The calculation of ramming forces during the installation of pipelines in microtunnelling technology – selected industrial examples

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Abstract: The design and construction of high-pressure gas transmission pipelines is a very costly and complicated undertaking in every respect, including interference with the natural environment. Limiting this interference and the necessity to use pipelines to cross the main communication routes encourages the use of trenchless technologies in such situations.

Currently, the most popular and available technologies of this type in Poland are: microtunnelling, horizontal directional drilling – HDD, and Direct Pipe. One of the most widely used of these technologies is the microtunnelling technology. In the article, the authors analyzed the procedures of calculating jacking forces popular in Poland. These calculations were compared with the jacking forces measured on completed projects. These calculations were made for three intersections constructed with microtunnelling technology with the use of 1280 mm GRP casing pipes as part of the construction of the high-pressure gas pipeline DN1000 MOP 8.4 MPa on the Zdzieszowice – Brzeg segment

Keywords: microtunnelling, jacking force, gas pipe line, trenchless technology

KALKULACJA SIŁ PRZECISKOWYCH PODCZAS INSTALACJI RUROCIĄGÓW STALOWYCH W TECHNOLOGII MIKROTUNELOWANIA – WYBRANE PRZYKŁADY PRZEMYSŁOWE

Streszczenie: Projektowanie oraz budowa gazociągów przesyłowych wysokiego ciśnienia to przedsięwzięcie bardzo kosztowne i skomplikowane pod każdym względem, również ingerencji w środowisko naturalne. Dążenie do ograniczenia tej ingerencji oraz konieczność przekraczania gazociągami głównych szlaków transportowych skłaniają do wykorzystania technologii bezwykopowych (*trenchless technologies*).

Obecnie najpopularniejszymi i dostępnymi w Polsce tego typu technologiami są: mikrotunelowanie, horyzontalny przewiert sterowany – HDD i *Direct Pipe*. Jedną z najczęściej stosowanych spośród wymienionych technologii jest technologia mikrotunelowania. W niniejszym artykule autorzy przeanalizowali popularne w Polsce procedury kalkulacji sił przeciskowych. Wyniki tych obliczeń porównano z zarejestrowanymi na wykonanych projektach wartościami sił przeciskowych. Kalkulacje te przeprowadzono dla trzech przewiertów wykonanych za pomocą technologii mikrotunelowania rurą osłonową GRP 1280 mm w ramach budowy gazociągu wysokiego ciśnienia DN1000, MOP 8,4 MPa na odcinku Zdzieszowice – Brzeg. Praca ta ma na celu wypracowanie nowej procedury obliczeniowej wartości siły przecisku w technologii mikrotunelowania w skomplikowanych warunkach geologicznych.

Słowa kluczowe: mikrotunelowanie, technologie bezwykopowe, siła przeciskowa

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1. Introduction

The development of the national gas transmission network, mainly through the construction of new high-pressure gas pipelines, is an important element in the development of the European transmission system. These investments are carried out by the Polish operator Gaz-System S.A. with the help of European Union funds, which were launched in 2009. At present, the plans for the construction of gas pipelines date to 2028 and constitute an important part of the EU plan for the creation of new connections increasing the energy security of Poland and the European Union itself.

The design and construction of gas pipelines, mainly of large diameters, is a very costly and complicated undertaking in terms of engineering, as well as requiring the least possible interference with the natural environment. The limitation of interference in the environmental values of the regions through which the pipelines run and the need to cross the main transport routes induces the use of trenchless methods.

Currently, the most popular and available in Poland are: microtunnelling, horizontal directional drilling – HDD, and Direct Pipe. One of the most frequently used technologies is microtunneling. This article presents the calculations of ramming forces for three drillings with GRP 1280 mm pipe to cross the gas pipeline under A4 motorway, provincial road No. 423 and provincial road No. 414. Crossings in the first two cases were made in Gogolin, the third in Prószków, Opolskie province. These works were performed as part of the construction of the DN1000 high-pressure gas pipeline in the section Zdzieszowice – Brzeg.

Paper presents a comprehensive analysis and verification of the most popular methods of calculating the ramming forces in a microtunnelling by comparing it with the actual measured forces. Based on the analysis of industrial examples, the factors determining the value of the friction force of the pipe against the ground were determined. This work will allow for a rational selection of the pushing stations and cutting discs for microtunneling purposes. Thanks to this, it will be possible to reduce investment costs by minimizing the wall thickness and the type of casing while maintaining the safety of the work carried out. Recommendations were defined in this regard: the value of the friction coefficient and the organization of the time of microtunneling works 24/24 h. The effect will also be the minimization of fuel consumption and thus the reduction of exhaust emissions, including CO_2. Research gives direct benefits for industry.

