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SOME MORPHOLOGICAL FEATURES OF THE EOLIAN-ALLUVIAL SANDS OF THE INDUSTRIAL SITE AT THE ZAPORIZHZHIA NPP

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Abstract. ***Problem statement.*** The authors used a complex index of soil morphology in the research, with regard to the shape and character of grain surface in the entire volume of sands under research. A morphological assessment was carried out for the entire volume of the studied sandy soil. An important factor in the formation of the shape and character on the sand grains surface is the mineral composition of the sand. Quartz was the predominant mineral in most of the studied sands. Further research involves studying other mineral differences. This will provide data on the formation of contacts between sand grains, which are different from spheres and can be plate-like shape or other shapes. For the first time, the main morphological characteristics of eolian-alluvial and alluvial quaternary sands in the Dnipro Valley were obtained for the industrial site at the Zaporizhzhia NPP in Enerhodar City. Moreover, it was for the first time in a vertical section of the sand mass. One can note the identified decrease in the morphology index in the river sands of the Dnipro Valley from the sources to the mouth. Numerous values about the morphology indices of sands at the NPP site were obtained. Criteria for separating eolian and eolian-alluvial sands in the section were also proposed. ***Purpose of the article*****.** Obtaining data on the morphology of eolian-alluvial and alluvial sands for the industrial site at the Zaporizhzhia Nuclear Power Plant (NPP) in Enerhodar City, which is missing. Or more precisely, obtaining reliable quantitative indices that can be used in calculations of soil foundations. ***Conclusions and results*****.** This paper presents the results of determining the morphology index for the industrial site at the Zaporizhzhia NPP in Enerhodar City. It also presents studying the shape and character of the sand grains surface of alluvium for the vitachevo-bug horizon of the first supra-floodplain terrace in the Dnipro Valley in this area. Additionally, the results of similar works on the study of genetic types of Quaternary sands of the different genesis for the Dnipo Valley were analyzed. As a result of the research, data were obtained on the morphology of monomineralic oligomictic alluvial sands, their shape, and the character of the sand grains surface. The results of the research can be implemented into the subgrade soils of NPP buildings and structures. Also, they can be applied to calculations for the post-war reconstruction of hydraulic engineering and transport structures at the NPP site – inlet and outlet channels, as well as the dam of the cooling pond.

Keywords: *sandy soils sand particles; contacts between grains; number of grains; grain sphericity; grain morphology; sand fractions*

МОРФОЛОГІЧНІ ОСОБЛИВОСТІ ЕОЛОВО-АЛЮВІАЛЬНИХ ПІСКІВ МАЙДАНЧИКУ ЗАПОРІЗЬКОЇ АЕС

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Анотація. ***Постановка проблеми.*** У дослідженнях був використаний комплексний показник морфології ґрунтів, що враховує форму і характер поверхні зерен пісків, що досліджувалися. Важливим фактором утворення форми та характеру поверхні піщаних зерен є мінеральний склад піску. У більшості досліджених пісків переважаючим мінералом був кварц. У подальших дослідженнях намічено вивчення інших мінеральних відмінностей. Це дозволить отримати дані про формування контактів між піщаними зернами, які відмінні від округлої форми і можуть мати пластинчасту та інші форми. У статті були запропоновані критерії поділу у розрізі еолових та еолово-алювіальних пісків. Результати проведених досліджень можуть бути імплементовані в ґрунти основ будівель і споруд АЕС. Також, результати досліджень можуть бути застосовані для розрахунків у післявоєнній реконструкції гідротехнічних та транспортних споруд майданчика АЕС (каналів, що підводять і відводять), а також греблі ставка-охолоджувача. ***Мета статті.*** Визначення даних про морфологію еолово-алювіальних та алювіальних пісків для проммайданчика Запорізької АЕС у м. Енергодар (які відсутні), а саме: достовірні кількісні показники, які можуть бути використані у розрахунках ґрунтових основ. ***Висновки.*** У роботі наведено результати визначення показника морфології проммайданчика Запорізької АЕС у м. Енергодар. Також у роботі досліджено форму та характеру поверхні піщаних зерен алювію вітачівсько-бузького горизонту першої надзаплавної тераси долини м. Дніпро у цьому районі. Додатково проаналізовано результати аналогічних робіт з вивчення генетичних типів четвертинних пісків різної генези долини Дніпра. В результаті досліджень були отримані дані про морфологію мономінеральних олігоміктових алювіальних пісків, їх форму і характер поверхні. Вперше для проммайданчика Запорізької АЕС у м. Енергодар були отримані основні морфологічні характеристики еолово-алювіальних та алювіальних четвертинних пісків долини Дніпра, причому, вперше і у вертикальному розрізі товщі пісків. Можна відзначити виявлене зниження показника морфології у річкових пісках долини Дніпра від витоків до гирла.

Ключові слова: *піщані ґрунти; піщані частинки; контакти між зернами; число зерен; сферичність зерна; морфологія зерен; піщані фракції*

Formulation of the problem. During data analysis of high-precision geodetic observations about the condition of the main buildings and structures of NPP units, an assumption has emerged that the load-bearing properties of sandy subgrades are influenced by many factors, including the morphological features of sands of eolian-alluvial genesis. The data from engineering surveys that were carried out at the site throughout the entire operating

cycle of the NPP were also worthy of attention. The changes in the features of sandy soils affected the surface artificial structures of the site to the greatest extent. These include hydraulic structures and the main one is the dam of the cooling pond. This also applies to the sites where the main transformers of power units are located. This article is devoted to resolving questions about the possible causes of the hitherto unstabilized settlements of individual buildings and structures at the NPP site.

