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REVIEW ARTICLE

# ANALYSIS OF RESEARCH RESULTS AND APPLICATION OF PILES AS PART OF HYDRAULIC FACILITIES

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**Abstract.** *The review article analyzes the results of research and application of various types of pile structures as part of hydraulic structures, including hammered, bored, tongue-and-groove piles. The results of the analysis of the study of foreign and domestic experts have shown the effectiveness of the use of piles in hydraulic engineering. The applications of piles as anti-filtration curtains of dams, for blocking riverbeds, the base of trough channels, aqueducts, mooring, embankments, fencing, shore-strengthening and other hydraulic structures are described. The features of the work of various types of driven piles (prismatic, wedge-shaped, conical, tongue-and-groove) and pile foundations of various hydraulic structures (trough channels, aqueducts, mooring, embankments, fencing, shore-strengthening, etc.) are considered. structures). The use of bored piles in the construction of the base of various hydraulic structures is described. The overall dimensions of the well piles for the installation of drilling piles are given. The distinctive features of various hydraulic structures on pile foundations under the influence of static, dynamic and special loads are revealed. Methods for calculating the parameters of immersion, deformability, stability and bearing capacity of piles and pile foundations are considered, which allow taking into account the patterns of their joint work with hydraulic structures. The analysis of the study shows a number of positive examples of the use of piles as part of hydraulic structures: cost-effectiveness, manufacturability, quickness and efficiency, etc.*

**Keywords:** *hydraulic engineering construction, bored pile, secant drilled pile, driven pile, sheet pile, bearing capacity, energy intensity.*

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# ГИДРОТЕХНИКАЛЫҚ ҚҰРЫЛЫМДАР ҚҰРАМЫНДА ҚАДАЛАРДЫ ПАЙДАЛАНУ ЖӘНЕ ЗЕРТТЕУ НӘТИЖЕЛЕРІН ТАЛДАУ

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**Аңдатпа.** *Шолу мақаласында гидротехникалық құралымдардың құрамындағы қадалар құрылымдарының әртүрлі түрлерін зерттеу және қолдану нәтижелеріне талдау жасалды, оның ішінде қадалар, бұрғылау, шпунт, бұрғылап-кесу қадалары. Шетелдік және отандық мамандардың зерттеу нәтижелері гидротехникалық құрылыста қадаларды қолданудың тиімділігін көрсетті. Қадаларды бөгеттердің сүзгіге қарсы перделері ретінде, өзен арналарын, науа арналарының, су құбырларының, айлақ, жағалау, қоршау, жағалауды нығайту және басқа да гидротехникалық құрылыстардың негізін жабу үшін қолдану сипатталған. Әртүрлі гидротехникалық құрылыстардың (науа арналары, су құбырлары, айлақ, жағалау, қоршау, жағалауды нығайту және т.б. құрылыстар) әртүрлі типтегі қадалардың (призматикалық, сына тәрізді, конустық, тілдік, тілдік) және қадалардың іргетастарының жұмыс ерекшеліктері қарастырылған. Әр түрлі гидротехникалық құрылыстардың негізін салу кезінде Бұрғылау қадаларын қолдану сипатталған. Бұрғылау қадаларын орнатуға арналған ұңғымалар қадаларының жалпы өлшемдері келтірілген. Статикалық, динамикалық және ерекше жүктемелерге ұшыраған кезде қадалардың іргетастарындағы әртүрлі гидротехникалық құрылымдардың айрықша ерекшеліктері анықталды. Қадалар мен қадалардың іргетастарының деформациялануын, тұрақтылығын және көтергіштігін батыру параметрлерін есептеу әдістері қарастырылады, бұл олардың гидротехникалық құрылымдармен бірлескен жұмысының заңдылықтарын ескеруге мүмкіндік береді. Зерттеуді талдау гидротехникалық құрылыстардың құрамында қадаларды қолданудың бірқатар жағымды жақтарын көрсетеді: үнемділік, технологиялылық, тез салынатын және перспективалық және т.б.*

**Түйін сөздер:** *Гидротехникалық құрылыс, бұрғылама қадалары, бұрғылау-кесу қадалар, қағылмалы қадалар, шпунтттық қадалар, жүк көтергіштігі, энергия сыйымдылығы.*

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ОБЗОРНАЯ СТАТЬЯ

# АНАЛИЗ РЕЗУЛЬТАТОВ ИССЛЕДОВАНИЙ И ПРИМЕНЕНИЯ СВАЙ В СОСТАВЕ ГИДРОТЕХНИЧЕСКИХ СООРУЖЕНИЙ

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**Аннотация.** *В обзорной статье выполнен анализ результатов исследования и применения различных видов свайных конструкций в составе гидротехнических сооружений включая забивные, буронабивные, шпунтовые, буросекущие сваи. Результаты анализа исследований зарубежных и отечественных специалистов показали эффективность применения свай в гидротехническом строительстве. Описаны применения свай в качестве противофильтрационных завес плотин, для перекрытия русел рек, основании лотковых каналов, акведуков, причальных, набережных, оградительных, берегоукрепляющих и других гидротехнических сооружений. Рассмотрены особенности работы различных видов забивных свай (призматических, клиновидных, конусных, шпунтовых) и свайных фундаментов из них различных гидротехнических сооружений (лотковых каналов, акведуков, причальных, набережных, оградительных, берегоукрепляющих и др. сооружений). Описано применение буронабивных свай при устройстве оснований различных гидротехнических сооружений. Приведены габаритные размеры свайи скважин для устройства буронабивных свай. Выявлены отличительные особенности различных гидротехнических сооружений на свайных фундаментах при воздействии статических, динамических и особенных нагрузок. Рассмотрены методы расчета параметров погруженияя деформируемости, устойчивости и несущей способности свай и свайных фундаментов, позволяющие учитывать закономерности их совместной работы с гидротехническими сооружениями. Анализ исследований показывает ряд положительных примуществ применения свай в составе гидротехнических сооружений: экономичность, технологичность, быстровозводимось и перпективность и др.*

**Ключевые слова:** *гидротехническое строительство, буронабивная свая, буросекущая свая, забивная свая, шпунтовая свая, несущая способность, энергоемкость.*

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## 1 INTRODUCTION

Pile structures are widely used in the construction of hydraulic facilities for various purposes. In many cases, this is the only possible rational solution for such structures erected in unfavorable engineering-geological, natural-climatic and cramped conditions (**Fedorovsky et al., 2003; Popov et al., 2015; Popov et al., 2015**). In hydraulic engineering construction the most widespread are bored piles, secant drilled piles, driven piles and tongue-and-groove piles. The results of studies and experience of their application for the construction of a number of hydraulic structures are considered below.

