TRENCHLESS EXECUTION OF MICROTUNNELS FOR MUNICIPAL INFRASTRUCTURE IN URBANIZED SITE – CONCEPTION OF A NEW SOLUTION

Krzysztof KOTWICA
AGH University of Science and Technology

Hubert SUFFNER
KOMAG Institute of Mining Technology

Andrei ANDRAS
University of Petrośani

Abstract:
The technologies for trenchless execution of mini and microtunnels for an installation of municipal infrastructure in urbanized sites, used at present, are described in the article. The emphasis is laid on uncontrolled methods, in the case of the diameters of installations which do not exceed 200-250 mm and their length not bigger than 30-40 m. Some issues connected with making the installations of this type, using conventional methods, are also presented. A conception of equipment (ground rocket) for an trenchless execution of short-distance microtunnels of the diameter up to 200 mm and the length up to 30 m with an innovative electric drive, developed at the Department of Machinery Engineering and Transport of the AGH in Cracow as an alternative for the solutions applied nowadays, is described. An electric linear motor, whose conception is presented in the article, was installed in the head of the device. The goal of these works was possibility of using new solution of ground rocket without additional equipments for pneumatic supply with compressed air. New concept of proposed ground rocket can be used with feeding directly from the domestic electric network. The device is intended for execution of installation in incoherent and low-compact ground.

Key words: microtunnelling, trenchless methods, ground rocket, municipal infrastructure

INTRODUCTION

A development of housing industry, in particular in big cities gets bigger and bigger. The sites which are often situated in heavily urbanized areas are often used for this purpose. An installation of municipal infrastructure network – municipal sewage system, water-pipe, gas, electric etc. networks is indispensable as regards proper functioning of new objects. Conducting this work with use of traditional methods – strip or half-strip ones, with use of heavy construction equipment (excavators, dump trucks) quite often causes big problems for a municipal organism – e.g. stopping of road traffic, a displacement and storage of excavated material, an occupation and a devastation of big ground surfaces, a long time needed for making a connection [21, 22, 23, 24]. An example of making the sewage system installation, using traditional methods, with an application of a big number of groundworks is shown in Fig. 1. Besides, even in the case of a correctly made installation, due to the ground settlement, a trough is often generated on the surface. The

ground settles, so it requires doing additional work to return the initial condition as before starting an investment.

Fig. 1 Example of making sewage system installation using traditional methods with a big number of groundworks
Source: [4].

On the base of the literature review the technologies alternative for traditional methods or trenchless systems of driving mini- and microtunnels, belonging to special methods, are described in the article. They reduce the problems described above [5, 9, 13, 21, 22, 23] to a big extent. A division of these methods due to a possibility of controlling the direction of the installation execution and the way of its realization by soil compacting, its excavation or by the combined method [3, 8, 10, 11, 23, 25] is shown in Fig. 2. Uncontrolled methods, used for making short distance microtunnels of diameters up to 250 mm and the length not exceeding 30-35 m, marked in the diagram with the darker background, are described in the article.
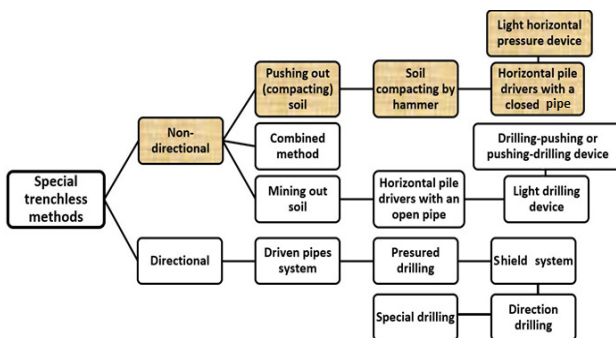
Fig. 2 Division of special trenchless methods used in mini- and microtunnelling
Source: acc. [8, 10].

Use of additional supply devices, pneumatic or hydraulic supply hoses and control devices is required as regards the described methods. A conception of a new solution of one of the described methods, so called "ground rocket", equipped with an electric drive of the dynamic head, was developed at the Department of Machinery Engineering and Transport of the AGH Cracow. The method of selecting the type and parameters of this drive as well as a design solution of the ground rocket are described in the following chapter.

