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Research paper

Optimization of innovative design solutions in geotechnical engineering

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Abstract: The demands placed on industry today are increasingly challenging and demanding. To meet these challenges, designers, contractors, and technology managers are constantly looking for effective solutions. Industry has always thrived on new technologies and innovations to achieve better results, so it is critical to undertake new developmental research to simulate and test new technological proposals. In this paper, the author describes a new direction in civil engineering technology that interdisciplinary couples solutions known to the bridge industry with geotechnical aspects in the technology space and the possibility of implementation in the construction industry. The author proposes the application of prestressing together with technological aspects of this solution to diaphragm walls, which are not only a temporary housing but also the foundations of a new investment. Thanks to this solution it is possible, among other things, to resign from one level of diaphragm expansion of diaphragm walls, which translates into cost optimization. It is an innovative approach to designing and most of all constructing the load-bearing structure, which directly influences the technological optimization of selected issues of completing the underground parts of the investment. Additionally, the presented solution contributes to the balanced execution of the investment by reducing the use of materials and construction equipment. The author discusses technological, execution and implementation problems related to the application of innovative solutions in construction companies together with examples of cost optimization. The author presents the results of conducted research with application of the proposed solution in the implementation of the underground commercial investment.

Keywords: cost optimization, deep excavation, geotechnical engineering, innovation, prestressing structures, technology

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1. Introduction

Innovative approaches to technology development have always been a topic frequently discussed in the scientific community. Additionally, industry stakeholders are interested in this topic. This is good news for those involved in technology development in engineering. There is a tendency for the representation of people dealing with scientific issues to meet the needs of the market. In Poland, there are more and more research projects that involve not only university staff, but also employees who are daily associated with work in industry [1]. These kinds of trends give the main idea that it is necessary to develop new technologies for many reasons. Firstly, newly emerging regulations pay special attention to ecology. It is impossible to develop technologies that are not conducive to increasing ecological efficiency. For several years, the number of the so-called Green Building has been strongly developed [2]. This shows an increased awareness, especially of large contractors, of the need to reduce the carbon footprint and to propose "tailor-made" solutions [3]. Green solutions are known not only in the space of material solutions such as the production of cement with reduced carbon footprint [4], or the use of solutions that can recover energy using building materials adapted for this purpose [5]. It becomes more and more important to use ecological construction solutions, which e.g. minimize CO_2 emission. The introduced standards of exhaust gas emissions have become part of the construction sites for good, which significantly translates into ecological aspects, as heavy construction equipment used for several months of the investment on the construction site emits huge amounts of environmentally harmful CO_2 [6]. Another very important issue is the development of technology aimed at reducing the execution time of individual tasks. This is, of course, the main task for contractors, because the reduction of time to complete a particular contract task directly translates into financial savings [7]. Thus, each contractor tries to use proven methods and technologies to minimize the risk of contract failure. What if current technology developments have been achieved in parallel by all bidders? Where to look for new solutions to become competitive? Is it possible to implement new technology that meets today's expectations, maintains minimal risk, and increases cost effectiveness? These are questions that certainly arouse a lot of emotion, as well as controversy, because many parties claim that it is impossible in the coming years to find a new technology that would increase the currently accepted as standard efficiency. The author will try to present the concept of a new solution that may come closer to answering the above questions. This article presents the concept of prestressing the diaphragm wall constituting the excavation casing, which will allow to resign from the necessity to use additional casing strut. Additionally, thanks to prestressing it is possible to reduce the amount of classical reinforcement needed for the reinforced concrete section. The author will pay attention to the technological aspects such as the speed of investment implementation and freedom of operation inside the facility, which optimizes time and costs.

2. Current approach

The question posed essentially concerns two areas of implementation, namely the design and execution of the underground parts of the project. The design part is certainly related to geotechnical issues, but the execution part, in addition to requirements specifically related to geotechnics, boils down to agile management of material deliveries, coordination of execution work, optimal use of equipment, and control of ongoing processes [8]. In each of these spaces, the parties involved use known and proven methods to complete the project as designed [9].

