

Investigation of the Ultimate Excavation Depth for Pits Supported by a “Diaphragm Wall”

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Abstract. A diaphragm wall is one of the most widely used types of retaining structures for vertical excavation support in dense urban environments, where deformation control and the stability of the soil mass are of critical importance. Despite the extensive application of diaphragm wall technology, the problem of selecting an optimal wall thickness—considering excavation depth, temporary support configuration during construction, and site-specific geotechnical conditions—remains highly relevant for both designers and researchers.

The aim of this study is to determine the relationship between diaphragm wall thickness and the maximum achievable excavation depth, as well as to assess the influence of different support schemes (cantilever and temporarily braced) on the stress–strain behavior of the structure. The investigation considers wall thicknesses ranging from 300 mm to 1000 mm, which correspond to typical parameters for medium- and large-depth urban excavations. Numerical modeling was performed using the finite element method, accounting for nonlinear soil behavior, staged construction, and soil–structure interaction.

The analysis shows that increasing the diaphragm wall thickness has a limited effect on reducing bending moments, particularly in the cantilever configuration. In contrast, the use of a temporary strut significantly alters the deformation pattern and enables an increase in excavation depth at each construction stage. For the examined range of wall thicknesses, the maximum depth of a single excavation stage is approximately 1.0 m for the cantilever scheme, whereas the introduction of a temporary strut allows this value to increase to as much as 2.4 m, depending on wall thickness and



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the stiffness of the bracing element. Thus, the key factor governing the achievable excavation depth is not the wall thickness itself, but rather the structural support scheme employed during construction.

The obtained results have practical significance for optimizing excavation technologies in complex urban environments. Increasing the excavation depth at a single stage reduces the number of construction cycles, shortens the overall construction duration, and lowers the risks associated with deformations of retaining structures and adjacent buildings. The findings demonstrate that a rational combination of diaphragm wall thickness and temporary bracing elements can enhance the efficiency and safety of the construction process without substantially increasing the material consumption of the retaining structure.

Keywords: diaphragm wall; open-cut method; excavation depth; retaining wall thickness; stress–strain state; excavation support systems.

PROBLEM STATEMENT AND REVIEW OF PREVIOUS RESEARCH

In modern urban construction, the need to develop underground structures under complex engineering–geological conditions and within densely built-up areas is becoming increasingly common. One of the key stages of such construction is the open-cut excavation supported by a diaphragm wall, which may serve either as a temporary retaining structure or as a permanent load-bearing and enclosing element of the building. To minimize wall deformations, it is essential to determine its rational parameters, particularly the wall thickness, which directly influences the stress–strain behavior of the structure and the maximum feasible excavation depth at each construction stage.

Ukrainian design requirements for ensuring the stability of excavation retaining structures are specified in DBN V.2.1-10:2018 and DBN A.3.1-5:2016. The study also considers the provisions of the American standard ASCE 7-22 “*Minimum Design Loads and Associated Criteria for Buildings and Other Structures*” and FHWA-NHI-05-046. *Earth Retaining Structures* (2005) which regulates loading conditions, stability requirements, and general principles of safe underground structure design. However, neither Ukrainian nor American standards provide a methodology for determining the maximum excavation depth as a function of diaphragm wall thickness, which highlights the need for further research.

Thus, the relevant research task is to identify the ultimate excavation depth achievable by the open-cut method when the excavation is supported by a diaphragm wall, taking into account the wall thickness and the configuration of temporary bracing elements installed within the excavation.

PURPOSE OF THE STUDY

The objective of this study is to identify the relationship between the maximum achievable excavation depth and the thickness of the diaphragm wall under two support

configurations: a cantilever system and a system incorporating temporary struts.

MAIN STUDY

In the context of investigating the influence of diaphragm wall thickness and temporary support schemes on the ultimate excavation depth, it is essential to consider the technological aspects of diaphragm wall construction. described Makhynia, O., & Yaremko, N. (2025). *Modern methods of construction of tunnel-type underground structures using the open-cut method* The construction process involves forming a guide trench, followed by the excavation of individual panels under the protection of a bentonite or polymer slurry. This slurry ensures the stability of the trench walls during excavation and prior to their subsequent filling with structural material; therefore, its properties must meet established requirements to guarantee the stability of the surrounding soil mass.