OVERVIEW OF SELECTED METHODS FOR TRENCHLESS EXECUTION OF MINI AND MICROTUNNELS

According to the diagram in Fig. 2, trenchless methods are usually applied for driving micro- and minitunnels in the ground and they can be divided, according to the direction of driving, as uncontrolled ones-making installations in the straight line and controlled ones, in which the trajectory of a driven tunnel can be changed. Taking as a criterion a way of work ofthe driving device, these methods can be included among the methods of thickening the ground or among the methods which excavate this ground. The methods, thickening the ground, can be used for a limited diameter and length of a driven tunnel. It is connected with the resistances of the ground environment during a dislocation of the cutting head [8].

In the case of uncontrolled, pushing-out ground thickening methods ramming and ground pushing devices, called ground rockets, are used very often. In Poland these devices have a common name "mole" [1, 10]. The first

ground rocket was designed in England in 1916. This device consisted of a metal cylinder with a sharpened front. Rams, controlled with compressed air, were installed inside the cylinder. In Fig. 3 a diagram of this ground rocket of Terra-Hammer type, made by Terra Company [19], is presented and in Fig. 4 a solution, developed by the Terra Max Company [17], is shown.
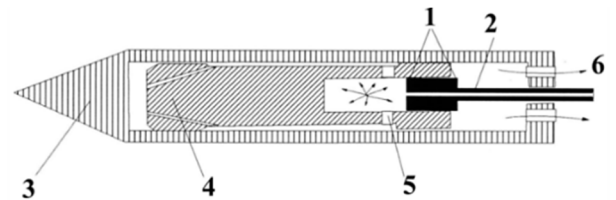
Fig. 3 A diagram of Terra-Hammer ground rocket
1 – control edges, 2 – control hose, 3 – front conical part of housing, 4 – core, 5 – transverse drill hole, 6 – air outlet
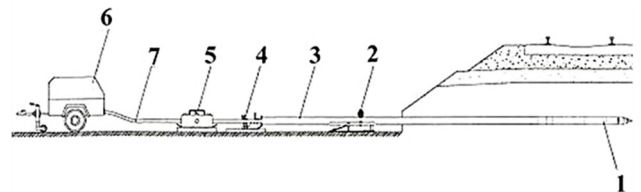Source: [17].
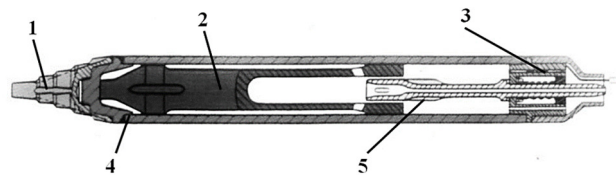
Fig. 4 Construction of Terra-Max ground rocket
1 – head of punch, 2 – piston (ram), 3 – elastic shock absorber, 4 – conical housing, 5 – control sleeve
Source: [16].

The schematic diagram of this method, consisting in an implementation of an in-coming installation with the dynamic head is presented in Fig. 5.

Fig. 5 Schematic diagram of introducing the installation behind the dynamic head:
1 – dynamic head, 2 – starting platform, 3 – installation, 4 –device pressing down the pipe, 5 – control device, 6 – compressor, 7 – hose delivering compressed air
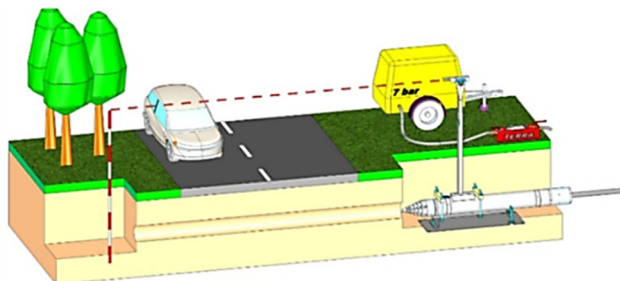Source: [10].

