# Piling Technologies in Ukraine: Some Recent Developments

George MESHCHERIAKOV
*Chief process engineer, EC Transzvuk, Odessa, Ukraine*
Michael DOUBROVSKY
*Professor and Head of Sea and River Ports Department, Odessa National Maritime University, Odessa, Ukraine.*
*Director, International Press-In Association.*
*Email*: *doubr@tm.odessa.ua*
Olga DUBROVSKA
*Senior Project Engineer, DeepOcean, Haugesund, Norway*

**ABSTRACT**

The first part of the paper sets the actual scientific task to develop the integrated piling process aimed at the automated construction of pile foundations and sheet pile walls for civil and industrial buildings/structures. The technology is based on the application of the Modular Aggregative Piling System (EC Transzvuk), intended for pressing into the ground precast pile elements by a flow-production method with the highest possible performance at the lowest cost of labor. High productivity of piling works is provided by non-stop operation of the equipment, due to the integrity of the basic non-interruptible automated process: pile installation – piling machine displacement. The second part of the paper considers some recent innovations of piling technologies developed to simplify tubular piles press-in installation by prevention of the soil plug formation. One of the proposed approaches uses separate (step-by-step) driving of pile tip (shoe) and pile shaft concentrating energy of pile driving machine on tip or on shaft. Another approach is based on alternate driving of tubular pile and internal core avoiding formation of soil plug at the pile tip.

***Key words:*** *Coordinate piling method, Automated piling system, Process modeling, Piled cluster, Mono-piled dolphin*

## 1. Introduction

### 1.1. Status of the problem

Industry 4.0's strategy to improve industry efficiency through the integration of cyber physical systems (CPS) into manufacturing and construction processes, aims at overcoming the nonconformity between the pace of urbanization, population growth and the possibilities of conventional construction technologies. For this purpose, conceptual equipment and automated construction processes are being developed all over the world, for instance, the large-scale 3D Printing systems (Khoshnevis & Hwang, 2006). However, the problem of the disproportion between the pace of overground parts of buildings erection and the underground parts installation, still remains unsolved. Underground construction which consumes considerable labor expenses, from 20% to 50% of the total volume of construction and installation works, still remains slow, most hazardous and expensive. Auxiliary operations associated with the positional motion of piling equipment take up to 90% of the machining.

The piling works automation on the basis of the flexible structure of technological operations under the conditions of industrial construction, corresponds to the current world trends.

### 1.2. Background and objectives

The integrated automated technological processes described below, are the result of the complex research work of the EC Transzvuk team. The results of full-scale physical and technological modeling of pile installation processes, as well as the experimental and field research of the presented technology, were used. Huge data base has been accumulated during the industrial exploitation of the Piling System (more than 100 large-scale projects since 2008). The research is aimed to developing:

flow-speed production methods for pile foundations and retaining structures; unmanned operation for piling works under the radioactive contamination;

safe, labor protected and environmentally friendly construction methods.

## 2. Construction machinery

### 2.1. Piling system

A Modular Aggregative Piling System (MAPS) is a multifunctional construction equipment intended for installation of precast pile elements by a flow-production method (Meshcheriakov & Vakulin, 2011). The MAPS as exemplified in **Fig. 1** is equipped with the original Piling Machine and a Modular Coordinating Skidding System, designed according to the general principles of the International Standard (ISO 2848:1984) for building engineering. The MAPS is applied for the construction of pile foundations and sheet pile cutoff/retaining structures for civil buildings. Its main technical specifications are given in table 1.

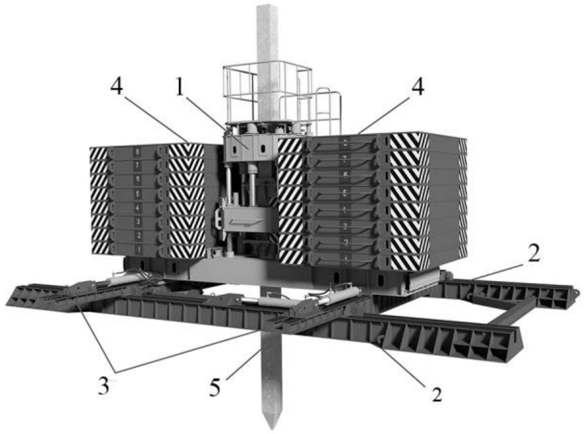


**Fig. 1** Modular Aggregative Piling System
1 – Piling machine; 2 – Basic module; 3 – Cross carriage; 4 – Anchor loads; 5 – Concrete pile

**Table 1.** MAPS specifications

| | |
|---|---|
| Insertion force, max, kN | 2300 |
| Insertion speed, m/min | 1.5 ÷ 3 |
| Displacement speed, m/min | 2.1 |
| Positional precision, mm | ± 10 |