2. Microtunnelling technology

Microtunnelling technology is one of several methods of trenchless construction of underground networks known to the market. The beginning of this method, in its present form in the world, dates back to the 1970s, and its first application occurred in Japan (Milligan and Norris 1999, Madryas et al. 2006).

In Poland, the first project using a microtunnelling machine was made in 1998 by the Warsaw company BETA. These were sections of the sewage network with a diameter of 1600 mm and a total length of 973 m in Toruń (Zwierzchowska 2009, Ziaja et al. 2018).

The microtunnelling technology consists in the execution of a single-stage hydraulic ramming which consists in the drilling of the tunnel by means of a cutting disc with simultaneous ramming of casing pipes. This disc is placed on the front of the microtunnelling device, also called the head (Fig. 1). The drilling head, driven by a hydraulic motor, causes preliminary ground crushing. Then it goes to the crushing chamber, where it is further crushed into particles of a size that makes it possible to transport them through a mud pipeline.

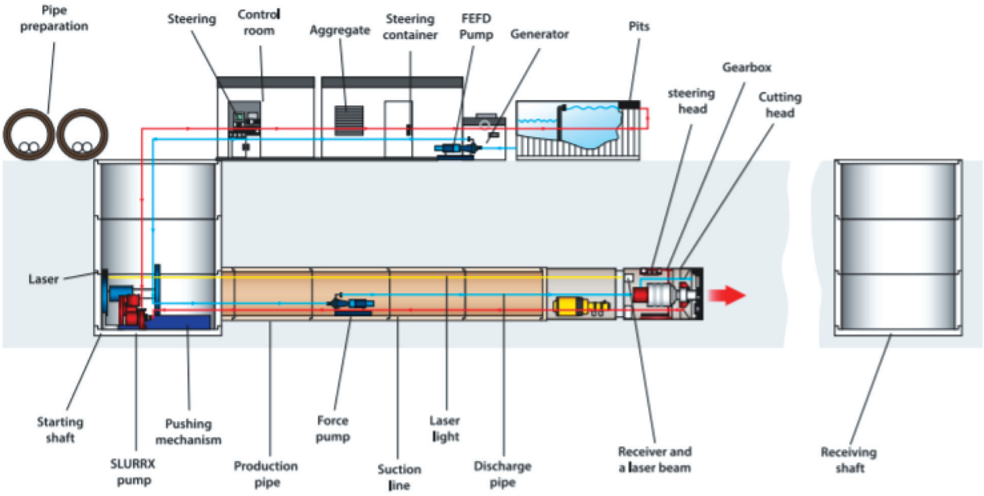

Fig. 1. Microtunnelling process diagram
Source: Madryas et al. (2006)

At present, microtunnelling technology is considered the least invasive compared to other trenchless technologies.

Microtunnelling is mainly used to build linear underground infrastructure. It includes, among others:

- sewage and water supply pipes,
- gas and oil pipelines,
- casing pipes for other lines, e.g., heating lines,
- multi-pipe tunnels (Fig. 2).

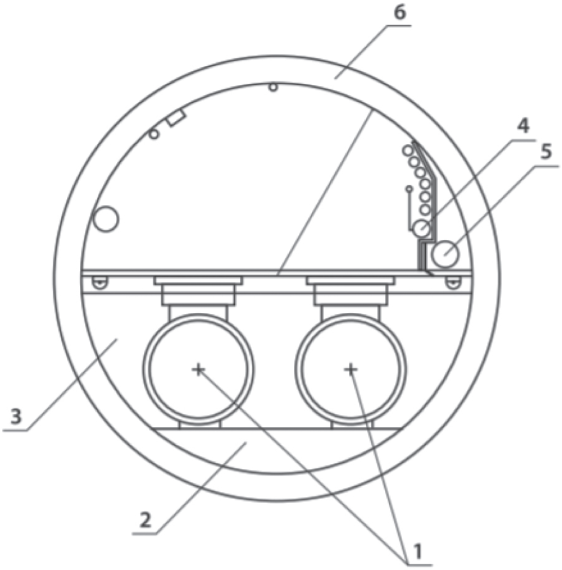

Fig. 2. Example of the development of a multipipe tunnel in Zurich:
1 – sewerage system, 2 – concrete support, 3 – lean concrete casing,
4 – water supply pipe, 5 – process pipes, 6 – ramming pipe
Source: Milligan and Norris (1999)

Therefore, it is very often used in the construction of new gas networks.

3. Calculation of the necessary ramming force

The critical moment for design crossings in trenchless technology is the estimation of the maximum installation force. The correct estimation of its value is necessary for selecting the strength parameters of the ramming pipe. And on this basis, the selection of the appropriate actuator construction and the construction of the retaining wall for the starting chamber. Properly estimated, the expected installation force allows for safe conduct of work and minimizes the costs of microtunnel work.