This article mainly covers the realization of the underground in dense urban development due to the complexity of the work and the possibility of adaptation of innovative solutions, by the clarity of the effectiveness of the results. By the realization of the underground the author means the execution of the shoring of a deep excavation with the use of diaphragm walls, the execution of the bottom slab and the intermediate floors of the underground floors. This kind of work can be performed using known methods of realization of underground part of the building such as top&down or celling method [10]. In each of these methods, the idea of realization of the underground comes down to the challenge of maintaining adequate stability of the structure. This requires the use of struts in the form of steel struts or ground anchors. In both cases, the introduction of additional wall support, reduces the displacement of the shoring and preserves its stability, which significantly affects safety. The proposed method can be used in other, unconventional types of investments where resigning from one strut level or reducing the amount of traditional reinforcement is effective. This allows the stability of the shoring to be maintained without the use of struts and anchors. Giving up these types of materials not only saves money by not using them, but more importantly, the lack of struts in the excavation space significantly streamlines the work. The lack of ground anchors is also a saving due to the lack of payment to the manager of the neighbouring plot, who does not have to agree to their use [11].

2.1. Known ways to implement undergrounding of buildings and their limitations

A well-known practice increasingly used for civil engineering projects is the use of the "Design and Build" formula. This formula is more and more often used not only for public procurement, but also for private contracts. This is convenient not only for the investor, who can treat a given order as a package of works, which binds him to the contractor with one contract, but it is also a convenient solution for the contractor himself, who can independently undertake the design work using his "know-how" and original solutions. All the risk in this type of approach is on the side of the contractor, who must have an independent design unit and implementation department. The biggest advantage is the simplification of contact procedures between the designer and the contractor, because they are usually units operating within one company. In both cases, the formula "Design and Build" and "Build" general contractors have one main indicator that can be used in negotiations – the margin. The design procedure, the materials used, the methodology for conducting the project, and the technology selected accordingly are generally similar for each contractor. Differences in procedure are minor and have little impact as a negotiating value. Of course, a properly selected and organized team is able to work more efficiently and effectively, making it possible to be competitive. However, this has the consequence of increasing costs, as training and development of the team as well as specialists represent a significant cost.

This is met by the need to change the existing methodology of organizing the course of investment projects. The most competitive and noteworthy part that can be changed in the current approach is technology [12]. The solution proposed by the author significantly influences the time of investment realization, thus the real value of realized contract. This kind of approach becomes a new argument in negotiating the final value of the contract, because it is not necessary to reduce the margin imposed, but to maintain the markup while reducing operating costs. The limitation of using new technology is the potential risk of not having a significant amount of implementation. However, today's simulation methods are so advanced that with knowledge and experience, it is possible to simulate a new case using numerical methods [13]. Advanced mathematical models can describe a given computational case very precisely, so that the obtained results are convergent in an implementation sense to the actual results. In the following parts of the paper, the author presents the proposed solution performed using numerical methods, which provide a feasible simulation for the construction site.

3. Proposed innovative technological approach

In this paper, the author suggests an alternative solution that allows the contractor to present a significantly competitive bid against competitors which are using popular solutions. There are several well-known and widely used methods of implementing the underground part of a project using slurry walls. Particularly in the case of multiple underground floors, the use of slurry walls is justified due to the simultaneous use of slurry walls as an excavation casing. This kind of view of slurry walls as an excavation enclosure while functioning as a building foundation is invaluable in the implementation of projects in urban areas, where structures are located around the project that cannot be disturbed by implementing a deep excavation. In such cases, it is common to use the floor method in various variants: full, hybrid. In addition, these approaches are mixed in order to implement foundation work as efficiently as possible.

All such approaches are based on a scheme:

– Creation of walls leading to slurry walls;
– Deepening the soil fissure within them while filling with bentonite;
– Placing a prefabricated reinforcement basket in the bentonite-filled soil crack;
– Concreting the diaphragm wall using contractor technology.

