UDC УДК 624.155.39
IRSTI 67.11.29
RESEARCH ARTICLE

# DETERMINATION OF THE DIMENSIONS OF THE COMPACTED ZONE OF THE NEAR-PILE SOIL DURING PIT STAMPING

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**Abstract.** *The paper presents research results on the development of a method for predicting the dimensions of the compacted soil zone forming around a single pile when a pit for a local grillage is stamped after the pile has been driven. This method was developed for a new type of single-pile combined foundation that integrates the functions of a driven pile and a foundation in a stamped-out pit. The relevance of this research stems from the lack of existing solutions regarding pit stamping conditions within the peripile soil. The objective of the study is to derive fundamental formulas for determining the dimensions of the compacted soil zone during the pit stamping process. These solutions are based on the mass conservation equation for the peripile soil within the compacted zone before and after the pit is stamped. The study utilizes established calculations and techniques from mathematics, physics, and soil mechanics. Two variations of possible compacted zone configurations are considered. Analytical formulas were obtained that allow for the determination of the diameter and depth of the compacted zone (below the bottom of the pit), taking into account the density and moisture content of the peripile soil, as well as the dimensions of the driven pile and the pit stamped over the pile head. Comparative calculations performed using these formulas showed that the results are closely aligned, with the difference not exceeding 20%. The fundamental formulas include parameters for which recommendations must be developed based on experimental research. The method is recommended for use in engineering practice following experimental verification.*

**Keywords:** *near-pile soil, pile, stamp, stamping, tamping, pit, compacted zone*

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**https://doi.org/10.51488/1680-080X/2026.1-09**
Received 08 January 2026; Revised 14 February 2026; Accepted 27 February 2026

ӘОЖ 624.155.39
ҒТАМР 67.11.29
ҒЫЛЫМИ МАҚАЛА

# ҚАЗАНШҰҢҚЫРДЫ ШТАМПТАУ КЕЗІНДЕ ҚАДА МАҢЫНДАҒЫ ТОПЫРАҚТЫҢ ТЫҒЫЗДАЛҒАН АЙМАҒЫНЫҢ ӨЛШЕМДЕРІН АНЫҚТАУ

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**Аңдатпа.** *Зерттеулер нәтижесінде жалғыз қада маңындағы топырақта, қада қағылғаннан кейін оның үстіңгі бөлігінде жергілікті ростверкке арналған қазаншұңқырды штамптау кезінде қалыптасатын тығыздалған аймақтың өлшемдерін болжауға мүмкіндік беретін әдіс әзірленді. Әдіс қада мен штампталған қазаншұңқырдағы іргетастың функцияларын біріктіретін бір қадалы құрамдастырылған іргетастың жаңа түріне бейімделіп жасалған.Әдісті әзірлеудің өзектілігі қада маңындағы топырақта қазаншұңқырды штамптау жағдайына қатысты ұқсас шешімдердің болмауымен негізделеді. Зерттеудің мақсаты - қазаншұңқырды штамптау кезінде қада маңындағы топырақтың тығыздалған аймағының өлшемдерін анықтауға арналған негізгі формулаларды алу.Шешімдер тығыздалған аймақтағы қада маңындағы топырақтың штамптауға дейінгі және кейінгі күйіндегі масса сақталу теңдеуін қолдануға негізделген. Сонымен қатар математика, физика және топырақ механикасы салаларындағы белгілі тұжырымдар мен әдістер пайдаланылды. Топырақтың тығыздалған аймағының ықтимал пішіндерінің екі нұсқасы қарастырылды.Есептік формулалар алынды, олар қада маңындағы топырақтың тығыздығы мен ылғалдылығы көрсеткіштерін, сондай-ақ қағылған қаданың және қада үстінен штампталатын қазаншұңқырдың өлшемдерін ескере отырып, тығыздалған аймақтың диаметрін және оның тереңдігін (қазаншұңқыр түбінен төмен) анықтауға мүмкіндік береді.Ұсынылған формулалар негізінде салыстырмалы есептеулер жүргізілді. Нәтижелердің бір-біріне жеткілікті дәрежеде жақын екені және айырмашылығы 20%-дан аспайтыны анықталды. Әдістің негізгі формулаларының құрамына кіретін параметрлер бойынша ұсыныстар эксперименттік зерттеулер нәтижесінде әзірленуі тиіс.Әдіс инженерлік тәжірибеде оны эксперименттік тексеруден өткізгеннен кейін қолдануға ұсынылады*.