## 2 APPLICATION OF BORED AND SECANT PILES

Research results and peculiarities of designing, calculation and arrangement of bored piles for erection of hydraulic facilities are reflected in works of Kruglitsky N.N., Milkovsky S.I., Skvortsov V.F., Sheinblum V.M., Fedorov B.S., Smorodinov M.I., Baranov A.E., Pridanova O.V., Vdovenko A.V., Mityunina G.P., Unaibaev B.B. and etc.

The most widespread application of bored piles in hydraulic engineering construction is their use as an impervious dam barrier. For the first time such a barrier drilled was arranged in 1948 during the construction of the Haleys Dam in the California, USA (**Kruglitsky et al., 1973; Fedorov et al., 1975**). A similar method of dam impervious blanketing was developed in the former USSR by the Gidrospetsstroy Trust. This method was implemented by Soviet specialists in 1959 during the arrangement of the foundation of Sherubai-Nurinsk (Churubai-Nurinsk) reservoir of Karaganda State District Power Station-II. In subsequent years the impervious curtains from bored piles were also successfully erected in the foundation of the dams of the Yerevan HPP (Armenia) and Sion HPP (Georgia) (**Ayrapetyan, 1991**).

Pile structures of these first impervious curtains are arranged by preliminary drilling of holes with diameter of 0.6-1.0 m and their subsequent filling with concrete. In order to form a continuous pile wall, the works were carried out in two stages (**Zhivoderov, 1991; Chugaev, 1979**). The first phase of works included preparation of wells at a certain distance and their concreting. In this case, the distance between the wells of the first phase was taken no more than their diameter. The second phase of works consisted in drilling wells between the prepared piles and concreting them. As a result, a solid wall of bored piles of the required length and depth was made. So the length of the pile wall-curtain of Sherubay-Nurinsk dam made 950 m, and its depth - 23 m. The curtain under the dam is arranged in sandy-pebble soils with a thickness of 7-40 m. At the Yerevan and Sion hydropower plants the depth and length of the impervious curtains were smaller.

Drilled piles are often used as foundation structures for a number of hydraulic facilities. So foundations made of two rows of bored piles are arranged under the supports of the Zaragskaya HPP water pipeline. The length of the water pipeline is 649 m, and the inner diameter of the pipes is 7.5 m. Each 40-meter long section of the water pipeline weighed 150 tonnes. The use of bored pile foundations helped to reduce uneven settlements of the structure (**Neporozhnykh, 1982**).

Bored piles were also arranged at the base of the foundation slab of the head of the bottom spillway - the outfall of the Yumaguzinsky waterworks (**Andrianov et al., 2003**). At this site, piles with a diameter of 0.5 m and a length of 20 to 44 m were used, which increased the bearing capacity of the foundation and eliminated the appearance of uneven settlements of the foundation.

**Baranov** (**2008**) during the construction of Yumaguzinskiy waterworks along with the developed anti-cast measures to ensure stability and durability of the tower water inlet, it was proposed to install redundant bored reinforced concrete piles in its base. This design proposal implemented at this site was aimed at increasing the level of safe operation of the structure in conditions of karst manifestations. The results of the relevant monitoring have confirmed the effectiveness of the adopted solution.

Traditionally, bored piles used in the construction of buildings and structures are made of concrete and reinforced concrete. Pridanova (**2009**) performed experimental and theoretical assessment of the possibility of using bored piles made of ash-and-slag mixtures as part of hydraulic structures. The use of ash-and-slag mixtures as the material for bored piles gives them undeniable advantages in comparison with traditional concrete piles. Indeed the increase of ash-and-slag material durability in the course of 15-20 years increases the bending (by 30-35%) and compressive (40-50%) strength of pile structures. This in turn improves the carrying capacity of piles. It is also significant that in the manufacture of these piles is not required the use of traditional building materials such as sand and gravel. The bored piles made of ash-and-slag mixtures are recommended to be used to reduce the active pressure of backfill soil on the quay embankment walls. The research showed that the arrangement of pile rows in the backfill back body (in the reversal prism area) relieves the quay sheet wall, reducing the efforts in its anchor rods by 14%, deflections - by 27% and displacements of the wall top - by 17 mm. Thus, the use of ash-and-slag bored piles reduces the stress-strain state of the quay walls and contributes to improving the environmental safety of areas with ash-and-slag wastes.

Specialists (**Sainov & Shaimerdianov, 2018**) recommended to use a diaphragm made of bored piles instead of concrete bored piles, but of bored piles made of clay-cement concrete for the arrangement of the impervious element of the rock-fill cofferdam. Such decision is substantiated by the results of the studies on the stress-strain state of the concrete diaphragm under the action of seismic forces. It is established that the effect of horizontal seismic load increases bending deformations of concrete diaphragm and causes the appearance of tensile stresses in it, which may exceed the tensile strength of concrete piles. The most dangerous (vulnerable) place of the diaphragm under the action of seismic load is the conjugation zone between the piles and the rock foundation. For this reason, the authors have proposed to increase the slip resistance of the diaphragm by means of a special "cushion" of glycement concrete to connect it with the rock foundation.