The jacking forces are comprised of two components: the face pressure force and the frictional force, as schematically shown in Figure 3. The face pressure force is made up of the earth and fluid pressure acting on the face of the machine. Microtunneling machines are designed with the intent to be operated in a “pressure-balance” fashion.

If the operational speed is too fast, the face pressure forces will increase, resulting in increased torque on the head causing the machine to stall. If the operational speed is too slow, the torque readings will be low and the material will tend to slough into the machine resulting in over excavation. This has the potential to manifest as settlement at the ground surface, depending on ground conditions and depth of cover.

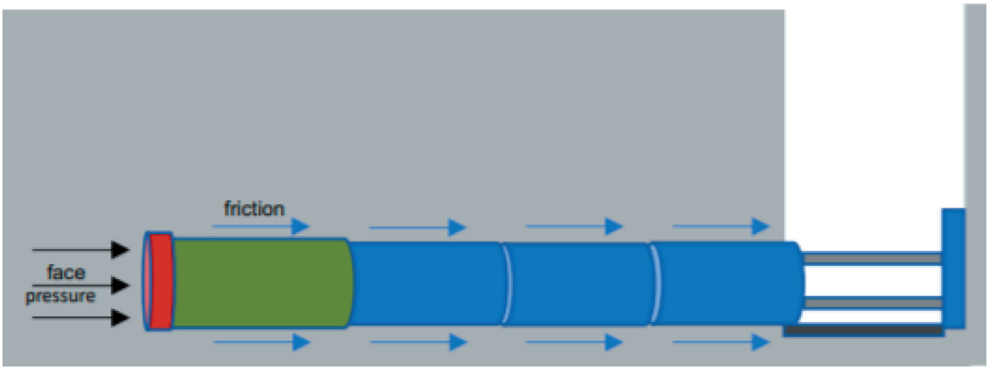

Fig. 3. Schematic view of the components of jacking forces

A great amount of effort has been spent trying to predict the face pressure forces. In general, field experience shows that face pressure forces represent a very low percentage of the overall jacking force. They are also the primary indicator used by the machine operator to determine advance rates. Therefore, the operator should constantly regulate the machine advance speed to control the force of pressure on the forehead.

Usually, two approaches are used for calculations: the analytical method and the statistical method.

For this article, the theoretical ramming forces have been calculated and then the obtained values have been compared with those measured on real projects during the microtunnelling work. Calculations of the theoretical necessary ramming force were carried out using several methodologies, most frequently used in the literature (ATV-DVWK-A 127 2000, Osumi 2000, Madryas et al. 2006, Kędracki 2008) are presented below.

3.1. Methodology according to H. Kalisz

The methodology according to H. Kalisz is expressed by the following equation:

$$T = \mu \cdot L\left[2\left(P_1 + P_2\right) + g\right] + G_h \ [\mathrm{kN}] \tag{1}$$

where:

T – calculated ramming force [kN],
μ – friction coefficient between the ground and the outer surface of the pipe [–],
L – ramming length [m],
P_1 and P_2 – vertical and horizontal ground pressure on 1 m of pipe [kN/m],
g – dead load of 1 m of pipe [kN/m],
G_h – head resistance of pipe [kN].

3.2. Paul's empirical equation

Paul's empirical equation has the following form:

$$P_P = S + \mu \cdot \left[2A(1+a) + R \right] \cdot L \, [\mathrm{kN}] \tag{2}$$

where:

P_P – calculated ramming force [kN],
S – cutting force at the perimeter of the pipe (for sand: 70–100 kN, for clays 50–70 kN),
a – ground pressure coefficient (for sand ~0.25, for clays ~0.50) [–],
μ – friction coefficient between the ground and the outer surface of the pipe [–],
L – ramming length [m],
A – load over the pipe [kN/m],
R – dead load of 1m of pipe [kN/m].

3.3. Methodology according to Stiegler

The methodology according to Stiegler is expressed by the equation:

$$P_S = \frac{\pi}{4} D_a{}^2 \cdot B + \pi D_a \cdot L \cdot M \, [\mathrm{kN}] \tag{3}$$

where:

P_S – calculated ramming force [kN],
D_a – diameter of ramming pipe [m],
B – head resistance of pipe [kN/m^2],
L – ramming length [m],
M – frictional resistance of the pipe against the surrounding ground:

$$M = \mu \left[\gamma_c \left(H_w + \frac{D_a}{2} \right) \cdot \left(\frac{2 + K_1 + K_2}{4} \right) + \frac{G}{4D_a} \right] \left[\mathrm{kN/m^2} \right] \tag{4}$$

where:

K_1 – ground active pressure coefficient according to Rankine:

$$K_1 = \mathrm{tg}^2 \left(45 - \frac{\theta}{2} \right),$$

K_2 – ground passive pressure coefficient according to Rankine:

$$K_2 = \mathrm{tg}^2 \left(45 + \frac{\theta}{2} \right),$$

μ – friction coefficient between the ground and the outer surface of the pipe [–],
H_w – depth of ramming carried out [m],
G – dead load of 1 m of pipe [kN/m],
γ_c – ground weight [kN/m^3].