It is one of the simplest excavationless methods and it is based on an introduction into the ground of the installation 3 (usually flexible) directly behind the dynamic head, [1, 10]. In the head of a cigar shape there is a ram put into reciprocating motion, which hits the head, relocating it in the ground. The ram motion is obtained due to compressed air from the compressor 6 conducted to the device through the hose 7. The air flow can be controlled by the control equipment 5. The frequency of the ram strokes onto the head, in relation to the design solution and the device diameter, varies from 150 and 600 strokes per minute. The ground rocket is supplied and controlled pneumatically at the pressure of 0.6-0.7 MPa but it can also be supplied and controlled hy-

draulically. Ground rockets can be equipped with the following kinds of pushing heads [17]: conical stepped and smooth head (Fig. 6).

**Fig. 6 Conical stepped and smooth head**
Source: [17].

The heads, described above or other ones being a combination of their shapes, are used for making such installations as drainages, water draining systems, rebores etc. at the diameter up to 250 mm and the length not bigger than 35 m at depth to 5 m. An example of the installation under the road is shown in Fig. 7.

Fig. 7 Diagram of a rebore under the road
Source: [17].

The work is started with making ditches and chambers – initial and final ones [1, 10]. Next the ground rocket is dynamically introduced in the ground from the starting ditch. Supporting elements, which are usually pipes made of plastic, are pulled or pushed in the free space behind the dynamic head. This system can be used in loose grounds exclusively.

The geometric parameters, i.e. the diameter and the length are limited due to an accuracy of the generated passage. Uncontrolled systems, capable of making passages only along a straight trajectory, are very sensitive to a position of a starting platform (the sensitivity increases as the passage length increases) and to local impediments in the ground compression caused e.g. by inclusions of rock formations (a possible deviation of the passage trajectory). Lack of the passage line correction renders to introduce corrections impossible in the case of a mistake.

Another method of soil compacting is a so called horizontal pile-driver with a pipe closed by the head in conical shape [1, 10]. An execution of the passage causes local soil compacting, which in a significant way limits the dimensions of the introduced installation as in the case of the ground rocket. The way of introducing the final installation is also different – not pulling but pressing into the ground and the type of installation is also different – rigid pipes usually steel ones. A diagram of the described method is presented in Fig. 8.
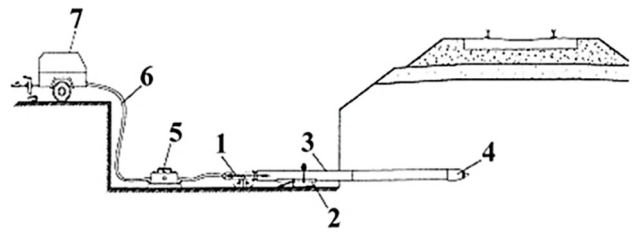
Fig. 8 Diagram of driving method of the pipe closed from the front
1 – pneumatic hammer, 2 – starting platform, 3 – element to be pressed into ground, 4 – pipe conical lock, 5 – head control device, 6 – hose delivering compressed air, 7 – compressor
Source: [10].

Pressing a rigid, usually steel pipe 3, ended with conical head 4, is realized with use of a pneumatic hammer 1, connected with supply hoses 7, delivering compressed air from the compressor 6 [1, 10]. A control of the device operational parameters enables a check up of the pressing process which is realized by the control device 5. The pneumatic hammer is installed on the starting platform 2, ensuring a correct device positioning and an introduction of the installation into the ground according to the planned route. There is no possibility of controlling or correcting the passage trajectory during the pressing process. It is possible to make microtunnels of the diameter up to 200 mm and of the length up to 35 m using this method. The maximal advance is 10 m/h.

In the method of pneumatic pressing it is possible to use the elements opened from the front as well [1, 10]. An installation of open elements causes that the extracted ground gets into the installation from the front, filling it in completely. A removal of the ground is carried out after reaching the final excavation by pushing it out with use of a so called air-lock. Due to lack of the soil compacting necessity, the dimensions of installed elements reach even 1400 mm. A diagram of the described method is presented in Fig. 9.
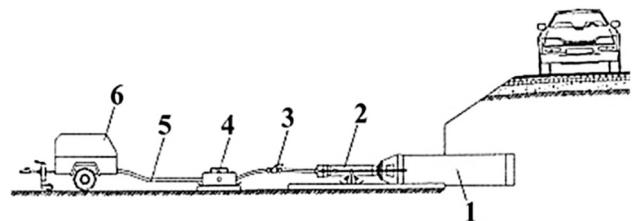

Fig. 9 Diagram of pressing the pipe open from the front:
1 – pressed element, 2 – pneumatic hammer, 3 – control valve, 4 – supporting device, 5 – hose delivering compressed air, 6 – compressor
Source: [8].

