Modelling of series of types of automated trenchless works tunneling

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Abstract. Microtunneling is the newest method for making underground installations. Show method is the result of experience and methods applied in other, previous methods of trenchless underground works. It is considered reasonable to elaborate a series of types of construction of tunneling machines, to develop this particular earthworks method. There are many design solutions of machines, but the current goal is to develop non–excavation robotized machine. Erosion machines with main dimensions of the tunnels which are: 1600, 2000, 2500, 3150 are design with use of the computer aided methods. Series of types of construction of tunneling machines creating process was preceded by analysis of current state. The verification of practical methodology of creating the systematic part series was based on the designed erosion machines series of types. There were developed: method of construction similarity of the erosion machines, algorithmic methods of quantitative construction attributes variant analyzes in the I-DEAS advanced graphical program, relational and program parameterization. There manufacturing process of the parts will be created, which allows to verify the technological process on the CNC machines. The models of designed will be modified and the construction will be consulted with erosion machine users and manufacturers like: Tauber Rohrbau GmbH & Co.KG from Minster, OHL ZS a.s. from Brna,. The companies’ acceptance will result in practical verification by JUMARPOL company.

1. Introduction
Series of types orientated process of construction and design varies from the traditional one in inserting a defined set of needs to be satisfied by optimally diversified set of technical means as input [4]. Typical system of ordered series of types of construction of tunneling machines used for trenchless earthworks that corresponds to one Reo mapping relation, may be defined as: „underground tunneling according to given direction and gradient for power leeds or channels”

Microtunnel is performed in following stages, figure 1 [1-3]:
• Construction of starting and end shaft;
• equipped of starting and final shaft in controlling and steering room, hydraulic power unit, excavated material installations system;
• installation of drilling machine in the starting shaft;
• microtunnell execution;
• dismantling of microtunneling machine in the end shaft;
• the land reclamation and transportation of equipment.

Figure 1 show realization process of trenchless tunnel drilling.
The creating process of series of types of construction of tunneling machines was preceded by analysis of current state. There are a variety of design solutions for tunneling machines according to the microtunnel creating system. There are tunneling machines with a manipulator accessorized in a ripping head or a special scoop or a full cutting shield, with simultaneous pipe introduction into the tunnel, figure 2.

In the pressing method assumes hydraulic excavation material disposal (benthonic washer) or mechanical one, by: platform augers, rail cars, belt conveyors. For rinsing transportation, figure 1, excavation materials and compound of bentonic is pumped into the face, where the excavation material is removed from the drilling fluid by separation equipment or by gravity sedimentation. The tunneling process is circular while applying the mechanical disposal method, e.g. rail cars. This is due to the fact that the car filled with material being transported from the end of the mining machine to the starting shaft, where it is being elevated by a crane into the surface and emptied. Such a solution significantly slows down the process of tunneling, however one of its advantages is avoiding the use of expensive machines (for the separation of bentonic and excavating material) or device introducing the benthonic washer to the ripping head.

The basic criteria that should be considered while creating a new design solution for a drilling machine in relation to the existing ones are:

K1. reduction of tunneling energy;
K2. robotics of trenchless works;
K3. use of the maximum number of listed (catalogued) elements and sets.
The reference solution was a design of a German TAUBER Rohrbau tunneling machine, figure 3.

![Figure 3. System illustration of reference solution.](image)

**stage A** - excavator 2 molds the ground in the forehead and passes it to the conveyor belt 4;
**stage B** – in the resulting excavation tunnelling pipe 1 is moved using the hydraulic cylinder 3 and bend 6 pushing away from the end part of the tunnel;
**stage C** - bend 6 is hidden by the cylinder 3, in order to create new space for installation of tubing creating the next segment tunnel;
**stage D** – after installation of tubes the empty space 5 between the external surface of the tunnel and the surrounding ground is filling the cycle is completed and followed by stage A of the following cycle.

Assembling pipes are three-piece (Mayer tubs) and introduced after the machining device, figure 4.

![Figure 4. Tubes of MEYER.](image)

Reasoned variety of construction series is caused by diversity of needs of defined class of technical means [5]. Such a diversity formally enters constructional-designers assumption set identified by characteristic features values [6]. In the tunneling machines series of types of design basic parameter is
the drilled tunnel’s diameter. Based on the analysis of Tauber trenchless earthworks needs in Poland identified the following unified diameter tunneling: 
D= 1000, 1200, 1600, 2000, 2500, 3150 [mm].