This is followed by deepening the excavation within the diaphragm walls to the level of strutting needed, depending on the given design and technological concept. Here three basic types are used to ensure the stability of the slurry wall excavation shoring: strut floors, struts or ground anchors. It is also necessary to mention the top&down technology, which is much less frequently used, due to greater schedule and cost risks. This method is based on the simultaneous construction of underground and above-ground floors. Prior to the completion of the underground part, all the heavy lifting is based on temporary columns located in the carrels. Once the underground part is completed, the temporary columns are removed, and the weight of the entire project is taken over by the target foundations in the form of diaphragm walls, jetties and a foundation slab. The top&down method also uses systems to ensure the stability of the excavation shoring similarly to the methods described above. Figure 1 shows the traditional approach to completing the underground of a project using steel struts.

Fig. 1. An example of a commonly used approach for implementing the underground part of a project based on the use of steel struts [14]

The methodology described by the author retains an analogous framework, but optimizes one process that is very costly in terms of materials and technology – ensuring the stability of the trench shoring. We are talking about maintaining stability by using a system of prestressing the trench shoring, which will allow stability without the need for additional strutting, which shows cost savings in terms of materials, but also translates into technological efficiency due to the open space inside the trench shoring. As a result, the execution of construction work can be carried out more efficiently with a low level of risk.

This innovative concept is the prestressing of a shear wall in different variations, depending on the given design situation (Fig. 2). It is possible to have linear or non-linear prestressing tendons at different spacings using appropriate prestressing steel. A natural consequence of the prestressing aspect is the reduction of the required amount of traditional reinforcement resulting from the calculation of the reinforced concrete structure.

The concept presented above can, in some cases, help optimize the cost of the implemented investment through material savings and time gains resulting e.g. from the lack of need to assemble and disassemble steel struts. The implementation aspect seems relatively easy in the design and execution context due to the simple in general principle of

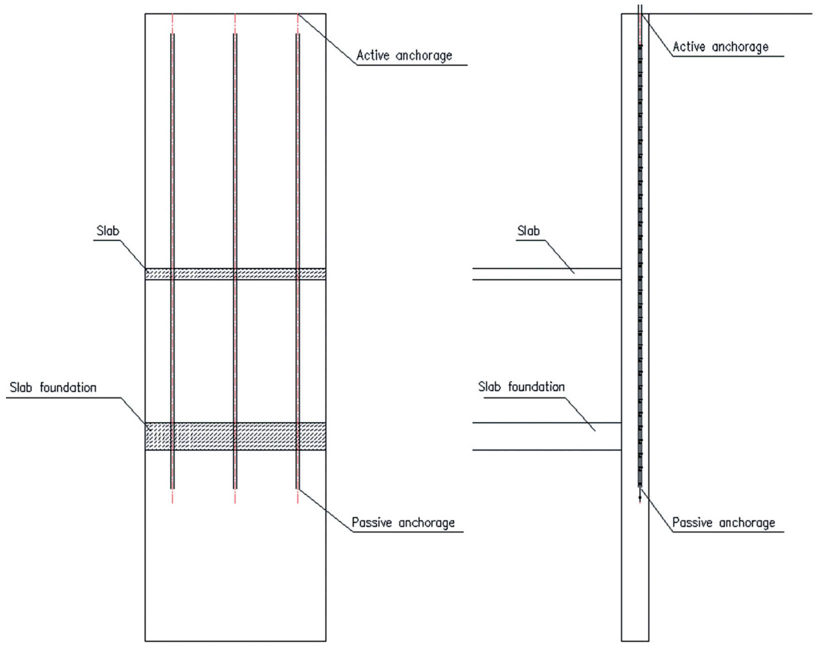


Fig. 2. Cross sections of the method described for one section of the shear wall with three prestressing tendons installed. In the presented case, prestressing tendons were installed linearly, i.e. parallel to the external wall face [own source]

prestressed structures. However, it is important to actually implement the concept on the construction site in the light of the applicable regulations, especially in the context of the well-established methods of managing the execution of construction works. It would be very beneficial to consider the issue in the context of value engineering [15]. This is the subject of the author's research, and in this article the author focuses only on technical, methodological and theoretical issues.