**Түйін сөздер:** *қада, қада айналасындағы топырақ, қазаншұңқыр, штамп, штамптау, тығыздап қалыптау, тығыздалған аймақ*

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**https://doi.org/10.51488/1680-080X/2026.1-09**
Алынды 08 қаңтар 2026; Қайта қаралды 14 ақпан 2026; Қабылданды 27 ақпан 2026

УДК 624.155.39
МРНТИ 67.11.29
НАУЧНАЯ СТАТЬЯ

# ОПРЕДЕЛЕНИЕ РАЗМЕРОВ УПЛОТНЕННОЙ ЗОНЫ ОКОЛОСВАЙНОГО ГРУНТА ПРИ ВЫШТАМПОВАНИИ КОТЛОВАНА

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**Аннотация.** *Изложены результаты исследований по разработке метода, позволяющего производить прогноз размеров уплотненной зоны грунта, формирующейся в околосвайном пространстве одиночной сваи при выштамповывании в нем котлована под локальный ростверк после забивки сваи. Метод разработан применительно к новому виду односвайного комбинированного фундамента, сочетающего в себе функции забивной сваи и фундамента в выштампованном котловане. Актуальность создания метода обусловлена отсутствием подобных решений применительно к условиям выштамповывания котлована в околосвайном грунте. Целью исследований является получение основных формул по определению размеров уплотненной зоны околосвайного грунта при выштамповывании котлована. Решения базируются на использование уравнения сохранения массы околосвайного грунта в уплотненной зоне до и после выштамповывания в нем котлована. Использованы также известные выкладки и приемы в области математики, физики и механики грунтов. Рассмотрены два варианты комбинации возможных форм уплотненной зоны грунта. Получены расчетные формулы, которые позволяют устанавливать диаметр уплотненной зоны и ее глубину (ниже дна котлована) с учетом показателей плотности и влажности околосвайного грунта, а также размеров забитой сваи и котлована, выштамповываемого поверху сваи. На основе представленных формул выполнены сравнительные расчеты, которые показали, что результаты по ним достаточно близки друг-другу и их разница не превышает 20%. В состав основных формул метода входят параметры, рекомендации по определению которых, должны быть выработаны на основе результатов экспериментальных исследований. Метод рекомендуются к использованию в инженерной практике после его экспериментальной проверки.*

**Ключевые слова:** *околосвайный грунт, свая, штамп, выштамповывание, вытрамбовывание, котлован, уплотненная зона*

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**https://doi.org/10.51488/1680-080X/2026.1-09**
Поступила 08 января 2026; Пересмотрено 14 февраля 2026; Принято 27 февраля 2026

**ACKNOWLEDGEMENTS/SOURCE OF FUNDING**

The study was carried out within the framework of the project "Development of technology for the production of works on the installation of strip pile foundations with grillages in stamped trenches", funded by the committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan AR26197175.

**CONFLICT OF INTEREST**

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

**АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ**

Зерттеулік жұмыстар Қазақстан Республикасы Білім және ғылым министрлігі Ғылым комитеті (AR26197175) қаржыландыратын «Штампталған траншеяларда ростверктері бар таспалы қадалы іргетастар орнату жұмыстарын жүргізу технологиясын әзірлеу» жобасы аясында жүргізілді.

**МҮДДЕЛЕР ҚАҚТЫҒЫСЫ**

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

**БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ**
Исследование проводилось в рамках проекта «Разработка технологии производства работ по устройству ленточных свайных фундаментов с ростверками в выштампованных траншеях», финансируемого комитетом науки Министерства образования и науки Республики Казахстан (AR26197175)

**КОНФЛИКТ ИНТЕРЕСОВ**

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

## 1 INTRODUCTION

It is well known that surface soil compaction, as well as the tamping and stamping of pits, trenches, and depressions, results in the formation of a compacted zone in the surrounding soil **(Keller et al., 2025; Seth et al., 2024)**. Research results conducted over various years indicate that the shape and dimensions of compacted soil zones depend on the following factors:

- Excavation tamping conditions and the distance between them;
- Properties and state of the soil prior to compaction;
- Tamper shape and its energy parameters;
- Slope angle of the tamper's side faces relative to the vertical;
- Shape and dimensions of foundations within the tamped excavations.