In the practice of hydraulic facilities construction and research there is an experience of using bored piles for overlapping river channels, providing preservation and stability of slopes, banks, hillsides, etc. For example, 25 cm diameter bored piles were used to cover the Huanhe River bed (China). The pile row is arranged for the whole length of the river bed with the length of 28 m. The lower ends of the piles were sunk 2.0 m into the bedrock. The piles have been strengthened with metal chocks and anchored into the river bank to increase their settling ability (**Yerakhtin & Yerakhtin, 2007**).

**Vdovenko & Mityunina** (**2014**) presented a variant of anti-slide structure from bored piles. The peculiarity of this design is that the bored piles are interconnected by two tiers of inclined slabs that perform unloading functions. To ensure stability, the piles are anchored with steel ties embedded in ground anchors at the bottom of the slope. At the top of the slope, the piles are secured with wedge-shaped anchors. Unloading plates are threaded onto the piles through holes in the piles and fastened to them by means of embedded parts. In contrast to the driven pile structures, bored piles as part of the landslide prevention and shore protection structures can be arranged in cramped conditions, with the exclusion of industrial noise and shock and vibration effects on the subgrade and nearby objects (**GOST R. 58744.1-2019, 2020**).

**Unaibayev et al.** (**2021**) are described the results of studies on the arrangement of bored piles in the base of the retaining wall, erected on the Koktobe mountain (Almaty). Piles with a length of 4 m and a diameter of 0.4 m are arranged with a protective silicate shell in saline soils. Comparative experiments revealed that the bearing capacity of piles with a protective silicate shell in 2.5-3.2 times higher than the bearing capacity of conventional bored concrete piles. It is also found that the process of moistening of saline soils causes a decrease in the bearing capacity of bored piles under the static indentation load. Furthermore, for piles with a protective silica casing the share of bearing capacity reduction is 8.9%, and for the conventional pile - 27.7%. The bored piles with a protective silicate shell, giving a higher bearing capacity, are recommended for use in saline silt-clay soils.

Along with the traditional bored piles in hydraulic engineering construction, for the erection of impervious barriers and elements, secant piles are also successfully used, which can be referred to their varieties. Secant drilled piles, like bored piles, are arranged in two technological stages, but differ in size and are made with a partial overlap of the cross sections of the neighboring piles. The reinforcement of such piles can be volumetric or rigid (from profile elements). Both concrete and other materials are used as pile filler.

**Isichenko & Nizhne-Bureyskaya (2012), (Pat. 151898 RU, 2015)** the first experience in the use of bored piles in Russia is outlined. So, in 2016, for the arrangement of the impervious element in the form of a diaphragm of the stone-and-earth dam of the Nizhne-Bureisk HPP, the bored piles were used. When constructing the diaphragm, 417 main wells and 47 additional wells were drilled and filled with clay-cement concrete. The height of the bored piles from the specified filtration-resistant material, within the dam, was 37 m. The thickness of the diaphragm was 1.2 m. The lower ends of the piles were sunk into the rocky soils. The piled diaphragm was arranged instead of the dam core of loamy soil.

The effectiveness of using clay-cement concrete as a material for pile impervious diaphragm is confirmed by studies of **Sainov & Kudryavtsev (2016)**. The authors found that the type and properties of the diaphragm material have a significant impact on its resistance to bending under the action of hydrostatic pressure. It was found that in the bored pile diaphragm made of clay-cement concrete tensile stresses at its bending are not manifested (at the strain modulus of clay-cement concrete less than 1000 MPa). At the same time, this ensures reliability and stability of the dam's impervious elements.

The use of bored piles in construction, including hydraulic engineering construction, is known to have limitations, which are primarily related to the depth of their installation. So the depth (length) of bored piles traditionally does not exceed 30-40 m. At greater depths it is difficult to ensure the integrity of the pile shaft. Therefore, the use of bored piles for impervious elements of high dams is a great risk, which often leads to rejection of their use. Considering this circumstance, the specialists of JSC "Gidrospetsproekt" suggested to arrange a multilevel impervious diaphragm during the construction of Gotsatlinsk HPP (Russia) with a height of 69 m (**Sainov & Kotov, 2018**). According to the idea of experts, such a diaphragm should consist of several pile tiers (rows) in height. The lower tier of bored piles is sunk into the soil base, and each subsequent pile tier is arranged with the surface of a monolithic slab that is laid on top of the underlying pile tier. The height of each yard should not exceed 30 m. Both bored piles and the slabs between them are proposed to arrange of clay-cement concrete. Researches (**Sainov & Kotov, 2014; Radzinsky et al., 2014; Sainov et al. 2018**).

Specialists (**Sainov & Kotov, 2018; Sainov & Kotov, 2014; Radzinsky et al., 2014; Sainov et al. 2018**), including numerical modeling, established that the use of multilevel and one-tier impervious elements of bored piles made with the use of soil-cement concrete increases their reliability. The closer the material of bored piles is to the ground of the dam in terms of deformability, the higher the operability of impervious diaphragms.

The dependence of deformability and hence the serviceability of pile impervious elements on the properties of clay-cement concrete led to the conduct of **Korolev et al. (2013)** a set of tests of samples of different composition of clay-cement concrete, called by them composite materials. Studies were carried out to select the optimal composition of composite material for bored piles according to its physical and mechanical characteristics exhibited in the design of Gotsatlinsk dam. It was found experimentally that the composite material which includes sulfate-resistant Portland cement 400, crushed stone with a fraction of 5-10 or 5-20 mm, washed sand with grain modulus 3.32, bentonite clay powder PBN, powder sodium lignosulfonate and superplasticizer C-3 is the most rational for bored piles. The cement consumption should be 180 kg/m$^3$. To verify the results of studies, as well as to refine the technology of manufacturing bored piles, experts have also carried out pilot works. The results of the works showed a good borehole filling with the optimal composition of the composite material as well as its sufficient density and strength.