In most studies of technical structures, it is necessary to check whether the assumptions made will contribute to obtain the intended results. For this purpose, it is very helpful to simulate certain phenomena [16]. Assuming appropriate assumptions and knowing the basic laws governing a given phenomenon, many threads can be iteratively analysed, thus saving time and without creating a prototype, it is possible to check the validity of the application of the considered solution. To check the validity of the use of the described technology, the author used the finite element method. A model was prepared describing ground conditions and a diaphragm wall with parameters most commonly used in Poland. Basic information on the modelling of the proposed solution is presented below, since the main purpose of the article is to draw attention to the cost and technological aspects. The author conducts numerical research on the possibility of fast analysis of the proposed solution due to the limitations of the available computer software.

The parameters adopted for the calculations are presented in Tables 1–3.

Table 1. Material parameters accepted for analysis: concrete [own source]

Concrete class	C	30/37	
Young's modulus	E	34077.00	MPa
Poisson's ratio	µ	0.20	–
Shear modulus	G	14199.00	MPa
Compression modulus	K	18932.00	MPa
Nominal weight	γ	25.00	kN/m^3
Mean density	ρ	2400.00	kg/m^3
Strength	fc	35.00	MPa
Nominal strength	fck	35.00	MPa
Tensile strenght	fctm	3.21	MPa
Tensile strenght	fctk.05	2.25	MPa
Tensile strenght	fctk.95	4.17	MPa
Bond strength	fbd	3.37	MPa
Service strength	fcm	43.00	MPa
Fatigue strength	fcd.fat	17.06	MPa
Tensile strenght	fctd	1.50	MPa

Table 2. Parameters of the material accepted for analysis: soil with mathematical model Hardening soil [own source]

E 50 ref	25.00	MPa
E oed ref	25.00	MPa
Eur ref	75.00	MPa
E0	250.00	MPa
K	66667.00	kN/m^2
γ	21.50	kg/m^3
φ	32.00	MPa
c'	12.00	kN/m^2
m	0.60	–
G0 ref	68.00	MPa
µ	0.30	–

Table 3. Material parameters accepted for analysis: prestressing steel Y1860 [own source]

Class of prestressing steel		Y1860	
Young's modulus	E	195000.00	MPa
Poisson's ratio	μ	0.30	
Shear modulus	G	75000.00	MPa
Compression modulus	K	162500.00	kN/m^2
Nominal weight	γ	78.50	kg/m^3
Mean density	ρ	7850.00	kg/m^3
max. Thickness	t-max	18	mm
Relaxation	ρ (1000 h)	2.50	%
Yield stress	fy	1600.00	MPa
Compressive yield	fyc	1600.00	MPa
Tensile strenght	ft	1860.00	MPa
Compresive strength	fc	1860.00	MPa

Based on the basic principles of the finite element method, a geometric model, a material model, and a load model were created. The geometric model was formed by 3D cuboid objects. The material model adopted the parameters shown in Tables 1–3. The load model is the most complicated because the load is induced by three independent environments:

– Soil pressure on a diaphragm wall.
– Ground load of work equipment.
– Water pressure behind the diaphragm wall.

It is extremely difficult to create a consistent environment that allows loads to be applied according to the design situation. It is extremely difficult to describe the soil medium correctly. Currently the best-behaved mathematical model describing the soil medium is the Hardening Soil model, which uses several modules to describe the soil [17]. To best reflect the real work at the interface between reinforced concrete structure and soil, it is necessary to introduce in a numerical way a new material commonly called interface. Introduction of interface has been widely described, among others, in [18].

The following interface values were assumed for the analysis: $k_N = 0.1$; $k_T = 0.1$. These calculations were based on the known and described relationship [18]:

$$k_N = \min\left(\frac{E_1}{h_2}; \frac{E_2}{h_2}\right) \cdot \frac{A}{\sqrt{\text{Neq}\varepsilon}} \tag{3.1}$$

where:

E_1 – modulus of element made of material 1
E_2 – modulus of the contacting element of the second material
h_1 – dimension of element with modulus E_1
h_2 – dimension of element with modulus E_2

A – arbitrary factors (default $A = 10e - 4$) set by numerical experience

Neq – total equation number in the system

ε – precicion (machine dependent small number

The results of the analysis indicate that the applied prestressing is very effective, which makes it possible to maintain stability without the use of a single strut level. A load of 5 kN/m^2 was assumed as the ground load (Fig. 3).