Another used method is the system of mechanical drilling which enables to make a passage in an trenchless technology, making a horizontal rebore with use of the head disintegrating the ground and with use of the right transport system [1, 8]. A rotary motion of the head ensures cutting of the ground and the platform auger, coupled with it, enables a transport to the initial excavation. Drilling can be made in one stage or in two stages. The drilling - pressing

device consists of a pressure unit together with a hydraulic cylinder, a feeding screw with a drilling head and with pressed elements of the pipe. A diagram of one-stage drilling, using the drilling-pressing device, is presented in Fig. 10. This method enables to execute rebores of the diameters up to 300 mm and of the length up to 20 m. In the case of an operation in the ground of low firmness the length of the rebore can reach 50 m. Maximal speed of drilling is 15 m/h.
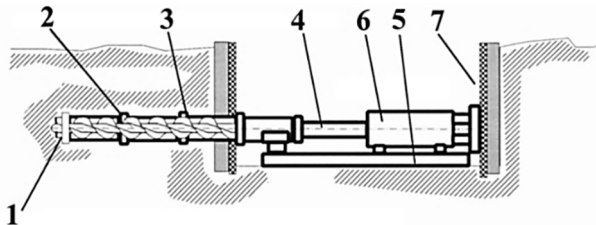

Fig. 10 Diagram of drilling-and-driving device:
1 – drilling bit, 2 – drilling hose with screw wound, 3 – pipe, 4 – hydraulic cylinder for pushing pipes, 5 – load-bearing frame, 6 – assembly of drilling rig with hydraulic unit, 7 – starting ditch with retaining wall
Source: [1].

Two-stage method of mechanical drilling enables a very accurate, in accordance with the planned direction, execution of the tunnel. In the first stage, i.e. pilot drilling is possible, due to the pilot head in the shape of a wedge, to correct the passage trajectory [1] which is presented in Fig. 11a. In the second stage (Fig. 11b) i.e. due to broadening drilling the final diameter of the microtunnel is achieved. The process of broadening the rebore is executed with use of the enlarging head 4 connected directly to the platform auger 5, which transports the excavated material to the initial chamber. The housing 6 of the worm conveyor, in practice, is temporary lining. The final installation 7 is pressed into the passage, replacing the conveyor housing. This process is shown in Fig. 11c.
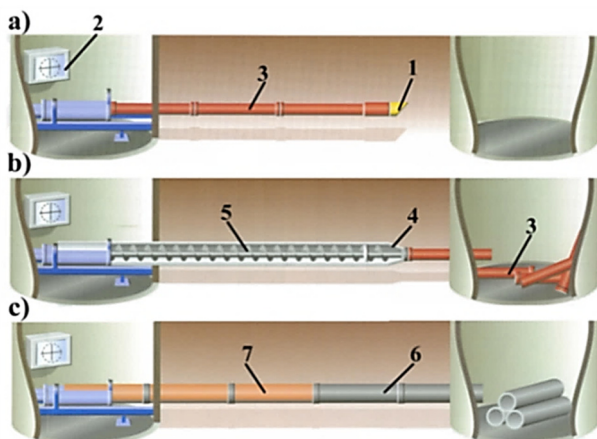
Fig. 11 Diagram of two-stage mechanical rebores method:
a) pilot drilling, b) broadening drilling, c) pushing of final installation
1 – drilling head, 2 – light-sensitive matrix, 3 – drilling rods, 4 – enlarging head, 5 – platform auger, 6 – conveyor housing, 7 – final installation
Source: [19].

