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# RATIONAL PLANNING OF PILE FOUNDATIONS

*The existing methods (design directory) recommend using nomograms depending on the eccentricity of bending moment and numbers of piles while acting only vertical loads. These methods have a number of shortcomings and are inconvenient, because of lack of adequate alternatives and they do not provide the greatest efficiency. The convenient method of pile foundation designing (grillages and fields), depending on the load values, is the foundation proposed by the authors in this article. The results of numerical investigations determined the optimal grillages dimensions and numbers of pile in "bush" of pile, showed that this method gives optimal options for pile foundation under single column with large bending moments and minimum material expenditures and also provides its bearing capacity*

***Keywords**: the foundation, pile, bearing capacity calculation.*

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# РАЦІОНАЛЬНЕ ПРОЕКТУВАННЯ ПАЛЬОВИХ ФУНДАМЕНТІВ

*Існуючою методикою, яка наведена в довіднику проектувальника, передбачено проектування пальового фундаменту за допомогою номограми залежно від ексцентриситету дії згинального моменту та необхідної кількості паль при дії лише вертикального навантаження. З'ясовано, що вона досить громіздка, незручна і має ряд недоліків, а саме: не вказує на будь-який альтернативний варіант і не забезпечує одну з основних вимог щодо того, що запроектований варіант повинен бути найбільш економічним. Розроблено зручну та зрозумілу методику розрахунку й конструювання пальового поля та ростверків залежно від дії розрахункових зусиль на фундамент з використанням таблиці або графіка, які є зручними при проектуванні. Виконаними числовими дослідженнями й установленими оптимальними параметрами розмірів ростверків та кількості паль у кущі показано, що застосування запропонованої методики дозволяє запроектувати пальовий фундамент з оптимальними параметрами під окремо стоячу колону при дії значного згинального моменту з мінімальними витратами матеріалу з одночасним забезпеченням його несучої здатності.*

***Ключові слова:** фундамент, паля, несуча здатність, розрахунок.*

**Introduction**. The main task of pile field and metal grills planning is to provide maximum allowable pile load capacity, to ensure the uniformity of foundation materials and pile-soil, to determine optimal sizes and unification of piles and grills, to calculate the lowest cost of installation and placement, as well as the minimum earthwork volumes at their installation.

As a rule, under bearing walls piles are placed in a single row and this does not cause any special complications for the designer. Frame structures determine usage of minimal number of piles in the bush with minimum-size grillages. The methods that are used for eccentric foundations and concentrically loaded foundation depending on the eccentricity of bending moment are simple and clear [2 – 4]. When stand-alone columnar foundation perceives significant bending moments, there are complications caused by the impossibility to ensure the fulfillment of all conditions.

These options are appropriate for industrial steel or reinforced concrete framed buildings with a heavy crane load, for high-rise buildings, which perceive significant wind loads, for pressure gravity retaining walls, etc.

**Analysis of recent researches and publications**. According to the design standards [5, 6], calculation and planning of pile concentrically loaded foundation with separately standing columns on the same plane defines carrying capacity of hanging piles $F_d$ and allowable load $P$. Further, depending on size of the external load, the required number of piles is determined and the pile bush is constructed. Then the following conditions are checked:

$$\left.\begin{aligned} N &= G_{nI} + \frac{N_I + G_{pI}}{n} \le P \\ N_{max} &= G_{nI} + \frac{N_I + G_{pI}}{n} + \frac{(M_I + Q_I \cdot h) \cdot x_{max}}{\sum x_i^2} \le 1{,}2 \cdot P \\ N_{min} &= G_{nI} + \frac{N_I + G_{pI}}{n} - \frac{(M_I + Q_I \cdot h) \cdot x_{max}}{\sum x_i^2} \ge 0 \end{aligned}\right\}, \qquad (1)$$

where $N_{max}$, $N_{min}$ – maximum and minimum load on extreme piles;

$G_{pI}$ – grillage and soil weight;

$n$ – number of piles in the bush;

$G_{nI}$– the pile weight;

$x_{max}$– distance from the main axis to the extreme pile axis;

$x_i$ – distance from the main axis to the axis of each pile;

$M_I$ , $Q_I$ – moment and horizontal component of external influences at the level of the foundation trimming to the corresponding axis;

$h$ – distance from the grillage bottom to its top;

$P$ – pile allowable loads.

