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# A REVIEW OF PILE MACHINES AND THEIR SELECTION CRITERIA***

## 1. INTRODUCTION

The quick development of road infrastructure and dynamic development of city centers made the deep foundation systems commonly applicable [4, 11]. The piles are frequently used for transmitting external loads onto deeper layers or for improving mechanical properties of the ground, especially [1–3, 6, 10, 13]:

a) loads exerted by buildings are transmitted on to stronger ground through aquifers or weak layers,
b) foundation of an object below the ground level which may be washed out or removed or disturbed while performing construction works in the future,
c) ground anchors against the buoyancy force,
d) protections on bridges and water objects against floating objects and units,
e) stabilization of landslides – piles are driven to the layer below the slide surface,
f) limitation of earthworks and avoidance of drainage works. The use of piles may reduce the trenches and so the disturbance of natural landscape areas,
g) simplification of foundation or surface object, e.g. introduction of piles to the level of bridge bearing may simplify the design and performance of a pillar,
h) acceleration of works.

Among other specialist foundations, it is the deep foundation based on piles which can be the most efficiently mechanized and quickly performed.

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## 2. DIVISION OF PILES

Piles can be classified on the basis of [2, 6–9, 13]:

- the way in which loads are transmitted onto the ground; the piles may transmit loads through the column footing, side surfaces or partly through the column footing and partly through the side surfaces,
- the kinds of pile load; they may undergo side loads, i.e. horizontal forces and torques, or their combination,
- performance, i.e. hammered piles, SDP piles, suction piles, vibrated piles, screwed piles and CFA (drilled) piles,
- material, i.e. timber, steel and concrete (concrete, reinforced concrete and prestressed concrete),
- performance, i.e. ready piles tripped into the ground and formed piles (e.g. CFA piles),
- length:
  1* short (to 6 m),
  2* medium or normal (to 25 m),
  3* long (over 25 m).

Piles classified according to the character of work in ground are divided into:

- piles driven in a bearing layer,
- supported piles (poles),
- suspended piles.

In practice the above enumerated ‘pure’ forms of piles operation can be only rarely encountered. Intermediate forms are usually observed, where the weaker top layers cooperate and overtake the loads with the stronger, deeper strata. Piles can be formed in the ground with (or without) soil displacement. In the second case the soil gets thicker around the pile (Tab. 1) [6].

**Table 1**

Classification of piles

| SDP and VDP PILES | | |
|---|---|---|
| PREFABRICATED | MONOPILE FOUNDATION | |
| (ready to drive) | In permanent casing | In temporary casing |
| – reinforced steel<br>– reinforced steel–rebar segments<br>– prestressed<br>– steel–pipe<br>– steel–profiled | – steel pipe driven from the bottom through the plug or from the top through the oak core<br>– thin pipe introduced on the core<br>– prefabricated thin pipe introduced on the core<br>– prefabricated thin pipe (ofter underreamed) | – steel cage driven from the top<br>– steel cage driven from the bottom through the plug<br>– as above – with a larger pile base |

**Table 1** cont.

| DRILLED PILES | | | |
|---|---|---|---|
| (with augers or pickers, concrete applied to all of them *in situ*) | | | |
| Without casing | With temporary casing | With drilling mud | Drilled-injected |
| – simple shape (percussion or rotary drilling)<br>– with increased pile base (percussion or rotary drilling)<br>– mostly concreted (only in coherent and compact ground) | – rebar casing introduced while drilling the hollow shaft<br>– rebar (oscillating) casing while drilling the hollow shaft<br>– vibrated or soil displacement protection introduced prior to drilling<br>– hollow shaft concreted (pipe if underwater) | – rotary<br>– with back flow<br>– with right flow<br>– concreting through a pipe | – through the auger sealing slurry displaces the soil<br>– mixed by the auger sealing slurry with chemical additives and soil |