The results of studies on the composition and properties of clay-cement concrete for pile and trench impervious elements of dams are presented by **Radzinsky** (**2014**). Based on the analysis of experimental results and data of some foreign specialists, the author states that the amount of cement used to produce clay-cement concrete piles should be not less than 100 kg/m$^3$ and not more than 200 kg/m$^3$, and the amount of bentonite clay - not less than 15-20 kg/m$^3$ and not more than 100 kg/m$^3$. It has been revealed that instead of bentonite clay, ordinary clay, or its mixture with bentonite clay, can be used. It is also noted that with stronger compositions of soil-cement concrete in piles there is an increase in vertical operating stresses, almost 5-7 times. This is caused by a higher deformation modulus (100 MPa and higher) of strong pile material compositions. The results of the study show that for large values of the filtration coefficient of foundation soils it is advisable to use bored piles.

Secant drilled piles, in addition to the arrangement of the impervious elements of dams, are also used for the construction of protective structures of hydro-technical facilities (**Rus Hydro Dagestan branch**). Thus, during the construction of the Zaramagskaya HPP-1 in the Republic of North Ossetia, the bored piles are used for the construction of the enclosing wall. This pile wall is designed to protect the excavation of the HPP building from filling with water during construction and installation works. The wall was erected as an integral structure of 580 concrete piles ranging in length from 9 to 40 m (Fig. 1). During the construction of the mentioned HPP the bored piles were also used as foundation structures of the retaining wall. More than 500 piles with a length of 24 m were installed under the retaining wall. The retaining wall was erected as a protection structure of the hydropower plant building from rockfall.

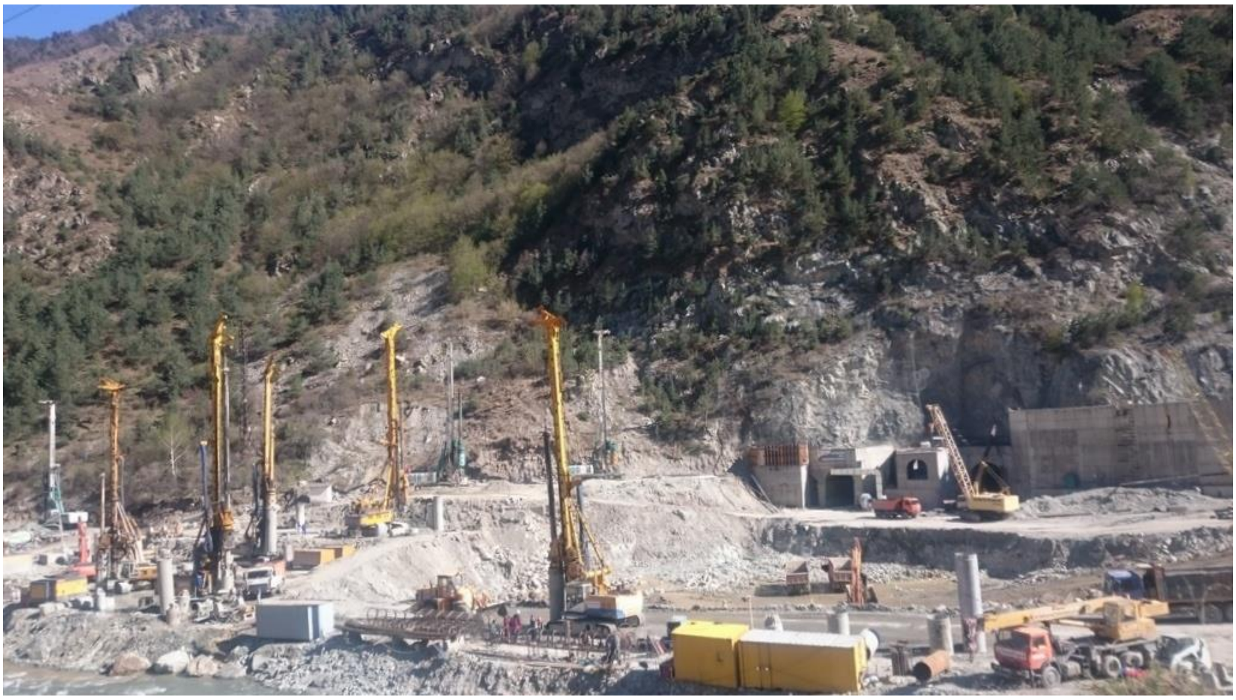


**Figure 1** – Installation of secant drilled piles to protect the excavation of the Zaramagskaya HPP-1 building
https://osetia.rushydro.ru/hpp/zaramagskaya-ges-1/

Secant drilled piles used as the main load-bearing structures of dams' impervious elements may be damaged during operation in the form of cracks, spalling, etc. This may be caused by changes in the temperature regime of dams, the impact of seismic loads and a number of other natural and man-made factors. **Kotlov et al.** (**2014**) and **Orishchuk** (**2019**) present the results of studies on self-healing of secant drilled piles of impervious diaphragms of soil dams. It is proposed to fill inclined and horizontal cracks in the shaft of piles by means of a special protective (healing) layer of sand along their lateral surface. When opening a crack in the pile, sand from the healing layer gets (washed) into the crack and moving inside it fills its cavity. On the reverse side, the crack is closed by the material of the downstream transition zone of the dam. As a result of field experiments, facts of washing out (filling) of holes in the body of diaphragm piles to the depth of 33-44 cm were fixed.

Drilled secant piles in hydraulic engineering construction are used not only in the construction of new facilities, but also in the liquidation of emergency situations of operating structures. **Bardyukov et al.** (**2000**) the peculiarities of arrangement of an impervious diaphragm made of bored piles at the emergency section of the Kureyskaya HPP dam are considered. At this section, the core of the dam was in extreme cracking condition, which was the reason for repair works. Works on clay concrete piles were performed from the crest of the dam. Piles 35 m long crossed the core of the dam, cut through mesko-grained sands at the base of the dam and were sunk 3-5 m into dense loamy and sandy loam soils. Piles were built using casing pipes. The length of the constructed diaphragm was 140 m. The impervious diaphragm made of bored piles was made without reducing the water head acting on the dam.