Physico-geographical and technogenic conditions. Geomorphologically, the research area is located within the first supra-floodplain (sandy) left bank vitachevo-bug terrace of the Dnipro River. The research area is located on the left bank of the Kakhovka Reservoir (Note: at the time of writing this article, it no longer exists).

Before the start of construction, the research area was represented by the waters of the Kakhovka Reservoir. This reservoir was formed in the flooded floodplain of the Konka River as well as on the shore terrace of the Dnipro River with eolian relief forms (so-called "vegetated sand dune/kuchuhurs") and absolute surface elevations from 18.00 m to 25.0 m.

Currently, the surface of the site for blocks 1−6 is planned to absolutr elevation of 22.0 m. The relief of hydraulic structures and the dam body of the cooling pond is slightly hilly, predominantly eolian, formed by the re-winnowing of sands. In some places, the sands are supported by woody and herbaceous vegetation.

Engineering-geological characteristics of the site. Granites of the Archean-Proterozoic age take part in the geological structure of the site. They form the crystalline foundation of the Ukrainian Shield and at depths of 55−85 m are covered by a stratum of kaolin weathering crust. There are embedded higher the clays of the Serogozian stage of the Paleogene and sandstones of the Buchak stage. The clays are greenish-gray, dense, with rare inclusions of sandstone nodules. They were defined at a depth of 33−35 m. Paleogene clays underlie a layer of Quaternary alluvial sands. Alluvial dense sands of intermediate size up to 12 m thick underlay on the clays. Small eolian-alluvial sands of medium-dense and dense composition with a maximum thickness of up to 20 m overlay above. Flood-plain sandy loams and dark gray loams with an admixture of plant remains, sandy loams and loams of soft plastic consistency with 0.2−3.8 m thickness are found in the stratum of fine sands. The entire sand sequence below the groundwater level (GWL) is water-encroached. Fine-grained sands of medium density form the basis of most buildings and structures in the industrial zone of the NPP, the state district power station (SDPS), and Enerhodar city.

The widespread distribution of bulk sandy soils is a special feature of the NPP site. Bulk soils were formed as a result of large-scale planning measures during the construction of facilities.

Based on the results of dynamic sounding, static sounding, and radioactive logging, the sand thickness is conventionally divided into 4 engineering geological elements. They are characterized by heterogeneous indicators of physical and mechanical properties. Bulk soils are fine yellowish-brown sands, of medium density and dense structure, low-moisture and water-saturated, with a thickness of 0.5 to 4.5 m. There are also fine, loose, and extremely loose sands, low moisture, and saturated with water. The thickness of loose sands is from 1 to 10 m. The thickness of extremely loose sands is from 0.3 to 5.0 m. Extremely loose sands are found at depths of 4.0−7.5 m (below the groundwater level). Fine sands are characterized by a sharp predominance of the 0.1−0.25 mm fraction over the 0.25−0.5 mm fraction. At the same time, the content of other fractions is insignificant.

The content of the 0.1−0.25 mm fraction in loose and especially loose varieties of fine sand reaches 65 % or even more. In addition to fine sands, medium-sized sands are also found at the base of the dam. The dam of the NPP cooling pond was built on fine bedrock alluvial sands using the hydraulic alluvium method. The dam body is also heterogeneous in density. It consists of fine and medium sands of medium density and dense structure. Based on the results of engineering surveys, loose and

extremely loose, dynamically unstable, fine, and medium sands were also identified in certain sections of the dam. On the sections of the dam that were constructed using the dry method, fine, loose, and medium-density sands are also identified. The delineation of zones of loose and extremely loose sands has not yet been completed. This is especially true for sections of the dam on the side of the Kakhovka Reservoir.

It was noted above that a feature of the entire area where the Zaporizhzhia NPP and the Enerhodar City are located is the presence of the so-called. “kuchugur” relief forms of eolian genesis. These relief forms are also characteristic of some other areas of the Dnipro Valley. Eolian relief forms have been preserved near the sites of NPP and SDPS. It was pointed out in the survey materials during the NPP construction that the Paleogene deposits are covered precisely by the stratum of eolian-alluvial sands of the upper and modern sections of the Quaternary system. However, in subsequent materials of engineering-geological study of the area, the term “eolian” actually disappears. However, this type of deposits is very interesting and little studied from an engineering viewpoint. In many geological reference books, these deposits are conventionally classified as deposits of problematic age (eolQIII-IV). The boundaries of eolian and eolian-alluvial deposits in the territory under consideration in a vertical section have never been precisely defined. The principles of their separation are also have not been fully defined. The morphological features of the sands themselves are still unclear.

Analysis of engineering survey materials during the operation of facilities.

