Збірник наукових праць. Серія: Галузеве машинобудування, будівництво
Academic journal. Series: Industrial Machine Building, Civil Engineering

http://journals.pntu.edu.ua/znp
https://doi.org/10.26906/znp.2018.51.1300

UDC 624.131

Review of design solutions for nominally strip (continuous) foundations

Samorodov Oleksand[1]*, Khrapatova Iryna[2], Krotov Oleg[3], Tabachnikov Sergii[4]

[1] Kharkiv National University of Civil Engineering and Architecture https://orcid.org/0000-0003-4395-9417
[2] Kharkiv National University of Civil Engineering and Architecture https://orcid.org/0000-0003-3404-5349
[3] Kharkiv National University of Civil Engineering and Architecture https://orcid.org/0000-0002-7588-1370
[4] O.M. Beketov National University of Urban Economy in Kharkiv https://orcid.org/0000-0002-2619-8612
*Corresponding author: *osamorodov@ukr.net*

The paper reviews the existing designs of nominally strip (continuous) foundations that are offered in foundation engineering, that due to their shape (configuration) of contact with the base enable more rationally to design foundations for continuous structures of buildings and facilities. The advantages and disadvantages of continuous foundations different types are shown, and some calculation methods and methodologies when calculating these foundations in interaction with soil bases are given.)

Keywords: soil base, foundation, conditionally banded, shape of bottom, longitudinal cutout, efficiency

Аналіз конструктивних рішень умовно стрічкових (протяжних) фундаментів

Самородов О.В.[1]*, Храпатова І.В.[2], Кротов О.В.[3], Табачніков С.В.[4]

[1] Харківський національний університет будівництва та архітектури
[2] Харківський національний університет будівництва та архітектури
[3] Харківський національний університет будівництва та архітектури
[4] Харківський національний університет міського господарства імені О.М. Бекетова
*Адреса для листування: *osamorodov@ukr.net*

Проаналізовано існуючі конструкції умовно стрічкових (протяжних) фундаментів, які за рахунок своєї форми (конфігурації) контакту з основою дозволяють більш раціонально проектувати фундаменти протяжних конструкцій будівель і споруд. Показано переваги та недоліки різних типів протяжних фундаментів, а також наведені деякі методи й методики розрахунку таких фундаментів при взаємодії з грунтовими основами. Встановлено, що розробка нових конструктивних рішень умовно стрічкових фундаментів та удосконалення методик їх розрахунку враховує тільки вертикальні навантаження на фундаменти. Однак, існує клас споруд, типа масивних підпірних стін, що сприймають значні моментні навантаження по підошві, які потребують розробки ефективної конструкції фундаментної частини із забезпеченням розрахункового опору грунту основи. Запропоновано запатентовану комбіновану конструкцію стрічкового фундамент з поздовжнім вирізом по підошві, що складається з фундаментної частини шириною (2b+a) та вирізу шириною a і висотою Δ, що заповнюється низькомодульним матеріалом, наприклад, пінопластом. З одного боку, така конструкція фундаменту ефективно сприймає ексцентричні навантаження у порівнянні з суцільною формою підошвою з дотриманням нормативних вимог за крайовими тисками на основу. З другого боку, конструкція дозволяє збільшити розрахунковий опір грунту основи фундаменту з вирізом за рахунок заповнення порожнини вирізу низькомодульним матеріалом, за рахунок чого відбувається «сприятливий» перерозподіл напружень в основі фундаменту з вирізом у порівнянні із суцільним фундаментом при прийнятті будь-якого критерію розвитку зон граничної рівноваги під фундаментом. Тому, розрахунковий опір грунту запропонованого стрічкового фундаменту може бути до 2-х разів більше у порівнянні із суцільним фундаментом шириною 2b.

Ключові слова: ґрунтова основа, фундамент, умовно стрічковий, форма підошви, поздовжній виріз, ефективність

Introduction. Increasing the economic efficiency of foundation construction, which cost can in some cases amount to 40% of buildings construction total cost, is currently a priority area. Cast in-situ and precast strip foundations for walls are the most common type of shallow foundations, which is used in residential construction, although types of nominally strip (continuous) foundations with various shapes of bottoms in contact with the base have been provided recently. Using other shapes of continuous foundations bottoms alters favourably the stress-strain state of the soil base, that is, from the plane to the space ("plane-space") state; hence, they are more rational than strip foundation classical shape.