The parameters of this zone are essential for the effective design of foundations on compacted soils, as well as foundations in tamped-out pits and stamped trenches or basins(Bessimbayev et al., 2022). This is due to the fact that the soil within the compacted zone possesses increased density, and its deformation and strength characteristics are significantly higher than those outside this zone **(Alenov et al., 2025)**. Therefore, when determining the bearing capacity and settlement of foundations, it is crucial to consider both the geometric parameters of the compacted zone and the soil property indices within it . Undoubtedly, such an approach will contribute to a significant increase in the reliability and cost-effectiveness of foundations constructed on compacted bases **(Melese, 2022).**

The arguments presented underscore the relevance of research aimed at developing a method for determining the dimensions of the compacted peripile soil zone during pit stamping following pile driving **(Kido et al., 2022a)**. This assertion is further supported by the fact that the pile foundation-comprised of a pile and a grillage installed in a stamped pit within the peripile soil after driving -represents a new type of combined pile foundation for which no such studies have been conducted **(Bekbasarov et al., 2025)**. This foundation type is characterized by a higher soil compaction effect compared to piles with shaft enlargements or pyramidal-prismatic piles **(X. Li et al., 2026).** This advantage is attributed to the specific stress-strain state (SSS) of the foundation soil resulting from sequential mechanical impact: initially through soil displacement by the volume of the driven pile, followed by additional radial and vertical compression during the stamping process of the footing cavity. However, despite the evident structural advantages, contemporary regulatory technical literature and existing calculation methods lack analytical dependencies that allow for a reliable determination of the geometric parameters of this 'dual' compaction zone. Current methodologies are either limited to the calculation of individual rammed (stamped) cavities or consider pile performance in isolation from the influence of the densified soil space beneath the footing.

Based on the analysis of changes in the physical characteristics of the near-pile soil after driving the pile into theground, a method for calculating the compacted zone of the near-pile soil has been developed with and without taking into account possible soil uplift at different degrees of soilwater saturation, including completely water-saturated soil **(Gotman et al., 2025).**

## 2 LITERATURE REVIEW

Given the complexity of predicting the shape and geometric parameters of compacted soil zones through analytical methods, it is generally advisable to determine these parameters through field testing at construction sites. However, as is well known, this method-despite its reliability-is quite labor-intensive and costly **(Skejić et al., 2023).** Therefore, in most cases where field testing is absent or unfeasible, specialists establish the dimensions of compacted soil zones using engineering methods. Currently, there are several such methods for determining the dimensions of soil zones subjected to impact compaction. A brief analysis of their features is provided below **(Fang et al., 2019).**

In the work of, a method is presented for determining the maximum depth of soil compaction when using pneumatic impact devices. It is proposed to determine this parameter using the following formula:

$$h_{max} = \beta_1 d_s, \qquad (1)$$

where: $\beta_1 -$ a coefficient equal to: * 1.0-1.2 for clayey and filled soils; 1.2-1.4 for loamy soils; 1.4-1.7 for sandy soils; $d_s -$ the diameter of the bottom of the stamp.

This method is simple to apply; however, it lacks sufficient reliability because it does not account for the influence of the following factors on the soil compaction depth:

- the mass and drop height of the tamper;
- the density and moisture state of the soils.

When compacting soils with heavy tampers, the thickness of the compacted soil layer is determined using a simplified method. According to this method, the thickness of the compacted soil is calculated using the following formula, which depends on the diameter of the tamper base.

$$\mathrm{H}_{cs} = kd \qquad (2)$$

where: $k$- a coefficient equal to: 1.55 for sand; 1.45 for loam; 1.3 for loessial sandy loam; 1.2 for clayey fill; 1.0 for clay; $d -$ the diameter of the tamper base.

Formulas (1) and (2) differ insignificantly from one another in both their structure and the values of their coefficients.

The Guidelines recommend determining the dimensions of the compacted soil zone beneath the base of a tamped-out pit using the following formulas:

$$h_{comp} = 1{,}5b_m \qquad (3)$$

$$d_{comp} = 2b_m \qquad (4)$$

где: $h_{comp}$ - толщина уплотненной зоны грунта под котлованом; $b_m$- width of the pit at the mid-height section; $d_{comp}$- width of the compacted zone at a depth of (0.15-0.25) $b_{\text{ср}}$ from the pit base.

Similar recommendations are contained in departmental and republican building codes, all of which pertain to the process of pit tamping.

Building codes provide for determining the dimensions of the compacted soil zone around a tamped-out pit based on the condition that the shape of this zone in a vertical section corresponds to an ellipse. In this case, both the thickness and the width of the compacted zone are established proportionally to the width of the pit at the mid-height section (Table 1).

**Table 1.**
Dimensions of the compacted soil zone around a tamped-out pit .

| Type of foundation in a tamped-out pit | Taper angle of the lower part of the foundation | Dimensions of the compacted soil zone | |
|---|---|---|---|
| | | Thickness $h_s$ | Width $d_s$ |
| With a flat bottom end | - | $1{,}5b_m$ | $2b_m$ |
| "With a pointed bottom end | 45° | $0{,}7b_m$ | $1{,}4b_m$ |
| | 60° | $b_m$ | $1{,}6b_m$ |
| | 90° | $1{,}3b_m$ | $1{,}8b_m$ |
| Примечание: $b_m$ - размер котлована в его среднем сечении по высоте. | | | |

The method under consideration is characterized by the same drawbacks as the methods described above. This is due to the fact that they lack a theoretical basis and are based solely on correlation dependencies derived from experimental research results.