Overloading of extreme piles in the bush for 20% (1,2$P$) from the allowable load is possible in the calculation of bases with regard to wind and crane loads (while the crane load should be more than 30% of the total load on the bases), i.e. $N_{max} \le 1{,}2P$.

If $N_{min} < 0$, then it is necessary to calculate driving force for pulling loads.

In the design directory [1] the parameters of unified bush piles of square section for the single-storey and multi-storey buildings are listed, and the methods of using nomograms depending on the eccentricity of bending moment and numbers of piles while acting only vertical loads are characterized.

**Identification of general problem parts unsolved before.** The current methods of nomogram is used to determine the required number of piles and the distance between the centers of their axes. These methods have a number of shortcomings and are inconvenient, because of adequate alternatives lack and they do not provide the greatest efficiency. For example, in some cases if the first and third conditions of expression (1) are provided, the second condition is not ensured. In this case we need to increase the distance between the extreme driving axles, which will increase the size of grillage and therefore the construction costs; or it will increase the number of piles in the bush, leading to failure of the third condition as piles location will be changed, while bending moment influence will increase and the effect of vertical load will be reduced. So, there's no definite salvation of the problem: whether to develop methods within the frame "bush - pile", or determine the optimal number and size of piles.

Thus, there is a need to develop convenient method which clearly designs and plans the best option pile foundation without further recalculation because of one failure of the expression three conditions (1).

**Setting objectives**. A key point in the calculation of the foundation with large value of eccentricity is to provide third condition (1), it is true when driving bush takes considerable largest bending moments. The most rational option will be when the vertical load in the most dumped pile from the longitudinal force $N_I$ and bending moment $M_I$ are equal:

$$N_{min} = G_{nI} + \frac{N_I + G_{pI}}{n} - \frac{(M_I + Q_I \cdot h) \cdot x_{max}}{\sum x_i^2} \geq 0 . \quad (2)$$

After some mathematical operations, it is got the following expression:

$$\frac{n \cdot G_{nI} + N_I + G_{pI}}{M_I + Q_I \cdot h} = \frac{n \cdot x_{max}}{\sum x_i^2} . \quad (3)$$

The left side of the expression (3) is inverse eccentricity of the bending moment ($M_I + Q_I h$) relative to the bottom of the grillages, and the right side of the expression depends on the number of piles and their location in the bush and is constant for an unaltered number of piles and the same distance between the axes of the adjacent piles $x$ for unified bushes.

Numerical studies were conducted to determine the relationship $1/e = (n \cdot x_{max})/\sum x_i^2$ for the unified bush piles, results of which are listed in the design directory [1] and in Table 1 or graphically in Figure 1.

**Basic material and results**. According to the above stated, calculation of concentrically loaded columnar foundation, depending on a bending moment, should be taking with the regard numbers of pile from the first part of the expression (1), and considering pile foundation has only 60% vertical load $N_I$, providing implementation of the second condition of the expression with the allowable load 1,2$P$, and providing the third part, which determines that the most dumped piles of bending moment and longitudinal forces are equal, i.e.

$$n = \frac{N_I + G_{pI}}{0{,}6 \cdot P - G_{nI}} \approx \frac{N_I}{0{,}6 \cdot P} . \quad (4)$$