The diameter of drill tunnel corresponds to the external tube’s diameter and is closely related to diameter of head. Consequently affect influence on the characteristic features of the construction and features tunneling machine.

| Tunneling diameter [m] | Diameter of head [m] | Ground pressure (vertical) [kN] | Pressure power (horizontal) [kN] | Head’s cutting torque [kNm] |
|-----------------------|----------------------|-------------------------------|---------------------------------|---------------------------|
| 1.0                   | 1.45                 | 36.20                         | 421.05                          | 16.15                     |
| 1.2                   | 1.60                 | 44.08                         | 651.60                          | 25.95                     |
| 1.6                   | 2.15                 | 55.08                         | 1008.68                         | 48.1                      |
| 2.0                   | 2.45                 | 67.62                         | 1272.12                         | 82.21                     |
| 2.5                   | 3.15                 | 83.23                         | 1874.13                         | 142.99                    |
| 3.15                  | 3.60                 | 103.59                        | 3096.74                         | 263.4                     |

On the basis of the developed program tunneling machine’s dependent parameters were assigned [1-3]:
- vertical ground pressure power $F_V$;
- horizontal power of the pressing tunneling device – $F_H$;
- head’s maximum cutting torque $M_S$ for the most inconvenient ground structures;
- device’s relocating speed;
- tunneling machine’s efficiency.

2. Conception of tunneling machines
The variety of of qualitative design features of the family construction is included in the structure of the system and structure of the variant of the family structure [5]. System structure defines elements of technical mean’s priorities distinguishing the following construction forms:
- sets;
- subsets;
- elements and their parts.

Relations characterized by the lowest priorities structure and representing the whole spectrum of design possibilities for a family of constructions are called isomorphous relations. The structure of the variant defines a variety of design solutions for hierarchically structured relationship. Basing on the system structure of the tunneling device described by $Re^0$ relation and adopted set of criteria; the following tunneling machine sets were defined:
$Re^0$ – ground mining $\rightarrow$ mining equipment;
$Re^1$ – mining device movement $\rightarrow$ use of robot;
$Re^a$ – movement of the tunneling machine $\rightarrow$ movement of tunneling machine;
$Re^e$ – shaping a ground opening $\rightarrow$ rotation set;
$Re^t$ – transportation of the excavated material from the forehead $\rightarrow$ belt conveyor;
$Re^a$ – transportation of the excavated material into the starting shaft $\rightarrow$ rail car;
Re\textsuperscript{m} – assembly of tubes → robot of tubes assembly;
Re\textsuperscript{l} – relocation of rail cars and tubes assembly robot → engine.

2.1. Mining device
The heads and scoops are basic mining devices. In this regard, there is a large variety of construction, which expanded about their own ideas. The area of possible design solutions and created the system of criteria became the basis for the development two construction solutions of tools \( R_1^n \) and \( R_2^n \), figure 5.

![Figure 5. The concept of mining devices.](image)

Constructional solution consists of lengthwise mining ripping head. The basis for creating the concept was Remag Erkat and Tramac heads. In the tool distinguishes the structure of the system as:

- \( R_1^{n1} \) - hydraulic fluid energy conversion into mechanical energy → hydraulic engine, type A2FE, Rexrot;
- \( R_1^{n2} \) - conversion of mechanical energy → mechanical gear;
- \( R_1^{n3} \) - transmission of torque → drive shaft;
- \( R_1^{n4} \) - transmission of torque from the shaft to the ripping head → frictional rings (Peter type PSV);
- \( R_1^{n5} \) - ground mining → head.

The head has the following structure system:

- \( R_1^{n1} \) - load transfer → head’s body;
- \( R_1^{n2} \) - mounting of machining tools → tool’s holder;
- \( R_1^{n3} \) - machining of ground → rotational tangential knives;
- \( R_1^{n4} \) - maintaining the tools in holder → cotter pins.

The design solution \( R_2^n \) is equipped with a scoop-shaped mining tool. It may alternatively be mounted on a robot’s arm and is sand and clay-orientated.