In the works, a method is presented that allows for the determination of the diameter of the compacted soil zone around a tamped-out pit. According to this method, the required parameter of the compacted zone is established by formula (5):

$$d_s = \left\{ \frac{\left[ \left( \frac{\alpha V_p}{a} \right) + V_p' + V_c \right]}{\left[ \frac{\pi H_e}{3} \right]} \right\} \quad (5)$$

$$a = [\rho_d'(1 + w')/\rho_d(1 + w)] - 1, \quad (6)$$

where: $V_p$ - volume of the tamped-out pit; $\rho_d'$ и $w'$ - the average values of the dry soil density and its moisture content, respectively, within the compacted zone after pit tamping; $\rho_d$ и $w$ - the same parameters prior to pit tamping.

All other parameters included in formula (5) are determined according to the recommendations specified in. In the development of this method, the shape of the compacted soil zone was assumed to be a truncated ellipsoid **(Moldamuratov et al., 2024)**. The method applies to soil compaction processes implemented using flat-bottomed tampers and tampers with bottom taper angles ranging from 45 to 120 degrees **(Moldamuratov et al., 2023)**. Unlike other methods, this approach is theoretically grounded, and its calculation accuracy is high. For instance, the relative error in determining the diameter of the compacted soil zone using formula (5) is 9.8-13.1% **(Qiu et al., 2011)**.

As the presented analysis indicates, existing methods are more thoroughly developed primarily for determining the dimensions of the compacted soil zone formed around tamped-out pits-specifically for those constructed in a soil mass free from any structures or other obstacles. Consequently, these methods cannot be effectively utilized in cases where a pit is stamped over a driven pile and is formed within the peripile soil **(Getter et al., 2015)**.

It is well known that during pile driving, the soil around it is partially loosened (near the ground surface), while deeper within the stratum, it becomes compacted within the deformed zone. Therefore, tamping out a pit over a driven pile-given the presence of both loosened and compacted areas within the peripile soil mass-is a relatively complex process **(Kido et al., 2022b)**. This process involves the compaction of the loosened section by the stamp and the additional densification of the deformed soil zone already surrounding the pile**(Yang et al., 2023)**. In this context, the trajectory of soil particle displacement under the impact of the stamp likely follows a specific pattern: during the initial hammer blows, soil particles move downward and laterally at an angle to the vertical **(Wu & Qiu, 2020)**. At this stage, the volume of particles moving downward beneath the stamp base exceeds the volume of particles displaced laterally away from the stamp**(Wang et al., 2023)**. Subsequently, as the stamp penetrates further, soil particles move more significantly in the lateral direction rather than downward along the side faces of the pile. As a result, it is hypothesized that a compacted zone will form around the pit and the pile's side faces, with an outer contour resembling a pear shape **(Xiao-ling et al., 2020)**.

Thus, the conditions of the peripile soil will influence its deformation and particle displacement during the stamping of a pit within it **(Sabri et al., 2022; Tatyana et al., 2015)**. Therefore, the shape and dimensions of the compacted peripile soil zone will differ from those formed around a pit stamped in the absence of a pile **(Isa et al., 2021)**. Based on these assumptions, the development of a method to determine the dimensions of the peripile soil zone during pit stamping after pile driving is a relevant task for ensuring the rational design of individual combined pile foundations in construction **(Y. Li et al., 2026)**.

## 3 MATERIALS AND METHODS

The methodology is based on the fundamental law of soil mass conservation within the compacted zone, originally adapted from I.I. Bekbasarov's principles. This study integrates analytical methods from soil mechanics, physics, and mathematics to derive dependencies for a new type of single-pile foundation. The research specifically focuses on the unique condition where a pit for a local grillage is stamped into the soil after a pile has already been driven. To model the process, the authors analyzed two geometric variations of the compacted zone's outer contour to approximate its real shape. The first variation models the densified area as a combination of a cylinder and a truncated cone, while the second uses a series of cylinders. A core mass-balance equation was formulated to relate the initial state of the peripile soil to its compressed state after mechanical stamping. This equation incorporates a coefficient, which accounts for the specific fraction of soil mass displaced into the target zone during the process. From these theoretical foundations, new analytical formulas were derived to calculate the maximum diameter and depth of the compacted soil region. To verify the proposed mathematical model, comparative calculations were performed using varying parameters such as pit depth and soil dry density. The resulting method provides a practical tool for engineering design, allowing for the prediction of densified zone dimensions under different technological conditions.