## 3. REVIEW OF PILE MACHINES

Piles have been used for geoengineering purposes for years [12], as this is one of the most popular deep foundation methods. The piles [11] are performed with various machines and in various technologies. These are mostly universal devices, which can be adjusted to various piles. For instance, if a multifunction basic pile machine is equipped with rotary heads and pressing down systems, the Continuous Flight Auger (CFA) or screwed piles can be drilled. The basic differences in particular types of piles mainly refer to the design of augers and technological details. What is more, the large-diameter piles can be drilled with an additional tool and head; if an oscillator is added, then a cased pile can be drilled. A double-rotation machine is needed for making cased auger piles. The head is usually dismounted; it allows for relatively vertical tripping of both parts. One of them rotates the cage and the other rotates the auger (in opposite direction). While drilling the well is being cased, which provides stability to the borehole during drilling operations. Importantly for CFA technology, the auger should be powered by the base rotary table, which improves the accuracy of performance of the pile and adds life to the head. Depending on needs, the pile machines can cooperate with hydraulic hammers or vibrators. Depending on the piling technology, the tools used for multifunction pile machines are presented in Figure 1.

Extraction force and pressing down force are very important for pile making operations. The limiting element in the latter case is the weight of the machine; the extraction force can be bigger than the weight of the machine thanks to an appropriate hydraulic system. Modern machines are equipped with electronic systems monitoring their operation and informing about potential hazards. Pile machines are frequently equipped with expandable tracks, which increases their stability and mobility. They may move on soft ground, on steel or timber plates. If necessary they may be installed on vessels or dinghies. The piles may be frequently performed at a greater depth than the height of the mast thanks to the use of telescopic extensions. In most machines the mast can be inclined in any plane, which is useful when the pile has to be performed at an angle, the maximum value of which is determined by the type of machine used. A typical pile machine with its basic elements is presented in Figure 2 [7–9, 14, 15].

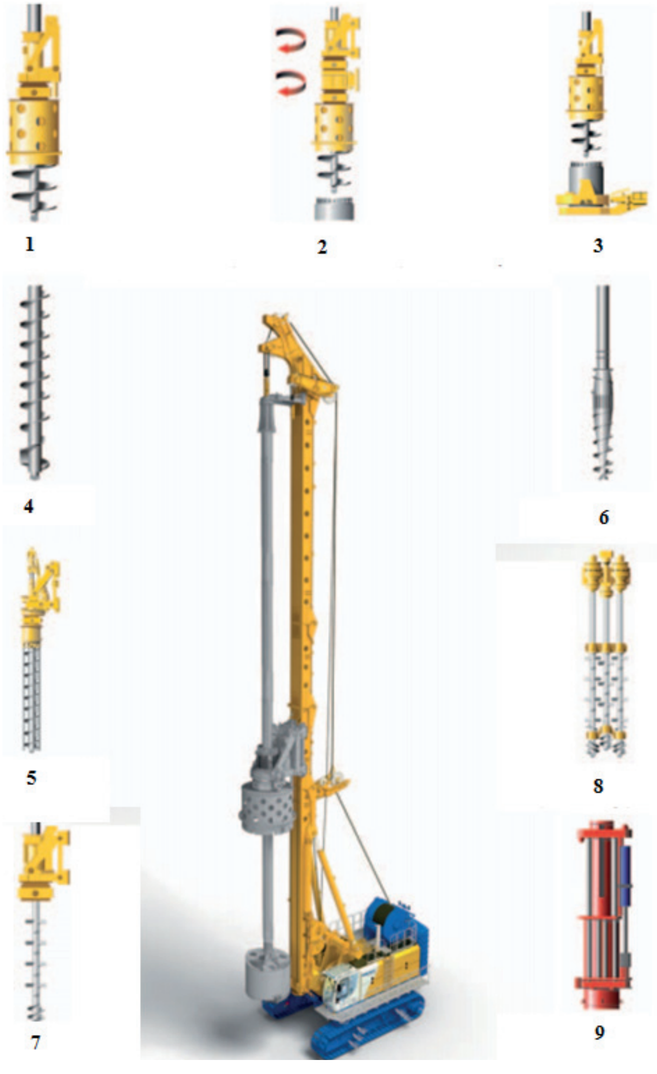



**Fig. 1.** Tools for making piles in various technologies mounted on Bauer pile machine
1 – kelly, 2 – cased string with BTM, 3 – cased string with oscillator, 4 – plate pole for CFA piles, 5 – string for cased CFA piles, 6 – tool for FDP, 7 – setup for downhole soil mixing with a single blade, 8 – setup for downhole soil mixing with a triple blade, 9 – hydraulic hammer head [7]

