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# ANALYTICAL AND NUMERICAL METHODS FOR DETERMINING THE CARRYING CAPACITY OF A PILE BARETT ON WEAK SOILS IN DEEP PITS

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**Abstracts**: The article provides an analysis of the bearing capacity of barrett piles in difficult geological conditions at a construction site in the city of Hanoi, Vietnam based on the results of analytical calculations according to Russian building codes, mathematical modeling and field full-scale tests. The paper describes a numerical test of a single barrette for Mohr-Coulomb and Hardening Soil models in the Midas GTS NX software package. The bearing capacity of a barrette in soft soils is also proposed to be determined by an analytical solution for calculating the settlement of a single pile, taking into account the unloading of the pit after soil excavation. The results of full-scale tests at the site of future construction, graphs of "load-settlement" of the barrette head from the applied vertical load and the general assessment of the bearing capacity of the barret pile by various methods are shown.

**Keywords**: pile-barrett, settlement-load dependence, bearing capacity, FEM, analytical solution, mathematical modeling

# АНАЛИТИЧЕСКИЕ И ЧИСЛЕННЫЕ МЕТОДЫ ОПРЕДЕЛЕНИЯ НЕСУЩЕЙ СПОСОБНОСТИ СВАЙ-БАРЕТТ НА СЛАБЫХ ГРУНТАХ В ГЛУБОКИХ КОТЛОВАНАХ

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**Аннотация**: в статье приводится анализ несущей способности свай-баретт в сложных инженерно-геологических условиях на строительной площадке в городе Ханой, Вьетнам по результатам аналитических расчетов по Российским строительным нормам, математического моделирования и полевых натурных испытаний. Описывается проведение численного испытания одиночной баретты для моделей грунтов Mohr-Coulomb и Hardening Soil в программном комплексе Midas GTS NX. Несущую способность баретты в слабых грунтах также предлагается определять по аналитическому решению расчета осадки одиночной сваи с учетом разгрузки котлована после разработки. Показаны результаты натурных испытаний на площадке будущего строительства, графики «нагрузка-осадка» оголовка баретты от приложенной вертикальной нагрузки и общая оценка несущей способности сваи-барреты по различным методам.

**Ключевые слова**: свая-баретта, зависимость осадка-нагрузка, несущая способность, МКЭ, аналитическое решение, математическое моделирование

## INTRODUCTION

Currently, the demand for the construction of high-rise buildings is very high in large metropolitan areas of the world [1]. Difficult geotechnical conditions dictate special requirements for the design of zero cycle structures for such facilities [2]. Therefore, piles-barrettas are gaining great popularity as deep foundations, which can perceive significant longitudinal and transverse forces due to the increased bearing capacity both in material and in soil compared to alternative types of pile foundations [3]. At the preliminary design stage, when full-scale tests of piles have not yet been carried out, in order to assign the main structural parameters of foundations, a computational design method is used based on analytical and numerical calculations for limit states [1]. Taking into account the base formed by a layer of weak soils, the great depth of the excavation and the laying of barrett piles, a special approach to the calculation of the bearing capacity of the piles, taking into account the stress-strain state of the enclosing soil mass, is required [4,5,6]. On the construction site of a high-rise building with a developed underground part in the city of Hanoi, Vietnam, barrettas with a section of 800x2800 mm and a length of 37 meters were designed as foundations. In order to determine the bearing capacity of a single barrette on the ground, analytical calculations were carried out according to the method of Russian standards and mathematical modeling in the geotechnical software package. After assigning the parameters of the pile foundation, at the construction site, full-scale tests of a single barrette with a static indentation load were made and carried out.

## GEOTECHNICAL CONDITIONS OF THE CONSTRUCTION SITE

According to the results of engineering and geological surveys, the geological zone under the well has a depth of 61 m, consists of 9 soil layers: IGE-1: compacted embankment; IGE-2: fluid clay, brownish-gray, mixed with organic inclusions; IGE-3: loose sand, ash-gray, medium brown of medium density, unimportant IGE-4: fluid-plastic clay, brownish-gray, mixed with organic inclusions; IGE-5: fine, gray and yellowish-gray sand, medium density, unimportant; IGE-6: soft-plastic loam, brownish-gray; IGE-7: fine sand, medium size, unimportant; IGE-8: fluid-plastic loam, brown-gray, dark gray, mixed organic; IGE-9: gravel and pebble soil. The engineering and geological conditions of the construction site are relatively difficult with layers of weak soils and a high level of groundwater at an elevation of -4.50 m from the earth's surface. The physical and mechanical properties of soils are shown in Table 1. A barrette with a section of 800x2800 mm and a length of 37 meters rests on a strong layer of IGE-9 – gravel-pebble soil (Figure 1).