## 4 RESULTS AND DISCUSSION

"Based on the principle of mass conservation set forth in, we shall write the fundamental equation (7) for the condition of stamping a pit in the peripile soil after pile driving:

$$m_{gc,p} = \alpha m_{g,p}, \tag{7}$$

where: $m_{gc,k}$ - mass of the soil within the compacted zone after pit stamping; $m_{g,k}$- mass of the soil within the volume bounded by the outer limits of the compacted zone prior to pile driving and pit stamping; $\alpha$ - a coefficient determining the fraction of the soil mass $m_{g,k}$, that is displaced into the compacted zone during pile driving and pit stamping.

Expressing the soil mass in terms of its volume and density, equation (7) can be transformed and presented in the following form:

$$V_{c,p}\rho' = \alpha V'_{c,p}\rho, \tag{8}$$

where: $V_{u,k}$ - volume of the compacted soil zone; $V'_{u,k}$ - volume of the soil within the mass bounded by the outer limits of the compacted zone prior to pit stamping (after pile driving); $\rho'$- average density of the soil within the compacted zone; $\rho$ - o average density of the soil prior to pit stamping (after pile driving).

From equation (8), the volume of the compacted soil zone V_ can be determined as follows:

$$V_{c,p} = \alpha V'_{c,p}\rho/\rho' , \tag{9}$$

Conventionally, two variants for determining the volume of the compacted soil zone can be considered. In each variant, various possible combinations of geometric shapes are examined which, in aggregate, allow for a compacted zone shape that closely approximates the hypothesized (pear-shaped) form. This form is characteristic of the peripile soil during the stamping of a pit following pile driving.

First variant: the volume of the compacted soil zone $V_{u,k}$ is determined by the following formula (**Figure 1**):

$$V_{u,k} = [(V_c - V_{sp} - V_p) + (V_{tc} - V_p^u)], \quad (10)$$

where: $V_c$ - volume of the cylinder; $V_{sp}$ - volume of the stamped-out pit; $V_p$ - volume of the pile segment with a height equal to the pit depth $h_k$; $V_{tc}$ - volume of the truncated cone; $V_p^u$ - volume of the pile segment with a height equal to depth $h_{cp}$; $h_{uk}$ - depth of the compacted soil zone below the bottom of the pit.

It follows from equation (10) that the outer contour of the compacted soil zone is close to the shape of a cylinder ACBG in its upper part, and to the shape of a truncated cone JZKL in its lower part (Figure 1).

The parameters included in equation (10) are determined as follows:

- cylinder volume according to formula (11);
- pit volume according to formula (12);
- volume of the pile segment (within the depth of the pit) according to formula (15);
- truncated cone volume according to formula (16);
- volume of the pile segment (from the bottom of the pit to the lower boundary of the compacted soil zone) according to formula (17).

$$V_c = \pi 0{,}25 D_{cp}^2 h_p, \quad (11)$$

$$V_p = \left\{\left(\frac{1}{3}\right) h_p \left(S_{p1} + S_{p2} + \sqrt{S_{p1} \cdot S_{p2}}\right)\right\}, \quad (12)$$

$$S_{p1} = (\text{B}_{1p}^2 - d^2), \quad (13)$$

$$S_{p2} = (\text{B}_{2p}^2 - d^2), \quad (14)$$

$$V_p = d^2 h_p, \quad (15)$$

$$V_{tc} = \left(\frac{1}{3}\right)\pi h_{cp}\left(0{,}25 D_{cp1}^2 + 0{,}25 D_{cp1} d + 0{,}25 d^2\right) = = \left(\frac{1}{12}\right)\pi h_{cp}\left(D_{cp1}^2 + D_{cp1} d + d^2\right), \quad (16)$$

$$V_p^u = d^2 h_{cp}, \quad (17)$$

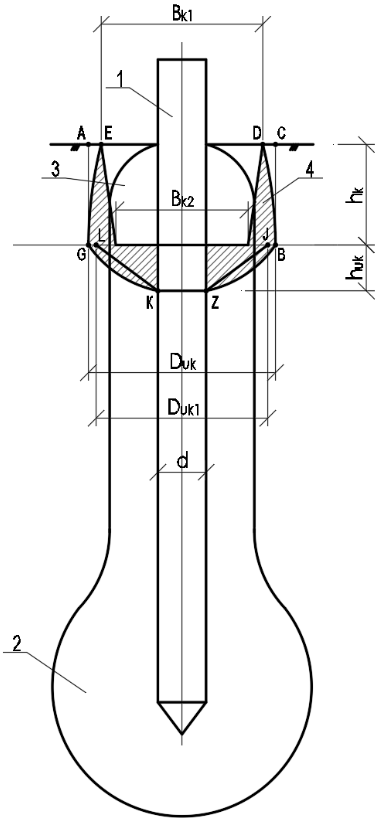
where: $D_{uk}$ - the maximum diameter of the compacted soil zone; $S_{p1}$- cross-sectional area of the pit at the top; $S_{p2}$ - cross-sectional area of the pit at the bottom; $\text{B}_{p1}$ - pit dimension at the top; $\text{B}_{p2}$ - pit dimension at the bottom; $d$ - pile cross-sectional dimension; $D_{uk1}$ - diameter of the upper base of the truncated cone JZKL (**Figure 1**).