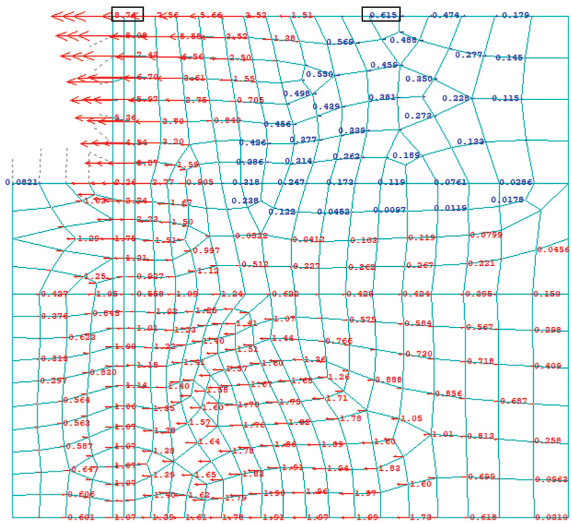


Fig. 3. Horizontal displacement results demonstrating the effectiveness of the proposed method for a 6.0 m deep excavation with a cantilevered static arrangement [own source]

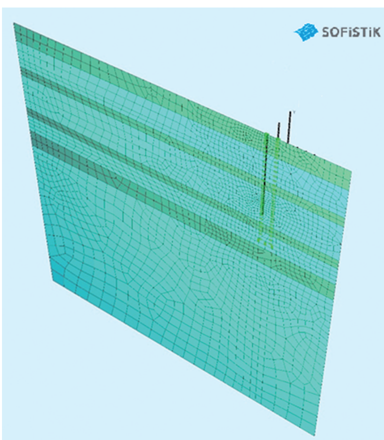


Fig. 4. Geometric model with material model for one section of the diaphragm wall [own source]

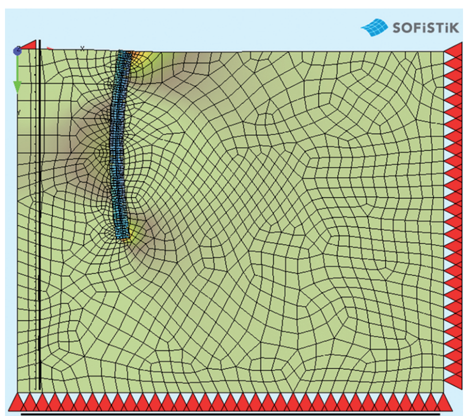


Fig. 5. Operation of the prestressing algorithm with a linearly specified prestressing tendon located on the excavation side [own source]

4. Pricing and estimation of working time

Cost optimization as well as technology optimization is widely studied and applied in various construction industries due to its overt economic benefits [19]. This section will present an optimization proposal using the innovative technology described in this paper. The implementation technology assumes the installation of passive anchoring along with cable channel and prestressing tendon into the reinforcement basket of the shear wall. In the next steps the reinforcement cage will be inserted into the previously dug soil crack. This is followed by concreting of the section. Active anchoring is installed after the upper part of the executed slurry wall has been scraped off. Scraping of the top layer of the diaphragm wall is necessary due to poor quality of concrete. After scraping off the top layer of the slurry wall, the active anchor is installed to the reinforcement of the slurry wall cap. Once the diaphragm and the diaphragm wall reach sufficient compressive strength, a compressive force is introduced, and the force is locked in the active anchorage. Innovative activities such as those described in this article should be considered comprehensively with value engineering, which is capable of estimating real financial and technological benefits accurately and objectively [20].