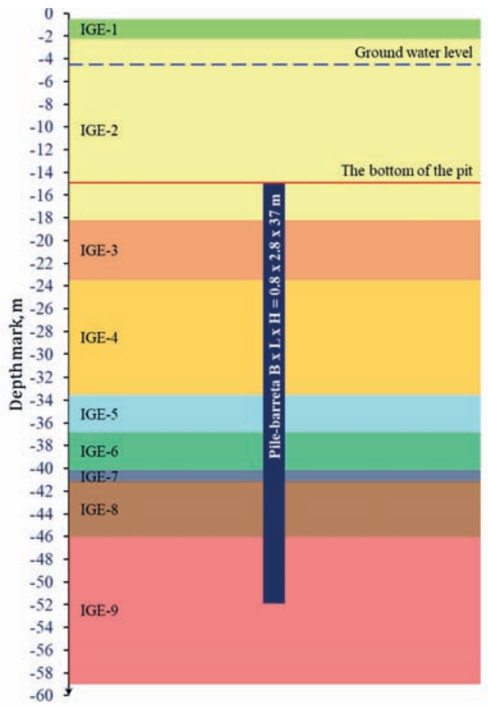



*Figure 1. Layout of the pile-barrets in the ground*

## DETERMINATION OF THE BEARING CAPACITY OF PILES BY ANALYTICAL METHODS

In accordance with Russian standards [7], the bearing capacity of hanging piles is determined depending on the physical and mechanical properties of the foundation soil and the depth of the pile. Analytical calculations have shown the value of the total bearing capacity of this barrette equal to $F_{d,calc1}$ = 27285 kN. At the same time, 77% fell on the heel of the pile and only 23% on the side surface.

*Table 1. Physical and mechanical properties of soils*

| No. layers | Soil | $h$, м ($m$) | $\gamma$, кН / м$^3$ (kN/m$^3$) | $I_L$ | $e$ | $\varphi$, град. (degree) | $c$, кПа (kPa) | $E$, МПа (MPa) |
|---|---|---|---|---|---|---|---|---|
| 1 | Compacted embankment | 1.6 | 16.00 | - | - | - | - | - |
| 2 | Fluid clay | 16.1 | 17.00 | 1.408 | 1.246 | 6.30 | 7.00 | 1.5 |
| 3 | Fine sand | 5.1 | 19.00 | 0.350 | 0.771 | 30.00 | - | 13.5 |
| 4 | Fluid-plastic clay | 10.2 | 17.20 | 0.811 | 1.171 | 18.00 | 9.10 | 15.0 |
| 5 | Fine sand | 3.0 | 19.20 | 0.350 | 0.746 | 30.00 | - | 13.5 |
| 6 | Soft-plastic loam | 3.4 | 17.80 | 0.695 | 1.002 | 7.40 | 9.60 | 5.0 |
| 7 | Fine sand | 1.0 | 19.10 | 0.035 | 0.755 | 30.00 | - | 13.5 |
| 8 | Fluid-plastic loam | 4.8 | 17.50 | 0.930 | 1.082 | 8.00 | 9.50 | 3.0 |
| 9 | Gravel and pebble soil | >15.8 | 20.10 | 0.300 | 0.524 | 38.00 | 2.00 | 50.0 |

Taking into account the significant thickness of soft soils with a low modulus of deformation within the barrette shaft, the deformability of the pile under load will play a significant role. Therefore, in the calculations, it was decided to limit the bearing capacity on the ground by the limiting settlement of a single pile, equal to 40 mm, similar to full-scale and numerical tests. The method for determining the settlement of a single pile depending on the average value of the soil shear modulus $G$ within the pile and under its lower end is also described in the provisions of the Russian standard [7]. According to the results of the analytical calculation, it was found that the bearing capacity of the barrett from the condition of limiting the settlement to 40 mm was $F_{d,calc2}$ = 18450 kN. The depth of the projected pit is almost 15 meters. At depths of more than 5 meters, the effect of "unloading-reloading" becomes most pronounced for a certain thickness of the base as a result of excavation of the pit. This phenomenon will manifest itself especially in foundations composed of weak soils with a low modulus of deformation. Therefore, to calculate the settlement of barrett in deep pits, it was proposed to determine the shear modulus $G$ taking into account the unloading of the base. For this purpos, a new term Hur is introduced, which means the depth of the unloading strata. The lower boundary of the unloading stratum is taken at a depth z = $H_{ur}$, where the condition is fulfilled:

$$\sigma_{z\gamma} = 0,5\,\sigma_{zg}, \qquad (1)$$

where $\sigma_{z\gamma}$ is a vertical stress from the own weight of the soil, selected when cutting the excavation, at a depth $z$ from the level of the bottom of the excavation, kPa. Determined according to the provisions of the Russian standard for geotechnical construction [8].

