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PILE FOUNDATIONS USED IN SEISMIC REGIONS

M.M. Bakhromov
Fergana State Technical University
baxromovmahmud393@qmail.com

Abstract

The seismic resistance problem of pile foundations; the influence of the design seismicity of the construction site; the horizontal component of seismic actions; the reduction of seismic force due to denser soils; vibrations of the "structure–foundation" system; clay soils and sandy soils; determination of bearing capacity for various soil conditions and for insufficiently studied pile types; and methods for determining the bearing capacity of pile foundations under seismic loading conditions.

Keywords. Pile foundations, site seismicity, seismic actions, soil, horizontal loads, "structure–foundation" system, bearing capacity.

Introduction

The problem of seismic resistance of foundations is an integral part of the overall problem of seismic resistance of buildings and structures, and it must be solved based on the fundamental principles and approaches used to address the general problem. It is well known that the seismic design of structures is carried out in the following sequence: after the construction site is selected, the design seismic intensity of the site is determined relative to the seismic intensity of the entire region, in accordance with the properties of the soil layers; then the dynamic characteristics of the structure are evaluated—that is, its natural vibration frequencies and mode shapes are determined. In addition, the seismic loads acting on the structure are specified, and the structural elements of the building or

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structure are designed for bearing capacity according to special load combinations that take seismic actions into account.

Methodology

In the process of analyzing structures under the general seismic actions described above, pile foundations may manifest their effects at various stages.

First, for example, the question arises as to the influence of pile foundations on the design seismicity of the construction site. This issue is to some extent theoretical and has not yet been fully resolved. Nevertheless, certain considerations can be expressed in this regard. For instance, if end-bearing piles that penetrate loose soil layers and rest on a rock stratum are used, under certain conditions the structure may experience effects close to those of a structure directly founded on a rock base in terms of carrying vertical loads. In other words, pile foundations can, to a certain extent, reduce the vertical-direction seismic effects acting on a structure.

The question may also arise as to the possibility of reducing the horizontal component of seismic actions, since it is known that piles densify the soil; therefore, according to general concepts, it can be expected that denser soil reduces the intensity of seismic effects. In principle, this assumption is to some extent confirmed by the results of experiments conducted under natural conditions.

However, in general, the available data on the influence of pile foundations on seismic forces are still insufficient; therefore, there is no solid basis for providing specific practical recommendations at present, although this issue undoubtedly deserves the attention of researchers.

Secondly, the presence of pile foundations is taken into account when evaluating the dynamic characteristics of structures. Pile foundations of various configurations (high or low pile caps (grillages), the conditions of pile–cap connections, and the dimensions of the pile cross-section) can, to a certain extent,

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influence the natural vibration frequencies and mode shapes of a structure, as well as modify the loads that arise in the structure during these vibrations.

Thirdly, when assessing the bearing capacity of structural elements, it is also necessary to evaluate the bearing capacity of the pile foundation itself as one of these elements. In this case, the issue of the relationship between the intensity of seismic forces and the presence of pile foundations is not considered [1-10].

Pile foundations have always been considered a reliable base and have been used even under the most unfavorable soil conditions; therefore, it can be assumed that this reliability may also manifest under seismic conditions. According to the results of studies on earthquake effects, structures built on pile foundations exhibited smaller residual settlements and significantly less damage to superstructures. However, when designing pile foundations for seismic loads, it is necessary to take into account the behavior of piles under bending forces arising from horizontal seismic loads, as well as the potential reduction in their bearing capacity under vertical loads.

If we consider the behavior of piles during an earthquake, they are part of a single dynamic system referred to as the "structure–soil" system. In this system, on one hand, the piles transmit ground vibrations from the soil to the structure, and on the other hand, while participating in the vibration process, they receive seismic loads coming from the structure and, as a structural element, must retain their bearing capacity longer than other parts of the structure. In this regard, the following questions arise: during seismic actions, is there a difference in soil–structure interaction between structures built on pile foundations and those founded directly on natural soil? How does the pile foundation component of this complex system behave? And finally, how can the bearing capacity of pile foundations be evaluated?