### 2.2. Piling machine

The hydraulic Piling Machine CO-450 (PM) of a gravity type is intended for automated pressing into the ground precast building elements: concrete piles with cross-section up to 450×450 mm, metal pipes and sheet piles not more than 500 mm width, with insertion force up to 2300 kN. The PM weight is 14.3 tons. It is the best performance for piling equipment in relation: insertion force of the machine to it weight. The operation of the PM incorporates the principle of a pile self-centering by side wedge-operated clamping system and its cyclic pressing into the ground an automatic mode. The PM is anchored by a crane with metal loads (**Fig. 1**) a total mass (up to 200 tones) is determined by the soil resistance forces. When installing the piles below the ground level (up to 12 m), a metal inventory pile is used. The inventor of the Piling Machine CO-450 is A.Vakulin, EC Transzvuk, 1998.

### 2.3. Modular skidding system

The concept of the Modular Coordinating Skidding System (MCSS) provides highly precise (± 10 mm), two-axis controlled, coordinated (X - Y) positioning of the PM without remounting and reanchoring operations.

The hydraulic push-pull skidding system of the ground type consists of the main and auxiliary longitudinal modules (fixed) and a cross carriage (movable). The modules are identical and interchangeable. They can be connected to each other in a wide range of combinations. For the synchronized two-dimensional skidding motion MCSS employs four hydraulic driving cylinders of 500 kN.

## 3. Piling methods

### 3.1. Classification

In order to unify and typify the technological solutions, the author proposed to classify the existing methods of piling works, by the technological sequence of piling and the methods of PM positional displacements. We took into account non-interrupted positioning control and non-readjusted technological processes.

The classification distinguishes: 1) Point; 2) Lineal (X); 3) Coordinate (X, Y) piling methods. According to the classification, three construction piling methods have been developed. Each method uses the standard automated piling equipment and new typical technological processes.

They were developed taking into account the standard geometrical configurations and other parameters of pile foundations for civil/industrial buildings, providing the ultimate architecture flexibility.

### 3.2. Point method

The point (**P**) method represents the piling machine repositioning the to the next operation point by service crane. It is used for installation of single piles, (anchor, stabilization piles), including the piles of increased liability by PM CO-450 in case when the safety of nearby buildings is the determining factor. The **P** method remains indispensable in conducting pile works under conditions of maximum proximity to existing structures, foundations, communications (less than 1m for concrete piles, and less than 0.5m for steel sheet piles), during reconstruction, restoration foundations of the historical buildings. Average productivity of **P** piling method is not more than one installed concrete pile per hour.

### 3.3. Lineal method

The lineal (**L**) piling method represents the PM one-coordinated movement along the longitudinal X coordinate and along the axis of the pile row, using fixed longitudinal skid tracks as exemplified in **Fig. 2**.

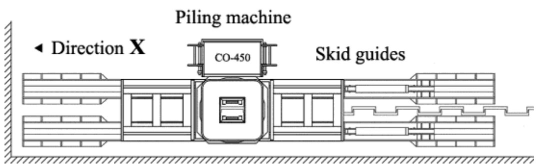


**Fig. 2** Sheet piling by lineal method

This method is used for single-row arrangement of building elements: reinforced concrete piles, steel tubes, sheet piles ets. The advantages of the **L** method are obvious for all types of linear works, be it cutoff and retaining walls of sheet pile type or a single-row anti-landslide concrete pile 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 need for frequent readjustment of the main technological process.

### 3.4. Coordinate method

The coordinate (**C**) piling method represents the PM two-coordinated positional movement along the longitudinal X and transverse Y coordinates, using the cross carriage 3, as shown in Fig. 1.

The **C** method is used for a cluster and multi-row arrangement of piles, including the construction of anti-landslide piling structures. The technological process for **C** method using two modules with longitudinal connection, as well as point piling method for pile testing, was described by Doubrovsky & Meshcheriakov, 2015. It was displayed, that the implementation of the **C** method together with the accuracy of the pile installation cuts down the production time providing higher productivity. However, in the restricted workspace, reconnection of modules is difficult due to the limitations of the service crane operation area, especially on cites with weak, water-saturated soils. There is a need for some additional operations rising the machining time, such as the equipment repositioning by a crane into a new working space, MCSS remounting, PM reanchoring. Again, there is an interruption of the main technological process, and as a consequence, the impossibility for automation.

### 3.5. Flow-production method

The new method for a pile foundations construction, based on the modular support system (Meshcheriakov, 2017) of three longitudinal guides and two cross carriages (the main and auxiliary) processing equipment for moving along the longitudinal X and transverse Y coordinates as exemplified in **Fig. 3**.