Review of recent research and publications. A number of researchers such as V. Alekseev, L. Anshin, D. Arkhipov, B. Barykin, V. Ermashov, M. Fidarov, R. Furunzhiev, E. Livshits, F. Lyalin, E. Sorochan, P. Poyta, R. Mangushev, A. Pilyagin, E. Neiburg, A. Razoryonov, V. Solomin, V. Tarshish, E. Vinokurov, G. Skibin, S.Yevtushenko, V. Pankov, T. Krakhmalny, Yu. Tugayenko, N. Kiselev and many others have devoted their work to developing methods of calculation and designing non-conventional continuous foundations (discontinuous strip foundations, adjacent foundations, etc.), and optimizing foundation designs on the whole. Designs of nominally strip (continuous) foundations have been intensively improved and investigated up to the present time, as evidenced by recent theses defended abroad [1, 2, 26-30]. Currently, using discontinuous strip foundations enables, under otherwise equal conditions, to increase the allowable pressure on the soil base up to 1.3 times due to the change of the stress-strain state from the plane to the space state, which was introduced back in SNiP 2.02.01-83* «Buildings and structures» foundation has been implented in force according to date in the national standards DBN [3].

Uninvestigated parts of general matters defining. Development of new design solutions for nominally strip foundations, experimental and theoretical research of their combined behaviour with soil bases, and improvement of their calculation and designing methods are an area of current interest in soil mechanics and foundation engineering.

Research objective is to analize nominally strip (continuous) foundations design solutions .

Main content and findings. In the Research Institute of Bases and Underground Structures named after N.M. Gersevanov, the first attempt has been made to change the traditional way of transferring load in a way that substantially improves the service behaviour of the foundation and the base itself. It has been experimentally confirmed that the ultimate load on base soils increases 1.5 times. Therefore, it is possible to transfer more load on a discontinuous foundation, under otherwise equal conditions, or, using the principle of calculation from the second limit state, reduce the area of the foundation bottom and hence its materials intensity. This principle was implemented in 1954 under the guidance of E. Sorochan [4] when developing precast discontinuous strip foundations (Fig. 1) which were first used in Moscow.

Experimentally, the behaviour of discontinuous strip foundations started to be studied for the first time by E. Sorochan [4], however, studies dealt with the linear phase of base behaviour . The limit stress state of discontinuous strip foundations base soil was particularly covered by studies of M. Fidarov [5]. The proposed theory of discontinuous foundations and bases combined behaviour studied by M. Fidarov is based on the solutions to soil limit stress-strain state and soils pressure over the roofs of underground mining have been studied by M. Protodiakonov. This theory considers the emergence of an arching effect in the soil between the pad blocks, due to them foundation bottom can be considered as continuous. In his doctoral thesis, P.Poyta [6] provides considerable theoretical and experimental studies on the combined behaviour of base soils and discontinuous foundations, involving the theory of arching effect occurrence, thus, the simple formula can be derived to determine the space between the slabs in a discontinuous foundation (see Fig. 1):

$$a = b\ sin\varphi. \tag{1}$$

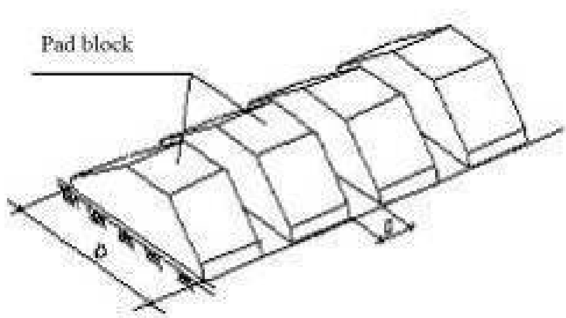

Figure 1 – Precast discontinuous foundation

To date, the current DBN [3] standardize the use of structures of discontinuous strip foundations, including those with angular cut-outs, which enables, under otherwise equal conditions, to increase the allowable pressure (design resistance R) on the soil base up to 1.3 times, which was already introduced in the Soviet regulatory documents.

The design solution close to discontinuous foundations in terms of the behaviour peculiarities with the base is sleeper foundations (Fig. 2), which were considered in depth in the works by Yu. Tugayenko and S. Kushchak [7], P. Poyta [6] and V. Pankov [8].

Later on, strip foundations structures improvement was aimed at developing pad blocks with rectangular cut-outs in the corners, thus, pad blocks area is 12% smaller than typical blocks area (see Fig. 3).