The diaphragm wall is constructed in discrete panels whose geometric dimensions and excavation sequence depend on the capabilities of the excavation equipment and the need to maintain continuous concreting. Stop-end elements are used to isolate adjacent panels; they must withstand unilateral pressure from the fresh concrete and prevent leakage between panels described Makhynia, O., & Yaremko, N. (2023). *Influence of earthmoving machine parameters on the structural design of barrette piles*. Their removal requires consideration of material friction, the vacuum effect at the lower end, and the self-weight of the element; extraction is performed after the initial setting of the concrete. Prior to concreting, the sand content in the slurry is controlled and must not exceed 4% near the bottom of the trench, which is critical for ensuring the quality of the structure and the uniform displacement of the slurry

Incorporating these technological aspects into the overall research methodology is essential, as the conditions under which the diaphragm wall is formed—slurry properties, concreting quality, and the structural behavior at early stages—determine its subsequent stiffness, deformation characteristics, and

ability to resist bending moments. These factors directly influence the maximum permissible excavation depth and the effectiveness of different support schemes, which are key parameters in the design of excavations in complex urban environments.

When precast reinforced-concrete elements are used, the construction technology of the diaphragm wall has its own specific features associated with the need to ensure installation accuracy and the reliability of panel joints. The soil excavation for placing precast panels is carried out to a depth exceeding the panel length by 15–20 cm, which enables precise positioning of the element and the formation of the required protective layer. A layer of cast-in-place concrete at least 0.5 m thick is placed at the bottom of the prepared trench, into which the lower part of the panel is embedded, ensuring its fixation and the transfer of loads to the foundation soil.

After installing the precast panel, the inner gap on the excavation side is filled with a soil mixture that can be easily removed during subsequent excavation stages described Halenko, Ye., & Makhynia, O. (2025). *Modelling the manufacturing process of underground wall structures using the gravitational extrusion method*. The outer gap, in contrast, is filled with a hardening cement-based grout, which ensures reliable contact between the panel and the soil mass and increases the overall stability of the structure. Open wedge-shaped joints between panels are constructed progressively as the excavation deepens, and they are subsequently filled with concrete or shotcrete to provide spatial rigidity and structural continuity. Closed tongue-and-groove joints are filled with concrete immediately after the installation of adjacent panels, with concrete placed from the bottom upward until it appears at the surface, ensuring the absence of voids and uniform compaction.

In the numerical modeling of the excavation supported by a diaphragm wall, the soil mass was considered homogeneous within each layer, using generalized physical and mechanical properties representative of typical urban engineering–geological conditions described CIRIA C760. *Embedded Retaining Walls – Guidance for Economic Design* (2015).

Soil behavior was modeled with nonlinear characteristics, but creep, rheological effects, and long-term deformations were not considered. The soil–structure interaction was represented using a contact model without accounting for potential local defects in concreting, material heterogeneity, or technological deviations during wall construction. described Bowles, J. E. *Foundation Analysis and Design*. 5th ed. (1996) and Das, B. M. *Principles of Foundation Engineering*. 8th ed. (2015).

The diaphragm wall was modeled as a continuous element with uniform thickness along its entire depth, without considering joints, construction seams, deviations from verticality, or stiffness irregularities. In the braced configuration, the strut was modeled as a perfectly rigid element with a prescribed axial stiffness, without accounting for possible deformations of connection nodes, bending of the strut, or buckling effects.

The staged excavation process was simulated by sequentially removing soil layers, with each stage forming a new working condition for the retaining structure. In practice, the depth of each excavation stage depends on the support scheme of the wall.

The excavation process is performed step by step, and each stage follows a specific technological sequence:

1. Removal of the first soil layer
2. Transition to the next excavation stage
3. Reaching the limiting depth for cantilever behavior
4. Installation of a temporary strut (for the braced scheme)
5. Further excavation after strut installation
6. Repetition of the cycle for subsequent levels (if required)

For the cantilever support scheme, the depth of a single excavation stage is typically limited to 0.8–1.2 m, since increasing the unsupported height of the wall leads to a sharp rise in bending moments and horizontal displacements. In the braced scheme, by contrast, once a temporary strut is installed at a given elevation, deeper excavation stages of 2.0–2.4 m can be performed, reducing the

number of cycles and accelerating construction.

Each stage includes: removal of a soil layer of specified thickness, redistribution of earth pressure on the wall, formation of a new free surface, and, if necessary, installation of support elements. At early stages, the load on the wall is minimal, but as the excavation deepens, bending moments, horizontal displacements, and overall stiffness requirements increase. Therefore, staged excavation is critically important for accurate numerical modeling, as it allows the actual stress–strain state of the wall to be reproduced at each depth increment.