A different method includes pressure drilling. This method consists in a simultaneous, together with cutting the rock, introduction of pipe housing [1, 19]. An execution of a rebore is preceded by a construction of two chambers: starting one and final one, also called shafts. Cutting is carried out with use of the drilling head, and then the excavated material is removed to the starting chamber. In relation to the environment under cutting, different kinds of cutting heads-slicing ones or equipped with disc tools and haulage systems-mechanical, helical or hydrotransport, are used. This method can be applied for drilling of the diameters from 250 mm to 1000 mm and the length of 70 m. The drilling advance varies from 1 to 2.5 m/h. An exemplary system for pressure drilling, made by Zűblin Company, is presented in Fig. 12. It is possible to correct the passage trajectory in the solution, taking advantage of a set of control cylinders.
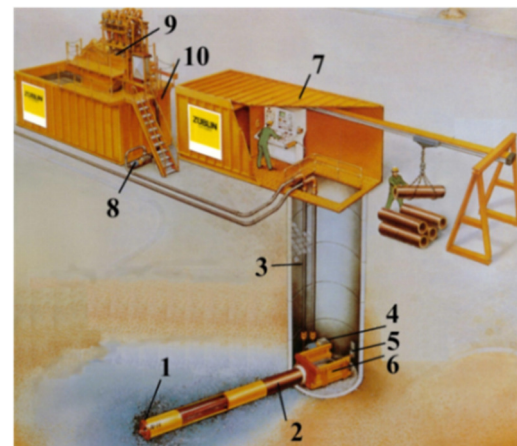
Fig. 12 System for pressure drilling made by Zűblin Company
1 – cutting head, 2 – pipes of housing, 3 –starting drift, 4 – pump for draining of flushing liquid, 5 – laser device, 6 – pushing device, 7 – control container, 8 – pump for forcing flushing liquid, 9 – separating device, 10 – tank of water and sludge
Source: [19].

In the case of a changeable trajectory of an introduced hose, controlled hydraulic and mechanical drillings are used, so called HDD – Horizontal Directory Drilling. These methods, developed in the middle of XX century, constitute a solution enabling a full check-up of the excavation route. The technology of introducing the final installation is divided into the stage of a pilot drilling and the stage of introducing the installation. They can be used for overcoming such obstacles as road infrastructure, buildings or overcoming of natural obstacles – rivers, lakes. The length of rebores can even reach several kilometres and their diameter is up to 2 m [18]. They are described in detail in [8].

NEW CONCEPTION OF GROUND ROCKET WITH ELECTRIC DRIVE

A necessity of using additional devices in the ground rocket method such as: a compressor, a control device, a hose delivering compressed air (Fig. 13) was an inspiration for considering a possibility of their elimination. It forced a change of driving and supplying the dynamic head of a ground rocket. It was suggested to replace a pneumatic

drive with an electric one. An application of an electric motor gives a chance to increase the efficiency of the drive system and a possibility of its supply from the domestic network or from the switchbox. On the basis of the literature a type of such a motor was selected and the parameters of the motor which can be built in a selected solution of the ground rocket were assessed. It is described in the following chapters.

Fig. 13 Fittings for supply and control of ground rocket
Source: [15, 16].

Selection of electric motor

Electromagnetic forces can be used for a generation of a linear, rotary or resultant motion. In the case of a ground rocket a linear motion is required. It is possible to get it while using linear induction motors. It is an electric motor generating translational motion, which can be obtained due to a location of the motor windings perpendicular to the direction of its motion. Its design results from a transformation of magnetic and electric circuits of a conventional motor. In the result an arc motor is obtained in the first phase and then a linear flat induction motor (Fig. 14a), and in the final effect-after winding around the axis parallel to the direction of the magnetic field dislocation – a linear tube motor (Fig. 14b) is generated. In such a motor the primary part, called a magneto and the secondary part called a run, can be distinguished. The magneto, supplied from the electric network, generates a migratory magnetic field through the linear structure. This field induces currents in the secondary part and in the result a tractive force, causing a linear motion of the movable part which can be both the run and the magneto, is generated. Such a motor is characterized by a constant linear velocity dependent onthe supply voltage frequency and it is expressed in m/s as well as an acceleration expressed in m/s^2 and power of the current taken from the network in kW. Instead of the torque an ability for a dislocation of big weights, a value of the force in N, is given. In these motors very big values of accelerations and velocities are achieved due to a direct transmission of the driving force to linear motion [7, 12, 14, 28].
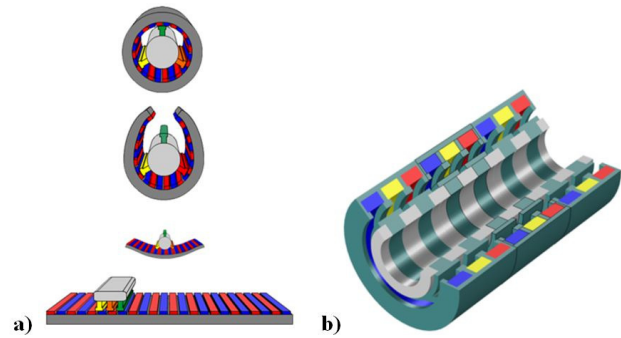