**Table 1 – Inverse eccentricity of the bending moment *1/e***

| Number of piles in the bushes *n* | Distance between the axes of the adjacent piles *x*, м | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0,3 | 0,6 | 0,9 | 1,2 | 1,5 | 1,8 | 2,1 | 2,4 | 2,7 | 3,0 |
| 2 | 6,667 | 3,333 | 2,222 | 1,667 | 1,333 | 1,111 | 0,952 | 0,837 | 0,741 | 0,667 |
| 3 | 11,560 | 5,780 | 3,853 | 2,890 | 2,312 | 1,927 | 1,651 | 1,445 | 1,284 | 1,156 |
| 4 | 6,667 | 3,333 | 2,222 | 1,667 | 1,333 | 1,111 | 0,952 | 0,837 | 0,741 | 0,667 |
| 5 | 4,811 | 2,406 | 1,604 | 1,203 | 0,962 | 0,802 | 0,687 | 0,601 | 0,535 | 0,481 |
| 6 | 5,000 | 2,500 | 1,667 | 1,250 | 1,000 | 0,833 | 0,714 | 0,625 | 0,556 | 0,500 |
| 7 | 4,490 | 2,245 | 1,497 | 1,123 | 0,898 | 0,748 | 0,641 | 0,561 | 0,499 | 0,464 |
| 8 | 3,421 | 1,711 | 1,140 | 0,855 | 0,684 | 0,570 | 0,489 | 0,428 | 0,380 | 0,342 |
| 9 | 5,000 | 2,500 | 1,667 | 1,250 | 1,000 | 0,833 | 0,714 | 0,625 | 0,556 | 0,500 |
| 10 | 3,733 | 1,867 | 1,244 | 0,933 | 0,747 | 0,622 | 0,533 | 0,467 | 0,415 | 0,373 |
| 11 | 3,023 | 1,512 | 1,008 | 0,756 | 0,605 | 0,504 | 0,432 | 0,378 | 0,336 | 0,302 |
| 12 | 4,015 | 2,011 | 1,352 | 1,014 | 0,831 | 0,673 | 0,569 | 0,505 | 0,451 | 0,401 |

Next step in the calculation is to determine the inverse eccentricity of bending moment in accordance with the expression

$$\frac{1}{e} = \frac{n \cdot G_{nI} + N_I + G_{pI}}{M_I + Q_I \cdot h} \approx \frac{N_I}{M_I + Q_I \cdot h} \tag{5}$$

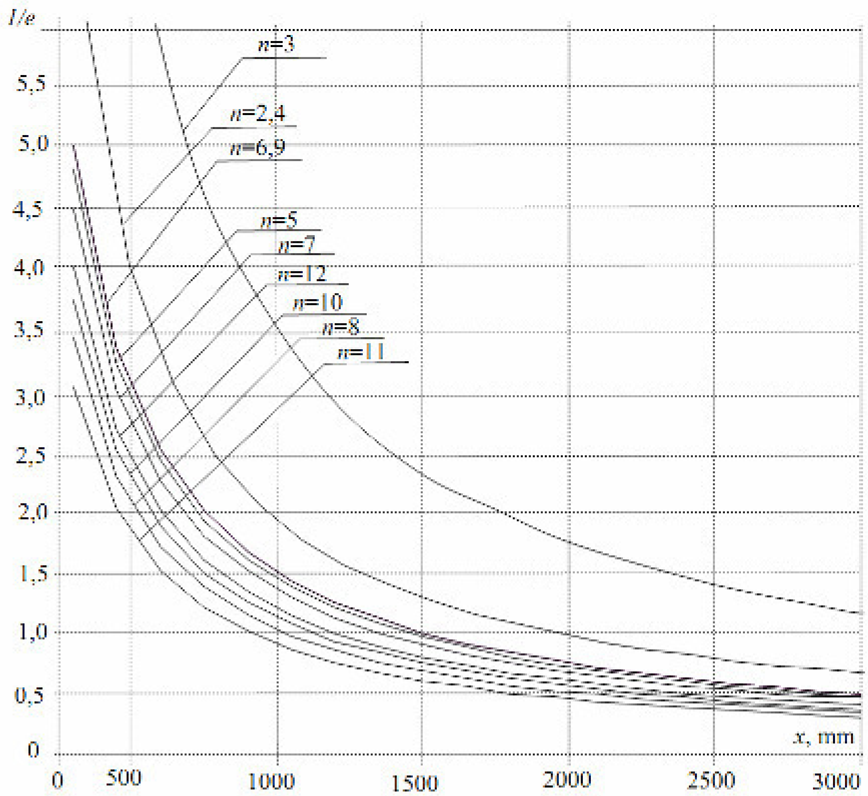


**Figure 1 – Determination of the optimal parameters for bush piles planning**

In the expressions (4) and (5) during the first stages of calculations the weight of the pile itself $G_{nI}$ and the weight of the grillages $G_{pI}$ can be neglected, because their exact values are unknown. In addition, planning of $G_{nI}$, $G_{pI}$ load pile is slightly compared with vertical load $N_I$ (≈5%), and while checking the third part of the expression (1), to neglet of their values in the beginning contributes to strength of construction.