All models were developed under plane-strain conditions, which is a typical assumption for the cross-sectional analysis of excavations but does not account for three-dimensional effects such as non-uniform loading along the wall length or the influence of corner zones. It was also assumed that the slurry used during diaphragm wall construction fully ensures trench stability and that the concreting quality meets all regulatory requirements.

Thus, the modeling was based on idealized conditions for both the structure and the soil mass, allowing the analysis to focus on the key parameters of the study—wall thickness, support configuration, and their influence on maximum bending moments and the ultimate excavation depth.

The soil mass was modeled as a multilayer medium using the elastoplastic Mohr–Coulomb constitutive model, which captures nonlinear soil behavior, shear strength parameters, and deformation characteristics. This approach provides sufficient accuracy for engineering tasks related to determining bending moments, horizontal displacements, and evaluating the stability of the excavation wall. The soil–structure interaction was represented using a contact model with the possibility of partial separation and sliding, enabling realistic simulation of the wall’s behavior under non-uniform earth pressures.

All numerical calculations, stress–strain modeling, bending-moment diagram generation, and analysis of the ultimate

excavation depth were performed using the DeepEX 2026 software package, which specializes in the design of retaining systems for deep excavations. The use of this software made it possible to account for staged excavation, nonlinear soil behavior, soil–structure interaction, and the influence of different support schemes on structural performance. DeepEX 2026 provided a unified computational environment for comparing cantilever and braced configurations, ensuring consistent and reliable results across the entire range of wall thicknesses.

The study included a comparative analysis of two approaches to the behavior of retaining structures in deep excavations: the cantilever scheme and the scheme with a temporary strut. This comparison made it possible to evaluate the influence of structural stiffness and support conditions on the stress–strain state of the wall and on the maximum permissible excavation depth.

Identical input data were used for comparing the three excavation configurations.

Soil conditions:

1. Unit weight and density
 - $\gamma = 21 \text{ kN/m}^3$ — natural unit weight of the soil.
 - $\gamma_{\text{bulk}} = 19 \text{ kN/m}^3$ — bulk unit weight in natural conditions (may correspond to partially saturated sand).
 - $\gamma' = 11 \text{ kN/m}^3$ — submerged (effective) unit weight below the groundwater level.
2. Shear strength parameters
 - $c' = 0 \text{ kPa}$ — drained cohesion is absent, which is typical for sandy soils.
 - $\varphi' = 34^\circ$ — internal friction angle characteristic of dense or medium-dense sand.
3. Poisson’s ratio
 - $\nu = 0.35$
4. Lateral earth pressure coefficients
 - $K_0\text{NC} = 0.440807$ — coefficient of lateral earth pressure at rest for normally consolidated soil (NC).
 - $n\text{OCR} = 0.5$ — exponent describing the dependence of K_0 on the overconsolidation ratio (OCR).

- $K_0 = K_0NC \cdot OCR^{n_{0cR}}$ — formula for determining the actual K_0 value.

Structural characteristics of the reinforced-concrete diaphragm wall:

Type of reinforced-concrete section The model employs a standard monolithic reinforced-concrete section without additional reinforcement layers or special configurations. The reinforcement is assumed to be uniform along the wall height, which corresponds to typical diaphragm walls constructed using the slurry trench method.

For modeling the diaphragm wall, heavy concrete of class C35/45 was used in

accordance with DSTU 9208:2022, which meets modern requirements for retaining structures of deep excavations.

Reinforcement of the diaphragm wall was modeled using hot-rolled reinforcing steel of class A500C, in accordance with DSTU 9130:2021, which satisfies current standards for reinforced-concrete structures operating under complex stress conditions.

At the next stage, the ultimate excavation depth and the critical bending moment for the cantilever-supported diaphragm wall were investigated (Fig.