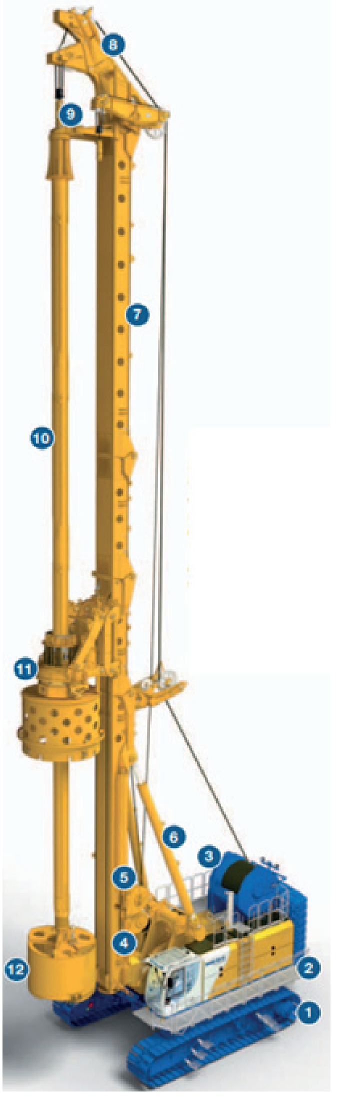



**Fig. 2.** Pile machine
1 – tracks, 2 – carrier, 3 – main hoist, 4 – auxiliary hoists, 5 – motor, 6 – kinematic system, 7 – mast, 8 – top mast, 9 – upper string, 10 – kelly, 11 – rotary table KDK, 12 – auger [7]

A number of companies produce specialist pile machines, e.g. Soilmec offering SR series, where the successive numerical denotations stand for the weight of the machine in megagrams. These machines are applicable to: large diameter piles (LDP), full displacement piles (FDP), CFA piles and cased auger piles (CAP, CSP). Presently, the biggest pile machine of this type is SR-100 for CSP with a double head. Soilmec offers pile machines of SF series which are designed for making only CFA piles (see Tab. 2), and multifunction pile machines presented in Table 3 [9].

**Table 2**

Soilmec CFA pile machines [9]

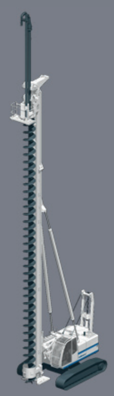
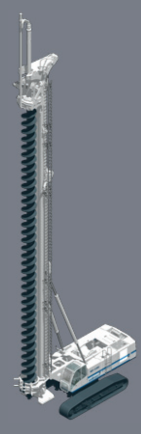
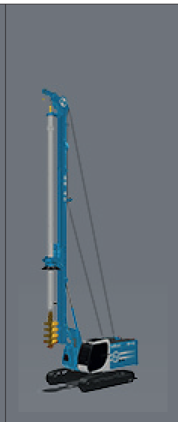
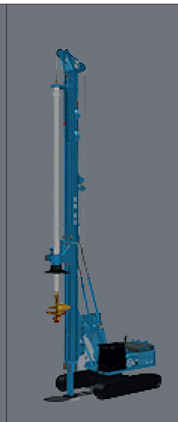
| | | | |
|---|---|---|---|
| |  |  |  |
| | SF-50 | SF-65 | SF-120 |
| Power [kW] | 164 | 205 | 350 |
| Weight [Mg] | 39 | 52 | 100 |
| Torque [kN·m] | 100 | 165 | 300 |
| Main winch [kN] | 102 | 140 | 290 |
| Extraction force [kN] | 510 | 572 | 1160 |
| Depth of pile CFA [m] | 25 | 27 | 31 |
| Diameter of CFA pile [mm] | 900 | 1000 | 1200 |