3.4. Methodology according to the German guidelines ATV-DVWK-A 127

The solutions provided in the German guidelines (ATV-DVWK-A 127 2000), standard (PrEN 1916:1997), and industry recommendations (PJA 1995) were used for the calculation of ramming forces.

This methodology was also described in detail by Madryas et al. (2006).

4. Investment characteristics

To compare the presented methodologies, appropriate calculations of ramming forces were made for specific three crossings of the gas pipeline section. This section of the gas pipeline between Zdzieszowice and Brzeg has a nominal diameter of DN1000.

The gas pipeline route, 84 km long, runs entirely through the Opole Province. A total of 19 trenchless crossings were made in this section using the microtunnelling method with a GRP casing pipe with an external diameter of 1280 mm and a total length of almost 900 m.

4.1. Crossing the A4 motorway in Gogolin

The crossing installation was designed using microtunnelling technology, mainly due to the high level of groundwater table and its length of only 80 m. This disqualified the use of HDD technology. Figure 4 shows a schematic representation of the designed casing pipe trajectory.

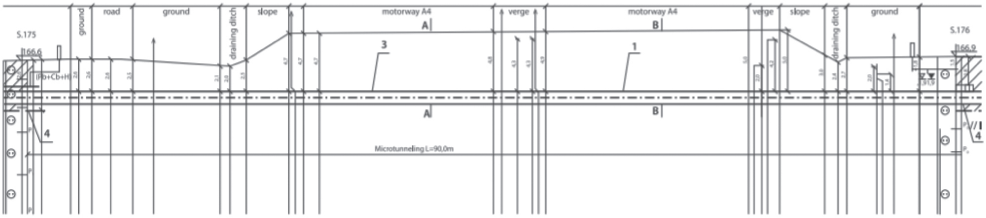

Fig. 4. Microtunnel route under the A4 motorway: 1 – axis of the pipeline, 3 – pipeline installed, 4 – starting/receiving chamber

Source: technical documentation of the project

Geological conditions along the microtunnel route

To recognize the geological conditions along the drilling route, it was decided to make two geotechnical drillings: No. 175 in place of the transmitting chamber and No. 176 in the receiving chamber (Fig. 5).

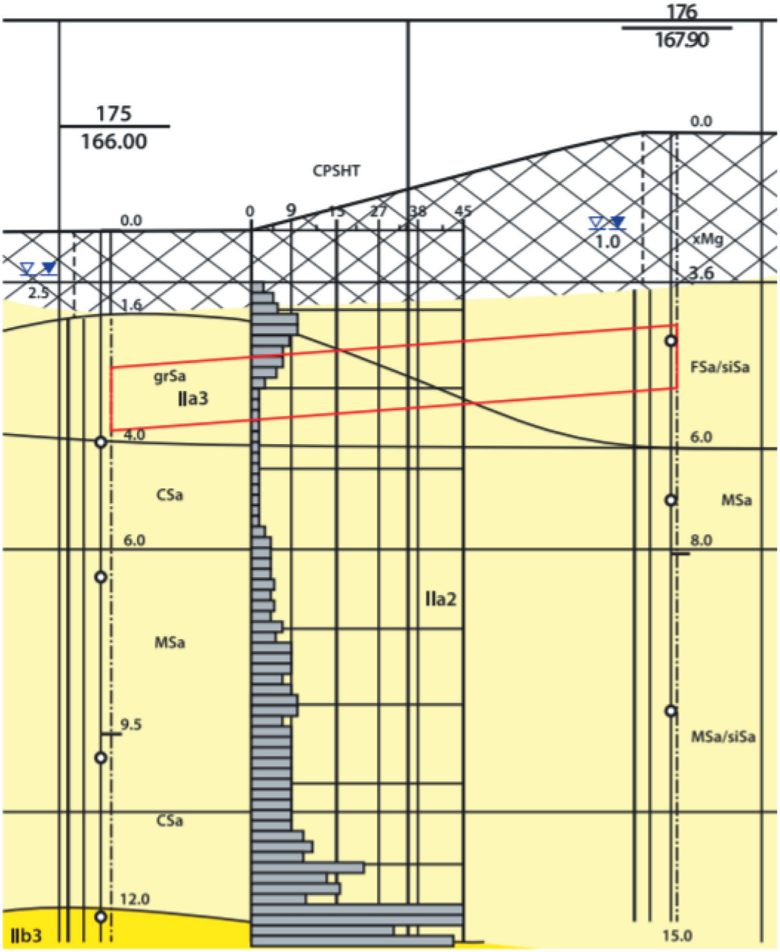

Fig. 5. Geological cross-section drawn on the basis of the 175 and 176 test drillings
Source: geotechnical documentation of the project

The basic parameters of layer IIa3, where the microtunnel was planned were:

- degree of compaction $I_D = 0.55$ [–],
- ground density 2.05 t/m^3,
- internal friction angle 38°.