The diameter of the upper base of the truncated cone JZKL in formula (16) is equal to such a dimension of the cone at which the following equality holds:

$$V_{u1} = V_{u2}, \quad (18)$$

where: $V_{u1}$ и $V_{u2}$ - are the volumes of the figures DCB (EAG) and JBZ (LGK), respectively (**Figure 1**).

The fulfillment of this equality ensures that the calculated volume of the compacted soil zone corresponds to its hypothesized volume. Overall, the diameter of the base of the truncated cone $D_{uk1}$ must be greater than the dimension of the pit at its mid-section $B_{kc}$, but smaller than the maximum diameter of the compacted zone $D_{uk}$. Based on this, the diameter $D_{uk1}$ can be approximately taken as equal to the dimension of the pit cross-section at the top $B_{k1}$.




1- pile; 2 - peripile soil compacted zone; 3 - stamped-out pit;
4 - compacted zone around the pit.

**Figure 1** - Schematic for determining the dimensions of the compacted soil zone around a pit stamped after pile driving

Equating the right-hand sides of equations (9) and (10), we obtain the final equality (19), from which expression (20) can be derived.

$$\alpha V'_{u,k}\rho/\rho' = [(V_c - V_{sp} - V_p) + (V_{tc} - V_p^u)], \tag{19}$$

$$\alpha(V_c + V_{tc} - V_p - V_p^u)\rho/\rho' = [(V_c - V_{sp} - V_p) + (V_{tc} - V_p^u)], \tag{20}$$

From equation (20), formula (21) for determining the cylinder volume can be obtained $V_c$ в in the following form:

$$V_c = \{[V_c(1-a) + V_c^u(1-a) + V_k] - V_{tc}(1-a)\}/(1-a), \tag{21}$$

$$a = \alpha\rho/\rho' \text{ или } a = \alpha\rho_d(1+w)/\rho'_d(1+w'), \tag{22}$$

где: $\rho'_d$ - average dry density of the soil within the compacted zone; $w'$- average water content of the soil within the compacted zone; $\rho_d$ - average dry density of the soil prior to pit stamping (after pile driving); $w$ - average water content of the soil prior to pit stamping (after pile driving).

By equating the right-hand sides of formulas (11) and (21), a formula for determining the diameter of the compacted soil zone can be derived $D_{uk}$ in the following form:

$$D_{uk} = \sqrt{b/(0{,}25\pi h_k)} \ , \tag{24}$$

$$b = \{[V_c(1-a) + V_c^u(1-a) + V_k] - V_{tc}(1-a)\}/(1-a), \tag{25}$$

When using formula (24) to determine the volume of the truncated cone $V_{tc}$, included in formula (25), it is necessary to specify the depth of the compacted zone below the bottom of the pit $h_{uk}$. It is recommended to preliminarily adopt this parameter in a form $h_{uk} = 1{,}5\text{B}_{kc}$, similar to formula (3). The proposed relationship is subject to refinement based on the results of experimental studies.

From equation (20), taking into account formula (22), a formula for determining the volume of the truncated cone $V_{tc}$ can be obtained in the following form:

$$V_{tc} = \{[V_c(1-a) + V_c^u(1-a) + V_k] - V_c(1-a)\}/(1-a), \tag{26}$$

By equating the right-hand sides of formulas (16) and (26), a formula for determining the depth of the compacted soil zone below the bottom of the pit can be derived in the following form:

$$h_{uk} = c/\left[\left(\frac{1}{12}\right)\pi(D_{uk1}^2 + D_{uk1}d + d^2)\right], \tag{27}$$

$$\text{c} = \{[V_c(1-a) + V_c^u(1-a) + V_k] - V_c(1-a)\}/(1-a), \tag{28}$$

When using formula (27) to determine the cylinder volume $V_c$, included in formula (28), it is necessary to know the diameter of the compacted zone $D_{uk}$. It is recommended to preliminarily determine this parameter using formula (24). If, after calculating by formula (27), the depth value $h_{uk}$ is equal or close to the preliminarily adopted depth $h_{uk} = 1{,}5\text{B}_{kc}$, the results of the calculations by formulas (24) and (27) can be taken as final. Otherwise, the diameter should be recalculated $D_{uk}$ by formula (24) using the depth value $h_{uk}$, obtained from formula (27), followed by a recalculation of the depth $h_{uk}$, by formula (27) using the refined diameter value $D_{uk}$.