In the whole on the basis of the results of researches of Russian and other foreign scientists the specialists of “Vedeneev VNIIG” JSC together with the specialists of JSC "Lengidroproekt" developed recommendations for design, calculation and construction of impervious elements of clay-cement concrete bored piles (**STP 310.02.NT-2017** (**2017**). The publication of these recommendations allowed to systematize and regulate the issues related to the use of bored piles as part of ground dams.

## 3 APPLICATION OF DRIVEN PILES AND TONGUE-AND-GROOVE PILES

The issues of research and application of driven piles and foundations made of them for hydraulic facilities in different years were dealt with by many scientists, among them it should be noted Kovalev V.A., Abdul Karim S.R., Kaganov G.M., Kubenov R.T., Kadirov O., Glagovsky B.B., Bakhtin B.M., Bekbasarov I.I., Usmanov R.A, Salimov S.V., Korovkin V.S., Rakharinusya A.P., Kostromin F.S., Sosnin S.A., Shekhovtsev V.A. A brief overview of their research results is presented below.

**Kovalev** (**1983**) considers the issues of improving the reliability, as well as reducing material costs and reducing the duration of construction of flume channels and network HS constructed on subsident loess soils, through the use of pile foundations of piles of different longitudinal shape. The prismatic, wedge-shaped and cone-shaped reinforced concrete piles with a length of 3-5 m were the object of research. Experimental piles were tested for the action of vertical indentation and horizontal loads. The author conducted a total of 27 experiments with twofold repetition, which indicates the sufficient reliability of the results. Experimental studies have shown that the bearing capacity of piles in subsidence soils largely depends on the compaction of soil around the pile during its driving. This is how, when driving a prismatic pile, the width of soil compaction zone in the upper part reached 10-15 cm and in the lower part - 35-40 cm. The maximum width of the soil compaction zone was 150 cm under the pile tip. The dimensions of compacted soil zones around the lateral surface of wedge and cone piles were larger than those of prismatic piles. Based on the results of static testing of piles, it was found that the resistance on the lateral surface of wedge and cone piles is up to 50% greater than the same resistance of the prismatic piles. Considering the identified features of the behavior of piles of different shapes, developed and proposed a method for calculating their carrying capacity in subsidence soils.

In addition to the experimental assessment of the carrying capacity of piles of different forms Kovalev V.A. conducted systematic long-term observations (over 15 years) of deformations of pile foundations of water-conducting flume channels. It was found that deformations (settlements) of flume structures on traditional supports are more than 20 cm, and on pile foundations - less than 3-4 cm. These data testify to the reliability of pile foundations. The author proposed a methodology for calculating the deformations of flume channels and network HS on pile foundations. The method allows to take into account the joint work of piles with the surrounding soil. The reliability of pile foundations in subsidence soils is shown, as well as the possibility of saving construction materials and reducing the construction period due to the use of pile foundations.

**Abdul Karim** (**1992**) studied the behavior of piles and pile foundations of hydraulic facilities in subsidence soils, taking into account the negative friction that occurs along the side surface of piles during their settling due to soaking of the soil with water. On the basis of theoretical studies the author has developed a generalized method of calculating the carrying capacity and settlement of piles, taking into account the forces of negative friction. To match the calculated and experimental results, coefficients characterizing interaction of the pile with the surrounding soil have been introduced into the method. We have obtained tabular values of these coefficients that allow to perform a preliminary calculation of piles bearing capacity. The developed method was tested as applied to the pile foundation of an aqueduct prohibited in loess subsidence soils.

**Kaganov** (**1992**), **Kaganov et. al.** (**1989**), **Kaganov & Adesman** (**1988**) presents the results of studies of the operation of pile foundations, which he considers as foundations of multi-arched low-pressure dams. Studies carried out on the models allowed to reveal that the strength of piles and strain-strain characteristics of soils of nonrock foundation of dams affect the carrying capacity of piles and the fractibility of pile cross-sections. Thus, it was found that under the action of horizontal load, the strength of the pile material has a significant impact on the bearing capacity of the flexible pile. It was found that an increase in the tangent angle of internal friction of loose sand by 60% (due to the addition of a rubber crumb) causes an increase in the bearing capacity of piles with a free head by 25%. A similar pattern is typical for a pile with a pinched head. However, the bearing capacity of the pile with the pinched head part is 25-30% higher than the bearing capacity of the pile without pinched head part. The experiments revealed a qualitative picture of the failure process of piles in the rooftop. Failure of piles in the rooftop occurred with the formation of more often two and less often one "plastic joint" along their length. The first joint was formed in the area of pile embedding in the ridge, and the second - at some depth from the bottom of the ridge. And the collapse of all piles in the dike occurs simultaneously. Based on the minimum values of horizontal, vertical and angular displacements, it was found that the more preferable of the pile foundations are foundations in which the piles are not arranged vertically and not inclined, but according to the gantry scheme, when the lower ends of the piles are spread in opposite directions.

**Kubenov** (**2000**) presented the fact of unsuccessful application of driven piles in subsidence soils under the network hydraulic structures of South Kazakhstan. Since the author points out that as a result of unexpected subsidence occurring in the medium subsidence soils of the Kzyl-Orda region, there was a massive destruction of the flume irrigation network built on driven piles. The flume structures, built in 1984, almost a year later turned out to be unusable due to excessive uneven subsidence deformations of pile supports. At the same time, the maximum subsidence was 20-40 cm. Costs of repair and restoration of flume structures almost 1,5 times higher than the cost of new construction of similar structures. Proceeding from the described negative fact it has been suggested to consider subsidence in the design of structures on subsidence soils as one of the mandatory design situations of the first group of limiting states.