**Table 3**

Multifunction Soilmec pile machine [9]

| |  |  |  |  |
|---|---|---|---|---|
| | SR-20 | SR-45 | SR-80 | SR-100 |
| Installed power [kW] | 119 | 201 | 328 | 480 |
| Weight [Mg] | 27 | 42 | 83 | 148 |
| Torque [kN·m] | 114 | 185 | 292 | 452 |
| Main winch [kN] | 103 | 165 | 260 | 370 |
| CCS pull up/down [kN] | 124/68 | 207/240 | 300/220 | 417/330 |
| Depth of LDP [m] | 40 | 63 | 77 | 92 |
| Diameter of LDP [mm] | 1200 | 2000 | 2000 | 3500 |
| Depth of CFA pile [m] | 15 | 21.5 | 24 | 31 |
| Diameter of pile CFA [mm] | 750 | 900 | 1200 | 1400 |
| AVAILABLE TECHNOLOGIES | | | | |
| Large-diameter piles tripped with a rotary head | + | + | + | + |
| Large-diameter piles tripped with an oscillator | + | + | + | + |
| CFA piles | + | + | + | + |
| CSP piles | + | + | + | + |
| Full Displacement Piles (FDP) | + | + | + | + |

The Italian company Casagrande offers machines of B series, multifunction devices used for performing cased piles, compatible with an oscillator and able to perform CFA piles. This series has a torque of 125 to 420 kN·m on the mast, and is designed for large-diameter cased piles max. 50 to 110 m deep. After minor modifications they may be used for works employing CFA, DSM or CSM technologies. Pile machines are also equipped with strong and quick hoists. Selected Casagrande pile machines for CFA piles are presented in Table 4 [8, 14].

**Table 4**

Casagrande pile machines [8]

| | B125 XP | B300 XP | B400 | B450 XP |
|---|---|---|---|---|
| Power [kW] | 164 | 403 | 480 | 563 |
| Weight [Mg] | 37 | 90 | 110 | 146 |
| Torque [kN·m] | 125 | 300 | 358 | 420 |
| Main winch [kN] | 160 | 270 | 320 | 420 |
| Extraction force [kN] | 148 | 400 | 400 | 600 |
| Depth of pile CFA [m] | 23 | 29 | 30 | 39 |
| Diameter of pile CFA [mm] | 800 | 1200 | 1200 | 3000 |
| Max. depth [m] | 50 | 90 | 87 | 110 |
| Max. diameter [mm] | 1500 | 2500 | 3000 | 3000 |

Among the leading producers of specialist pile machines in Poland is Bauer company. It offers pile machines of BG Premium Line and BG Value Line. These are multifunction devices operating in various technologies. Their configurations are shown in Figure 3 [7].

Among the most popular pile machines are: BG20H and BG28H. The pile machine BG20H, torque of 200 kN·m, is mainly used for performing CFA and FDP piles, gravel columns, traditional piles and for soil mixing (CSM). The second model BG28H has a much higher torque (280 kN·m) and is usually applied for large diameter CFA and FDP piles. The BG machines can be also equipped with a double pile system, rotary table and BTM. When the medium- and large-diameter piles have to be performed quickly, the BG46 or BG50 machines with BTM400 are recommended. The selected types of Bauer pile machines are presented in Table 5 [7, 15].