Fig. 14. Cutting and developed view of a traditional electric rotary motor:
a) obtaining arc and flat motor, b) linear tube motor with movable magnets
Source: [12, 14].

Linear induction motors differ as regards the length of the movable part stroke and by the kind of the movable part – a mandrel with permanent magnets or a movable coil. On the basis of the analysis conducted in the research work [6] and of the test results described in the work [2], it was stated that the best solution for the driving system of the ground rocket under elaboration would be a linear tube synchronous motor with permanent magnets and a movable run. Its geometry reminds compressed-air engines which will facilitate its implementation in ground rockets, used at present and besides, a distribution of forces in these motors is uniform.

It has a positive impact on the generated tractive force and balancing of radial forces. Its diagram is shown in Fig. 15. These motors require 3- or 5- phase supply systems. In the case of a 5-phase system it is possible to obtain better operational parameters, so it is worth accepting such a system and a supply through the PWM (Pulse Width Modulation) converter. Due to lack of commercial solutions of such motors on the market and due to big costs of existing models, an attempt of modelling a linear induction motor, to be used in a selected solution of a ground rocket, was made in the research work [6].
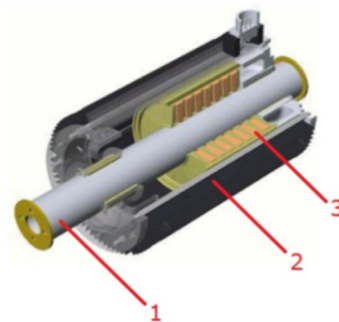

Fig. 15 Linear induction motor with a movable core:
1 – run, 2 – housing, 3 – coils
Source: [7].

A CONCEPTION OF A GROUND ROCKET WITH AN ELECTRIC DRIVE

For calculations of design parameters of a 5-phase synchronous tube motor it was assumed that it will be supplied with alternate current at the voltage U = 400 V and of frequency f = 50 Hz. Current density was assumed on the level J_a = 10 A/mm². Permanent magnets of the run will be made of NdFeBsinter and the rest of ferromagnetic elements – of low-carbon steel. The diameter of the coil winding wire was assumed as 2 mm. The motor external diameter should not exceed 180 mm. It will enable its installation in housings of ground rockets to be used for rebores of 200 mm diameter. The motor should generate a tractive force F of about 2000 N. The diagram in Fig. 16 shows half of a cross-cut of a cylindrical prototype linear induction motor, 5-phase, of tube type with permanent magnets and marked indispensable dimensions.
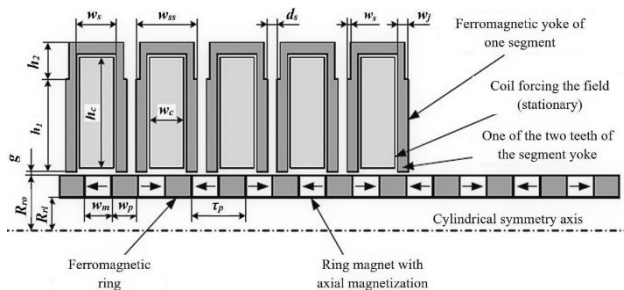
Fig. 16 Diagram of half cross-cut of cylindrical prototype linear induction motor, 5-phase, of tube type with permanent magnets and marked indispensable dimensions:
d_s – distance between stator segments, g – length of the air gap, h_c – coil height, R_{ri} – internal radius of the runner, R_{ro} – outer radius of the runner, R_{si} – internal radius of the stator, R_{so} – outer radius of the stator, w_m – magnet width, w_p – ferromagnetic ring width, w_c – coil width, w_s – stator segment cradle width, w_j – stator core yoke thickness, w_{ss} – width of a single stator segment, t_p – polar pitch
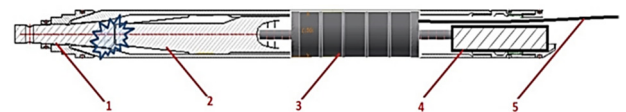Source: acc. [26].