The main geological risks at the Zaporizhzhia NPP site are associated with the development of exogenous geological processes. This is a widespread occurrence of technogenic soils with increased compressibility and low bearing capacity. In recent years, signs of technogenic decompaction of backfill sands have appeared. As a result of comparing dynamic-sounding data at adjacent points over several years, it was found that loose sands at the NPP site are being replaced by extremely loose sands. According to the results of engineering surveys, not only the widespread development of loose sands was noted, but also the great depth of their occurrence (up to 8.0... 10.0 m). The frequency of occurrence of sands of extremely loose structure is quite high (such sands were found in ~ 40 % of all sounding points). Not only the foundations of shallow structures but even part of the pile foundations of some objects were found in the stratum of unconsolidated loose sands. The most dangerous sands for structures are loose and extremely loose sands. This is due to the possibility of settlement with complete water saturation and liquefaction with complete loss of bearing capacity because of dynamic impact (earthquakes, aircraft, missile and artillery strikes, long-term vibration). Sands of extremely loose composition when soaked give a settlement of 25...30 % only due to their own weight. With a small dynamic impact (0.4...0.6 g), the settlement increases by another 10...15 %. The total linear settlement reaches 35...40 %. With an average thickness of extremely loose sands of 1.5...1.8 m, the settlement due to compaction of the base sands can be 50...60 cm.

The dam of the cooling pond at the Zaporizhzhia NPP is of particular interest. It is generally accepted that the main unfavorable technogenic factor is the high level of groundwater, which can slow down the stabilization processes of ground settlement in the dam body of the cooling pond. The influence of changes in the chemical composition and temperature of groundwater is also possible. But the degree of their influence on these processes has yet to be assessed. The quantitative degree of influence of groundwater with high temperatures on reducing the strength and deformation characteristics of the sands of the dam body has also not been determined. During the engineering surveys carried out in the stratum of the loose alluvial sands of the dam body, zones of their technogenic decompaction to a dynamically unstable state were also identified. It was noted that dynamically unstable layers of alluvial sands are confined to zones near the groundwater table. This was quite evident in almost all

dynamic-sounding graphs. At the very beginning of construction, facts of the slope slide during the alluviation of the dam body were noted. The cooling pond dam of the Zaporizhzhia NPP had no analogs in the USSR and was experimental. This predetermined the future problems associated with its stability. In addition to the sliding of slopes during construction, the following negative phenomena were recorded during operation:

− slope failure of the bucket adjacent to pumping station No. 1 supplying water to the cooling towers from the side of the spray pools;

− sliding of the coastal ledge composed of loose backfill sands in the area adjacent to the building of pumping station No. 1;

− the surfacing of a section of the pressure pipeline for supplying water to spray pools, etc.

It should be especially noted that during the period of engineering surveys at the design stage of the NPP itself, soils in this condition were not found in this section of the site. However, according to surveys of residents, it was revealed that even before the start of construction, areas of the spread of the so-called “quicksand” had been still noted in local plavni (marshy). Cases of missing large domestic animals have been repeatedly reported in these areas. Presumably, it was in such areas that the content of the main fraction (0.1−0.25 mm) in loose varieties of fine bedrock sands reached 85 % versus 57 % on average on the site.

For bulk soils at the NPP industrial site, a relatively high (65 %) content of fractions of 0.1–0.25 mm is typical. The vertical planning of the site was carried out by cutting off eolian landforms and backfilling the basins with eolian sands. Thus, the upper part of the geological section of the site was composed of eolian sands. Which was the root cause of all the negative processes and phenomena on it. Since it is known from numerous experiments that it is eolian sands that have the weakest structural connections.

Similar processes were observed at the site of the Zaporizhzhia SDPS, which is located next to the NPP. There, loose bulk soils were uncovered too in the area of the main block transformers. But they were mainly traced along the route of the city sewage collector with a diameter of 1 500 mm, which crosses the section of so-called light courtyards. The presumed cause is suffusion sand removal through poorly made joints. Loose fine sands produce significant settlements when moistened with destruction of the soil structure (liquefaction) under dynamic impact.

The purpose of the article. The reporting materials of additional engineering-geological surveys for the NPP site indicated that the causes of landslide processes and technogenic decompaction of soils in individual areas have not yet been clarified. In reports on the results of experimental studies of DCEI-PSACEA, it was recognized that the dynamic stability of sands also varies depending on their structural features.

The greatest influence on the dynamic stability of sands is exerted by the composition density, particle size, the presence of mixed-type “films” on their surface, and the degree of roundness of their grains. As a result of research on fine sands of various densities, it was concluded that loose sands under dynamic loads have low dynamic stability. And that this stability increases with the increasing density of sand particles. An increase in the number of silt-clay particles and the formation of a hydrophilic film leads to an even greater decrease in the dynamic stability of sands.

The phenomenon of vibro-creep is usually considered in calculations of the general settlement of foundations by introducing reduction factors to the deformation modulus. Stabilization of vibro-creep and settlement usually occurs within 3...4 years, but at the Zaporizhzhia NPP, vibro-creep of sands has been evident for 15 years. This indicates the influence of additional technogenic factors: an increase in the level and temperature of groundwater, a decrease in the density of sand foundations, saturation of groundwater with petroleum products, long-term technogenic microvibrations of the surface layers of sandy soils above the GWL, etc. Other reasons are quite possible.

The consequences of some of them, in particular, the mine-explosive effects of summer-autumn 2022 on the soils of the

industrial site have yet to be assessed. Such an impact took place in the area of the dry storage site for spent nuclear fuel, special building No. 1, blocks 1 and 6, and isotope storage. In the adjacent territory, this is a forest area near ORU-750 750 kW outdoor switchgear, a fire station, the mouth of a discharge canal from the SDPS, etc. Thus, there is an areal dynamic impact on the upper soil horizon of the industrial zone at the NPP and the SDPS. At one time, completely insufficient attention was paid to the study of the hydrogeochemical and geotechnical interaction of the elements in the "NPP cooling pond – dam – Kakhovka Reservoir" system.