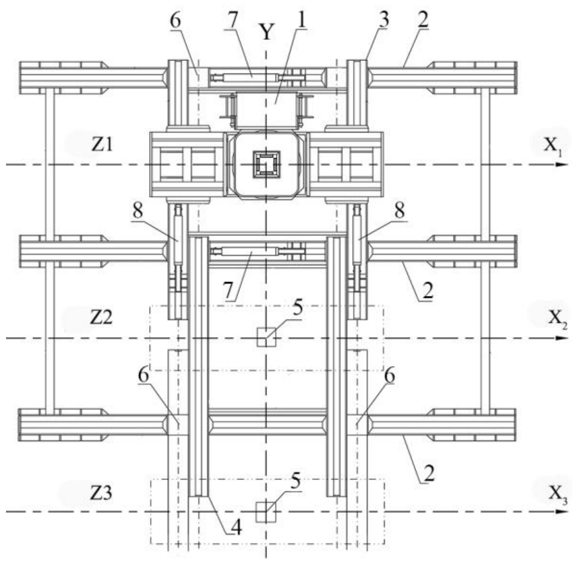


**Fig. 3** Modular support system: 1 – Piling machine; 2 - Longitudinal guides; 3 – Main cross carriage (transverse guides); 4 – Auxiliary carriage; 5 – Pile; 6 – Carriage slides; 7, 8 – Driving cylinders

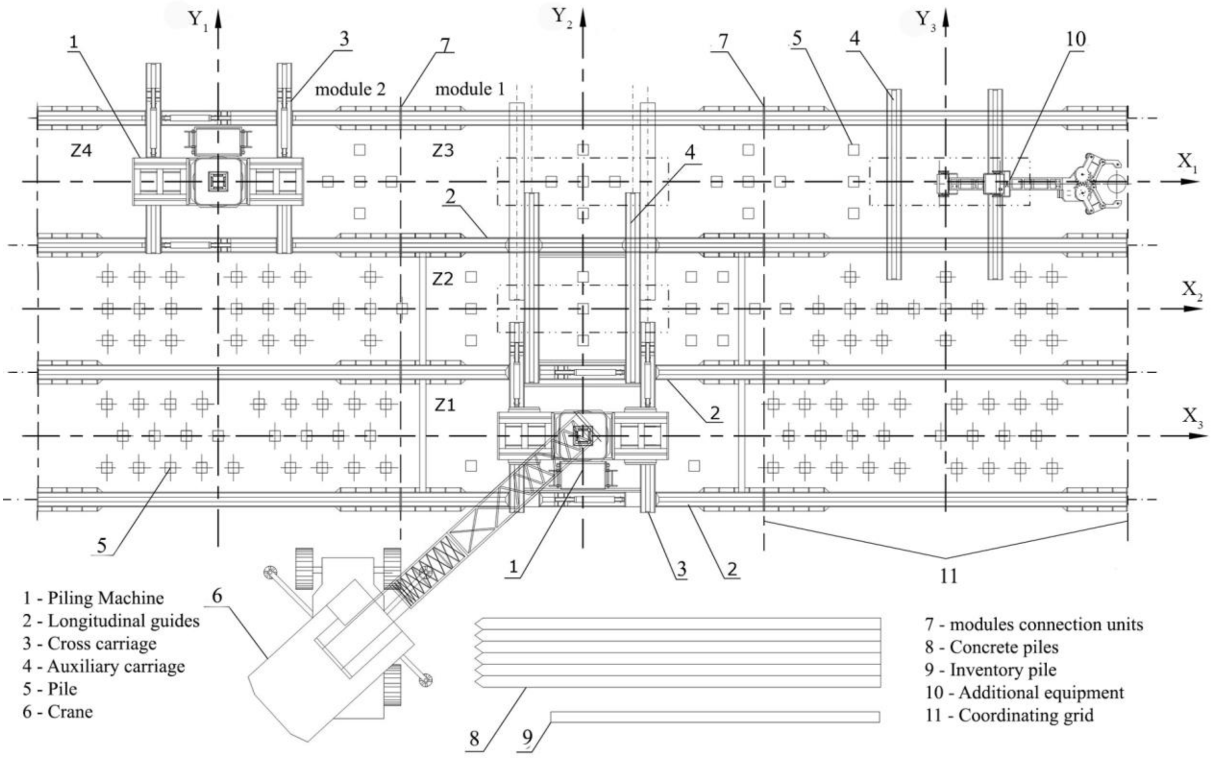


**Fig. 4** The layout of the flow-production piling method by MAPS

This construction method is used for multi-row and continuous arrangement of piles for large-scale production. In accordance with the proposed method, the assembly of the aggregate module of MAPS (**Fig. 3**) is performed first, including the mounting of the longitudinal guides 2 and the cross carriage 3, with slides 6 and driving cylinders 7 and 8. The main axis (X, Y) of the modules are controlled, related to the modular coordinating grid of the building/structure. Then the mounting of the main cross carriage 3 on the longitudinal guides 2 is performed. The mounting of the machine 1 on the carriage 3 is followed. Then we connect the hydraulic system of the module to the PM and mount anchor loads by a service crane. After anchoring the control of the PM horizontal position is finally performed.