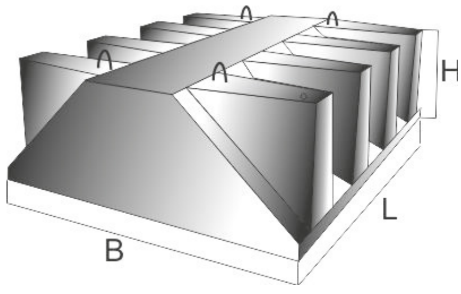

Figure 2 – Sleeper foundation

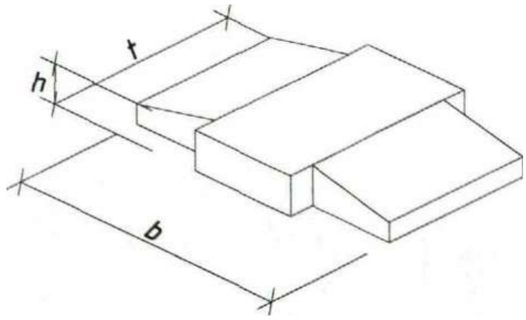

Figure 3 – Foundation pad block with angular cut-outs

The work of V. Ermashov [9] is devoted to studying foundation slabs with angular cut-outs shape influence ontheir bases stress-strain state. The research was experimental in a sand tray measuring 6.0 by 5.0 m in size with a height of 5.5 m. The variables included foundation stiffness, contact surface relative size, and reinforcement percentage. Consequently, it was found that the arrangement of angular cut-outs in slabs results in the formation of limit state local zones in the soil through concentrating the contact stresses in the central part of foundation bottom. It enables to reduce the bending moment in slab critical section and foundation materials intensity. Based on the conducted research, reinforced concrete slabs for strip foundations with a rational contour of the contact surface were developed, which use reduces the concrete consumption to 18 to 20% and steel consumption to 15 to 18% compared with solid slabs.

A number of researchers from South Russian State Technical University (Novocherkassk Polytechnic Institute) (Novocherkassk Polytechnic Institute) including G. Skibin, S.Yevtushenko, D. Arkhipov, T. Krakhmalny [1, 10-13] and others are deeply involved in developing continuous foundations for walls and retaining structures with various options of moving apart and turning pad blocks, and the broken contour of the base slab boundary zone (see Fig. 4).

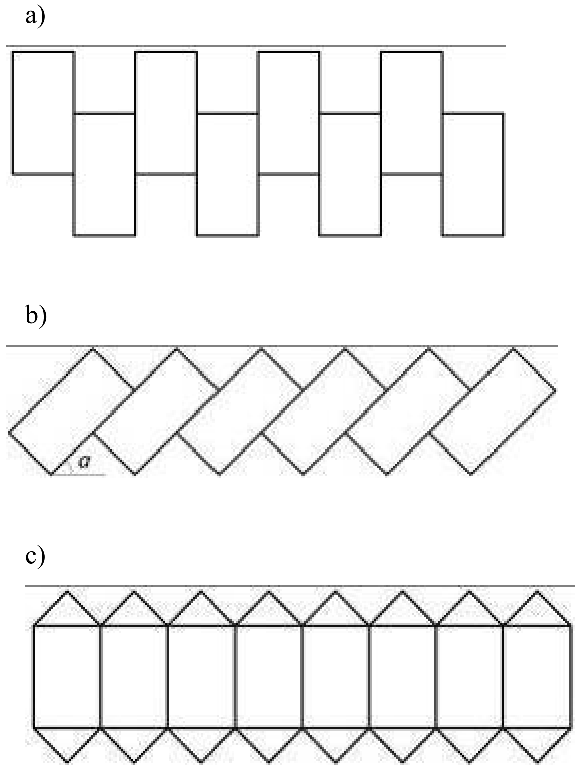

Figure 4 – Layouts of continuous foundations:
a) with blocks moved apart in the transverse direction;
b) with blocks turned at the angle *α*;
c) with the broken contour of the boundary zone.

The work of T.A. Krakhmalny [1], based on numerous laboratory experimental studies, provides foundations various layouts comparative analysis (Fig. 4) and dependence evaluation of base bearing capacity on bottom shape change. It is furthermore concluded that with increase of foundation model perimeter ratio to its area (ξ), the critical load ΔP to the base and its bearing capacity increase. Figure 5 shows the graph of change in model bearing capacity (ΔP) against foundation perimeter ratio to its area (ξ).