Also, little attention was paid to an in-depth study of the morphological characteristics of the Quaternary eolian-alluvial sands in the upper part of the soil section. These deposits were the main material for the layout of the site as a whole as well as for alluviation of the largest hydraulic structures at the NPP – the dam body of the cooling pond. All of the listed characteristics must be studied following the requirements of the regulatory document – RD 34 15.073-91 [8]. They needed to be carefully studied since they could directly influence the stabilization of settlements and tilts of critical buildings and structures of the NPP itself. However, this document was adopted after the completion of the main construction cycle work at the NPP site. After the liquidation of the USSR, its provisions were not taken into consideration and remained unfulfilled.

The numerical values of the main morphological characteristics of sands were still unknown, especially in the vertical section. The study of the morphological features of the vertical section of the sands at the Zaporizhzhia NPP site with obtaining reliable quantitative indicators was the main goal of the research.

Materials and Methods. The genesis of sands, as well as the complex and multifactorial nature of their properties, determine the need for an integrated approach to an in-depth study and assessment of their construction properties. A genetic approach to studying the construction properties of sands requires identifying and evaluating the main genetic characteristics with appropriate indicators.

According to the degree of specificity, the morphological features of sands should also be included among the main genetic characteristics [9]. Since they most significantly influence the construction properties of sands.

Morphological research is carried out to identify the characteristics of the shape, the nature of the surface of grains of various lithological-genetic and mineralogical-petrographic varieties of sands. In hydraulic engineering and energy construction, an accelerated assessment of the morphology of grains of sand fractions with a size of 0.05−2.0 mm is carried out by the so-called express method.

The method consists of "spilling a hinge plate of air-dry sand fractions from a standard glass funnel." A conventional characteristic of the general features of the morphology of sand grains is the grain morphology index λ. It is defined as a function of the spilling time of a hinge plate of the studied air-dry sand fraction from the funnel. The device for determining the morphology of sand grains and the necessary equipment are shown in Fig. 1.

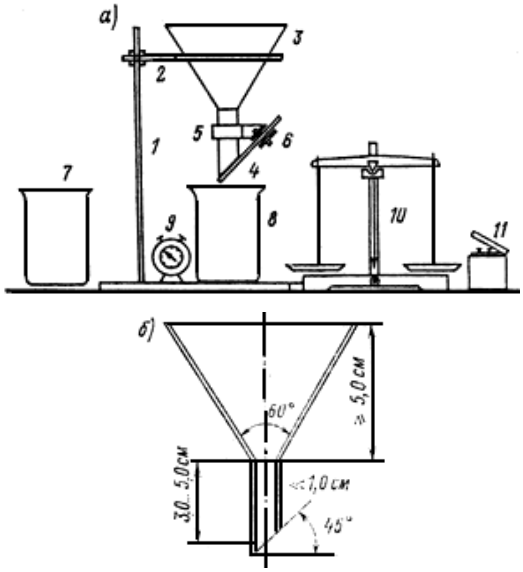

Fig. 1. Scheme of the device for determining the morphology of sand grains: a − equipment of the device set; b − drawing of the funnel; 1 − tripod; 2 − funnel holder; 3 − glass case of the funnel; 4 − latch; 5 − latch holder; 6 − the axis of the latch; 7 − a glass for dumping of a hinge plate; 8 − receiving glass; 9 − stopwatch; 10 − technical scales; 11 – heavy

At the beginning of the experiment, the sand from the samples is dried at a standard

temperature of 105°. After which the sand is scattered into fractions. The mass of each single fraction of sand should be 150 g. It is possible to study the morphology of sand grains with a smaller mass of controlled fractions (up to 50−30 g).

However, a decrease in the mass of fractions leads to a decrease in the accuracy of measuring the time of its spilling and also requires adjusting the calculated dependencies.

A hinge plate of each fraction is passed through a funnel and its spilling time is measured. The number of parallel experiments should ensure the determination of a reliable value for the average spilling time of a hinge plate of the sand fraction being studied. It is recommended to conduct at least 10−15 parallel experiments. At the end of the experiment, a control weighing of a hinge plate of the studied sand fraction is carried out.

Primary processing of experimental data is carried out during the experiment. It consists in calculating for each sand fraction the average spilling time of a hinge plate of the studied fraction ($t_{dcp.}$) and the corresponding morphology index of grains of this fraction (λ).

The average spilling time of a hinge plate of the studied sand fraction is determined as the arithmetic mean value of the spilling time from the number of experiments performed.

Table 1

Results of well testing during drilling

Mass of the studied fraction *m*, g	150	100	50	30
Factor K_1	1	1.3	3.0	5.4

For the purposes of operational geotechnical control over the construction of earthworks from sandy soils, it is recommended to use the following formula, namely:

$$\lambda = A / (K_1 \cdot t_{dcp.} \cdot a) \quad (1)$$

where,

$t_{dcp.}$ – spilling time of a hinge plate of the studied sand fraction, sec;

K_1 − coefficient depending on the mass of the hinge plate in the experiment;

a – coefficient equal to 4.3 with a funnel diameter of 1 cm;

A – a coefficient that generally depends on the size, density of solid particles, and the mass of a hinge plate of the sand fraction being studied (it is accepted from Table 2).