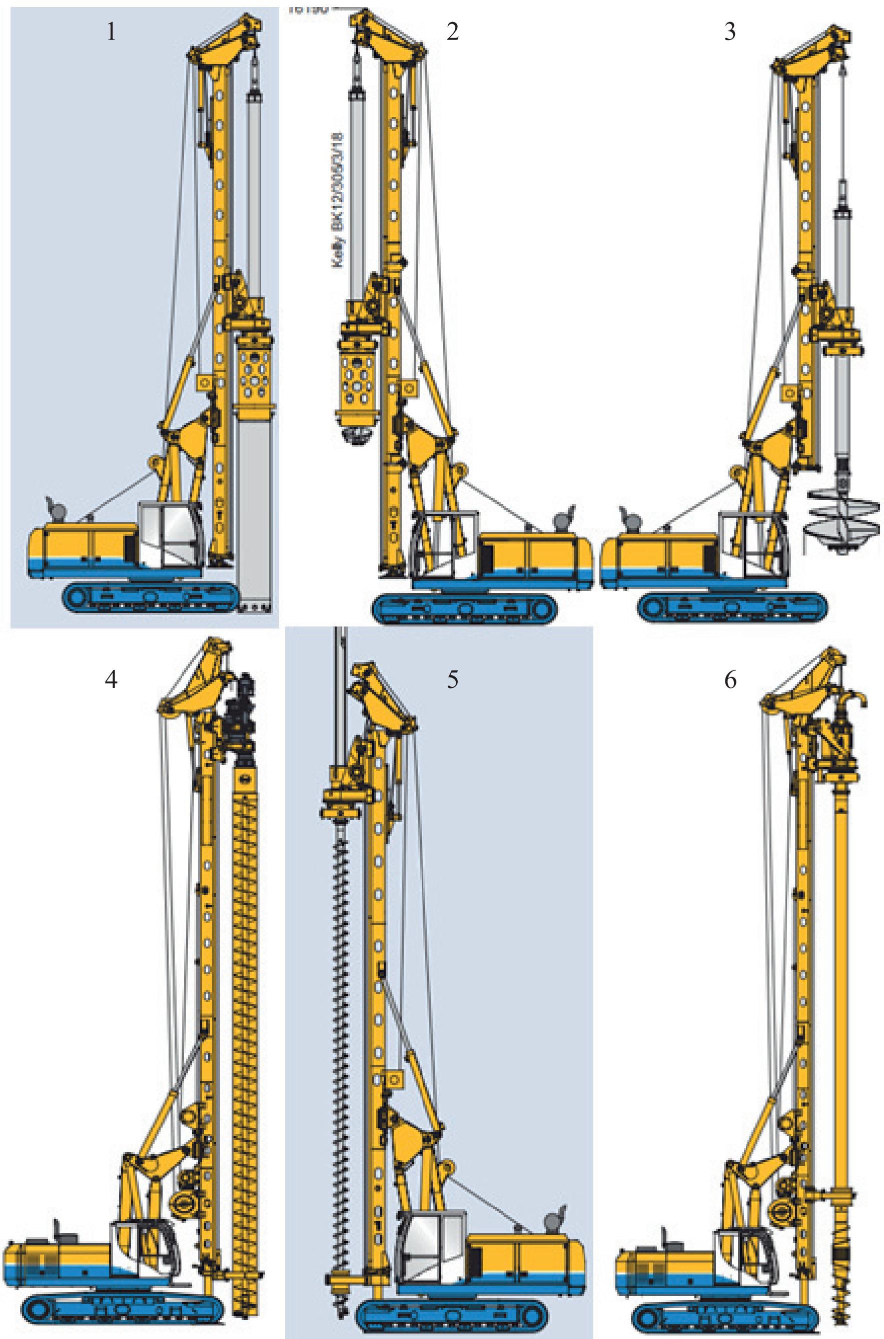
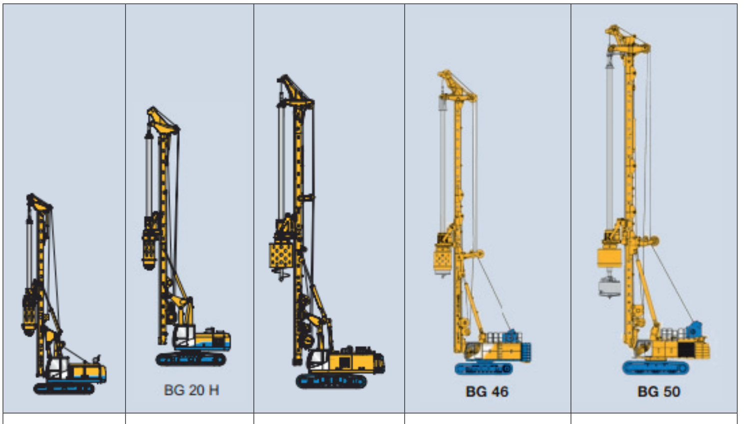