The main process (pile installation – machine displacement) inside operating space Z1 is followed. The mounting of the support system is performed simultaneously, without the main process interruption.

The additional longitudinal guide 2 and auxiliary carriage 4 is mounted by a service crane 6. Coordinating axis distance (X - Y) and relations to the modular grid system of the structure are permanently under control. After installation of all piles in Z1, the PM moves to the next operating space Z2, as exemplified in **Fig. 3**, **4.**

The main process is repeated: pile installation – machine displacement. At the same time the PM can execute the cross slide motion in the desired direction.

The remounting of support system is done simultaneously. PM 1 shifts from the auxiliary carriage 4 to main cross carriage 3 by driving cylinders 6. The main technological process is followed inside operating space Z3. After installation of all piles in Z3, the PM shifts to the next working position, depending on the direction of piling. At the same time in prolongation of module 1, module 2 is attached by crane, as shown in **Fig. 4.**

When installation of piles in the operating space Z3 of module 1 is completely finished, the PM shifts to module 2 into Z4. PM movement along the X axis of building is carried out by a method of modules sequential reconnection (Wahler, Meshcheriakov, 2010). At the same time, auxiliary cross carriage 4 can be used to mount additional technological equipment 10 (**Fig. 4)** on it: boring machine, crane manipulator, mechanisms for stone-columns, vertical energy wells, «smart piles» etc.

The functional interchangeability and modular aggregative principle allows to reuse the standard elements of the MCSS in various combinations. It also takes into account the standard geometrical parameters of pile foundations for civil buildings and makes it possible to cover the entire range of classified piling methods with just one set of equipment.

## 4. Construction process

### 4.1. Layout

Technological process parameters and MAPS effectiveness can be well illustrated on the example of the construction of a residential complex with its underground space 'Park Fontanov', Odessa, Ukraine. The complex is erected on a land plot of 12.8 hectares and consist of ten buildings with nine floors and underground car parking.

Performed: Sept. 2017 – Feb. 2018.

Foundation: more than 1800 installed concrete piles per a building. Pile type: reinforced concrete pile C140.35-9 and C120.35-9 with a cross-section 350×350 mm and length 14,0 m and 12,0 m.

Site conditions: soil subsidence properties (clay loam with limestone layers) category - II. The category of soils is II, according to seismic properties. Background seismicity of the site - seven points. Groundwater is at 10.5 m. The project provides the construction of a pile foundation by installing precast piles by sections. Pile heads have to be installed into prescribed depth (- 3 m) below the ground level without auguring and any soil extraction, in a short time period. According to the project the full-scale physical modeling, piles installation and testing were made without any additional equipment, essentially requiring no temporary work. It was allowed to determine the optimum parameters to realize the flow-production method of construction.

Equipment: Aggregative Piling System; PM SO-450 and a modular coordinating skidding system MCSS.

Piling data: The insertion force was from 1700 kN to 2000 kN, respectively, for the pile length 12.0 m and 14.0 m. The insertion speed was from 2.0 m/min to 1.5 m/min and the speed of PM positional displacement was 2.1 m/min. The integrated construction process of a piles installation by MAPS with the flow-production **C** method, together with the construction algorithm for a multistory building by sections is presented in **Fig. 5**.

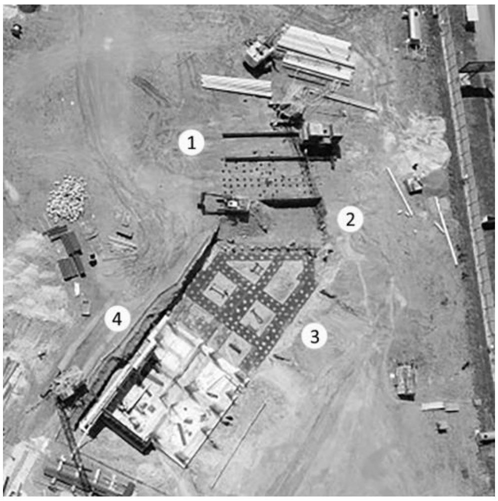


**Fig. 5** Construction algorithm: 1 – Piles installation by MAPS; 2 – Piles heads stripping; 3 – Grillage construction (underground); 4 – Erection of building (overground)

### 4.2. Technological process modeling

The technological modeling of the construction processes for sections of a pile foundation for a multistory building of 126 piles, was performed by three piling methods, according to the classification: Point (**P**), Lineal (**L**) and Coordinate (**C**).

The main technological processes for three piling methods have been identified:

– preparations, major axis control;
– MCSS assembly, mounting, anchoring;
– pile installation (basic automated process);
– positional displacement of the machine;
– modules sequential reconnection;
– machine unloading, MCSS disassembling.

The following parameters have been determined for the three piling methods: duration, productivity, labor and operating cost to the entire scope of piling work and per unit of output (one pile). The labor cost for the main operating processes are given in table 2.