Table 2

The value of the coefficient A for fractions

The density of soil particles, g/cm³	The value of the coefficient A for different densities of sand fractions, mm				
	0.05…0.	0.1…0.25	0.25…0.5	0.5…1.0	1.0…2.0
2.64	3.32	4.14	5.12	6.55	9.79
2.65	3.31	4.12	5.11	6.54	9.75
2.66	3.30	4.10	5.09	6.50	9.70
2.67	3.28	4.09	5.06	6.49	9.67

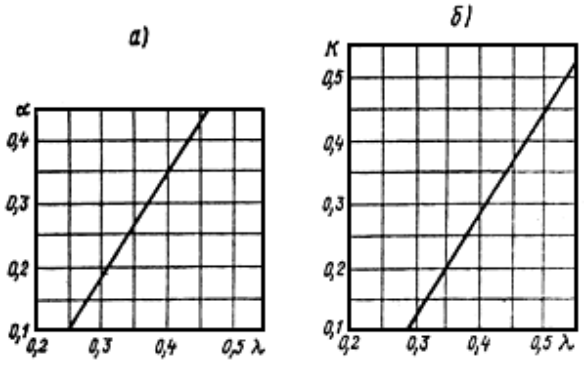

Fig. 2. Graphs of the dependence of the roundness coefficient (a) and the grain shape coefficient (K) on the values of the sand grain morphology index λ

The final processing of experimental data consists of determining the numerical values of (standard) the sand grains shape indices and classifying sands according to grain morphology in a graphical representation of the obtained results. Determining the numerical values of traditional grain shape indices α, β, K is carried out based on correlation dependencies between them and the grain morphology index λ. The value of the sphericity coefficient β is determined by the formula $\beta = K / \alpha$, where α and K is the roundness coefficient and grain shape coefficient, determined from graphs

(see Fig. 2) depending on the value of the grain morphology index λ.

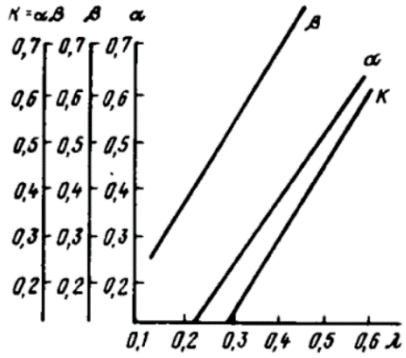

Fig. 3. Dependence of morphological parameters of sand grains of different genesis and composition on the generalized index of morphology λ (according to Potapov A.D.)

To facilitate the identification of sand characteristics, the following combined graph is also proposed (Fig. 3).

Based on morphological characteristics, sands for practical purposes can be divided into two groups according to the degree of processing the grains of the sand fractions as well as additionally into 4 more subgroups – according to the nature of roundness and sphericity of grains of the predominant fraction (Table 3). Also, the morphospecies of sand can be determined by visual observations of grains using a binocular microscope and also from photographs of grains on an electron scanning microscope [5; 6]. Analysis of materials from morphological research on sands in the Valley of Dnipro River.

Table 3

Classification of sand by basic morphological features

Group	Subgroup
I. Unprocessed, $\lambda \leq 0,4$	Angular-non-spherical, $\alpha \leq 0,35$; $\beta \leq 0,8$
	Angular-spherical, $\alpha \leq 0,35$; $\beta > 0,8$
II. Processed, $\lambda > 0,4$	Rounded-non-spherical, $\alpha > 0,35$; $\beta \leq 0,8$
	Rounded-spherical, $\alpha > 0,35$; $\beta > 0,8$

These researches were not the only ones of their kind. Various authors have paid close attention to this issue in previous years. In several types of sands of continental origin of Quaternary age were studied [2; 3; 7; 8]. A morphogenetic series was proposed that described the dependence in the formation of morphological parameters of sands (the degree of processing the sand grains) on the degree of exposure to external factors of particle processing in various conditions: fluvial, eolian, glacial, etc. This series is as follows: eQIV–eoQIV–mQIV – fgQIV – eo-mQIV – aQIV and shows that with increasing degree of impacts during redeposition, the morphology index of sand particles increases. The most characteristic form of sand particles is the form acquired as a result of processing and has minimal surface energy. This shape is a sphere or ellipsoid rotation. This is because, under continental conditions, predominantly quartz sands are formed, less often quartz-feldspar sands. Although oligomictic and even polymictic varieties are found quite often, this is due to the specific genetic environment of their formation. The predominance of quartz is dictated mainly by its properties, namely its high resistance to weathering, as well as its hardness and resistance to abrasion when transferred in water and air environments. For this reason, quartz grains, with their morphology, can serve as a completely accurate genetic indicator. From the viewpoint of assessing the general morphological features of sands, it is important to take into account the nature of the surface of sand grains. For these purposes, at one time the sand morphology index λ was proposed. This index comprehensively describes the features of the shape and nature of the surface of sand particles in the entire volume of sandy soil under study.

From the sandy deposits of the Dnipro Valley, several genetic varieties of sands were studied, which, as a result of postgenetic processes, acquired different shapes. Table 4 shows the characteristics of the composition and morphological features for the studied sands in the Dnipro Valley.