Studies conducted by various authors have shown that structures of the same type, whether on pile foundations with low pile caps or directly on natural soil, exhibit almost identical values for the main vibration periods. This indicates that the

Eureka Journal of Civil, Architecture and Urban Studies (EJCAUS)
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https://eurekaoa.com/index.php/8

elastic and damping (vibration-dissipating) characteristics of these two types of foundations are also nearly the same.

To determine the role of pile foundations as a partial system during the vibration process of the "structure–foundation" system, it is first necessary to identify the dynamic characteristics of pile foundations—that is, their natural vibration frequencies and modes. This issue has attracted considerable attention from researchers, not only because of tasks related to earthquake-resistant construction but also due to problems associated with the calculation and design of foundations for machinery.

The results of studying the dynamic characteristics of pile foundations under horizontal and vertical loads show that the natural vibration frequencies of a pile fully embedded in the soil are very high, expressed in tens of hertz. It is known that the vibration frequencies of structures during seismic effects usually do not exceed 10–15 Hz. Therefore, at such vibration frequencies, the dynamic stresses in piles differ very little from the static stresses, meaning that during seismic vibrations, the pile deforms quasi-statically as a partial system. As a result, when analyzing its stress-strain state, the inertial forces can be neglected.

The first experiments to determine the load-bearing capacity of piles under vertical loads while accounting for seismic effects were conducted by Sh. G. Napetvaridze and B. N. Samkov using models of suspended piles. The experiments showed that additional settlements occur in piles during seismic vibrations, indicating a reduction in their load-bearing capacity. This reduction was evaluated using a coefficient defined as the ratio of the pile's load-bearing capacity under seismic conditions to its load-bearing capacity under static conditions. According to the experimental results, this coefficient depends on the physical and mechanical properties of the soil, as well as the intensity and duration of the seismic effects.

Although the experiments were conducted on small-scale models and their results were not tested under natural conditions, the obtained "seismic coefficients"

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Eureka Journal of Civil, Architecture and Urban Studies (EJCAUS)
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https://eurekaoa.com/index.php/8

provided a certain understanding of how soil conditions and the intensity of seismic effects influence the reduction in the load-bearing capacity of piles.

Later, based on tests conducted under seismic blasting effects at certain construction sites—taking into account the established engineering-geological conditions, as well as the design and dimensions of the piles—coefficients for the reduction of the piles' load-bearing capacity were determined. These coefficients were usually applied only to specific structures.

The results of model and field tests of pile foundations conducted with consideration of seismic effects, along with practical construction experience, have made it possible to develop an approach for designing pile foundations for buildings and structures in seismic regions [11-20].

The essence of this approach is that the reduction in the vertical load-bearing capacity of piles is accounted for by introducing a working condition coefficient:

— For clay soils — 0.6–0.8;
— For sandy soils — 0.5–0.7.

At the same time, the horizontal loads transmitted from the building to the piles are also limited—either based on test results or, in the absence of tests, as follows:

— For piles with a 30×30 cm cross-section — 10 kN,
— For piles with a 35×35 cm cross-section — 15 kN,
— For piles with a 40×40 cm cross-section — 20 kN.

On this basis, pile foundation designs for buildings constructed in seismic regions may not be the most economically efficient option, and it is considered that there is potential for their further improvement.

Due to the insufficient study of the behavior of pile foundations under seismic effects, as well as the relevance of their use in widespread construction, there arose a need for comprehensive research on the seismic resistance of pile foundations. The authors conducted extensive studies, some results of which were published in sources [1,2]. As a result of this work, practical methods were developed for calculating the load-bearing capacity of pile foundations under

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https://eurekaoa.com/index.php/8

vertical and horizontal loads, and recommendations were provided for taking into account the deformation characteristics of pile foundations when considering the "structure–soil" interaction.