**Fig. 3.** Basic configurations of pile machines
1 – for cased auger drilling, 2 – classic kelly drilling, 3 – for large-diameter piles, 4 – for cased CFA piles, 5 – for CFA piles, 6 – for displacement piles [7]

**Table 5**

Bauer pile machines [7]




| | BG 12 H | BG 20 H | BG 28 | BG 46 | BG 50 |
|---|---|---|---|---|---|
| Power [kW] | 153 | 205 | 354 | 570 | 570 |
| Weight [Mg] | 41 | 59 | 96 | 170 | 250 |
| Torque [kN·m] | 100 | 200 | 270 | 460 | 468 |
| Main winch [kN] | 125 | 170 | 250 | 420 | 500 |
| CCS pull up/down [kN] | 140 | 260 | 330 | 460 | 600 |
| Max. depth [m] | 40 | 51 | 71 | 111 | 82 |
| Max. diameter [mm] | 1200 | 1500 | 2100 | 6500 | 3000 |

From among the machines presented above, the Bauer pile machines have the highest power and torque parameters, which allows for performing long piles of considerable diameter. This equipment is heavier and bigger than its counterparts produced by other companies.

## SELECTION CRITERIA

While performing geoengineering works it is important to select an appropriate machine. The optimally selected pile machine guarantees fast and efficient performance of assumed tasks at a lower cost. The optimization can be realized on the basis of technical parameters of the machines and their rank [5].

The machines for making piles or other geoengineering works can be selected on the basis of the multi-criteria optimization method with synthetic measure of the device. Using this method one can practically compare various criteria in view of their measures and significance. The number of criteria ($k$) can be arbitrary; they are reduced to nominal values, making them comparable. Any number of items of each type ($j$) can be analyzed and divided into groups ($l$) of similar characteristic properties. The evaluation is based on the significance of the assumed criteria ($W$) and the objective function of maximum or minimum [5].

The synthetic evaluation can be performed for a matrix of criteria, following the algorithm:

1. Establish significance of particular criteria $[x^l_{jk}]$ of a machine; its sum should equal to unity.
2. Establish minimum and maximum values for particular criteria:

$$x_k^{\min} = \min x_{jk}^l \qquad x_k^{\max} = \max x_{jk}^l \tag{1}$$

3. Calculate the range of values for particular criteria:

$$r_k = x_k^{\max} - x_k^{\min} \tag{2}$$

4. Transform the matrix $[x^l_{jk}]$ of particular criteria into a matrix of normalized values following the equation:

$$y_{jk}^l = \begin{cases} \dfrac{x_{jk}^l - x_k^{\min}}{r_k} & \text{dla } k = \min \\ \dfrac{x_k^{\max} - x_{jk}^l}{r_k} & \text{dla } k = \max \end{cases} \tag{3}$$

5. Calculate synthetic values of measures $d^l_j$ being relative distances of particular criteria from the respective optimum values for successive machines:

$$d_j^l = \sum_{k=1}^{h} y_{jk}^l \tag{4}$$

6. Calculate synthetic values of measures $D^l$ being relative distances of respective values in groups of machines:

$$D^l = \sum_{j=1}^{u} d_j \tag{5}$$

7. Calculated synthetic measures $y^l_{jk}$ should be multiplied by established values (*W*) for the respective criteria:
   where:
   - $l$ – number of analyzed machines, for $l = 1, 2, ..., z$,
   - $j$ – number of machines in analyzed population, for $j = 1, 2, ..., u$,
   - $k$ – number of assumed criteria, for $k = 1, 2, ..., h$.