**Kadirov** (**1993**) carried out studies of combined dams on models in which the head is arranged through from driven piles-shells, united by a rostrum. It is noted that combined dams, due to the presence of through part (of piles), in comparison with deaf dams have a smaller depth of erosion during operation. This is due to the passage of some water through the through part of the dam (through the space between the piles). Another important advantage of such dams is the use of prefabricated piles, the use of which reduces construction time and improves the quality of works. The optimal ratio of the size of the blind part of the combined dam to the size of its through part was established by the author.

**Glagovsky** (**2002**) developed and proposed methods for static and dynamic calculations of foundations of power and hydraulic structures. The author has developed a technique for determining displacements and rotation angles of shell piles in stratified soils. On the basis of this technique, a program for calculating similar parameters of piles has been compiled. The results are obtained on the basis of the theoretical solution of the problem about the deformation of the pile-shell under the action of the horizontal load considering the elastic-plastic model of the foundation soil. A method for calculating the load-carrying capacity of drawn piles widely used for securing offshore hydraulic structures has also been developed. Estimated effect on the bearing capacity of drawn piles of such factors as the size of piles, the depth and direction of application of the load on them, as well as the heterogeneity of soils of the base has been carried out. In addition, based on the results of the studies performed, a method of calculating the deformations of the pile foundation of a turbine unit, which allows taking into account its stiffness in the upper part, as well as the pile interaction features in the foundation.

**Bakhtin** (**2005, 1996**) presents the results of studies on the dynamic interaction of non-soil and soil elements of hydraulic structures erected on piles in seismic areas. The issues of optimal modeling of piles are considered in the studies. New criteria for modeling of pile structures allowing to increase reliability of research results are offered. The hypothesis describing the character of work of the system "pile-soil" under the action of dynamic load is also offered. The correctness of the hypothesis is confirmed by the results of tests of natural and model piles. It was found that the ratio of pile length and diameter has a direct impact on the accuracy of the results obtained. The optimum ratio of these pile parameters is determined, in which the discrepancy between the calculated and experimental data does not exceed 25%.

**Bekbasarov** (**2007**) reviewed the issues of piling and pile foundations for linear hydraulic structures such as aqueducts, mudflows, pipelines, flume structures, etc. The author took as an object of research the driven reinforced concrete prismatic piles of continuous section. On the basis of experimental and theoretical studies the author has developed and implemented a methodology of rational arrangement of reinforced concrete prismatic piles and pile foundations of them for supports of water and mud structures. The use of the method allows to design the pile foundations of structures taking into account the integrity of concrete piles when driving them, achieving their required carrying capacity and depth, as well as the sufficient capacity of hammers used for pile driving and a number of other important factors. The technique includes calculation methods, allowing to determine such parameters of pile-driving process as compressive stress in their head part during hammer strikes, hammer impact energy during pile immersion, the height of the protruding surface of the near-pile soil during pile-driving and a number of other parameters. The economic analysis of designs of a foundation part of water conducting hydraulic structures is carried out, by the results of which the correlation dependences are offered, allowing to carry out an operative estimation of cost of arrangement of pile foundations for such constructions. The main results of researches are included in some republican normative-technical documents on pile foundation construction.

Pile structures are also widespread in port construction, due to the extraction of energy resources from the seabed and the intensive development of logistics in the field of water transport. In port construction, driven wooden, steel and reinforced concrete piles are used for the construction of hydraulic structures (**Nikolaev, 1972**). In studies (**Salimov, 1993; Korovkin, 1994; Rakharinusi, 1999; Kostromin, 2000; Sosnina, 2006; Shekhovtsev, 2010**), the results of research and experience in the use of piles in this area are presented.

**Salimov** (**1993**) shows the results of studies to assess the load-carrying capacity of eccentrically compressed two-layer tube-cement piles under short-term and long-term loads. The piles were used as anchors and were intended for supporting marine hydro-technical structures. Along with the theoretical studies the author conducted and full-scale experiments using 38 samples of two-layer pipe-cement piles. Samples of piles were made of two pipes, external and internal. The diameter and thickness of the outer tube was respectively 159 and 6 mm, while the diameter and thickness of the inner tube was respectively 114 and 7 mm. The length of the pile samples was taken to be 1.0, 2.6 and 3.4 m. Two-layer pipe-cement pile specimens were filled with tamped Portland cement in two variants (in the first variant completely, and in the second variant - only the interpipe space). Off-center longitudinal and transverse loads were applied to the piles. The processing and analysis of experimental results show that in case of large eccentricity of load application the deformation covers the compressed and stretched zone of piles. On the basis of the obtained data the method of calculation of bearing capacity of two-layer tube-cement piles under short-term and long-term loads has been proposed.

**Korovin** (**1994**) considered the issues of improving the strength and durability of port hydraulic structures on a pile foundation. To assess the effect of soil moisture, as well as its freezing and thawing on the state of the piles, the author conducted seminatural studies on the territory of the embankment of the Volga Reservoir. On the basis of the research results a calculated method of predicting the reduction of bearing capacity of the pile base of quay structures, which takes into account the physical and mechanical characteristics of soils, was proposed.

The author also performed an examination of the Tyumen embankment structures, which revealed that their pile bases of reinforced concrete piles-shells 60 cm in diameter with wall thickness of 10 mm had multiple cracks of different nature. At the time of the survey the proportion of piles with cracks reached 70% of their total number. It was determined that the main causes of cracking in the piles were temperature changes and freezing of aggregates (hydrophobic mixtures) of the shell-piles during the winter period.

**Rakharinusi** (**1999**) outlined the features of the use of steel tubular piles with open bottom end for the construction of port hydraulic structures. It was found that the height of the soil core, which is formed in the cavity of piles during their immersion, for steel tubular piles is greater than for reinforced concrete pile-shells, and can reach their immersion depth. The influence of pile diameter, pile wall thickness and soil density on the formation of soil core in its cavity has been evaluated. The coefficients of soil conditions under the lower end and on the side surface of the piles to calculate their carrying capacity using the design resistance of soils have been suggested. It is recommended to use non-traditional Mises-Botkin strength parameters to determine the carrying capacity of piles using the strength characteristics of soils. In addition, we obtained dependences which allow us to determine settlements of steel tubular piles by constructing "settlement-load" diagrams both with and without using the results of static tests.