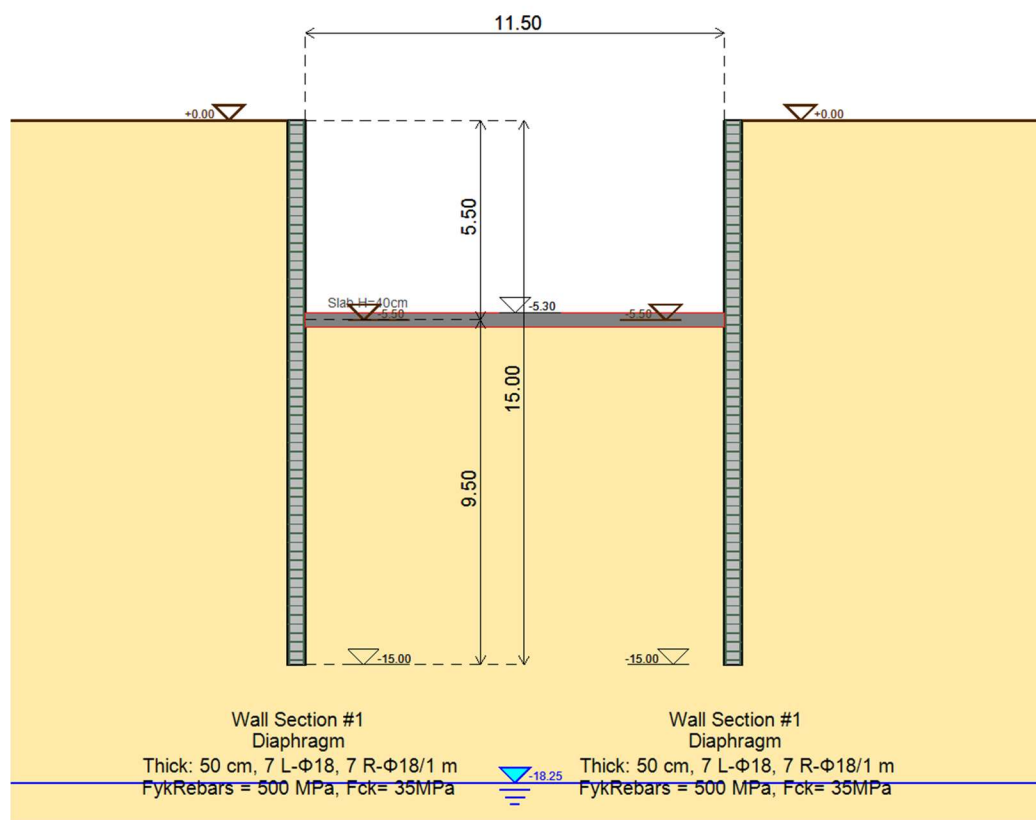


Fig. 1. Example of a cantilever-supported diaphragm wall in an excavation.

Рис. 1. Приклад схеми консольно закріпленої стіни в ґрунті у котловані з невеликими розмірами.

As a result of the numerical modeling, the relationships between the maximum bending moment in the diaphragm wall and the excavation depth under the cantilever support scheme were identified (Fig. 2).

The analysis of the maximum bending-moment dependencies on excavation depth for the cantilever configuration revealed

that, as the excavation deepens, the bending moment in the wall increases for all wall-thickness variants. However, the rate of increase and the absolute values differ significantly depending on the structural stiffness. For thin walls (300–400 mm), the maximum bending moments reach approximately 180–250 kN·m, whereas for

thicker walls (700–1000 mm), they increase to 500–720 kN·m. This indicates that increasing wall thickness substantially enhances structural stiffness, which in turn reduces deformations and increases the proportion of load carried by the wall in the form of bending moments. At the same time, the shape of the curves shows that as wall thickness increases, not only do the bending moments grow, but the depth at which the maximum moment occurs also increases: thicker walls are capable of functioning at greater depths before reaching a critical state.

The moment–depth curves illustrate the full distribution of bending moments along the wall, allowing assessment not only of the peak

value but also of the structural behavior throughout the entire depth range. It is evident that for thin walls, the bending moment rises rapidly and reaches its maximum at a shallower depth, whereas thicker walls exhibit a more gradual increase in bending moments and can operate at significantly greater depths without losing load-bearing capacity. This means that increasing wall thickness indeed allows for a greater maximum excavation depth under the cantilever scheme, but it simultaneously leads to a substantial increase in bending moments, which must be carefully considered when verifying the structural strength of the section.