Conclusion

As a result of the research conducted so far, reduction coefficients of load-bearing capacity under seismic effects have been determined for certain types of soils and pile designs. Therefore, for other soil conditions and unstudied types of piles, requirements have been developed for the methodology of testing piles under natural conditions in order to determine their load-bearing capacity.

The conducted research and the methods developed based on it for determining the load-bearing capacity of pile foundations under seismic effects later laid the groundwork for creating calculation methods, which were subsequently incorporated into regulatory documents.

The research made it possible to identify the reserves in the load-bearing capacity of pile foundations and, based on them, to develop calculation methods that allow the design of reliable and economically efficient structures. The results of the research indicate that:

1. First, when calculating the load-bearing capacity of pile foundations under vertical loads, higher values can be adopted by increasing the working condition coefficients.
2. Second, it became possible to calculate the horizontal loads transmitted to piles in significantly larger amounts. This is achieved not by limiting them to 1–2 tons, but by using precise calculation methods regardless of soil conditions and the type of pile reinforcement.

In addition, a calculation method was developed for a new design of pile foundation—that is, a pile foundation with an intermediate cushion. Using this method, horizontal seismic forces are not transmitted directly to the piles but are distributed through the soil, while all the advantages of the piles in bearing

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https://eurekaoa.com/index.php/8

vertical loads are preserved.

The calculation methods for pile foundations adapted to seismic effects have been tested in a number of design organizations and applied in the design of various types of residential, public, and industrial buildings. Pile foundations with a simple design and an intermediate cushion are widely used in mass construction in seismic regions.

For example, the following structures have been built based on pile foundations with an intermediate cushion:

- Five-story residential buildings in Chișinău;
- Six-story publishing house building in Tashkent;
- Cold storage building in Yerevan;
- And others.

The constructed buildings and structures, in some cases, were subjected to earthquakes close to the calculated seismic intensity. However, based on the study of the earthquake effects, no damage was observed in the foundations or the buildings.

Applying the established calculation methods in the design of earthquake-resistant pile foundations can, in some cases, provide significant economic benefits by reducing the number of piles by half.

A comparative analysis of design solutions implemented by a number of design organizations also demonstrated the economic efficiency of applying the methods developed by the authors. In 1997–1998, "Fundamentproekt" carried out variant design of various residential and industrial facilities and analyzed the technical solutions of the constructed objects. The results showed that the use of these calculation methods, included in the regulatory documents, provides an average economic benefit of 25%, which reduces the cost of the foundation, as well as labor and material consumption. This corresponds to an economic benefit of approximately 140.2 soums per 1 m² of area for residential and public buildings.

Eureka Journal of Civil, Architecture and Urban Studies (EJCAUS)
ISSN 2760-4977 (Online) Volume 01, Issue 02, December 2025

https://eurekaoa.com/index.php/8

Conclusion

However, it is not correct to consider that the conducted research has fully resolved the issue of the seismic resistance of pile foundations. Naturally, there are still questions that require further study. First of all, comprehensive research is needed to determine the additional settlements that occur in pile foundations during earthquakes.

It is also necessary to study other types of piles, for example, root-shaped piles, pyramidal piles with a slight slope of the side surface, piles expanded with a camouflet, and other types. In addition, research on large-diameter piles and pile-shell structures should continue, since dynamic effects may be stronger in them, and in many cases the quasi-static approach may be limited compared to driven and bored piles. This aligns with modern trends in improving the theory of structural calculation under seismic effects.

Of course, future research should be aimed at addressing questions arising in construction practice, for example, when buildings and structures are erected in areas previously considered unknown in terms of engineering-geological conditions. In such cases, it is necessary to increase the accuracy of calculations, and at a certain stage, there may be a need to revise the existing calculation methods for pile foundations used in buildings and structures constructed in seismic regions.

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