4.2. Crossing of provincial road No. 423

The crossing installations, similarly, to the A4 Motorway, are designed in the microtunneling technology. The main reason for choosing this technology was the prevailing soil and water conditions and the length of 78.0 m. Figure 6 shows the course of the designed casing pipe trajectory.

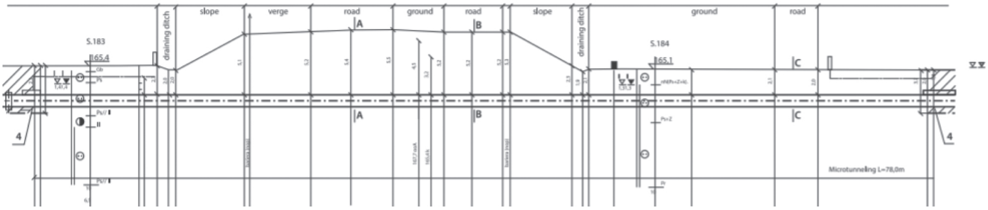

Fig. 6. Microtunnel route under DW423: 4 – starting/receiving chamber
Source: technical documentation of the project

Geological conditions along the microtunnel route

To identify the geological conditions along the drilling route, it was decided to make two geotechnical drillings: No. 183 in place of the transmitting chamber and No. 184 in the receiving chamber (Fig. 7).

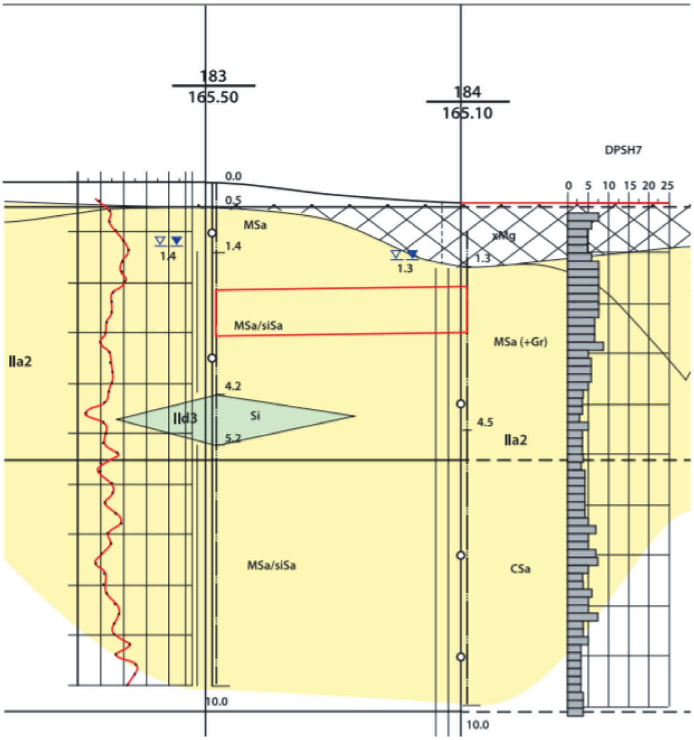

Fig. 7. Geological cross-section drawn on the basis of the 183 and 184 test drilling
Source: geotechnical documentation of the project

Basic parameters of layer IIa2:

- degree of compaction $I_D = 0.55$ [–],
- layer density 2.00 t/m^3,
- internal friction angle 33.3°.

4.3. Crossing of provincial road No. 414

The crossing installations are designed in the ramming technology. Due to the prevailing heavy ground conditions related to the necessity of drilling through hard plastic till with a tight ground water table, it was decided to replace the drilling technology with microtunneling. Figure 8 shows the course of the designed casing pipe trajectory.

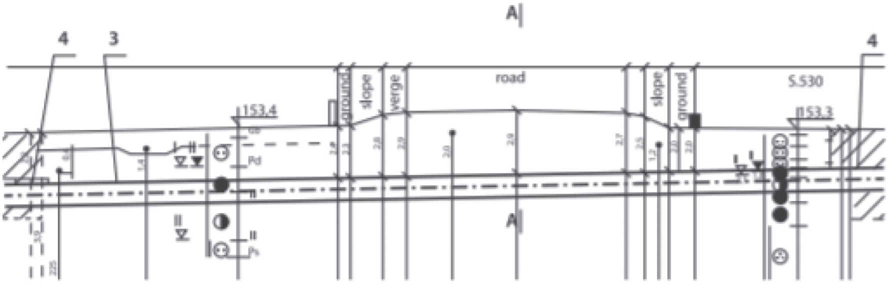

Fig. 8. Microtunnel route under DW414: 3 – pipeline installed, 4 – starting/receiving chamber
Source: technical documentation of the project

Geological conditions along the microtunnel route

To recognize the geological conditions along the drilling route, it was decided to make two geotechnical drillings: No. 529 in place of the transmitting chamber and No. 530 in the receiving chamber (Fig. 9). The drilling was made in layer IId3.