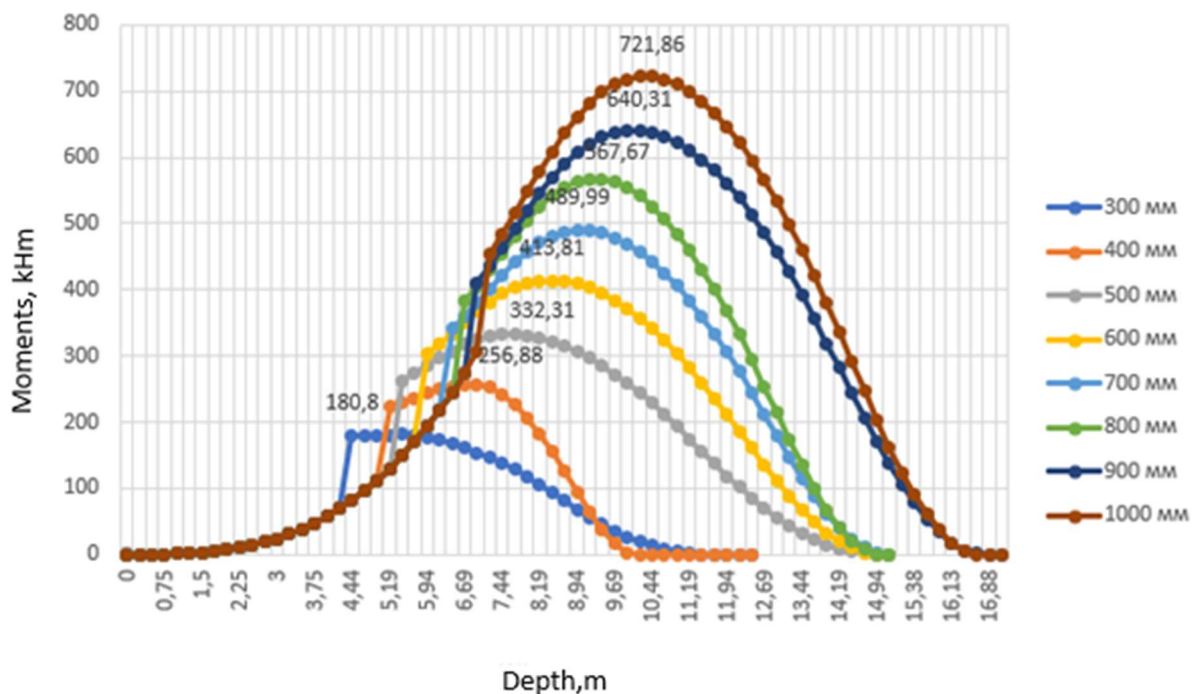


Fig. 2. Bending-moment distributions in the cantilever-supported diaphragm wall at different excavation depths for various wall thicknesses.

Рис. 2. Залежності згинального моменту в конструкції консольно закріпленої стіни при різних глибинах котловану невеликого розміру для різних товщин стіни

When evaluating the optimal wall thickness in terms of the “depth–bending-moment–material consumption” relationship, it becomes evident that the most rational range corresponds to medium-thickness walls (approximately 500–700 mm). Within this range, the increase in achievable excavation depth is significant, while the growth of bending moments remains controlled and

proportional. Thicker walls (800–1000 mm) allow for even greater excavation depths, but at the cost of a sharp increase in bending moments, reaching 600–720 kN·m, which requires substantially heavier reinforcement and increases construction costs. Thin walls (300–400 mm), on the other hand, quickly reach their limiting bending moments and do