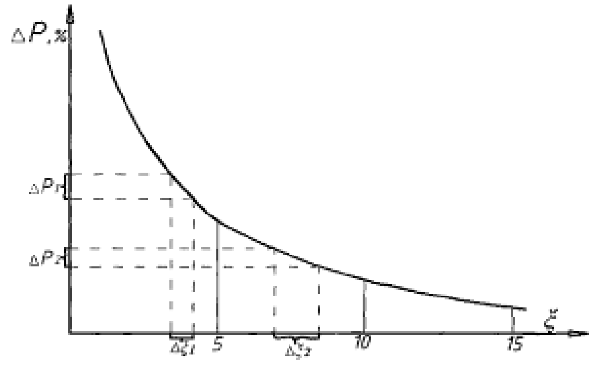

Figure 5 – The graph of change in bearing capacity of the model against foundation perimeter ratio to its contact area

According to the graph, change in the perimeter at ξ < 5 results in a greater increase in the bearing capacity ΔP_1 than the increase in the perimeter at 5 < ξ < 10, which gives an increase in the bearing capacity by the value ΔP_2.

Other conclusions of the authors have been considered, related to calculation methods peculiarities for bases of such foundations (see Fig. 4):

- performed calculations show the possibility of determining the design resistance of strip foundations base with the rotation of square and rectangular supporting blocks and base slabs broken contour according to SNiP (DBN) [3; 14];
- the design resistance of sandy soil R is 4.0 to 5.0 times lower than the actual range of the linear dependence of the foundation settlement on the load. Hence, the regulations [3, 14] greatly reduce the allowable load. To determine foundation size on a sandy base it is more appropriate to perform calculation from the first limit state using base ultimate resistance N_u, which more closely corresponds to the limit of sand base linear deformability than the value R does. The same conclusion was made in the works by V.A. Ilichev , A.B. Fadeev, and V.A. Lukin [15, 16], where calculation methods resilts are compared with Eurocode 7 [17].

Concepts for adjustable distribution of reaction pressure were developed in the works by E.A. Sorochan [18, 19], who suggested accumulating the contact stresses under the centre of strip foundations by arranging nonuniform stiffness in the centre by means of concrete, and along the perimeter by means of sand. Thus, foundation behaviour relative to base changes considerably: on the one hand, the bending moments in the overhanging lengths of slab decrease, on the other hand, the bearing capacity of base soil increases due to “closure” of plastic shear zones under the centre. It is possible to adjust the distribution of contact stresses in other ways: by laying plastic foam inserts under strip foundation edge or by producing precast blocks with concrete protrusions under centre and unsupported console overhangs (Fig. 6, a). Such approaches to adjusting reaction pressure under the foundations are intensively developed by Ya.O. Pronozin and N.Yu. Kiselev [2] when developing and studying the behaviour of slab foundations with a compensatory layer.

M.S. Gritsuk [20] has theoretically and experimentally proved the efficiency of strip foundations from precast slabs with convex curvilinear or trapezium-shaped bottoms (Fig. 6, b), which provides parabolic distribution of reaction pressures with zero values near the edges. V.F. Bai and A.N. Kraev [21] have investigated strip foundations of compressed curvilinear sand masses reinforced along the contour (Fig. 6, c).

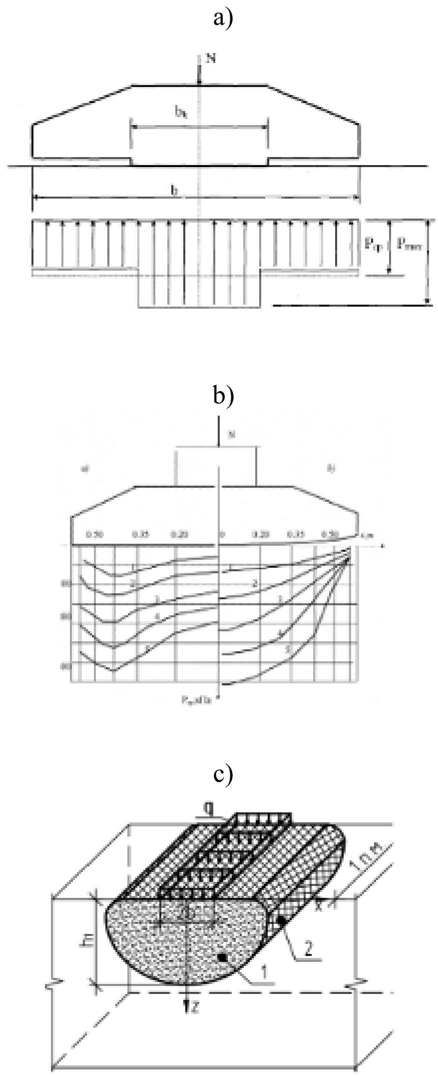

Figure 6 – The influence of the shape of a foundation on reaction pressures and settlements:
a) aoundation with an intermediate bed;
b) aoundation with a convex bottom;
c) aoundation with a curvilinear sand bed