First, there are 4 basic situations that influence the final cost of the described project:

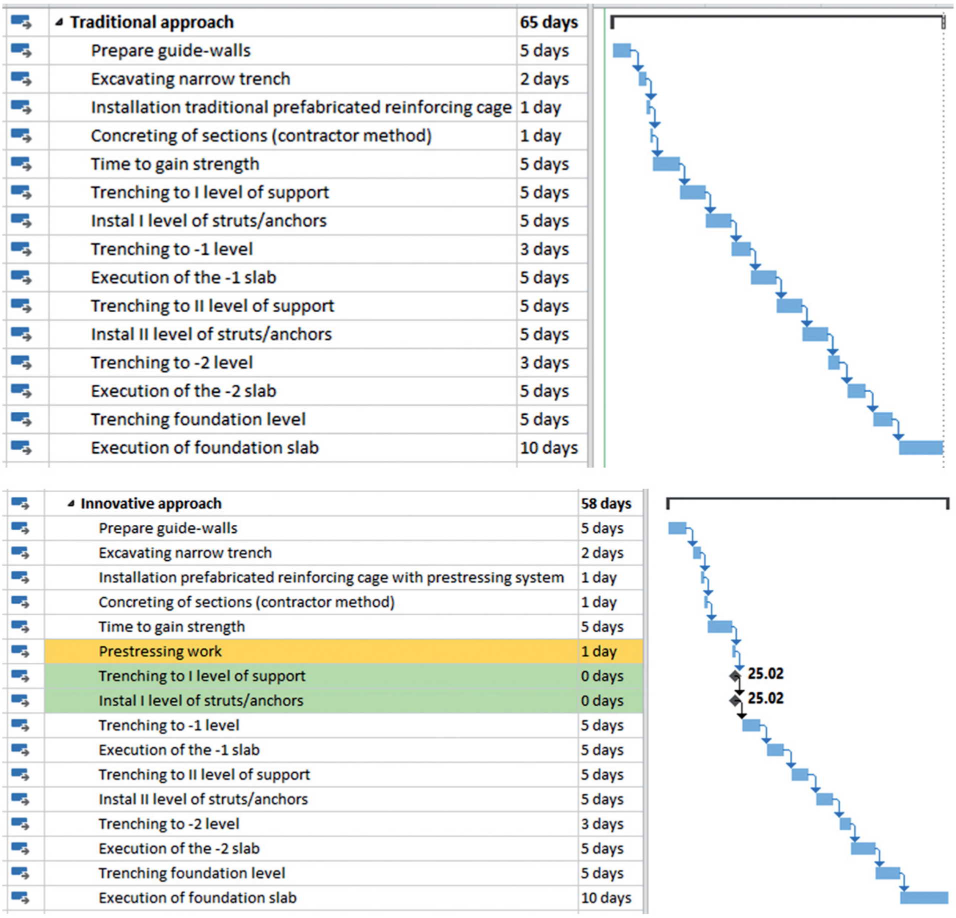
- Cost of execution of one slurry wall section with traditional approach.
- Cost of execution of a slurry wall with the use of pre-stressing while reducing the amount of traditional reinforcement.
- Cost of performing a wall with the use of pre-stressing but considering the lack of additional steel strut.
- Cost of performing a wall with the use of pre-stressing considering the benefits of reducing the amount of traditional reinforcement and the benefits of technological optimization (open excavation, faster construction of the building underground).

In the bridge industry, the design and construction optimization of spans has been known for years because of the clear financial benefits of the projects. Cost sensitivity analyses conducted as early as 2013 showed that a maximum 20% increase in steel costs leads to an 11.82% increase in costs, while a 20% increase in concrete costs increases costs to 4.20%, or 2.8 times less. The results also indicate that the characteristics of cost-optimized bridges are somewhat affected by different economic scenarios for steel and concrete costs, so when the cost of steel increases, the amount of concrete increases; surprisingly, the change in the amount of concrete is almost insensitive to its increasing price [21].

Cost optimizations for prestressed bridges are carried out by many representatives of science. Particularly interesting results are contained in studies based on genetic algorithms, which can be successfully applied in the optimization of bridge projects using the prestressing concept [22]. The economic aspects of prestressing in bridge construction are described in detail in [23].