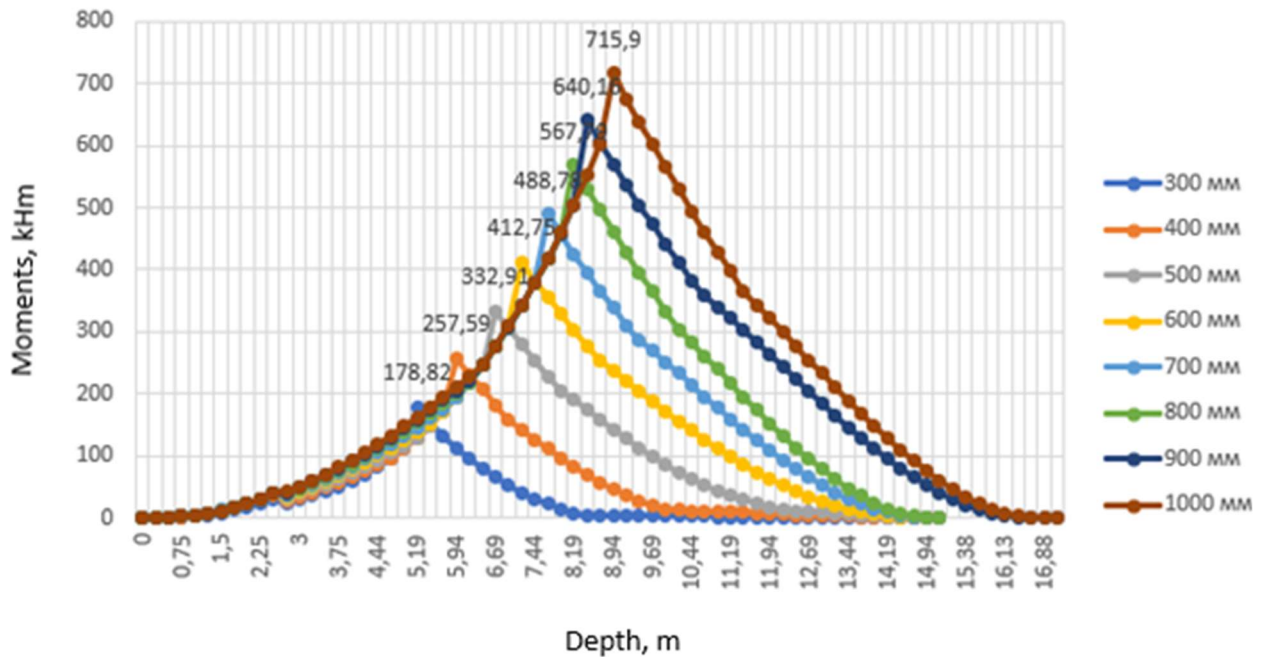


Fig. 4. Bending-moment distributions in the braced diaphragm wall at different excavation depths for various wall thicknesses in a small-scale excavation.

Рис. 4. Залежності згинального моменту в конструкції стіни із тимчасовою розпіркою при різних глибинах котловану невеликого розміру для різних товщин стіни

The analysis of the dependencies of maximum bending moments in an excavation supported by a temporary strut demonstrates that the structural behaviour of the retaining wall differs fundamentally from that of a cantilever system. For each strut diameter, an individual relationship was identified, reflecting the variation of the maximum bending moment in the wall as a function of excavation depth. As the excavation progresses, the bending moment increases, reaches a peak, and subsequently stabilises or changes at a lower rate. The maximum moment values for different strut diameters range from approximately 200–250 kN·m for the smallest diameters to about 700–720 kN·m for a 1000 mm strut, with the corresponding depths of peak moment formation occurring at approximately 8–9 m.

In the numerical model of the strutted excavation, a steel strut of type 60Б1 was used. This element is a hot-rolled I-beam with a height of 600 mm and a unit weight of 19 kg/m. It serves as a temporary structural member designed to resist compressive forces between opposite excavation walls during soil removal.

In the computational model, the strut carries only compressive forces, which corresponds to its actual behaviour. This means that the element does not transfer tensile forces but provides stabilisation of the walls and reduces their horizontal displacements. The use of the 60Б1 profile ensures an optimal balance between stiffness and weight, providing sufficient load-bearing capacity while minimally affecting the construction sequence. For the first calculation, the strut was installed at a depth of 2.5 m below the ground surface.

Unlike an excavation without a strut, where the wall behaves as a cantilever and resists the full lateral earth pressure, the introduction of a strut redistributes part of the load, altering the internal force distribution within the wall. As a result, the maximum bending moments develop at different depths and exhibit a different growth pattern. It is evident that increasing the strut diameter (and thus its stiffness and load-bearing capacity) enables the wall to operate safely at greater excavation depths. It was also observed that for identical or similar maximum bending moments in the wall (e.g., within the range of 500–700 kN·m),

the strutted system allows for a significantly greater excavation depth compared with the cantilever system. In other words, the bending moments remain at comparable levels but occur at larger depths, which is a clear advantage of the strutted configuration.

From the standpoint of structural optimisation, the strutted system enables achieving greater excavation depths for the same or nearly the same bending moment values in the wall compared with the cantilever system. This indicates that, for given soil conditions and wall parameters, the use of a strut is a more efficient method of increasing excavation depth than simply increasing wall thickness. As the strut diameter increases, its stiffness improves, allowing for better control of wall deformations and more favourable redistribution of internal forces. However, excessive increases in strut size lead to higher bending moments in the wall and increased construction costs. Therefore, from an engineering perspective, a balanced solution should be sought—one that provides the required excavation depth while maintaining acceptable bending moments and rational strut parameters. Combined with the results for the excavation without a strut, the obtained relationships (Fig. 2) clearly demonstrate that changing the structural system (introducing a strut), rather than merely increasing wall thickness, is the key factor for achieving safe and economically justified increases in excavation depth. For similar bending moment levels, significantly greater depths can be reached, which is a major advantage of the strutted system.