$\sigma_{zg}$ is a vertical stress due to the own weight of the soil at a depth $z$ from the level of the bottom of the excavation, kPa.

In this case, the depth of the unloading thickness $H_{ur}$ should be no more than $H_{max}$, equal to (4 + 0.1$b$) at 10 <$b$ ≤60 and 10 m at $b$> 60 m, where b is the width of the pit.

In the problem under consideration, $H_{ur}$ = 10 m.

To calculate the settlement when determining the average value of the soil shear modulus, within the unloading thickness $H_{ur}$ for soils, the elastic shear modulus Gur is taken, defined as

$$G_{ur} = \frac{1}{2(1+\upsilon_{ur})} E_{ur},$$

where $E_{ur}$ is a modulus of soil deformation upon removal / reapplication of the load,
$\upsilon_{ur}$ is a coefficient of lateral deformation of the soil when removing / reapplying a load.
According to the results of the analytical calculation, taking into account the unloading of the soil in the excavation, it was found that the bearing capacity of the barrette from the condition of limiting the settlement of 40 mm was $F_{d,calc3}$ =24600 kN.

## MODELING

Numerical modeling of changes in the stress-strain state of the soil mass in the process of virtual testing of the experimental barrette pile was carried out using the geotechnical software package Midas GTS NX in a spatial setting. A finite element model of the test barrette-surrounding soil mass system in Midas GTS NX is shown in Figure 2.
The dimensions of the computational area are taken in terms of 30.8 x 32.8 m and a depth of 66.2 m. For the formation of finite elements, a hybrid mixed mesh, mainly hexahedral types of finite elements, was used. The grid step is condensed in the area where the barrets are located and is discharged to the boundaries of the computational domain. Consideration of the behavior of the soil at the contact between the barrett and the base mass was modeled using special interface contact elements. The stiffness parameters are assigned taking into account the reduction in contact strength, taking into account the reduction factors given in the Russian design standards [7].
Mathematical modeling of the test was carried out step by step in several stages:
1. Formation of the initial stress-strain state of the soil mass;
2. Development of the foundation pit;
3. Barretta device;
4. Loading the barrette (Figure 2). Gradual application of a vertical indentation load to the test barrette of 2500 kN at each stage.
To calculate the bearing capacity of a barrette in the Midas GTS NX program, two subgrade models were considered:
– Ideal-elastoplastic Mohr-Coulomb model.
– Elastoplastic model of the hardening soil "Hardening Soil".
The deformed model diagram and vertical displacements at an intermediate stage of testing (at P = 20,000 kN) for various soil models are shown in Figure 3.

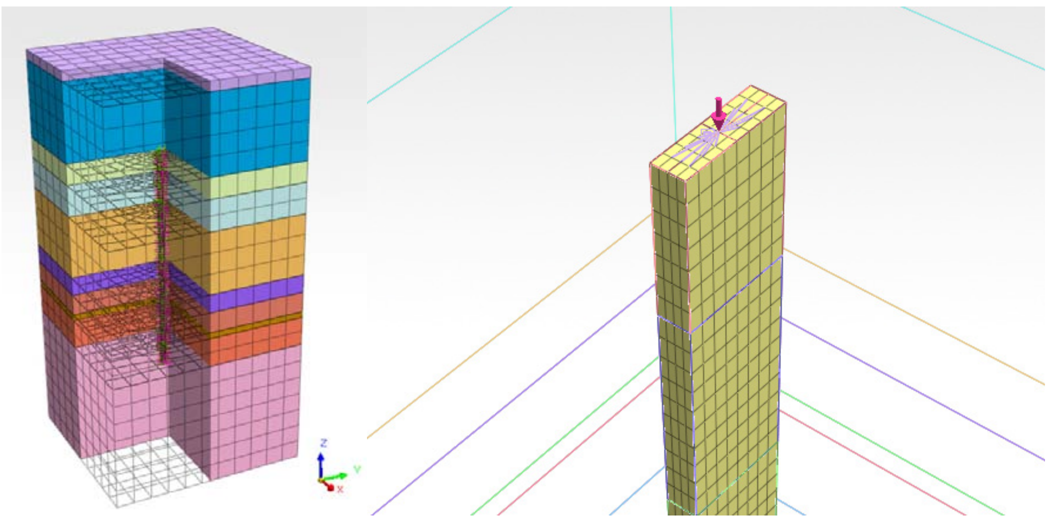
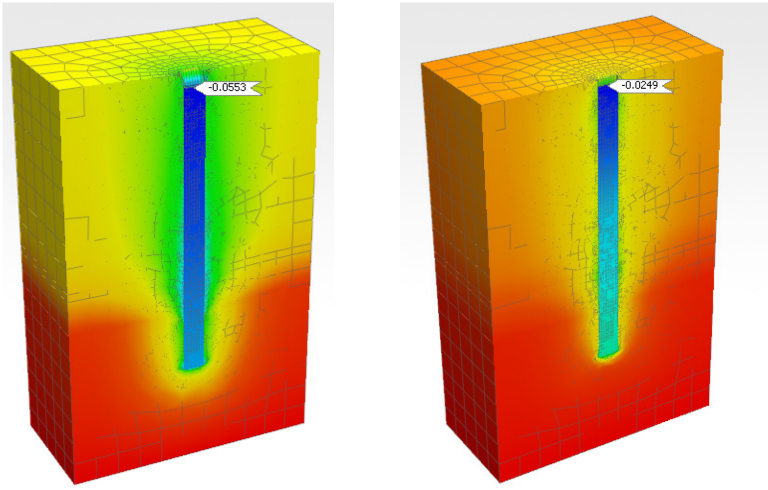