Basing on the information and formulae, presented in [2, 7, 15, 20, 26] and using a commonly available software FEMM (Finite Element Method Magnetics) [17], an initial design solution of the motor was modelled and the calculations were made. The results of calculations and simulations confirmed the initial assumptions and enabled to make a 3D linear model of the tube motor shown in Fig. 17. The obtained dimensions enable an installation of such a solution of the motor in ground rockets used for making rebores of about 160 mm dia.

An example of an installation of the developed motor solution in the housing of the ground rocket, made by Termamax Company, type K160 [16], is shown in Fig. 18. A reduction of the rocket length, due to lack of channels supplying compressed air, enables its use in smaller initial excavations. A certain problem may be caused by a generation of heat centres in the vicinity of the motor. It is the reason why a use of the material efficient in a passive carrying out of heat should be considered for the rocket housing or an installation of a fan forcing an artificial circulation of air.
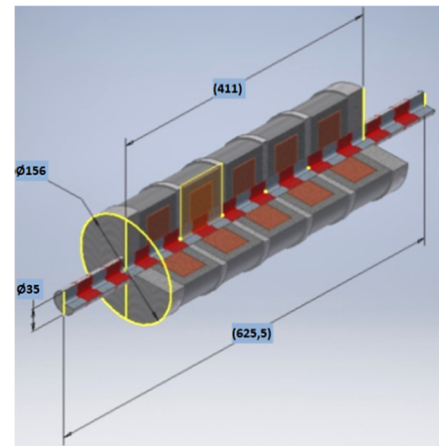
Fig. 17 3D model of a developed solution of tube linear induction motor
Source: [16].

Fig. 18 Example of an installation of the developed motor in the ground rocket of type Termamax 160
1 – head, 2 – ram, 3 – linear synchronous tube, 4 – reversion ram, 5 – supply hose
Source: acc. [16].

SUMMARY AND CONCLUSIONS

The efficiency of pneumatic systems, used in the devices of a ground rocket type, usually does not exceed 50%. It was the reason why a replacement of this type drives with much more efficient and more productive electric motors for very often used ground rocket was suggested. With the help of these devices, trenchless works are carried out to allow the installation of municipal infrastructure over a short distance, up to 30 m and with a diameter of not more than 200 mm.

The most advantageous synchronous linear tube motors, which have a good point consisting in a possibility of getting big values of velocities and accelerations, was suggested to be installed in the ground rocket. A solution of such a motor, assuming the parameters for calculations as in this article, without problems can be mounted in the existing construction designs of ground rockets. Use of domestic electric network for a direct supply of the device will enable to eliminate additional supply fittings such as a compressor, a control system and supply hoses. This was the main goal of the work carried out and it was achieved.

An application of a linear induction motor, apart from its advantages, has certain disadvantages. One of them is heating of linear induction motors (even to the temperature of about 100°C) what can cause a necessity of using additional cooling. Another problem concerns keeping a constant value of the tractive force within a full scope of the run stroke. Additionally, a supply from the domestic electric network will require an application of the PWM converter for controlling the phases.

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Krzysztof Kotwica
ORCID ID: 0000-0001-7696-5763
AGH University of Science and Technology
al. Mickiewicza 30, 30-059 Kraków, Poland
e-mail: kotwica@agh.edu.pl

Hubert Suffner
ORCID ID: 0000-0003-0308-5567
KOMAG Institute of Mining Technology
Pszczyńska 37, 44-101 Gliwice, Poland

Andrei Andras
ORCID ID: 0000-0003-2489-2552
University of Petrośani
Strada Universităţii 4, Petroșani, Romania