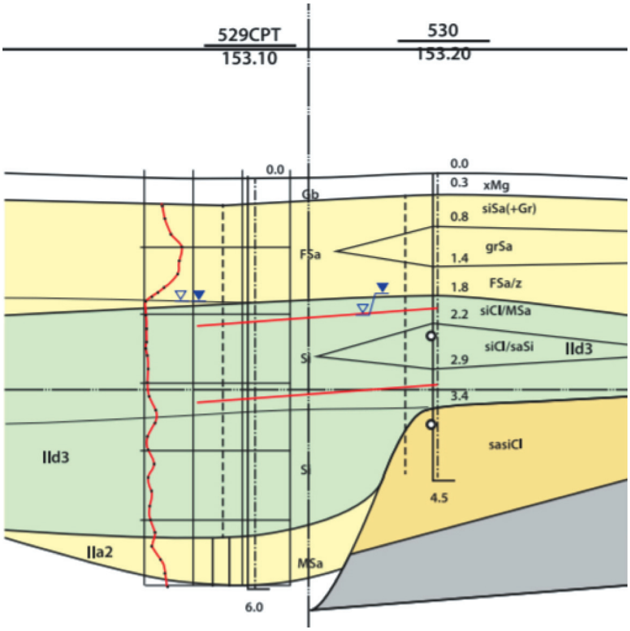

Fig. 9. Geological cross-section drawn on the basis of the 529 and 530 test drillings
Source: geotechnical documentation of the project

Basic parameters of layer IId3:

- degree of plasticity $I_L = 0.13$ [–],
- density 2.10 t/m^3,
- internal friction angle 14.4°.

5. Results of the ramming calculations

For the described methodologies, appropriate spreadsheets were created in Exel by the authors of the article. Tables 1–3 present the data entered into the spreadsheets and the obtained results of the ramming forces calculations.

Table 1

Values of individual components in the formula according to H. Kalisz

Crossing	μ	L	D	P_1	P_2	G_h	g	T
	Friction coefficient between the ground and the pipe surface [–]	Ramming length [m]	Pipe external diameter [m]	Vertical pressure of ground on 1 m of pipe [kN/m]	Horizontal pressure of ground on 1 m of pipe [kN/m]	Head resistance [kN]	Pipe weight [kN/m]	Calculated value of ramming force [kN]
Under A4 Motorway	0.10	80	1.280	34.00	20.04	281.34	4	1184
Under DW423	0.10	78	1.280	36.27	21.76	281.34	4	1218
Under DW414	0.10	41	1.280	28.40	22.72	200.96	4	637

Table 2

Values of individual components of the Paul's formula

Crossing	S	A	a	R	L	μ	P_P
	Cutting force on the pipe perimeter [kN]	Load over the pipe [kN/m]	Ground pressure coefficient [–]	Dead weight of 1 m of pipe [kN/m]	Ramming length [m]	Friction coefficient between ground and the pipe surface [–]	Calculated ramming force [kN]
Under A4 Motorway	80	71.80	0.25	4	80	0.1	1548
Under DW423	80	59.13	0.25	4	78	0.1	1264
Under DW414	50	63.36	0.50	4	41	0.1	846

Table 3

Values of individual components according to the Stiegler's formula

Crossing	μ	D	K_1	K_2	G	B	L	M	P_S
	Friction coefficient between the ground and the pipe surface [–]	Pipe outer diameter [m]	Active pressure coefficient [–]	Passive pressure coefficient [–]	Pipe weight [kN/m]	Head resistance [kN]	Ramming length [m]	Frictional resistance of the pipe against the surrounding ground [kN/m^2]	Calculated ramming force [kN]
Under A4 Motorway	0.10	1.280	0.231	4.19	4	281.34	80	19.50	6284
Under DW423	0.10	1.280	0.290	3.42	4	281.34	78	13.16	5760
Under DW414	0.10	1.280	0.600	1.65	4	200.96	41	8.86	1473

6. Industrial examples

On the basis of the crossings of the A4 motorway and two provincial roads, as part of the construction of the high-pressure gas pipeline in the Zdzieszowice – Brzeg section, the parameters of microtunnelling with a V15 VTP pressure sensor with recording frequency – one force measurement for each 0.252 m of microtunnel – were recorded. The sensor was placed on the hydraulic lines coming out of the hydraulic pumps responsible for the pressure given to the pushing stations. The pump unit is located in the control container. Figures 10–12 show diagrams of the recorded dependence, the ramming force on the ramming length for the abovementioned crossings.