Table 4

Characteristics of the composition and morphological features of the sands of the Dnipro Valley

Genetic index	Sampling location	Characteristic of ranulometric composition	Characteristic of mineral composition	Index of morphology λ	Characteristic of morphology
aQIV	Tripolskaya Thermic Power Plant (TPP)	Small homogeneous	Polymineral	0.449	Processed rounded-spherical, roughly polished, large-sized-pitted
aQIV	Chigirinskaya SDPS	Small homogeneous	Monomineral	0.324	Unprocessed angular-non-spherical, scaly
aQIV	Pridneprovsk, the area of the Samara river mouth	Small homogeneous	Monomineral	no Data Available	The grains are angular, slightly and well-rounded in equal proportions, with a smooth, shiny surface of the sand particles.
aQIV	Dnipro, Monastyrskiy Island	Medium homogeneous	Monomineral	0.210	The grains are classified as unprocessed angular-non-spherical

As can be seen from Table 4, there are no data on the numerical indices for the morphology of all types of sands in the lower reaches of the Dnipro River.

Analysis of previously completed research makes it possible to use the provisions of the V.I. Osipov's work for natural sandy soils of various compositions and morphological features [4]. Several previously published scientific articles have also shown that the morphological features of sands represent an integral structural characteristic of soils. And they largely determine the maximum molecular moisture capacity and the ultimate densities of sands texture. These characteristics, in turn, affect their strength and deformation properties. It has been established that, with different compositions of the liquid filtering through the stratum of sand, they also affect their suffusion stability.

Regarding the strength properties of sands, M.N. Goldstein noted in his works that the shear resistance of sand depends on many components, including the shape of its particles [1]. The shape of the part also affects the behavior of soils under dynamic impacts. At one time, K. Terzaghi noted that the most unstable sands from the viewpoint of liquefaction contain many rounded grains. Valishev I.T. when processing experiments with various sands, obtained a numerical dependence for critical acceleration, which also had the particle shape coefficient. It is known that construction on eolian sands encounters many difficulties. According to research results, even admixtures of sands of this origin with other soils can seriously deteriorate the deformation and strength properties of the foundation soils of a number of structures, especially for transport and energy purposes [4−9; 11].

Experimental results. Sandy soil samples for laboratory research were taken during the excavation of geophysical (logging) wells near the Zaporizhzhia NPP site. The wells were drilled on the border of the preserved natural relief and the planned territory of the NPP site.

The reactor compartment No. 1 site of the NPP was the closest to the sand sampling points. The bedrock sands of the upper Quaternary horizon in this area are fine quartz, yellow, and yellow-gray, of medium density, water-saturated. The grain composition is dominated by the sand fraction with a particle size of 0.10−0.25 mm in an amount of 33−56 %. Sands in the bulk are homogeneous in grain composition. There are thin layers of sandy loam and silty sand. The density of sand particles in the entire upper horizon is 2.65 g/cm³.

The lower Quaternary stratum in this area usually contain quartz, gray, medium-sized sands, saturated with water, and dense. But in some areas, fine sands again appear in the lower Quaternary strata, indicating the peculiarities of sand deposits' sedimentation in

this area of the "proto-Dnieper" valley. There are lenses of fine and coarse sands. The grain composition of the lower part of the sand stratum is dominated by the 0.25−0.5 mm fraction. The sands are heterogeneous. In the mass of sands there are lenses of quartz, gray, large, heterogeneous sands. The grain composition of coarse sands is dominated by the sand fraction of 0.5−1.0 mm in an amount of 33−42 %. The particle density of the lower horizon is also 2.65 g/cm³.

Processing and analysis of sand samples were carried out by specialists of the soil laboratory at the State Enterprise "DneproGIINTIZ" of the DF State Enterprise "UkrNIINTIZ" (Dnipro) in May 2022. The determined weighted average granulometric composition of the sands in the upper part of the section is given in Table 5.

Table 5

The weighted average particle size distribution of sands in the upper part of the section of the studied stratum

Particle diameter, mm	Fraction content %
2–5	0.3
1–2	0.5
0,5–1	2.4
0,25–0,5	27.7
0,1–0,25	57.5
<0.1	11.6

For analysis, sand samples were taken from the upper and lower horizons. The upper part of the stratum traditionally belongs to eolian-alluvial deposits. The lower part of the stratum presumably belongs to the alluvial horizon.

The fine sands in samples from the upper part of the section are quartz, monomineral, and yellowish-gray. Fine sands in samples from the lower part of the section are quartz, monomineral, and light gray. The sands are homogeneous, but there are also sand bands that are heterogeneous in grain composition. Under a microscope, the surface of individual quartz particles is smooth, shiny, or less often matte.

The sand samples contain isolated inclusions of fine gravel. According to Table 5, fractions of 0.25−0.5 mm and 0.1−0.25 mm predominate. The specialized technical literature informs that determining the morphological parameters of sands with a fraction of less than 0.1 mm does not make sense. This is because the particles of small fractions are carried in a suspended state and therefore slowly change their shape. It also makes no sense to determine the indices of minor fractions. The use of electron scanning microscopes in mass research is also difficult. Thus, morphological indices are determined only for the predominant fractions of 0.25−0.5 mm and 0.1−0.25 mm. According to formula 1, the numerical values of sand morphology indices for fractions are:

0,25 – 0,5 mm – 0,230;

0,1 – 0,25 mm – 0,191.