2.2. Mining device movement
The study considered a wide range of applications of robots with different kinematic structure. Using a modular system of robots GEMOTEC, Gimatic, Güdel. Figure 6 presents a robot built basing on the
Güdel modular system. However, were used own projects robots. Examples of structures of robots are shown in figure 7.

Figure 6. Modular system of robot (On the basis of the Gudel system).

Figure 7. Model of robot.

The robot includes a kinematic structure \{X_R, C_R, B_R, X_L\}. The workspace is a spherical space.

- **X_R** – longitudinal movement, regional, along with X axis → is realized by a hydraulic cylinder moving the car on the running track;
- **A_R** – rotary motion, regional, along with Z axis → is realized by two cylinder moving the robot’s head on the arm. The robot’s head is attached by a 4-point Franke, type LEL bearing;
- **B_R** – rotary motion, regional, along with Y axis → is realized by cylinder moving the arm. The frame is mounted on roller bearings;
- **X_L** – longitudinal movement, local, along with X axis → is realized by an inside-arm cylinder, the forearm is run inside the robot’s arm by the THK type Flat Roller linear bearing.

### 2.3. Shaping a ground opening

Shaping a ground opening, relation Re^w, can be implemented in two ways, figure 8:

- **Re^w_1** - the tunneling machine’s body consists of two pipes, where the external one connected to the device’s body performs, with the use of cylinders, incomplete oscillatory rotational movement regarding the internal pipe;
- **Re^w_2** - The head performs rotary movements. Its bearing is in the device’s body.

The project uses both concepts. **Re^w_1** relation idea contains relations:

- **Re^w_{1,1}** - covering the drilled tunnel → external body;
- **Re^w_{1,2}** - internal protection → internal body of the tunneling machine;
- **Re^w_{1,3}** - internal body positioning relative to the external one → roller guides, figure 8;
- **Re^w_{1,4}** - internal body’s rotational movement → 4 hydraulic bearings according to our own hydraulic bearings’ modular system;
- **Re^w_{1,5}** - ground cutting → head’s crown.

The concept of second, relation **Re^w_2** figure 8, shaping a ground opening is realized by three consecutive relations:
$\text{Re}_2^{w1}$ - driving the head $\rightarrow$ head’s propelling systems include:

$\text{Re}_2^{w2}$

**Figure 8.** Constructional solutions for shaping ground.

$\text{Re}_2^{w11}$ - converting the hydraulic energy into mechanical energy $\rightarrow$ hydraulic engines of Rexroth type A2FM, figure 9.

$\text{Re}_2^{w12}$ - transformation of mechanical energy $\rightarrow$ planetary gear of Rexroth type GFBT2/T3;

$\text{Re}_2^{w13}$ - head’s toothed ring coupling relation $\rightarrow$ pinion;

**Figure 9.** Constructional solutions for hydraulic engine.
Re\textsubscript{2}\textsuperscript{w2} - implementation of rotational movement while moving loads → head’s bearing, Rother Erde double-row ball bearing with internal toothed ring;
Re\textsubscript{2}\textsuperscript{w3} - cutting of ground → head’s crown equipped in tapered knives like in the ripping head.

2.4. Transport of excavated material
Excavated material’s transportation into the starting shaft is performed by a basin-shaped belt conveyor, figure 10. Belt conveyors adapted to the construction variants of cutting machines. Transport of the carrier to the starting shaft is realized in a cyclic manner with the use of a wagon, Re\textsuperscript{w} figure 10. Conveyor and wagon are designed according to their own concept using the assemblies and components catalog.

![Figure 10. The concept of transport of excavated material.](image)

2.6. Installation of tubing and cars movement
Installation of tubing is performed by a robot, see figure 11. The robot is equipped with a suitable gripper for mounting tubing. Tubes are shared and made from composites.

![Figure 11. Model of robot to tube assembly.](image)
3. Results and conclusions
The result of the project is two design solutions of tunnelling machines. Both solutions are composed of robots with different structures system (operating principles), figure 12.

For assemblies and components developed algorithms for the selection of their parameters, while for the elements constructed algorithms selection of design features. Based on the developed algorithm selection quantitative design features will be created series of types of tunneling machines.

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