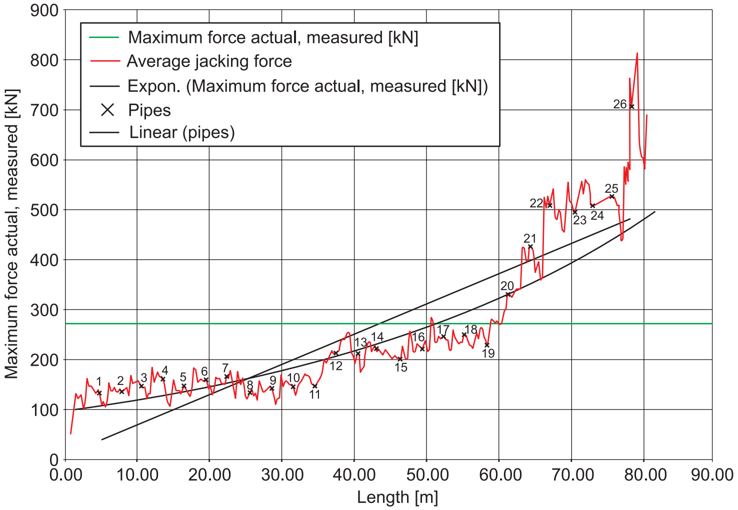

Fig. 10. Diagram of the dependence of the ramming force on the ramming length under the A4 motorway

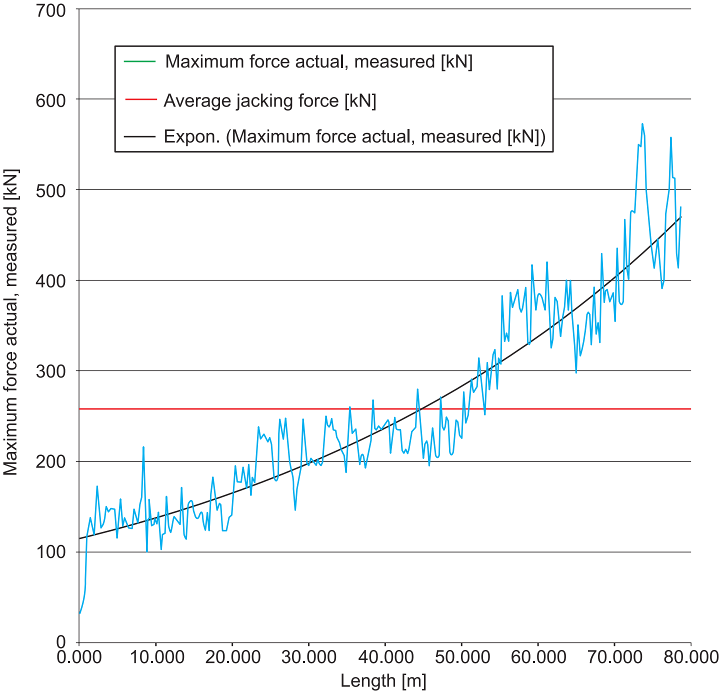

Fig. 11. Diagram of the dependence of the ramming force on the ramming length under DW423

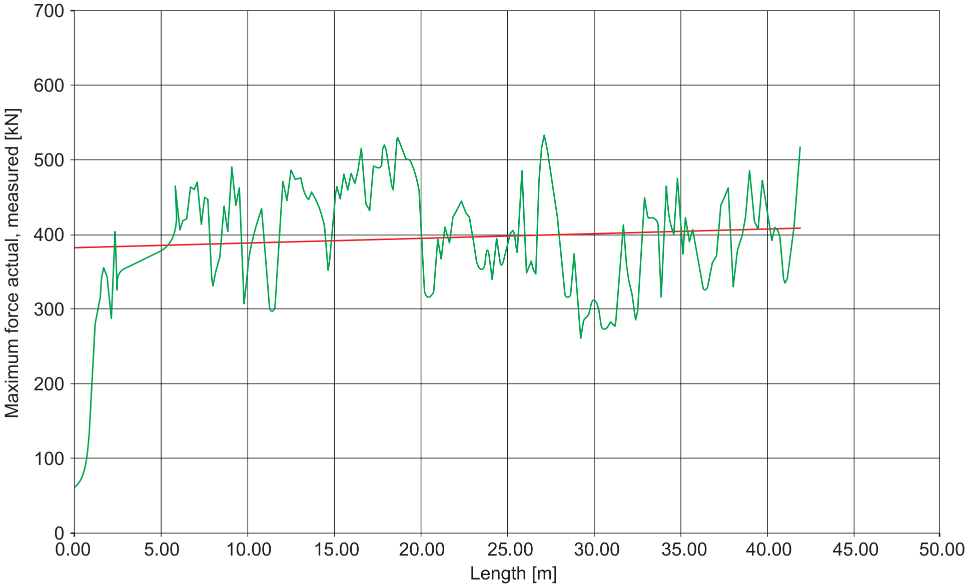

Fig. 12. Diagram of the dependence of the ramming force on the ramming length under DW414

Based on the analysis of the recorded parameters, the maximum values of the ramming force were read. The summary together with the comparison of the actual forces with the calculation forces is presented in Table 4 and Figure 13.