To obtain reliable results, a good direction is to investigate the above 4 examples based on current market offerings. Due to the research aspects of the work, in this section the author will focus on option 4 to indicate the direction of implementation of the presented concept. The author will not rely on specific prices because the valuation of innovative technologies is unitary in nature, and it is difficult to gather a sufficient database in a research manner to conduct econometric or statistical studies. The main advantages of the presented concept are shown below in a general way. Author plans further research to obtain detailed results.

An example is the implementation of a slurry wall for 3 underground floors. The schedule optimization is shown at Fig. 6.



Traditional approach	**65 days**
Prepare guide-walls	5 days
Excavating narrow trench	2 days
Installation traditional prefabricated reinforcing cage	1 day
Concreting of sections (contractor method)	1 day
Time to gain strength	5 days
Trenching to I level of support	5 days
Instal I level of struts/anchors	5 days
Trenching to -1 level	3 days
Execution of the -1 slab	5 days
Trenching to II level of support	5 days
Instal II level of struts/anchors	5 days
Trenching to -2 level	3 days
Execution of the -2 slab	5 days
Trenching foundation level	5 days
Execution of foundation slab	10 days

Innovative approach	**58 days**
Prepare guide-walls	5 days
Excavating narrow trench	2 days
Installation prefabricated reinforcing cage with prestressing system	1 day
Concreting of sections (contractor method)	1 day
Time to gain strength	5 days
Prestressing work	1 day
Trenching to I level of support	0 days
Instal I level of struts/anchors	0 days
Trenching to -1 level	5 days
Execution of the -1 slab	5 days
Trenching to II level of support	5 days
Instal II level of struts/anchors	5 days
Trenching to -2 level	3 days
Execution of the -2 slab	5 days
Trenching foundation level	5 days
Execution of foundation slab	10 days

Fig. 6. Technology optimization results for the described issue [own source]

Values shown in the Fig. 6 are examples only, as they are meant to show the idea and main concept of the method. Adopted durations of individual activities are exemplary and based on community interview and are intended to indicate the disproportion between individual durations. The adoption of durations of individual tasks in the implementation of the underground of the building is reasonable only based on a specific example of the project.

5. Conclusions

This paper presents the concept of prestressing diaphragm walls as a way out of the known methods of construction of underground buildings. The author touches upon the issues of cost optimization, thus its influence on the economic value of the implemented projects. The author presents general numerical results, which show the effectiveness of the method and its practical use based on schedule optimization. The main advantages of the presented solution are: reduction of the amount and use of steel and concrete construction materials in the implementation of the excavation shoring and, therefore, reduction of energy, thereby reducing emissions of pollutants to the environment; increase in the tightness of the cross-section of the excavation shoring, translating into an increase in the water-permeable parameters of the shoring and a decrease in the inflow of ground water into the excavation a large or even complete elimination of tensile strain in the concrete and, consequently, a reduction in the amount of reinforcement in the concrete cross-section due to strain; elimination or reduction of scratching of the trench shoring; increase in the durability of the trench shoring; reduction in the required thickness of the shoring while maintaining the same stiffness, which translates into no. limitation of the building volume due to the required thickness of the trench shoring, decrease in horizontal deformation of the trench shoring resulting in a decrease in vertical displacement of the area behind the trench shoring resulting in the safety of the buildings in the vicinity, increase in the spacing between temporary shoring struts, increase in the range of operation of the cantilevered trench shoring scheme up to greater heights (trench depths) without the need for shoring. The aforementioned advantages of the presented solution generate many financial benefits in the form of savings in the materials used by being able to dispense with steel struts or ground anchors. In addition, savings may result from a reduction in the amount of traditional reinforcement needed to transfer bending moments by using prestressing reinforcement. Precise values in financial terms are an area for further research by the author to present a specific case study.

The concept presented in this paper is a very complicated and multi-parametric issue and therefore a number of tests must be carried out before the results obtained can be considered reliable. Further research directions will be related to the dimensioning of individual structural elements and the development of a design methodology for a prestressed diaphragm wall.