A new development in the field of foundation engineering is new designs of strip foundations with longitudinal cut-outs on the bottom, which are highlighted in the works by I.Ya. Luchkovsky and O.V. Samorodov [22 – 24], where the authors offer the optimum shapes of eccentrically loaded strip foundations with a longitudinal cut-out bottoms, which can also be used for massive retaining walls (Fig. 7).

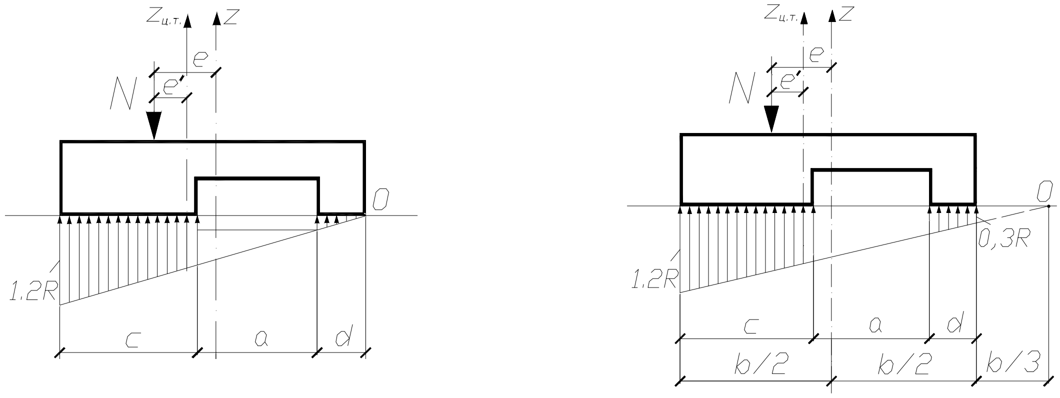

Figure 7 -- Eccentrically loaded strip foundations of retaining walls with asymmetrical cut-outs on the bottom

Foundations with longitudinal asymmetrical or symmetrical cut-outs on the bottom enable to make full use of soil base strength properties, while observing the regulatory edge constraints (Fig. 7), and the optimum geometric parameters of foundation bottom at given efforts *N* and *M = Ne*, and at base soil design resistance *R* are equal to:

- for the design with limiting edge pressures on the base $p_{max} \leq 1.2R$ and $p_{min} \geq 0$ (Fig. 7, a):

$$b = \left(e + 0{,}495m\right)\left[1 + \sqrt{1 + \frac{1}{5}\left(\frac{m}{e + 0{,}495m}\right)^2}\right], \qquad (2)$$

where

$$\bar{a} = 0{,}804\left[\sqrt{1 + 1{,}355\left(3 - \bar{N}\right)} - 1\right].;$$

$m = N / R$;

$\bar{N} = 5N / bR$,

and for the case of a centrally located cut-out at $c=d$:

$$b = \left(e + 0{,}833m\right)\left[1 + \sqrt{1 - \frac{1}{3}\left(\frac{1{,}666m}{e + 0{,}833m}\right)^2}\right], \qquad (3)$$

where

$$\bar{a} = \frac{a}{b} = 1 - \frac{\bar{N}}{3} \;;$$

- for the design with limiting the edge pressures on the base $p_{max} \leq 1.2R$ and $p_{min}/p_{max} \geq 0.25$ (Fig. 7, b):

$$b = \frac{e + 1{,}33m + \sqrt{\left(e + 1{,}33m\right)^2 - 2m^2}}{1{,}54}, \qquad (4)$$

where

$$\bar{a} = \sqrt{1{,}78 - 0{,}45\bar{N}} - 0{,}29,$$

and for the case of a centrally located cut-out at $c=d$:

$$b = \frac{e + 0{,}4m + \sqrt{\left(e + 0{,}4m\right)^2 - 0{,}213m^2}}{0{,}6}, \qquad (5)$$