Table 4

Collected values of the ramming forces calculated and measured on the microtunnelling machine for selected projects

Location	Calculated ramming force acc. to Kalisz [kN]	Calculated ramming force acc. to Paul [kN]	Calculated ramming force acc. to Stiegler [kN]	Guidelines of ATV-DVWK-A 127 statistical method [kN]	Guidelines of ATV-DVWK-A 127 analytical method [kN]	Maximum force actual, measured [kN]
Under A4 Motorway	1184	1548	6284	2073	897	812
Under DW423	1218	1264	5760	2022	761	572
Under DW414	637	846	1473	1071	653	594

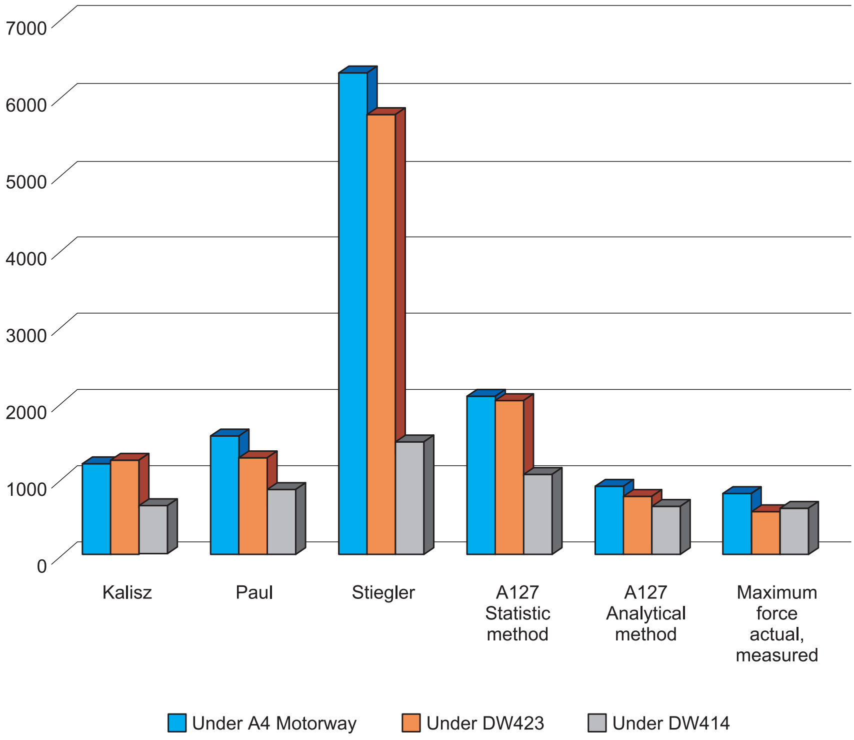

Fig. 13. Comparing calculation methods

7. Conclusions

The following conclusions can be drawn from the calculations carried out and the measured ramming forces:

1) The values of the forces calculated on the basis of the formulae provided are higher than the actual forces in all cases. The highest values were obtained based on the Steglier formula. The closest results to real values were obtained using the analytical methodology according to the ATV-DVWK guidelines.
2) The key factor determining the value of the friction force of the pipe against the ground is the friction coefficient. Taking the above into account, the authors of the article tend to calculate the theoretical installation forces for microtunneling purposes and estimate the key soil-dependent friction coefficient to be within the limits of 0.1 for non-cohesive soils and 0.2 for cohesive soils when used as a bentonite-based suspension lubricant.
3) Both over- and underestimation of the ramming force cause large problems at the stage of microtunneling machine selection. Too big machine is more expensive to operate, but a too small a machine may not be able to complete the work. Even more importantly, a correctly calculated ramming force has a decisive influence on the material and the type of the casing pipes (tubings) to be selected. Too big accepted value of this force may lead to the necessity of buying overly strong and usually more expensive tubing. On the other hand, too low a value may cause it to crash during installation.
4) Due to the fact that the drilling works were carried out in the 12/12 h system. Each time on the second day after the break, the jacking force increased by approx. 10–15%. In one case, when work was interrupted for 48 hours, the jacking force increased by 105 kN, i.e., by over 20% in relation to the force recorded before the work stoppage. It was undoubtedly the effect of the adhesion force, i.e., the pipe sticking to the hole wall. When adding another jacking pipe, significantly smaller jumps in pushing force were noted. Bearing this in mind, it is recommended to carry out microtunneling work without interruption, i.e., continuously 24/24 hours.

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