foundation, as well as random factors, which can be used for a comparative assessment of various work options.

The main and auxiliary technological processes, in which the crane is used, are determined by three methods:

- MCSS assembly, mounting, and anchoring
- Pressing a pile (basic automated process)
- Positional displacement of the machine
- Modules sequential reconnection
- Machine unloading, MCSS disassembling

The unit of output is one precast concrete pile (C100.35), with section 350×350 mm, length 10 m, pressed to a depth of 12 m in automatic mode. The speed of positional displacement is 2.1m/min, in manual mode.

5.1 Generalizing Mathematical Models

It has been found [10] that the dependence of the efficiency indicators, calculated per one pile, on the scale of production for three piling methods and different options of work is described by a single formula (1).

$$E = A + B/N \quad (1)$$

E – efficiency indicator, A and B – constant coefficients, N – number of project piles.

The relation of the specific (unit) weight of the load, moved by the crane, on the total number of project piles for various options, is described by formula (2).

$$w = \sum W/N \quad (2)$$

w – specific weight, Σ W – summary weight

A graphical illustration is shown in Figure 7.

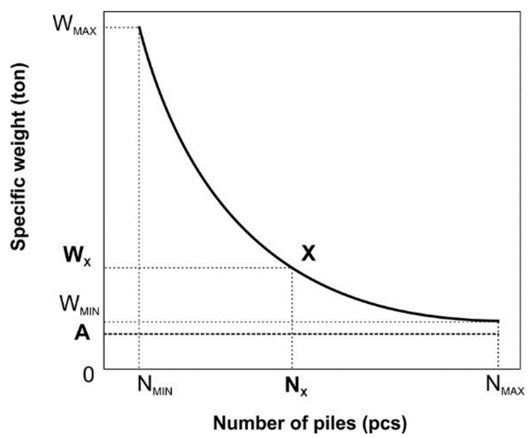

Figure 7. Relation between the specific weight of the load and the number of project piles

Graphically, function (2) represents a hyperbolic curve that approaches "A" asymptotically as "N" approaches infinity. The minimum number of piles required for any work option is one pile, which corresponds to the maximum value of the specific weight of the load. The minimum value of the specific weight is achieved when the maximum number of piles is used in the module space. For the current number of piles, a perpendicular line is drawn from the abscissa axis to the point of intersection with the hyperbola, and the corresponding value of the specific index on the ordinate axis is determined. If the number of piles exceeds Nmax, then the equipment is moved to a new workspace, which is represented by the corresponding step (not shown), after which the hyperbolic nature of the relationship is preserved. Mathematical models have been developed to quantify efficiency indicators, such as the specific weight of the load moved by a service crane, as a function of the total number of project piles, the number of modules used, and the different options for their use. These models are accompanied by graphic illustrations [10] and have practical value, making them suitable for use in the design and preparation stages of piling work. Similar approaches can be used to evaluate other specific efficiency indicators, such as productivity or direct cost, using appropriate algorithms and recommendations.

5.2 Technological Solutions Optimization

The algorithm for the variant design of the complex technological process is based on obtained mathematical models. It consists of three main stages:

1. Analysis of the foundation design
2. Evaluation of options for technological structure
3. Development of the final organizational solution

At each stage, the following main tasks are expected to be performed.

Stage 1: Selection of the main direction of MAPS movement along the longest (longitudinal) axes of the building; possible options for the production of works using a modular structural-planning (technological) grid are considered; a qualitative critical analysis of the planned options is carried out, taking into account the limitations of a particular construction site.

Stage 2: Using graphic illustrations, the planned options are evaluated according to the criterion of the specific (unit) weight of the load; the required production resources are determined, a set of equipment is selected and its layout is carried out at the installation site; the most effective option or a combination of options is determined, taking into account the restrictions of the site.

Stage 3: A decision is made on the choice of the final version, taking into account the possibility of its implementation under specified conditions; a typified technological scheme and appropriate set of machines and documents are selected; the calculation of efficiency indicators (productivity, labor input, machining time and cost of work) of the final version is performed.

Variant design of complex technological processes, using the indicated mathematical models, is based on the choice of optimum solution, according to the value of the specific efficiency indicator. The proposed methodology makes it possible to evaluate all methods of pile work, at the stage of foundation designing, and choose the most effective combination of options, especially, under complicated conditions, such as confined spaces and weak soils. It should be noted that complex automation should also include the system for positional movement and control, together with the list of parts and phases which have been described [5]. The trained network can then be used to make informed decisions that optimize the construction process based on the specific objectives and constraints of the pile fields.

6 Conclusions

This manuscript appears to be a technical report or research paper on the development of technology for the automated construction of pile foundations, based on the use of a Modular Aggregative Piling System (MAPS).

The system incorporates a modular approach to pile construction, which provides architectural flexibility and adaptability for different construction projects, especially in challenging conditions.

Currently, the main process of pressing piles into the ground is automated. However, the concept implemented in MAPS involves the automation of the positional movements of the equipment concerning the building's coordinating grid system. This can serve as a common platform for the interaction of construction machinery, compatibility of the CAD/CAM interface, and existing Building Information Models.

Full-scale experimental tests have been carried out, to establish a database, on real construction sites during the industrial operation of MAPS from 2014 to 2022.

The technological process modeling for 126 concrete piles in a multi-row arrangement on a site with a length of 50 m provided the basis for determining the efficiency indicators of the developed flow-production method and comparing it with the basic point method.

The total duration was reduced from 200 h to 36 h;

Labor inputs for the entire scope of pile work were from 856 man–hours to 77 man–hours;

Hourly productivity increased from one pile per hour up to four piles per hour;

Labor input for pressing one pile was reduced from 6.9 man–hours to 0.61 man–hours;

Machining time for one pile was reduced from 1.56 machine–hours to 0.36 machine–hours;

The volume of auxiliary processes was reduced from 84% to 8% of the total time spent on the production of the entire volume of work.

Mathematical models have been determined to establish the relationship between the specific weight of the load on the total number of project piles and the number of modules used, for various options of work.

The asymptotic minimum, for the equipment used and pile type C100.35, is 420 tons per pile for the point method and 6 tons for the flow coordinate method.

The further direction of research is focused on solving the problem of complex automation.

Since objects are heterogeneous and many factors have to be taken into account, a new approach to solving optimization tasks is needed, both in the design phase and in the construction process. One potential approach is to use machine learning to optimize the piling processes in a way that maximizes the desired outcomes while minimizing negative impacts or costs.

The following practical results of this study can be used to optimize data using artificial neural networks.

A database of construction processes and operations collected during industrial equipment operation is utilized. A single standardized mathematical function is used to describe these processes for various work options.

An optimization algorithm based on mathematical models is utilized to improve construction solutions.

The approach utilizes a framework that combines a modular grid of equipment with a building-coordinating grid system to capture data from building processes.

Overall, the use of a database, mathematical models, algorithms, and frameworks can improve the efficiency of aggregate-modular type piling systems in foundation engineering, particularly under challenging conditions.

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