*Figure 2. Mathematical FE-model*




*a)* *b)*

*Figure 3. Deformed diagram and vertical displacements of the model under a load of 20,000 kN: a) Mohr-Coulomb model, b) Hardening Soil model*

The criterion for ensuring the bearing capacity of the pile on the ground is the vertical displacement of the barrette head, equal to 40 mm. This condition is met at the calculated vertical load equal to $F_{d,MC}$ = 16440 kN for the Mohr-Coulomb model and $F_{d,HS}$ = 23600 kN for the Hardening Soil model.

## FULL-SCALE TESTS

Experimental barrette piles were made on the site for the construction of a high-rise building in the city of Hanoi. Tests of a single barrette with a section of 800x2800 mm and a length of 37 meters with a vertical static load were carried out using hydraulic jacks up to a maximum load of 30 MN using the Top-Down method.

The condition of the maximum settlement of the pile head under a load of 40 mm is achieved under a vertical load $F_{d,site}$ = 27500 kN (Figure 4). This value is taken as the bearing capacity of the barrette on the ground.

## RESULTS

The results of determining the bearing capacity of a barrette on the ground by analytical and numerical methods, as well as the results of field tests, are presented in Table 2.

The combined load-settlement graph for various considered methods for determining the bearing capacity of a barrette is shown in Figure 5.

## DISCUSSION

As it is well known, the ideal-elastoplastic soil Mohr-Coulomb model does not describe the behavior of the soil during unloading [9]. The same applies to the analytical method for determining the settlement of a single pile according to the Russian standard, where the soil is considered as a linearly deformed half-space, characterized by the shear modulus and Poisson's ratio. The results obtained by these methods are in good agreement with each other. The values of the bearing capacity differ by about 10% (Table 2), and at the initial stage of loading (at P <12500 kN) the graphs exactly coincide. However, the solutions based on these techniques do not agree well with the results of field tests and cannot be applied for practical purposes for conditions of soft soils and deep pits.

The proposed modification of the analytical method for calculating the settlement of a single pile in order to take into account the unloading of the base