**Kostromin** (**2000**) presented the results of theoretical and experimental studies aimed at developing methods for calculating hydraulic structures of gravity-pile type taking into account their interaction with the soil base. A physical picture of the operation of a gravity pile foundation in soils of different moisture content has been established. The parameters necessary to assess the interaction of the foundation and the base under the force impact have been determined. On the basis of studies using various modifications of models of foundations of structures, recommendations for the assignment of optimal parameters of the pile field, stiffness, conditions of fixing and location of piles under the foundation slab have been developed. Overall, the conducted research allowed us to form the basic principles of designing ice-resistant gravity-pile platforms for the joint action of external force factors under nonlinear soil conditions, as well as to make an algorithm for their calculation, with consideration of the mutual influence of the slab and piles.

The work performed by **Sosnina** (**2006**) includes studies on the development of a methodology for calculating the bearing capacity of steel tubular piles used to secure offshore hydraulic facilities on the shelf. The studies consider several types of anchor-type piles used to secure platforms in the Arctic shelf of Russia. Using flat models of piles, the influence of pile diameter, their immersion depth, places of cable fastening and the direction of force on their carrying capacity was studied. The results of FEM calculations have revealed a 1.7-fold increase in the carrying capacity of the pile being sucked, if the cable is fixed in its lower part, as compared to fixing it in the upper part. This effect can be attributed to the movement of the pile in the soil without turning it around its axis. The experimental and numerical research results testify to high carrying capacity of the drawn piles and possibility of their application in marine hydraulic engineering construction. An author, on the basis of research results, has proposed a methodology for calculating the carrying capacity of single piles and pile clusters under the influence of combined loads.

**Shekhovtsev** (**2010**) presents the results of studies to determine the strength and stability of pipe-concrete structures and support blocks of offshore stationary platforms under different loads. Static and dynamic calculations of TP-4 platform with dimensions of 46×18×0.8 m were performed. The platform is built on a pile foundation consisting of 28 vertical and 16 inclined piles of 1.22 m diameter. Piles made of tubular concrete filling, and immersed in the soil to a depth of 27.25 m.

The results of calculations show that TP-4 platform structures are designed with a large carrying capacity reserve. The author presents design features and examples of suction piles application for permanent or temporary securing of offshore hydraulic structures at great depths.

A methodology has been developed to assess the carrying capacity of the suction piles. The possibility of using retractable piles for fixing on the seabed platform designed for one of the deepwater fields of the Arctic shelf of Russia was substantiated. The influence of pile sizes, the magnitude of the pile load application point, the direction of the load, as well as heterogeneity of soils on the carrying capacity of piles has been revealed. The influence of the suppleness of the bearing layer under the lower ends of the piles on the deformation of the pile foundation of the platform was also studied. A method of assessing deformations of the pile foundation taking into account the interaction between the piles and the upper structure is proposed.

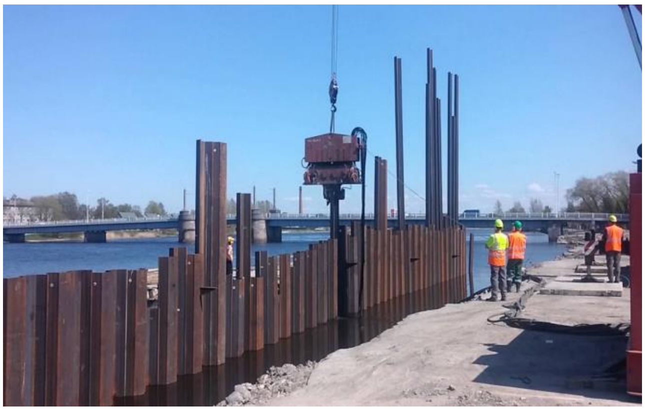
Along with driven piles, tongue-and-groove piles are widely used in hydraulic engineering construction. The main purpose of sheet piles is to be used as boundary constructions to hold back ground movement or prevent the ingress of moisture. They are also widely used to strengthen the banks of water bodies embankments and wharfs, as well as to build a number of other hydraulic engineering facilities (**NTU RK 03-05.1-2011, 2015; GOST R. 57365-2016/EN 12063:1999, 2017); RD 31.31.33-85, 1985**).

Tongue-and-groove piles are made of metal, reinforced concrete, PVC and composite materials. The most effective among the reinforced concrete sheet piles are flat reinforced concrete sheet piles with overall section dimensions of 50×45 cm and wide-striped sheet pile of T-section width of 1.6 m. The height of these sheet piles can reach up to 24 m (**Levachev et al., 1986)**. Composite sheet piles are less common in practice. Composite sheet piles are close to PVC sheet piles in terms of quality characteristics. The experience of the successful application of composite sheet piles is presented by **Levachev et al.** (**1986**). For example, the 22.0 m long anti-filtration diaphragm of the White River Dam (USA) was built with composite sheet piles, and the breakwater at the Marina in Austin (USA) was made of composite sheet piles.