The variation of the strut installation depth does not affect the ultimate achievable excavation depth, since the decisive factor is not its exact position but the presence of the stiffening element itself, which alters the

structural behaviour of the wall. Whether the strut is installed at 2.0 m, 2.5 m, or 3.0 m, it performs the same function—limiting horizontal wall displacements and reducing bending moments in the mid-height region. This allows for increasing the excavation depth per stage but does not change the overall limiting depth, which is governed by wall stiffness, soil parameters, and the boundary conditions at the wall base.

Thus, varying the strut installation depth affects only the local distribution of stresses and deformations but is not a determining parameter for the maximum excavation depth. Changes in strut parameters have a mirrored effect on the permissible excavation depth, since the stiffness and load-bearing capacity of the strut directly determine the magnitude of horizontal pressure it can resist. Larger cross-sections, thicker flanges/webs, or higher stiffness allow the strut to transfer greater compressive forces between the excavation walls, thereby more effectively limiting horizontal displacements and bending moments in the wall. This enables deeper excavation stages without exceeding deformation limits. Consequently, increasing strut stiffness proportionally increases the achievable excavation depth, whereas reducing its parameters decreases load-bearing capacity and reduces the allowable depth.

Based on the conducted analyses, the dependencies of the limiting excavation depth on the thickness of the retaining wall were established for both the cantilever system and the system with a temporary strut (Fig. 5). It was found that for wall thicknesses ranging from 300 to 1000 mm, the maximum excavation depth varies from 4.44 to 7.23 m for the cantilever system, and from 5.15 to 8.85 m for the cantilever system with an additional temporary strut.

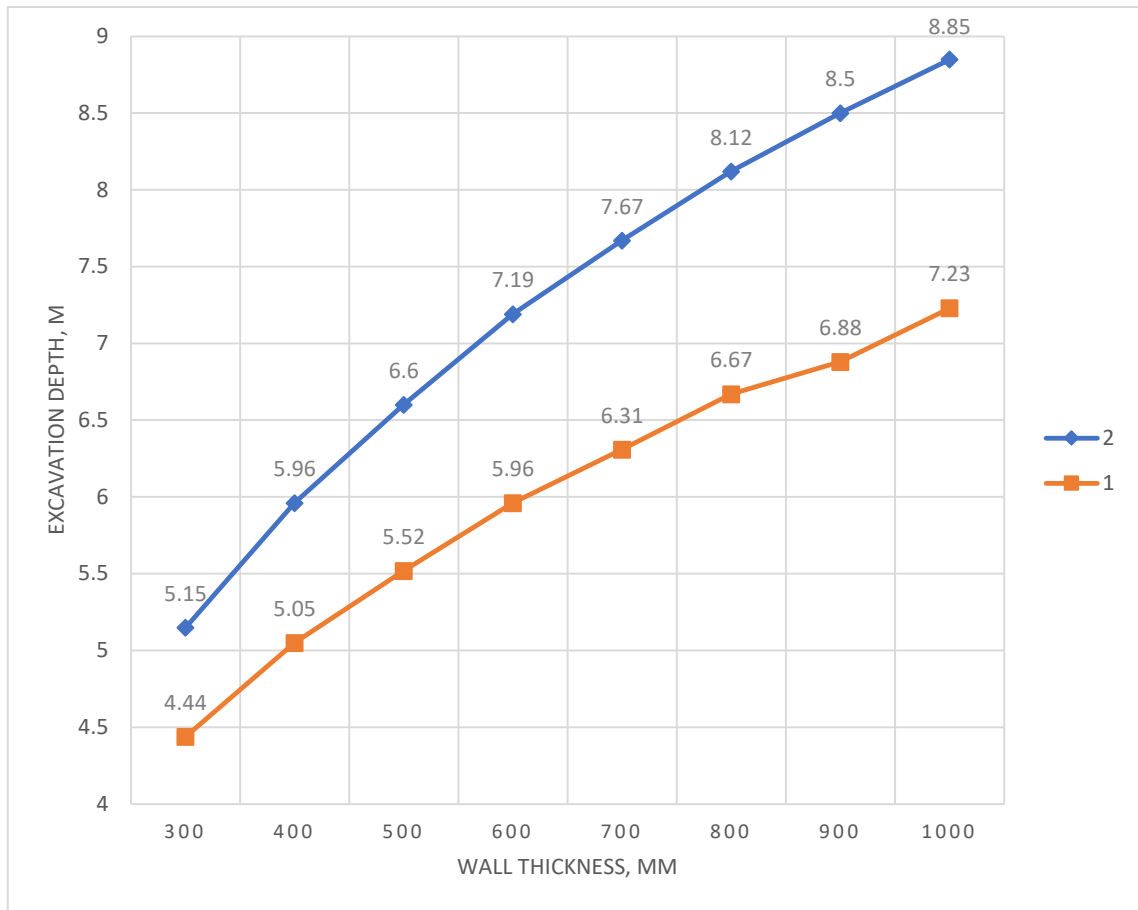


Fig. 5. Dependencies of the ultimate excavation depth on the thickness of the retaining wall in soil, where: 1 – cantilever wall support; 2 – the same configuration with an additional temporary strut.