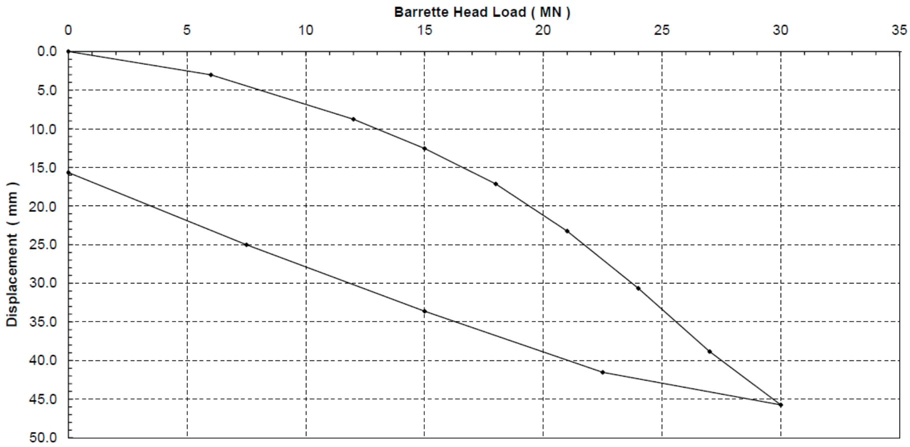



*Figure 4.* *Results of full-scale static tests of barrette piles*

*Table 2.* *Bearing capacity of pile-barrets by different methods*

| | Methodology for calculating the bearing capacity of a pile on the ground | Bearing capacity of the pile on the ground, kN |
|---|---|---|
| | Field test results, $F_{d,site}$ | 27500 |
| | Analytical classical method [7], $F_{d,calc1}$ | 27285 (-1%) |
| Taking into account unloading | Midas GTS NX software for *Hardening Soil* model, $F_{d,HS}$ | 23600 (-14%) |
| | Analytical method for settlement criterion (modified), $F_{d,calc3}$ | 24600 (-10%) |
| excluding unloading | Midas GTS NX software for *Mohr-Coulomb* model, $F_{d,MC}$ | 16440 (-40%) |
| | Analytical method according to the criterion of settlement [7] , $F_{d,calc2}$ | 18450 (-33%) |

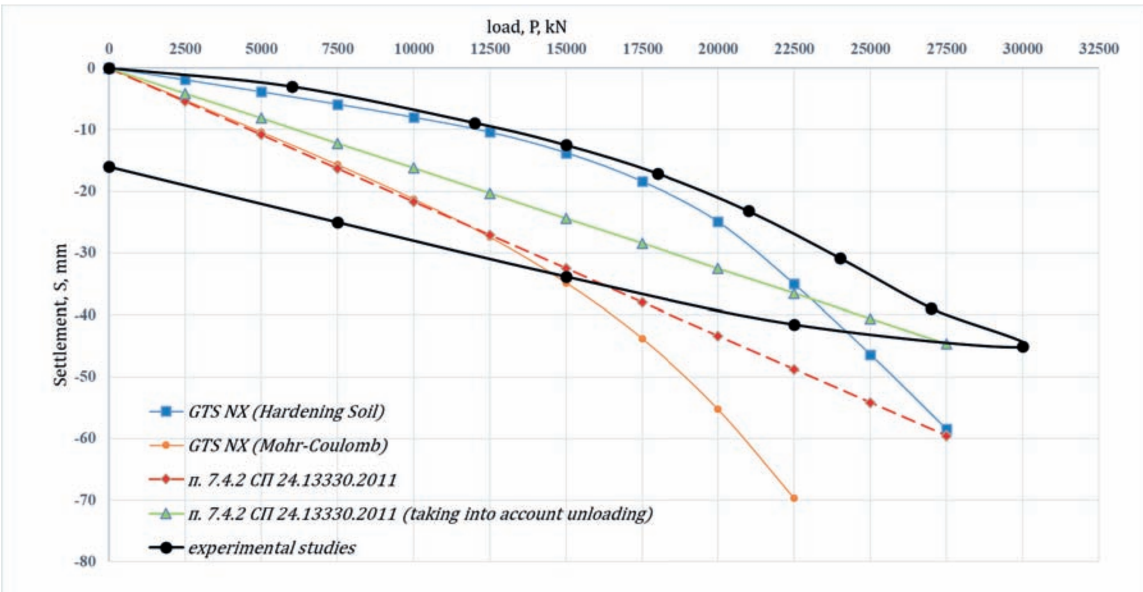



*Figure 5.* *Combined load-settlement graph based on the results of analytical calculations, numerical modeling and field tests*

during the development of a deep excavation made it possible to describe the behavior of a barrette under load with sufficient accuracy. The bearing capacity with a limiting settlement of 40 mm is in good agreement with the numerical solution (with the adopted Hardening Soil model), the analytical method for strength characteristics, and the results of full-scale static tests.

## CONCLUSIONS

1) Complex design solutions of the zero cycle and difficult geological conditions of the construction site require a special approach to the design of deep foundations.
2) When using different soil models (MC and HS) in mathematical modeling of the test of a barrette in a deep pit, the graphs of barrett displacement under load are significantly different. For numerical calculations of piles in soft soils and deep pits, it is recommended to use the Hardening Soil model, which takes into account the work of the soil along the secondary loading branch. This solution, with sufficient accuracy for practical purposes, describes the results of field tests.
3) A good convergence of the value of the bearing capacity of the barrett on the soil is shown by the analytical solution for determining the settlement, where the reduced shear modulus G is determined taking into account the thickness of the base unloading, for which the soil deformation modulus is applied when removing / reapplying the load Eur. This technique is applicable for preliminary calculations of settlement and bearing capacity of piles.

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