where

$$\bar{a} = \frac{a}{b} = 1 - \frac{\bar{N}}{3{,}75}.$$

However, preliminary calculations show that in the case of an empty space inside cut-out cavity *a* soil design resistance decreases sharply compared to the continuous bottom; therefore, there is provided a patented design of strip foundation with longitudinal cut-out (Fig. 8) [22] that consists of foundation part *1* of (*2b + a*) in width and cut-out of *a* in width and *Δ* in height, filled with low-modulus material *2* such as foamed plastic. Furthermore, it is possible to significantly simplify the technology of such foundations arrangement due to “low-modulus insert” location in the concrete bed *3* with thickness *Δ* under the foundation (see Fig. 8).

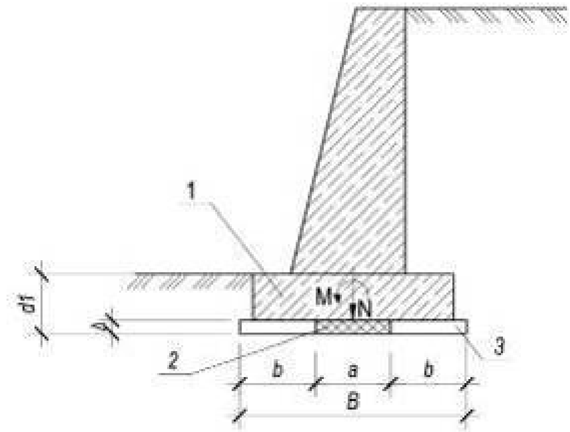

Figure 8 – Mass retaining wall with a longitudinal centrally located cut-out on the bottom

In this case, in order to determine soil design resistance *R*, it is suggested considering the calculation model of interaction between the foundation and the soil base, which is given in Fig. 9, where pressure equal to natural pressure $\gamma\, d_1$ outside foundation is transferred within the width of cut-out *a* when loading the foundation.

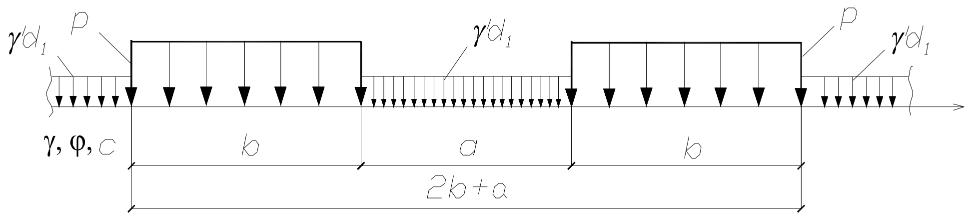

Figure 9 – Calculation model of interaction between foundation and soil base

The pressure inside the longitudinal cut-out of Δ in height is transferred by filling the cavity with a low-modulus material, such as foamed plastic, with a modulus of elasticity E, which is equal to

$$E = \frac{\Delta}{s}\gamma\ d_1\ , \qquad (6)$$

where s is forecasted settlement of foundation, m;
Δ is the height of the cut-out, m;
γ is soil specific gravity above foundation bottom, kN/m^3;
d_1 is foundation laying debth, m,
or, alternatively, by performing a cut-out of a in width and Δ in height, which is equal to

$$\Delta = \frac{E}{\gamma\ d_1} s\ . \qquad (7)$$

In this case, foundation soil design resistance with the cut-out R_{2b+a} of ($2b+a$) in width is equal to:

$$R_{2b+a} = R_b \cdot k_d\ , \qquad (8)$$

where R_b is foundation base soil design resistance of b in width to be determined according to the standard formula E.1 [3], subject to taking any criterion for boundary equilibrium zones development under the foundation;
k_d is the coefficient to be determined according to the graphs in Fig. 10 and obtained based on our analytical studies in the work [25].