**Table 2.** Labor cost, section 126 piles

| Processes labor cost, man-hour | **P** | **L** | **C** |
|---|---|---|---|
| Assembly, reanchoring | 536.8 | 16.5 | 6.7 |
| Installation – displacement | 54.5 | 58.7 | 58.7 |
| Modules reconnection | - | 6.0 | 2.0 |
| Unloading, disassembling | 263.4 | 7.8 | 4.4 |

**4.3. Productivity & labor cost**

There was a significant decrease in labor cost for the identified most labor-intensive operating process, the PM reanchoring by a crane. It is more than twice for **C** method, in comparison with **L** method and more than thirty times compared to **P** method. The process for sequential reconnection of modules by crane decreased three times from 6.0 (**L**) to 2.0 (**C**) man-hours, with constant characteristics for the basic process for each method, as it is displayed in table 2. The labor cost for the whole scope of piling work was decreased from 856 (**P**) to 92 (**L**) and to 77 (**C**) man-hours, section of 126 piles. It is less than ten times, when using MCSS by **C** method.

Reducing the labor costs of workers more than ten times, and, respectively, seven times for the crane operator as shown in **Fig. 6**, as well as reducing the operating costs of equipment more than seven times, was made possible by solving the issue of remounting and reanchoring processes, **Table 2**.

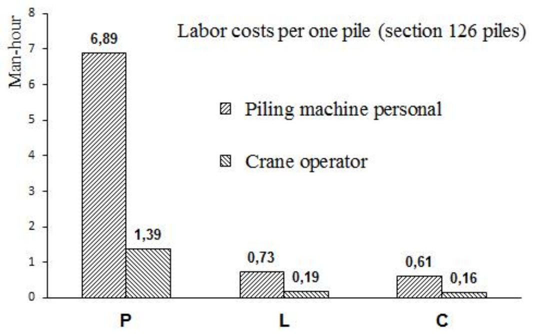


**Fig. 6** Labor costs for three piling methods

It was found that the coordinate piling method, with the MCSS use, is characterized by an increase in labor productivity, more than five times, as displayed in table 3. We took into account direct production time and machining time for: mounting MCSS, anchoring machine, reconnection of modules, unloading and disassembly processes.

**Table 3.** Construction process parameters

| Parameter \ Method | **P** | **L** | **C** | **A** |
|---|---|---|---|---|
| Productivity, pile-hour | 0.63 | 3.17 | 3.52 | 4.0 |
| Labor, 1 pile, man-hour | 6.8 | 0.7 | 0.6 | 0.5 |
| Movable mass per 1 pile, t | 419 | 16.0 | 8.5 | 6.0 |

Data given in table 3 display the construction process parameters for three piling methods: point (**P**), lineal (**L**) and coordinate (**C**) together with the flow-production automated (**A**) method while using the modular support system (3.5). It covers the entire range of classified construction methods with just one set of piling equipment.

The use of MCSS decrease the production time seven times and labor inputs of the crane more than eight times, with constant characteristics for the basic process, as exemplified in **Fig. 7.** This is the main distinguishing feature of the automated construction processes.

The total duration and cost (UAH) of the entire pile work by **C** method including equipment operational costs, have been decreased five and seven times, respectively, in comparison with the **P** method, as exemplified in **Fig. 8.**

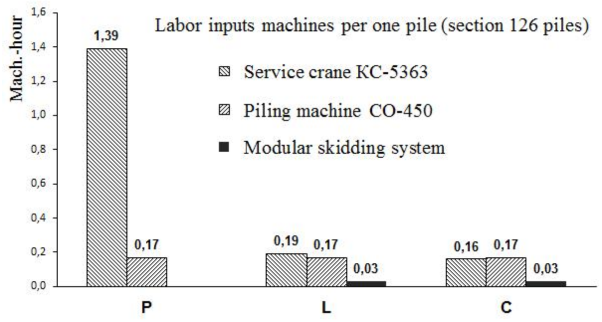


**Fig. 7** Machines inputs for three piling methods

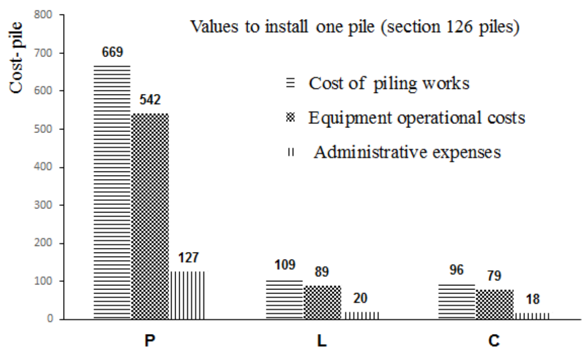


**Fig. 8** Cost of work

Crane operating inputs decreased from 419 t per pile for **P** method to 8.5 t per pile for **C** method and almost two times, in comparison with the **L** method (16.0 t per pile). If a flow-production method (**A**) is used, this figure is 6.0 tons per pile (table 3) while the mass of the reinforced concrete pile (C120.35-9) which has to be feeded by a crane is more than 3 tons.