To calculate the weighted average value λavg. for fine sands in the upper part of the section for the studied stratum, formula 3 was used (see Appendix 11 to RD 34 15.073-91). The weighted average of grain morphology λavg. for fine sands at the NPP site was 0.204.

According to the complex of morphological parameters, the grains of all fractions in the upper part of the section by the nomograms in Fig. 2 and Table 3, refer to unprocessed ($\lambda \leq 0.4$), angular-non-spherical ($\alpha \leq 0.35$; $\beta \leq 0.8$).

Under a microscope, the surface of individual quartz particles is smooth, shiny, or less often matte. A more in-depth characterization of sand grains of different fractions as per Table 11 "Recommendations for the comprehensive study and assessment of the construction properties of sandy soils" is as follows: fractions of 0.25–0.5 mm and 0.1–0.25 mm by the roundness coefficient a of the grain of the fractions are very angular, by the sphericity coefficient β, they are classified as non-spherical and anisometric, and by the morphology index λ (as very unprocessed).

Based on the difference in the granulometric composition of loose and extremely loose sandy soils at the NPP site, a criterion for their separation has been suggested. In line with this criterion, the boundary between eolian and eolian-alluvial fine sands can be the content of the 0.1−0.25 mm fraction in 65 %.

Fine sands in this area with a content of this fraction of more than 65 % can be

considered eolian. But only under the condition of a significantly lower content of the 0.25−0.5 mm fraction and negligibly small contents of other fractions. This criterion must be taken into account when placing engineering structures.

The overall criteria for identifying purely eolian sands in the Enerhodar region in the upper horizon of the sandy Quaternary alluvial strata can be as follows:

− content of fraction 0.1−0.25 mm is more than 65 %;

− absence of fractions is more than 0.5 mm and less than 0.05 mm;

− morphology index λ is not less than 0.20;

− the roundness coefficient is $\alpha \leq 0.35$;

− the sphericity coefficient is $\beta \leq 0.8$.

The angularity of the fragments in the studied sands may well be observed in deposits of eolian genesis as well as the absence of the clay fraction in the sands. The angularity of fragments is influenced by many factors: particle size, type of particle movement, wind speed and its direction, and duration of wind processes. An example is the sands of the Sahara Desert, which are distinguished by the obvious angularity of the grains.

The weighted average particle size distribution of sands in the lower part of the section of the studied stratum is given in Table 6.

According to formula 1, the numerical values of the sand morphology indices λ for individual fractions are: 0.25 – 0.5 mm – 0.232; 0.1 – 0.25 mm – 0.184.

To calculate the weighted average value λ_{avg}. for fine sands in the lower part of the section of the studied strata, formula 3 was also used (see Appendix 11 to RD 34 15.073-91). For sand samples according to Table 6, the weighted average of grain morphology λ_{avg}. for fine sands of the NPP site was 0.200.

Table 6

The weighted average particle size distribution of sands in the upper part of the section of the studied stratum

Particle diameter, mm	Fraction content %
2–5	–
1–2	–
0.5–1	2.3
0.25–0,5	28.3
0.1–0.25	59.3
< 0.1	10.1

According to the nomograms in Fig. 2 and Table 3 grains of all fractions of this sand in the lower part of the section are unprocessed ($\lambda \leq 0.4$), angular-non-spherical ($\alpha \leq 0.35$; $\beta \leq 0.8$). Under a microscope, the surface of individual quartz particles is smooth, shiny, or less often matte.

A more in-depth characterization of sand grains of different fractions following of Table 11 “Recommendations for the comprehensive study and assessment of the construction properties of sandy soils” [9] is as follows: grains of the 0.25–0.5 mm and 0.1–0.25 mm fraction is very angular according to the roundness coefficient *a*, according to the sphericity coefficient β they are classified as non-spherical and anisometric, and according to the morphology index λ – as very unprocessed.

The research results are presented in Table 7.

Table 7

The value of morphology λ for sand fractions in different parts of the Dnipro Valley

Title and sand gradation	Sand sampling location	The value of the morphology index λ for sand fractions				
		0.1…0.25	0.25…0.5	0.5…1.0	1.0…2.0	weighted average
Alluvial sand, mean size	Monastery Island, Dnipro city	0.196	0.210	0.250	–	0.210
Sand, eolian-alluvial, fine, upper horizon	Zaporizhzhia NPP site	0.191	0.230	–	–	0.204
Alluvial sand, fine, lower horizon	The same place	0.184	0.232	–	–	0.200

As follows from Tables 5 and 6, the indicators of sieving sand samples from the upper and lower horizons of the sand mass are not very different from each other. Also, according to Table 6, the morphological parameters of individual sand fractions are

similar. A feature of the fine sands in the study area is not only the actual two fractions (0.1−0.25 mm and 0.25−0.5 mm) but the closeness of the flow rates of sand hinge plate for the indicated fractions through a glass funnel, that had been revealed during laboratory experiments. All these points out the similar conditions for the formation of these geological layers and their probable belonging not to different, but to one type of deposit – eolian-alluvial. This, in particular, distinguishes the fine sands of the Enerhodar region from the usual medium-sized alluvial sands of Monastyrskiy Island in the Dnipro city (Dnipropetrovsk), which were subjected to similar research.