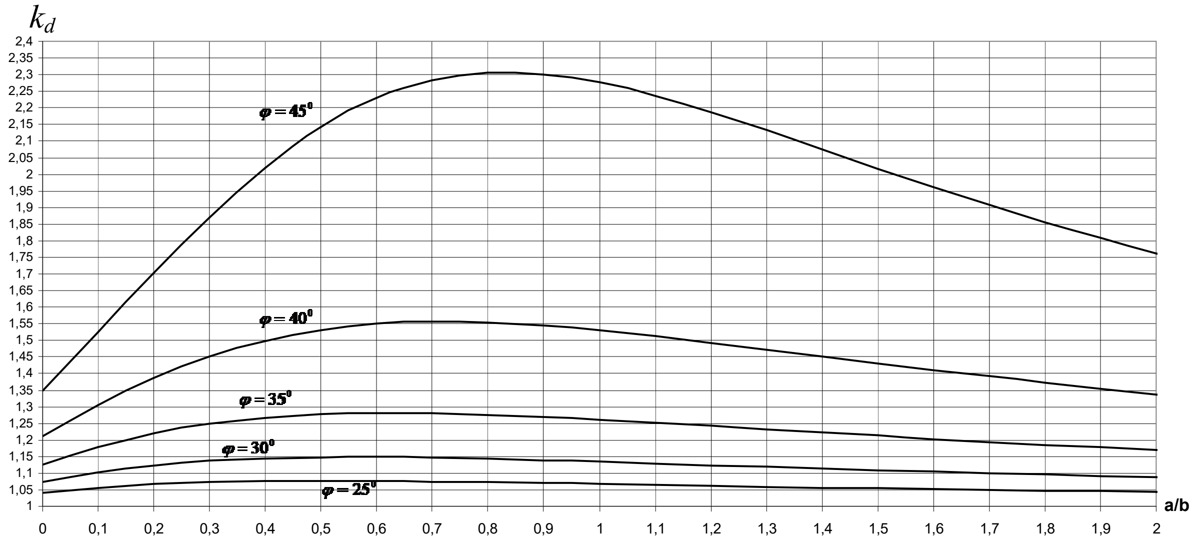

Figure 10 – Graphs of the coefficient kd against the relative width of the cut-out a/b

Conclusions. The analysis has been performed of the existing non-conventional nominally strip foundations such as discontinuous foundations, adjacent foundations, foundations with pad blocks turned at an angle, foundations with cut-outs, foundations with moving apart on the bottom and others that are more rational than the classical shape of a strip foundation, which enables to designefficient foundations for continuous structures of buildings and facilities.

References

1. Крахмальный, Т.А. (2010). *Исследования работы песчаного основания ленточного фундамента с ломаным очертанием опорной плиты.* (Дис. канд. техн. наук). СПбГАСА, Санкт-Петербург.
2. Киселев, Н.Ю. (2017). *Работа плитных фундаментов с компенсирующим слоем на грунтоваом основании.* (Дис. канд. техн. наук). Тюменский индустриальный институт, Тюмень, 2017. – 146 с.
3. ДБН В.2.1-10-2009. (2009). *Основи та фундаменти споруд*. Київ: Мінрегіонбуд України.
4. Сорочан, Е.А. (1959). Исследования вопросов применения прерывистых фундаментов. *Труды НИИОСП*, 40, 28-45.