Then taking into consideration the data from the Table 1 or Figure 1, it is determined the required distance between the axes of the neighboring piles depending on their number $n$ and the inverse eccentricity $1/e$, or according to the eccentricity inverse $1/e$ it is accepted another number of piles $n$ with the appropriate step $x$, but not less then in expression (4), as in this case first part of condition fails (1).

The graphic of the inverse eccentricity of bending moment $1/e$ shows that increasing of the piles number at the same distance between the axes does not always raise the reliability of the foundation, in particular, the foundations with three and four piles.

It is calculated the pile foundation (Figure 2) with such loads: vertical loads – $N_I = 1800$ kN; bending moment – $M_I = 1200$ kN·m transverse load – $Q_I = 60$ kN, $h = 1{,}5$ m; pile ПН 110.30; allowable pile load is $P = 800$ kN.

It is determined the required number of piles and inverse eccentricity

$n = \frac{N_I}{0{,}6 \cdot P} = \frac{1800}{0{,}6 \cdot 800} = 3{,}75$, we take 4 piles;

$$1/e = \frac{N_I}{M_I + Q_I \cdot h} = \frac{1800}{1000 + 60 \cdot 1{,}5} = 1{,}65.$$

In accordance with the Table 1 or Figure 1 distance between pile axes as $a = 1{,}2$ m is taken, alternatively it is possible to take 5 or 6 piles with the distance between them in 0,9 m and more.

Finally we check the implementation of conditions (1), determining the weight of piles and grillage:

$G_{nI}$=0,3·0,3·10,7·25·1,1=26,5 кN;

$G_{pI}$=1,8·1,8·1,65·20·1,12=119,75 кN,

$$\left.\begin{aligned} & N = G_{nI} + \frac{N_I + G_{pI}}{n} = 26{,}5 + \frac{1800 + 119{,}75}{4} = 505{,}44\,кH < P = 800\,кN; \\ & N_{max} = G_{nI} + \frac{N_I + G_{pI}}{n} + \frac{(M_I + Q_I \cdot h) \cdot x_{max}}{\sum x_i^2} = 505{,}44 + \\ & + \frac{(1000 + 60 \cdot 1{,}5) \cdot 0{,}6}{4 \cdot 0{,}6^2} = 959{,}57 < 1{,}2 \cdot P = 1{,}2 \cdot 800 = 960\,кN; \\ & N_{min} = G_{nI} + \frac{N_I + G_{pI}}{n} - \frac{(M_I + Q_I \cdot h) \cdot x_{max}}{\sum x_i^2} = 505{,}44 + 454{,}2 = 51{,}24\,кN > 0. \end{aligned}\right\}.$$

The conditions are fulfilled, so, the pile foundation is designed correctly.

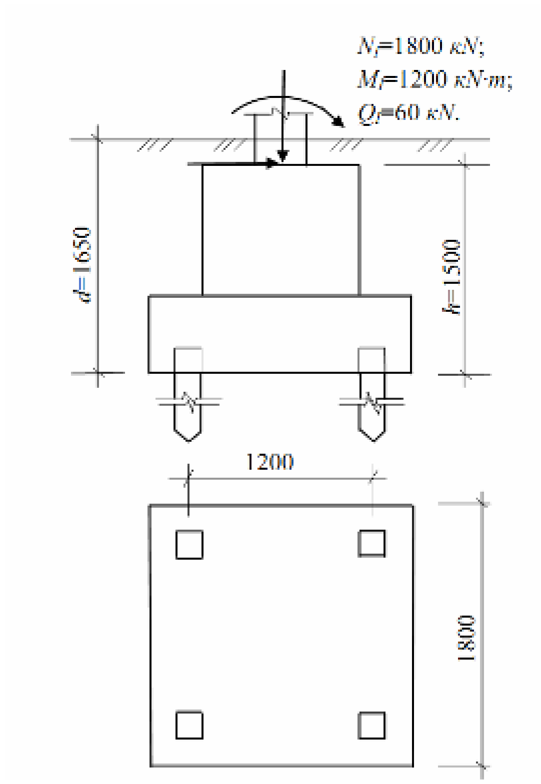


**Figure 2 – Calculation of pile foundation**

**Conclusions.** Applying of the proposed methods allows to design pile foundation with optimal options for single column with large bending moments and minimum material expenditures, while providing its bearing capacity.

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