Second variant: the volume of the compacted soil zone $V_{u,k}$ is determined by the following formula (Figure 2):

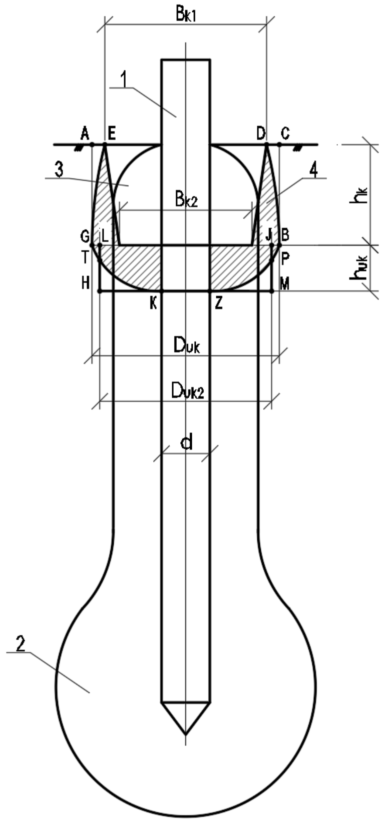
$$V_{u,k} = [(V_c - V_{sp} - V_c) + (V_c^{\text{н}} - V_c^u)], \tag{29}$$

when: $V_c^{\text{н}}$ - volume of a cylinder with diameter $D_{uk2}$ and a height equal to the depth of the compacted zone below the bottom of the pit $h_{uk}$; $V_c$, $V_k$, $V_{\text{c}}$ и $V_c^u$ - the same as in formula (19).

It follows from formula (29) that the outer boundary of the compacted soil zone is close to the shape of cylinder ACBG in the upper part (within the depth of the pit), and to the shape of cylinder LJMH in the lower part (Figure 2).

In formula (29), the included parameters are defined as follows:

- cylinder volume $V_c$ according to formula (11);
- pit volume $V_{sp}$ according to formula (12);
- pile fragment volume (within the depth of the pit) $V_p$ according to formula (15);
- cylinder volume $V_c^{\text{н}}$ according to formula (30);
- pile fragment volume (from the bottom of the pit to the lower boundary of the compacted soil zone) $V_c^u$ according to formula (17).




1- pile; 2 - peripile soil compacted zone; 3 - stamped-out pit;;
4 - compacted zone around the pit

**Figure 2 -** Schematic for determining the dimensions of the compacted soil zone around a pit stamped after pile driving

$$V_c^{н} = \pi 0{,}25 D_{uk2}^2 h_{uk}, \tag{30}$$

The diameter of cylinder LJMH (Figure 2) $D_{uk2}$ in formula (30) is established from the condition that the following equality is satisfied:

$$V_{u1} + V_{u3} = V_{u4}, \tag{31}$$

where: $V_{u1}$ , $V_{u3}$ и $V_4$ - respectively, the volumes of figures DCB (AEG), PMZ (THK), JBP (GLT) (**Figure 2**).

The satisfaction of this equality ensures that the calculated volume of the compacted soil zone corresponds to its assumed volume. In general, the diameter of the cylinder base $D_{uk2}$ should be larger than the pit dimension at its middle section $B_{kc}$, but smaller than the maximum diameter of the compacted zone $D_{uk}$. Based on this, the diameter $D_{uk2}$ can be approximately taken as equal to the dimension of the pit at the top $B_{p1}$.

By equating the right-hand sides of formulas (9) and (32), we obtain the final equality (32), from which expression (33) can be derived.

$$\alpha V'_{u,k} \rho/\rho' = [(V_c - V_{sp} - V_p) + (V_c^{н} - V_p^{u})], \tag{32}$$

$$(V_c + V_c^{н} - V_{sp} - V_p^{u}) \rho/\rho' = [(V_c - V_{sp} - V_p) + (V_c^{н} - V_p^{u})], \tag{33}$$

From equation (33), formula (34) for determining the cylinder volume $V_c$ can be obtained in the following form:

$$V_c = \{[V_p(1-a) + V_p^u(1-a) + V_p] - V_p^{н}(1-a)\}/(1-a), \quad (34)$$

where: $a$ - a parameter determined by the formulas (22).