Рис. 5. Залежності глибини стінки при порівнянні котловану із тимчасовою розпіркою та без неї.

CONCLUSIONS AND RECOMMENDATIONS

Within the framework of this study, a comparative analysis was performed for two structural configurations of the retaining system: an excavation developed in a cantilever scheme without additional stiffening elements, and an excavation supported by a temporary strut. The modelling results demonstrated that the introduction of a strut significantly alters the stress–strain behaviour of the wall and enables achieving substantially greater excavation depths while maintaining permissible bending moments and horizontal displacements. In contrast to the cantilever scheme, where the ultimate depth is governed by the attainment of the maximum allowable bending moment for a given wall thickness, the strutted scheme allows the same moment level

to be “shifted” to a greater depth, which represents a key advantage of this structural solution.

It is important to emphasise that the vertical position of the strut does not influence the final achievable excavation depth. Regardless of whether it is installed at 2.0 m, 2.5 m, or 3.0 m, the decisive factor is the presence of the stiffening element itself, which limits wall deformations and stabilises its behaviour. Changing the installation level affects only the local distribution of stresses but does not modify the ultimate depth, which is determined by soil parameters, wall stiffness, and the overall structural configuration.

It should also be noted that although the excavation depth increases proportionally with wall thickness, this increase is not linear. In the range of 300–600 mm, the depth increment is significant, whereas further thickening to 800–1000 mm yields only marginal benefits while

substantially increasing bending resistance demands and material consumption. Therefore, the selection of wall thickness should be based on identifying an optimal structural solution rather than simply enlarging the cross-section.

Thus, the comparison of the two schemes shows that for moderate excavation depths, the cantilever wall remains a rational solution, whereas for deep excavations, the decisive factor is the use of a temporary strut. The strut provides greater achievable depth, improved deformation performance, and a more efficient redistribution of loads.

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12. ДСТУ-Н Б В.2.1-29:2014 Настанова щодо проектування і улаштування заглиблених споруд способом стіна в ґрунті

та дозволяє збільшити глибину викопування ґрунту на кожному етапі. Для розглянутого діапазону товщин встановлено, що при консольній схемі закріплення «стіни в ґрунті» максимальна глибина одного етапу розробки котловану становить близько 1,0 м, тоді як при використанні тимчасової розпірки цей показник може зростати до 2,4 м залежно від товщини стіни та жорсткості розпірного елемента. Таким чином, ключовим фактором збільшення глибини викопування котловану є не стільки товщина стіни, скільки зміна схеми роботи конструкції.

Дослідження граничних глибин котловану при огороженні його «стіною в ґрунті»

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Анотація. «Стіна в ґрунті» є одним із найпоширеніших видів закріплення вертикальних стін у щільній міській забудові, де контроль деформацій та забезпечення стійкості ґрунтового масиву мають вирішальне значення. Незважаючи на широке застосування технології «стіна в ґрунті», питання оптимального вибору товщини стіни з урахуванням глибини котловану, схеми її кріплення на період розробки котловану та інженерно-геологічних умов залишається актуальним для проектувальників і дослідників.

Метою роботи є визначення залежності між товщиною «стіни в ґрунті» та максимальною глибиною викопування котловану, а також оцінка впливу різних схем закріплення (консольна та з тимчасовою розпіркою) на напружено-деформований стан конструкції. У дослідженні було розглянуто діапазон товщин стін від 300 мм до 1000 мм, що відповідає типовим параметрам для міських котлованів середньої та великої глибини. Моделювання виконано методом скінченних елементів із урахуванням нелінійної роботи ґрунту, стадійності розробки та взаємодії конструкції з основою.

Результати аналізу показали, що збільшення товщини «стіни в ґрунті» має обмежений вплив на зменшення згинальних моментів у конструкції, особливо у випадку консольної роботи. У той же час застосування тимчасової розпірки суттєво змінює характер деформацій

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