The obtained synthetic measures can be used for the evaluation and comparison of machines among themselves [5].

For better illustrating this methodics, the pile machines were pre-analyzed in view of their technical characteristics, without taking into account the economic aspects. The significance (*W*) was established for the assumed parameters (Tab. 6) and the objective function was defined as a maximum.

When selecting a pile machine attention was mainly paid to its multi-applicability. This is conditioned by the CCS pull up/down force and torque, which decide about the maximum depth and diameter of the pile. Thirteen pile machines underwent a 6-criteria analysis. The parameters of pile machines produced by the three leader companies were ranked in Table 6. The highest grade was awarded to Casagrande B450 XP and Bauer BG 50.

**Table 6**

Evaluation of pile machines for specific criteria [3]

| | Criterion no. | 1 | 2 | 3 | 4 | 5 | 6 | |
|---|---|---|---|---|---|---|---|---|
| | Significance criterion $W$: | 3.0 | 3.0 | 1.5 | 1 | 0.5 | 0.5 | |
| | Pile machines | CCS pull up/ down [kN] | Torque [kN·m] | Max. depth [m] | Max. diameter [mm] | Power [kW] | Main winch [kN] | Evalu- ation mark |
| 1 | Soilmec SR-20 | 124 | 114 | 40 | 1200 | 119 | 103 | 0.00 |
| 2 | Bauer BG 12 H | 140 | 125 | 40 | 1200 | 153 | 125 | 0.25 |
| 3 | Casagrande B125 XP | 148 | 125 | 50 | 1500 | 164 | 160 | 0.72 |
| 4 | Bauer BG 20 H | 260 | 200 | 51 | 1500 | 205 | 218 | 2.18 |
| 5 | Soilmec SR-45 | 240 | 185 | 63 | 2000 | 201 | 165 | 2.39 |
| 6 | Soilmec SR-80 | 300 | 292 | 77 | 2000 | 328 | 260 | 4.20 |
| 7 | Bauer BG 28 | 330 | 270 | 71 | 2100 | 354 | 317 | 4.21 |
| 8 | Casagrande B300 XP | 400 | 300 | 90 | 2500 | 403 | 270 | 5.53 |
| 9 | Casagrande B400 | 400 | 358 | 87 | 3000 | 480 | 320 | 6.35 |
| 10 | Soilmec SR-100 | 417 | 452 | 92 | 3500 | 480 | 370 | 7.67 |
| 11 | Bauer BG 46 | 460 | 460 | 111 | 3100 | 570 | 530 | 8.45 |
| 12 | Casagrande B450 XP | 600 | 420 | 110 | 3000 | 563 | 420 | 8.81 |
| 13 | Bauer BG 50 | 600 | 468 | 82 | 3000 | 570 | 640 | 8.83 |

## 4. CONCLUSIONS

Owing to numerous advantages, piles are more and more widely applied for road infrastructure and construction purposes. Their principal aim lies in transmitting outer loads onto layers deposited at greater depths or improving the mechanical properties of soil.

A number of companies produce specialist geoengineering equipment all over the world. Among them are very experienced companies which have existed on the market for years and who have systematically improved their products. Bauer, Casagrande and Soilmec dominate in the production of pile machines.

The most suitable pile machine fit for performing large-diameter piles at great depth should be selected on the basis of the multi-criteria optimization with synthetic evaluation of measures. Knowing the scope of work, one can establish the weight of particular parameters of pile machines on the basis of particular parameters of the machines, assess them and select the right one.

In the presented example of a pile machine for large-diameter and long piles, the selection was based on the multi-criteria optimization with the synthetic measure of evaluation. The analysis of the results revealed that the best pile machine BG 50 was produced by Bauer. It had the highest CCS pull up/down force and highest torque. Another machine is B450 XP by Casagrande and has slightly lower parameters than BG 50.

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