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Optymalizacja innowacyjnych rozwiązań konstrukcyjnych

Słowa kluczowe: geotechnika, innowacje, optymalizacja kosztów, sprężenie, technologia

Streszczenie:

Wymagania stawiane dziś przez przemysł są coraz bardziej ambitne i wyśrubowane. Aby wyjśc naprzeciw tym wyzwaniom, projektanci, wykonawcy oraz zarządzający technologiami, nieustanie szukają efektywnych rozwiązań. Od zawsze przemysł rozwija się dzięki nowym technologiom i innowacjom, które pozwalają osiągac lepsze wyniki, zatem niezwykle istotne jest podejmowanie nowych badań rozwojowych, które pozwolą symulowac i sprawdzac nowe propozycje technologiczne. W niniejszym artykule autor opisuje nowy kierunek rozwoju technologii w zakresie inżynierii lądowej, który interdyscyplinarnie sprzęża rozwiązania znane mostownictwu z aspektami geotechnicznymi w przestrzeni technologii i możliwości wdrożenia w przemyśle budowlanym. Postawione zagadnienie dotyczy zasadniczo dwóch obszarów realizacji, czyli projektowania i wykonawstwa podziemnych części inwestycji. Częśc projektowa z pewnością związana jest z zagadnieniami geotechnicznymi, lecz częśc wykonawcza oprócz wymagań dotyczących konkretnie geotechniki, sprowadza się do zwinnego zarządzania dostawami materiałów, koordynacji prac wykonawczych, optymalnego wykorzystania sprzętu oraz kontroli prowadzonych procesów. Autor proponuje zastosowanie sprężenia wraz z aspektami technologicznymi tego rozwiązania do ścian szczelinowych, stanowiących nie tylko tymczasową obudowę, ale także fundamenty nowej inwestycji. Dzięki temu rozwiązaniu możliwe jest m.in. zrezygnowanie z jednego poziomu rozparcia ścian szczelinowych, co przekłada się na optymalizację kosztów. Innymi zaletami są: ograniczenie ilości i wykorzystania materiał ów konstrukcyjnych stali i betonu przy realizacji obudowy wykopu i w związku z tym ograniczenie energii, tym samym emisji zanieczyszczeń do środowiska; zwiększenie szczelności przekroju obudowy wykopu, przekładające się na zwiększenie parametrów wodoprzepuszczalnych obudowy i spadek napływu wody gruntowej do wnętrza wykopu; duże lub nawet całkowite wyeliminowanie rozciągania w betonie, a w konsekwencji redukcja ilości zbrojenia przekroju betonowego ze względu na rozciąganie, likwidacja bądź ograniczenie zarysowania obudowy wykopu, zwiększenie trwał ości obudowy wykopu, zmniejszenie wymaganej grubości obudowy, przy zachowaniu identycznej sztywności, co przekłada się na brak ograniczenia kubatury budynku ze względu na wymaganą grubośc obudowy wykopu, zmniejszenie poziomych odkształceń obudowy wykopu wpływających na zmniejszenie przemieszczeń pionowych terenu za obudową wykopu, przekładające się na bezpieczeństwo zabudowy w sąsiedztwie, zwiększenie rozstawów pomiędzy rozparciem tymczasowym wykopu, zwiększenie zakresu działania wspornikowego schematu pracy obudowy wykopu do większych wysokości (głębokości wykopu) bez konieczności stosowania podparcia.

Jest to innowacyjne podejście do projektowania i przede wszystkim wykonania ustroju nośnego, które bezpośrednio wpływa na optymalizację technologiczną wybranych zagadnień realizacji podziemnych części inwestycji. Dodatkowo prezentowane rozwiązanie przyczynia się do zrównoważonego prowadzenia realizacji inwestycji za sprawą ograniczenia w użyciu materiał ów oraz sprzętu budowlanego. Autor porusza temat problemów technologicznych, wykonawczych oraz wdrożeniowych związanych z zastosowaniem innowacyjnych rozwiązań w przedsiębiorstwach budowlanych wraz z przykładami optymalizacji kosztowej. Autor przedstawi wyniki prowadzonych badań wraz z przykładami zastosowania proponowanego rozwiązania w realizacji podziemia inwestycji kubaturowej.

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