## 5. Pile installation with prevention of the soil plug

The problem of soil plug of open end pile is well known and there are various proposals to solve the problem. (De Nicola & Randolph, 1997, White *et al.*, 2000). Regarding possibilities of Press-In Method some innovations were worked out to facilitate tubular piles driving for hard soil conditions and/or for case of long piles (large penetration depth).

### 5.1. Tubular pile formed by "semi-tubes"

Soil plug initiation of open end pile during installation can be prevented by splitting the tube into two semi-tubes "1" connected by interlocks "2" (similar to sheet piles interlocks) as shown in **Fig. 9** [Doubrovsky & Litvinenko, 2009, Doubrovsky *et al*., 2011]. Interlock connections are to be made parallel to the longitudinal axis of the tubular pile.

This design enables a possibility of applying the pressing force either on the ring cross-section of the tubular pile at once or alternately by stepping on the semi-ring cross-sections of each semi-tube. In the latter case less soil plug is initiated because of the open/unclosed cross-section of the semi-tubular pile.

Regarding the Press-In Method application we assume that clamping ability of press-in machine provides reliable catching of the semi-tube for its driving.

Sequences of technological operations to install the pile of the considered structure is presented in **Fig. 10** (here and below presented figures demonstrate only idea and principles without real scale and correlations between sizes of elements; dash arrows show application of the press-in forces).

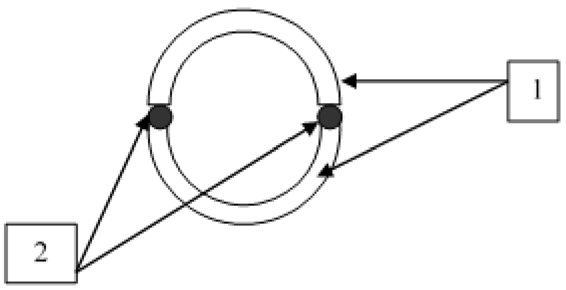


**Fig. 9** Tubular pile made of semi-tubes
1 – semi-tubes; 2 - interlocks

Initially both the semi-tubes are driven simultaneously like one solid tube until the soil resistance remains low (step 1). After that the semi-tubes are driven alternatively. Step 2 includes pressing-in of one of the semi-tubes (the left one); step 3 includes pressing-in of another semi-tubes (the right one). Steps 2 and 3 are alternated until the pile reaches the target depth. At the final step both semi-tubes are pressed-in again simultaneously (if necessary).

Therefore, due to semi-tubes penetration at each step only, tubular open end pile is driven without forming of soil plug. After achieving the target depth, both the semi-tubular parts of the open end pile may be clamped rigidly (crimped, welded, etc.) in the interlocks above the ground level to provide their simultaneous action and required bearing capacity.

Main advantages of this approach are:

(a) possibility to achieve large target depth when other method is not sufficient because of soil plug effects;

(b) possibility to apply driving (pressing-in) machine of less capacity to reach finally the same target depth as using machine of greater capacity (due to possibility to load the semi-tubular piles alternatively and by stepping instead of driving the open end pile at once);

(c) possibility to avoid such press-in auxiliary methods as auguring, water jetting, etc.;

(d) energy/fuel saving because of use of less powerful equipment;

(e) positive ecological effect due to use of less powerful equipment, avoiding drilling, jetting, etc.;

(f) simplifying of the pile removal (withdrawing each semi-tube separately - alternatively and by stepping).