The values of some characteristics of the physical and mechanical properties of fine sands were calculated using the obtained values of the morphology index λ based on the nomograms in paragraph 2.23 of Figure 14 “Recommendations for a comprehensive study and assessment of the construction properties of sandy soils” [9]. The obtained values are largely similar to the data from engineering surveys at the site. But except for the lower adhesion index inherent in the sandy soils of the upper horizon at the NPP site: 0.025 MPa according to nomograms versus 0.01 MPa or less. However, these differences can be explained by the genesis of the deposits themselves. It should be especially noted that it is very difficult to use these nomograms with values of the morphology index of 0.2 or less.

Also noteworthy is the rather significant content of the finely dispersed component in the samples. This directly affects the cohesion and internal friction in the sand mass. For this reason, some kinds of quicksand-thixotropic phenomena are quite possible in the sands of the upper horizon. They may be due to the presumably plasticized-coagulation type of structural bonds. With this type of bond, sands can easily liquefy during vibration [5]. But to confirm these assumptions, special additional research is necessary.

Originality and Practical value. The originality of this work can be considered the obtaining of numerical parameters of the morphology of aeolian-alluvial and alluvial sands of the Zaporizhzhia NPP site for the first time in a vertical section. The obtained numerical values supplemented the data missing in Table 3. One can confidently note a downward trend in the morphology index of the river sands of the Dnieper Valley from the source to the mouth. The genesis of sands also affects the morphology index. Based on the identified differences in the granulometric composition of loose and extremely loose sands in the upper part of the geological section, a genetic criterion for their separation can be proposed. According to this criterion, the content of the 0.1−0.25 mm fraction of 65 % can serve as the conventional boundary between aeolian and aeolian-alluvial fine sands of the region, with a sharply subordinate value of other fractions. Above the fraction content of 65 %, the fine sands of the site clearly belong to aeolian varieties.

The value of the morphology index for purely aeolian sands in the area should be at least 0.2. But this assumption needs to be checked with mass determinations. The previously stated assumption about the good roundness of the sands of the upper part of the section in this section of the Dnieper Valley was not confirmed. However, it should be noted that all the studies performed are still, in fact, point-by-point. To confirm the data obtained, it seems necessary to conduct additional studies of the sands of the entire nuclear power plant site. It is mandatory to study the morphological features of medium sands of deep horizons. And also conduct massive research in the Kakhovka region (especially carefully in the area of the destroyed hydroelectric power station) and Kherson. To accurately establish the interface boundaries between sands of different origins, it is necessary to clarify the process of sampling sand from exploration wells. It is necessary to increase the number of testing intervals along the wellbore and the volume of samples. The sample weight of sand dried to constant weight for morphological studies must be at least 5 kg.

The practical value of the research was to obtain numerical indicators of the morphology of the sands in this area. Genetic criteria for identifying aeolian and aeolian-alluvial sands at

the top of the local section were also proposed. This may explain the reasons for the unstabilized settlements of some buildings and structures of NPP over a long period of time. Also, determining the numerical indices of the morphology of eolian-alluvial sands at a NPP site can help predict the behavior of hydraulic structures built on them under external stress impacts. These may also include a sudden short-term significant increase or decrease in the level of the Kakhovka Reservoir (including due to damage to the dams of the Dnipro cascade). This is what happened in practice, as a result of the destruction of the Kakhovska hydroelectric power station dam. However, this problem requires a separate study, given the supposed similarity of the sandy soils of the hydroelectric power station area with the soils of the NPP site. In particular, to identify a possible connection between the stability of buildings and structures of hydroelectric power stations and the quality of the sandy soils of their foundations.

Conclusion

In the course of the conducted research on sand samples, it was found that the weighted average morphology index for fine eolian-alluvial sands in the upper part of the section at the Zaporizhzhia NPP site is 0.204. For fine, presumably alluvial sands in the lower part of the section, it is 0.200. According to the main morphological characteristics, the grains of all main sand fractions are classified as unprocessed, angular-non-spherical. The results of similar works on the study of genetic types of Quaternary sands of the different genesis in the Dnipro Valley were also analyzed. During this, data were obtained on the morphology of monomineral oligomict alluvial sands, the shape and nature of the surface of alluvial sand grains. It should be noted that some morphological characteristics of river Quaternary sands of the Dnipro Valley for this area were obtained for the first time. Further research involves studying the river sands of the Dnipro Valley from deeper horizons.

The originality of these research is the obtaining of numerical morphological parameters for eolian-alluvial and alluvial sands at the Zaporizhzhia NPP site. This is for the first time and in a vertical section. One can note the previously identified trend of a decrease in the morphology index of the river sands of the Dnipro Valley from the sources to the mouth. The dependence of the morphology index on the genesis of sediments was also confirmed.

The practical value of the research was that in addition to obtaining numerical indices of morphology, criteria for identifying eolian and aeolian-alluvial sands in the upper part of the local geological section were proposed. This may explain the reasons for the long-term unstabilized settlemnts of individual buildings and structures of NPP. The results of the research can be implemented to calculate the indices of sandy soils at the foundations of buildings and structures. And also, they can be used in calculations during the post-war reconstruction of hydraulic structures of energy facilities in the Dnipro Valley − cooling ponds of nuclear power plants and thermal power plants, various dams, and ground approaches to transport structures.

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