By equating the right-hand sides of formulas (11) and (34), a formula for determining the diameter of the compacted soil zone $D_{uk}$ can be derived in the following form:

$$D_{uk} = \sqrt{\vartheta/(0{,}25\pi h_k}\ , \quad (35)$$

$$\vartheta = \{[V_c(1-a) + V_p^u(1-a) + V_k] - V_c^{н}(1-a)\}/(1-a), \quad (36)$$

From equation (33), taking into account formula (22), a formula for determining the cylinder volume $V_c^{н}$ can be obtained in the following form:

$$V_c^{н} = \{[V_c(1-a) + V_c^u(1-a) + V_p] - V_c(1-a)\}/(1-a), \quad (37)$$

By equating the right-hand sides of formulas (30) and (37), a formula for determining the depth of the compacted soil zone below the bottom of the pit can be derived in the following form:

$$h_{uk} = \mathrm{c}/\pi 0{,}25 D_{uk2}^2 \quad (38)$$

$$\mathrm{c} = \{[V_p(1-a) + V_p^u(1-a) + V_p] - V_c(1-a)\}/(1-a), \quad (39)$$

Based on the obtained formulas, comparative calculations were performed to verify the similarity of the results for the two adopted variants of the method.

The initial data for the calculations are given in Table 1. The value of the coefficient is taken as 0.8. The density state parameters of the near-pile (clayey) soil are taken as follows: density $\rho$ = 1,56 t/m$^3$; density $\rho'$ = 1,75 t/m$^3$.

**Table 1.**
Initial data for calculations (authors' materials)

| Parametrs | Parameter values, cm | |
|---|---|---|
| Depth of the pit $h_p$ | 50 | 75 |
| Pit dimension at the top $B_{p1}$ | 60 | 60 |
| Pit dimension at the bottom $B_{p2}$ | 40 | 40 |
| Pit dimension at its middle section $B_{ps}$ | 50 | 55 |
| Pile cross-section dimension $d$ | 30 | 30 |
| Slope of the pit walls | 1:5 | 1:15 |

The results of calculations for determining the thickness of the near-pile soil compacted zone are presented in Table 2. The calculations were performed for the conditions of stamping pits with depths of 0.5 m and 0.75 m.

**Table 2**
Calculation results for determining the dimensions of the compacted soil zone (authors' materials)

| Formula variants | Diameter of the compacted zone $D_{uk}$, cm, at a pit depth of $h_k$, cm | | Depth of the compacted zone $h_{uk}$, cm, at a pit depth of $h_k$, cm | |
|---|---|---|---|---|
| | 50 | 75 | 50 | 75 |
| Variant №1 - formulas (24) и (27) | 82,35 (24) | 85,19 (24) | 76,40 (27) | 76,17 (27) |
| Variant №2 - formulas (35) и (38) | 67,33 (35) | 75,88 (35) | 75,58 (38) | 74,99 (38) |

Note: formula numbers used for the calculations are indicated in parentheses.

It follows from **Table 2** that the difference between the results obtained using formulas (24) and (35) ranges from 10.9% to 18.2%, while for formulas (27) and (38), it is 1.07-1.55%. The calculation results for formulas (27) and (38) are significantly closer to each other than those for formulas (24) and (35). Furthermore, the calculation data indicate that increasing the pit depth from 0.5 m to 0.75 m has a greater impact on the diameter of the compacted zone than on its depth. For instance, when using formula (24), a 1.5-fold increase in pit depth is accompanied by a 1.03-fold increase in the diameter of the compacted zone, whereas with formula (35), the increase is 1.13-fold. A slightly different pattern is observed in the results for formulas (27) and (38). As seen in Table 2, the depth of the compacted soil zone decreases slightly as the pit depth increases. This reduction amounts to 0.30% when calculating with formula (27) and 0.78% with formula (38).

The calculation results indicate that the formulas are mutually acceptable, as the difference between the results obtained from them does not exceed 20%. The formulas are subject to experimental verification.

## 5 CONCLUSIONS

Based on the results of the conducted research, the following main conclusions can be formulated:

1. Formulas (24) and (35) allow for determining the diameter of the compacted soil zone around a pile when stamping a pit after pile driving;
2. Formulas (27) and (38) allow for determining the thickness of the compacted soil zone around a pile when stamping a pit after pile driving;
3. The presented formulas are derived based on the principle of soil mass conservation during pit stamping in near-pile soil, which accurately reflects the physical process of soil mass redistribution during pit stamping under the considered conditions.
4. Recommendations for assigning parameters $D_{uk1}$ и $D_{uk2}$ , related to the dimensions of the compacted soil zone at the level of the pit bottom, as well as the functional dependencies for using the presented formulas $h_{uk} = f(В_{kc})$, must be developed based on the results of experimental studies;
5. The formulas are subject to experimental verification; the value of the coefficient $\alpha$, included in these formulas must be established based on the results of corresponding experimental research.

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