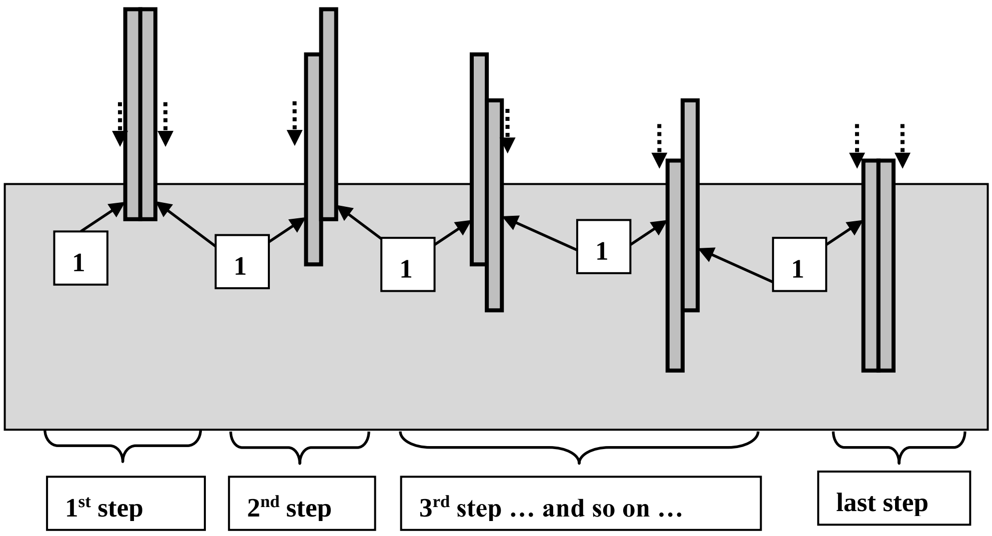


**Fig. 10** Installation operations for the tubular pile made of semi-tubes

### 5.2. Tubular pile with the core bar

The idea of the tubular pile with the core bar is based on the following [Doubrovsky & Guseynov, 2015].

Driving of the open end pile "2" (tube) of designed diameter "D" follows the driving of the core pile "1" (it may be tube or any other pile of size/diameter "d", d<D) inside the area limited by diameter "D" (**Fig. 11, 12**).

In the case of favorable soil conditions and powerful enough press-in machine, open end pile installation may be provided as just one-step operation (**Fig. 11**, **application** of press-in force is indicated by dot arrows).

This step includes, firstly, pressing-in of the core pile "1" (**Fig. 11**, a) to reach target depth and, secondly, pressing-in at once of the open end pile "2" enclosed the core "1" driven before (**Fig. 11**, b). So due to advanced core penetration, the tube is driven without forming of soil plug. After completing the tube driving the auxiliary core pile may be other removed (withdrawn) as shown in **Fig. 11**, c (left) or connected with the main open end pile using rigid coupling "3" to increase tube's strength and bearing capacity as presented in **Fig. 11**, c (right).

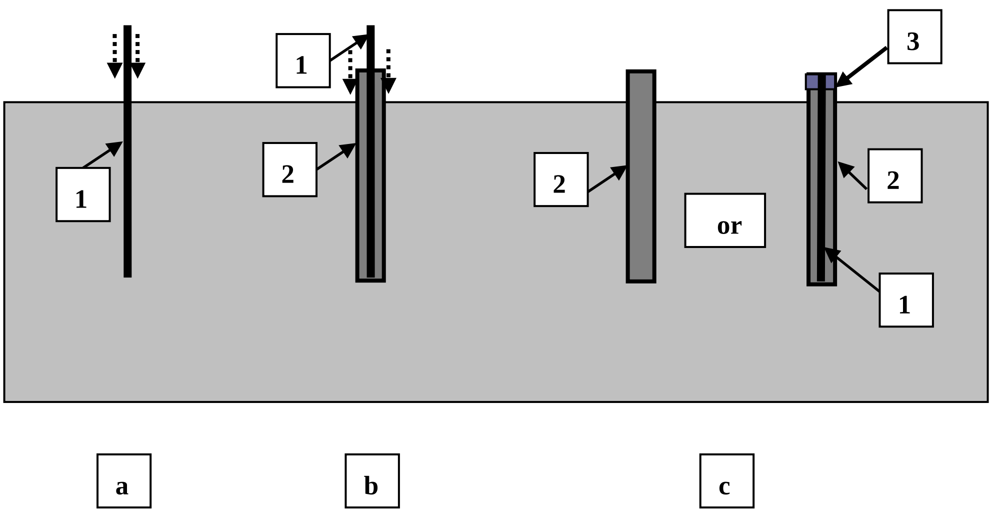


**Fig. 11** Tubular pile with the core bar**:** one-step installation

In the case of unfavorable soil conditions and/or not powerful enough press-in machine, open end pile driving may be provided as multistep installation (**Fig. 12**).

Driving both the piles (core pile first, tubular one next) is conducted alternately and by stepping until achieving the target depth of open end pile installation. Step 1 (**Fig. 12** a, b) includes driving the core pile "1" and driving the open end pile "2" then. During the step 2 (**Fig. 12** c, d) the core pile "1" is driven inside the tube "2" and then tube "2" is driven along the core pile "1". Step 3 repeats the step 2 at the newly achieved depth of driving, and the process continues for the following steps.

The total number of steps depends on the target depth and the available driving depth of the core and tube at every alternation. As the result of the multistep installation process, the tube is driven without forming of the soil plug. Additionally, due to the advanced tube's penetration the core pile driving is facilitated.

After completing tube driving at the last step, the auxiliary core pile may be either withdrawn as shown in **Fig. 12, g** or connected with the main open end pile using rigid coupling "3" to increase the tube's strength and bearing capacity as presented in **Fig. 12, g**.

Regarding peculiarities of the considered technological operations and in order to simplify and speed up the proposed multistep installation, two drivers can be used simultaneously: press-in piler drives the tubular external pile (pressing force is applied close to the ground level) while another machine (impact or vibro) hammer drives the internal core pile acting at the pile head.