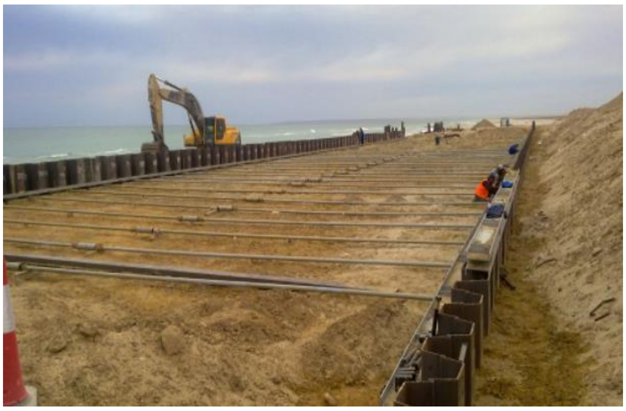
On the whole, metal tongue-and-groove piles are the most common of all sheet piles. Their share in the total volume of tongue-and-groove sheet piles used is more than 50% (**Krasov, 1982**). For example, during the construction of the Volgograd hydroelectric power station on the Volga River, 34,000 tons of metal sheet piles were driven (**Komissarov, 2010**). Steel sheet piles of flat and trough types (Larsen type) are manufactured in lengths from 8 to 22 m, which allows their use at hydroelectric facilities. For example, in the area of Pavshinskaya floodplain on the left bank of the Moskva-river in Krasnogorsk, Russia. Krasnogorsk (Russia) a sheet piling embankment was built (Fig. 2 (a)). The sewage collector is coupled with the embankment to ensure water outlet. The junction of the collector with the embankment is accepted in the form of sheet piers made of Larsen 5 UM sheet piles. The openings are covered with a reinforced concrete slab. The overlap is supported by both sheet piles and steel pipes (426 mm in diameter, 10 mm thick and 10-10.5 m long). The piles are sunk into the soil backfill of sheet pile openings (**Hydrotechnical Bureau LLC**).

Larsen-5 sheet piles were also used to build a pier at the seaport in Zarubino village (Primorsky Krai of the Russian Federation) located on the shore of the Pacific Ocean. The wharf with a total length of 650 m was erected in the form of a shanked metal bolver made of sheet piles 12-15 m deep (**Unex Stroy Company LLP**).

In Kazakhstan, steel sheet piles of the Larsen-5 type were used during the construction of a pier at the Kazakhstan Offshore Industries (KCOI) Ltd production base in the Akshukir village on the eastern shore of the Caspian Sea (Nosenko, 2016) (Fig. 2 (b)). The sheet piles were used to strengthen the shoreline of the wharf structure. The piles were driven by the domestic company "UnexStroy" to a depth of more than 5 m. Similar sheet piles were used in the reconstruction of the river port in Atyrau.



a)



b)

**Figure 2** – Installation of tongue-and-groove piles on the left bank of the Moskva River embankment in Krasnogorsk, Russia (a). Krasnogorsk (Russia) (a) https://arcticgs.ru/stati/stroitelstvo-prichalov and on the shoreline of the Kazakhstan Offshore Industries production base in Akshukir (Kazakhstan) (b) https://www.instagram.com/p/CU7Af8XILkT/?img_index=1

The issues of improving the design of sheet piles are reflected in the works of Nosenkov O.P., Novak Yu.V., Nemololotnov A.G. and others.

Nosenko (2016) developed the "U" shaped profile of the Larsen type sheet pile of increased carrying capacity. The author proposed a new concept of designing bending sheet pile profiles. In accordance with this concept, the steel sheet pile profile "Larsen-7H" was patented. Numerical investigations on prediction of the strength of U-profiles of sheet piles in bending under load have shown their efficiency in comparison with Larsen-5S steel sheet pile designed in accordance with Euro standards. It was found that 1 m of the new profile sheet pile wall provides 1.62 times higher moment resistance.

Novak et al. (2018) conducted work to assess the technical conditions and economic feasibility of using metal sheet piles as load-bearing elements of hydraulic structures. Analysis of the research results showed that beam and sheet piles have high strength and their use as elements of hydraulic structures is a rational solution.

Nemolochnov (2019) presented the results of comprehensive research on the improvement of sheet piles made of composite material. Laboratory tests of composite sheet piles bending bearing capacity were carried out. The results of semi-informational tests of the sheet piles as a part of the retaining wall of the shore protection structure showed that the movement of the sheet pile top under the horizontal impact reaches up to 4,39-4,47 cm, exceeding the admissible norms. Test vibro-dipping of sheet piles 8 and 12 m long has defined the limits of their defect-free sinking as well as the possibility of their use as a bearing structure. The analysis of the stress-strain state of composite sheet piles under load has determined the permissible stresses in them and the values of their material elasticity modulus, at which their safe operation is ensured.

## 4 CONCLUSIONS

The presented analysis of research experience and application of pile structures for erection of hydraulic structures allows drawing the following main conclusions:

1. Bored piles piles in hydraulic engineering constructions are used as impervious blankets for dams, for overlapping riverbeds, providing safety and stability of slopes, banks, slopes, etc. In addition, they are successfully used for construction of bases of hydraulic structures. In addition, they are successfully used in the construction of bases of hydraulic structures. The diameter of the piles used is 0.6-1.0 m and the depth is up to 40 m. In recent years, in addition to bored piles, bored piles are actively used as an impervious blanket for dams, as well as for the construction of protective structures of hydraulic structures. Such piles are arranged with a diameter of up to 1.20 m, and a depth of 40 m or more.
2. The secant-drilled piles are widely used in hydraulic engineering construction, which are characterized by such qualities as efficiency, manufacturability, fast construction and reliability. The features of various types of driven piles (prismatic, wedge-shaped, cone-shaped) and pile foundations for construction of a number of hydraulic structures (flume channels, aqueducts, sea and river piers, embankments, fencing, shore protection structures, etc.) are studied. Methods of calculating parameters of piles and pile foundations immersion, deformability, stability and bearing capacity, which take into account the regularity of their joint work with hydraulic structures, have been developed and used.
3. Along with other pile structures, tongue-and-groove sheet piles made of different materials, including composite ones, are effectively used in hydraulic engineering construction. Steel sheet piles of different profiles and lengths are most commonly used. Research is underway to develop new sheet piles that provide high carrying capacity and reliability of erected structures in the form of piers, embankment fences, slope protection, etc.

## CONFLICT OF INTEREST

The authors state that there is no conflict of interest.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