5. Фидаров, М.И. (1986). *Проектирование и возведение прерывистых фундаментов*. Москва: Стройиздат.
6. Пойта, П.С. (1985). *Совместная работа прерывистых ленточных фундаментов с продольным расположением разрыва и намывных песчаных оснований (для региона Белорусской ССР)*. (Дис.канд. техн. наук). БГТУ, Брест.
7. Тугаенко, Ю.Ф. Кущак, С.И. (1986). Деформации в основаниях фундаментов из шпальных элементов. *Основания, фундаменты и механика грунтов,* 2, 9-11.
8. Панков, В.К. (1971). *Исследование работы составных фундаментов из траверс и нестыкуемых подкладных плит.* (Автореф. дис. канд. техн. наук), СТИ, Свердловск.
9. Ермашов, В.П. (1985). Влияние формы фундамента на распределение нормальных контактных напряжений. *Основания, фундаменты и механика грунтов,* 2, 16-17.
10. Евтушенко, С.И. & Крахмальный, Т.А. (2008). Разработка новых конструкций протяженных фундаментов, эффективно использующих несущую способность основания. *Вестник Волгоградского гос. архитектурно-строительного университета. Серия: Строительство и архитектура,* 10(29), 122-127.
11. Евтушенко, С.И. & Крахмальный, Т.А. (2011). Исследование работы ленточных фундаментов со сложной конфигурацией подошвы. *Основания, фундаменты и механика грунтов,* 3, 14-17.
12. Евтушенко, С.И. & Крахмальный, Т.А. (2011). *Экспериментальные исследования работы новых конструкций ленточных фундаментов с ломаным очертанием краевой зоны на песчаном основании.* Новочеркасск: ЛИК.
13. Крахмальный, Т.А. & Евтушенко, С.И. (2008). Разработка новых конструкций протяженных фундаментов, эффективно использующих несущую способность основания. *Вестник Волгоградского гос. архитектурно-строительного университета. Серия: Строительство и архитектура,* 10(29), 122-127.
14. СНиП 2.02.01-83. (1985). *Основания зданий и сооружений. Нормы проектирования*. Москва: Стройиздат.
15. Ильичев, В.А. & Фадеев, А.Б. (2002). Европейские правила геотехнического проектирования. *Основания, фундаменты и механика грунтов*, 6, 25-29.
16. Фадеев, А.Б. & Лукин, В.А. (2006). Сопоставление методик СНиП и ЕК7 при расчете оснований фундаментов мелкого заложения. *Основания, фундаменты и механика грунтов,* 4. 19-24.
17. EN 1997-1. Eurocode 7. *Geotechnical design. Part 1: General rules*. CEN/TC 250. 2003. ICS: 93.020; 91.080.01.
18. Сорочан, Е.А., Быцутенко, О.В. & Лиховцев, В.М. (1991). Фундаменты на промежуточной подготовке переменной жесткости. *Основания, фундаменты и механика грунтов,* 1, 7-8.
19. Сорочан, Е.А. & Абуханов, А.З. (1988). Экспериментальные исследования напряженного состояния фундамента с промежуточной подготовкой на песчаном основании. *Исследование и расчет оснований и фундаментов при действии статических и динамических нагрузок: Межвузовский сборник*, 79-85.
20. Грицук, М.С. & Игнатюк, В.Ю. (1978). Напряженно-деформированное состояние фундаментных блоков с криволинейной поверхностью опирания. *Известия вузов. Строительство и архитектура,* 10. 31-33.
21. Бай, В.Ф. & Краев, А.Н. (2014). Исследование работы песчаной армированной по контуру подушки с криволинейной подошвой в условиях слабых глинистых грунтов. *Вестник гражданских инженеров*, 3(44). 107-110.
22. Самородов, О.В., Лучковський, І.Я., Конюхов, О.В. & Кротов, О.В. (2013). *Стрічковий фундамент з повздовжнім вирізом по підошві.* Патент України на винахід 100647, Київ: Державне патентне відомство Ураїни.
23. Самородов, А.В. (2005). *Внецентренно нагруженные фундаменты с вырезами по подошве*. (Дис. канд. техн. наук). Приднепровская государственная академия строительства и архитектуры, Днепр.
24. Самородов, А.В., Лучковский, И.Я. & Конюхов, А.В. (2010). Фундаменты с асимметричными вырезами по подошве при действии превалирующих односторонних моментных нагрузок. *Науковий вісник будівництва*, 61, 140-145.
25. Самородов, А.В., Лучковский, И.Я. & Кротов, О.В. (2012). Ленточный фундамент с продольным вырезом по подошве. *Збірник наукових праць. Серія: Галузеве машинобудування, будівництво,* 4(34)-2, 201-204.
26. Patra, C.R., Das, B.M., Bhoi, M. & Shin, E.C. (2005). Eccentrically loaded strip foundation on geogrid-reinforced sand. *Geotextiles and Geomembranes*, 24(4), 254-259. doi:10.1016/j.geotexmem.2005.12.001
27. Das, B.M. & Shin, E.C. (1996). Laboratory model tests for cyclic load-induced settlement of a strip foundation on a clayey soil. *Geotechnical & Geological Engineering*, 14(3), 254-259. Retrieved from https://link.springer.com.
28. Griffiths, D.V., Fenton, G.A. & Manoharan, N. (2002). Bearing Capacity of Rough Rigid Strip Footing on Cohesive Soil: Probabilistic Study. *Journal of Geotechnical and Geoenvironmental Engineering*, 128(9), 145-151. doi:10.1061/(ASCE)1090-0241(2002)128:9(743)
29. Yin, Jian-Hua, Wang, Yu-Jie & Selvadurai, A.P.S. (2001). Influence of Nonassociativity on the Bearing Capacity of a Strip Footing. *Journal of Geotechnical and Geoenvironmental Engineering*, 127(11), 81-89. doi:10.1061/(ASCE)1090-0241(2001)127:11(985).
30. Salih Keskin, M. & Laman, M. (2013). Model studies of bearing capacity of strip footing on sand slope. KSCE Journal of Civil Engineering, 17(4), 699-711. doi:10.1007/s12205-013-0406-x.