In the general case the described approach may be successively applied for several coaxial tubular piles forming the overall tube of the required very large diameter. Here every tube, which was an outer one relative to the inner core, is used as the core relative to the following outer tubes of larger diameters.

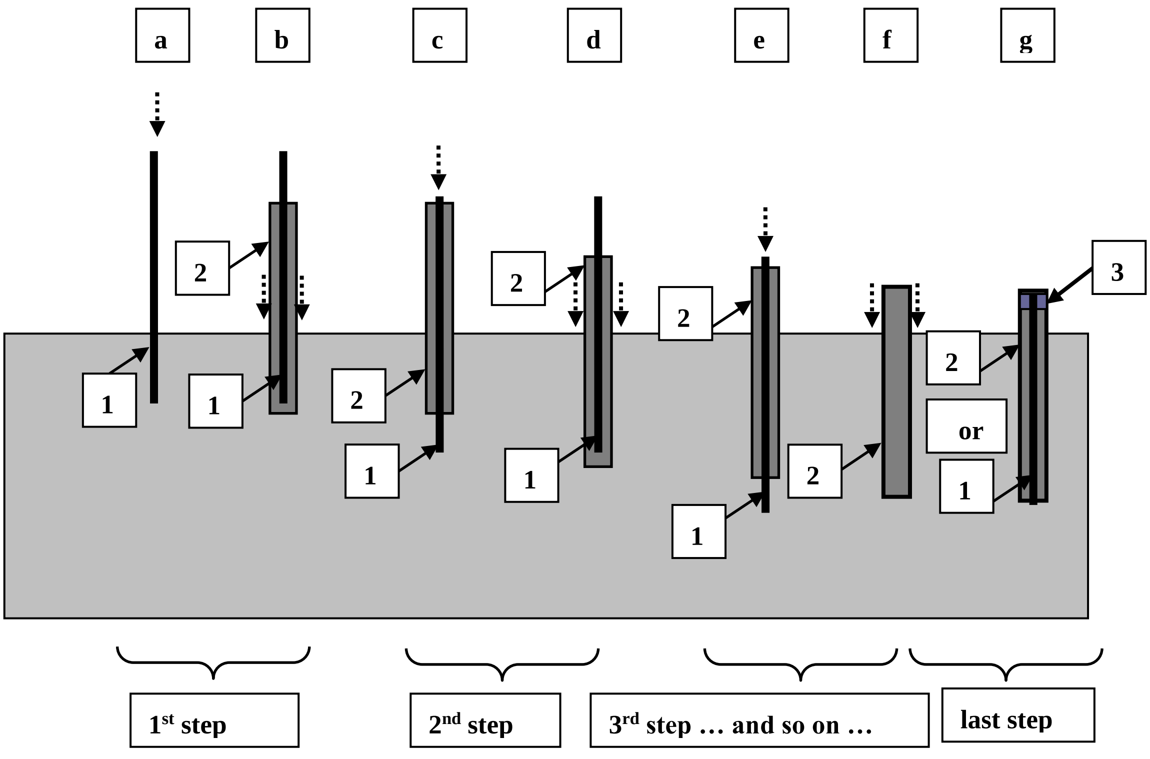


**Fig. 12** Tubular pile with the core bar**:** multistep installation

## 6. Concluding remarks

The piling technology, created by EC Transzvuk, represents a highly efficient multifunctional unit that can meet the demands of almost any kind of piling projects, as well as for automated high-rising construction or the preservation of historical buildings. It provides the highest possible performance at the lowest costs of labor.

The functional interchangeability and modular aggregative principle allows to reset the standard elements of the MAPS in various combinations. We also take into account the standard geometrical parameters of pile foundations for civil buildings which makes it possible to cover the entire range of classified piling methods with just one set of equipment.

The principles of automation of the basic processes (pile installation – piling machine displacement), while constructing the pile foundations, are shown for the first time as well as the MAPS integration into the large-scale Automated Building Systems and robotic complexes.

It has become possible thanks to the use of a unified modular coordinating system of the building/structure, that serves as a common platform for the interaction of construction machinery, compatibility of the CAD/CAM interface, as well as the principle for parametric operation and construction processes control.

Another useful application of the Modular Aggregative Piling System is the research opportunity. It was used as the testing stand to study peculiarities of sheet piles driving regarding development of friction forces in the interlocks (Doubrovsky & Meshcheriakov, 2015).

Main advantages of the described (“semi-tubes” and “tube with core”) innovative solutions are:

(a) the possibility to achieve much larger target depths when other methods are insufficient due to the soil plug effect or applying a less powerful driving machine to achieve the required depth;

(b) avoiding additional costly and power hungry techniques like auguring, water jetting, etc.;

(c) energy/fuel savings because of the efficient use of less powerful equipment

(d) reduced impact on the environment due to use of less powerful equipment.

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