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Research paper

Effect of nanosilica stabilisation on the bearing capacity under undrained conditions

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Abstract: Due to the increasing necessity of building on soils with insufficient bearing capacity, the development of methods for soil improvement is an important geotechnical engineering issue. One of the innovative methods of soil stabilisation is the use of nano-additives. The paper presents the influence of nanosilica on the bearing capacity under the footing under undrained conditions. For this purpose, a simple and quick unconfined compression test was used to evaluate the undrained shear strength of selected silty soil. Tests were conducted for soil without additives and with nanosilica contents of 1, 3 and 5%. All samples were compacted to the maximum dry density in a Proctor apparatus, and strength tests were conducted after 7 days of curing. The results clearly show an increase in undrained shear strength with increasing nanosilica content. Based on these data, a parametric analysis of the bearing capacity under the strip footing was performed for 4 variants of nanosilica content and for 9 loading cases. Thus, the impact of stabilisation in a practical engineering issue was presented. For all load cases the optimal dimensions of the foundation were determined. In addition, for the selected case, calculations were made for a fixed foundation dimension. All computations were performed in accordance with Eurocode 7 with GEO5 software.

Keywords: nanosilica, undrained shear strength, unconfined compression, bearing capacity, strip footing

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1. Introduction

The continuing process of urbanisation and the development of civil engineering increases the need for structures to be placed in areas with unfavourable geotechnical conditions. Structures are more often found on subsoils previously considered as unsuitable (with insufficient bearing capacity), such as organic soils, reconstituted soils or cohesive soils in plastic state. As a result, ground improvement has become a very important branch of geotechnical engineering in recent decades. There are many methods for the improvement, which are selected according to the type of construction, ground in the subsoil and design requirements. The methods can be divided, simply, into two groups: improving by changing the state or by changing the composition of the ground. One of the more popular techniques from the second group is a chemical stabilisation. It is a method of applying an admixture into the soil which, through ion exchange, interact with it and permanently transform physical and mechanical properties of the soil. For this purpose, the most commonly used materials are micro-additives such as cement, lime, fly ash or bituminous materials [1–3]. However, conventional methods cannot always be used and, in addition, their use is often associated with a significant environmental footprint.

Due to the strong development of nanotechnology in recent years, nano-additives have started to be used for stabilisation applications [4–8]. The major advantage of nano-additives, in comparison to micro-additives, is that the desired improvement in soil parameters can be achieved with a smaller percentage of admixture. This is mainly due to the intermolecular interactions between the soil and the nanoparticles, resulting in aggregates and agglomerates that reduce pore spaces [9–11]. The specific surface area is the key factor that determines the strength of superficial forces [12, 13], which always increases significantly when stabilising additives are changed from micro to nanoscale [14]. For the practical purposes of soil stabilisation, not all nano-additives are suitable – mostly carbon nanotubes, carbon nanofibres, nanoclay and nanosilica are used [15]. They are more expensive than conventional solutions, but can be an environmentally friendly alternative due to their lower consumption.

In terms of availability and cost, the most applicable nano-additive is nanosilica, for which numerous studies have shown a positive effect on soil parameters [16–22]. Over the years, it has mainly been used in civil engineering as an admixture for concrete [23, 24] or other materials [25, 26], but has also found applications in geotechnical engineering. Initially, it was only used as an admixture to micro stabilisers to enhance their performance, but it is now successfully used as a single additive. In both cases, studies confirm its positive effects on the physical and mechanical parameters of soils [9, 10, 15, 27–34].

The aim of the article is to determine the effect of nanosilica stabilisation on bearing capacity of soil under the footing. The previously mentioned research on the use of nano-additives in soil stabilisation has focused only on the determination of mechanical parameters in laboratory tests. Typically, the evaluation of the effect of admixtures on the bearing capacity of the subsoil is carried out by determining the load-deformation relationship in model or numerical tests [35–38]. Therefore, in this work, it was decided to carry out a case-based calculation in order to better illustrate the measurable advantages of the applied stabilisation method. Strip footing was selected as the most classic geotechnical issue. A similar approach has been presented, for example, in [39].

Depending on the ground and the design conditions, in the context of the bearing capacity of the subsoil situation with or without drainage is considered. In those cases, different test methods are used for the determination of strength for the calculations. The work focuses on undrained conditions, for which a quick and simple test of unconfined compression was used to assess the strength parameter. In practice, these conditions occur mainly in temporary situations, when there is a rapid increase in loading and the consolidation process doesn't occur. First, the laboratory tests were carried out to determine the strength parameters of the selected silty soil without and with 3 different nanosilica contents. Based on these data, an analysis of the bearing capacity of the soil under the strip footing was performed. The calculations were carried out for 4 soil variants and 9 load cases, determining the bearing capacity of the soil and the optimum foundation dimensions for all load variants. In addition, for the selected case, calculations were made for a fixed foundation dimension.

2. Influence of nanosilica stabilisation on soil strength

2.1. Materials and methods

Cohesive soil – in which conditions without drainage can occur – was selected for analysis. The study was conducted on soil samples taken from a deposit located in west-southern Poland in the Trzebnica Hills area in the neighbourhood of the city of Wrocław (Lower Silesia Voivodeship). On the basis of a hydrometer test (in accordance with [40]) the soil was classified as sandy clayey silt (further denoted as "silty soil") [41]. The grain size distribution curve is shown in Fig. 1. As a stabilising admixture a nanosilica (further

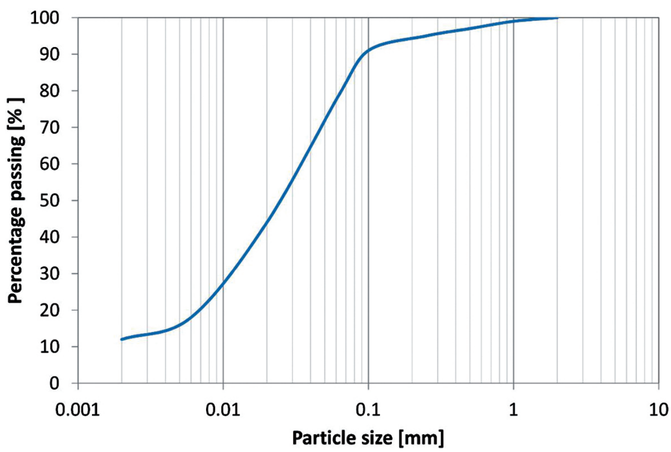

Fig. 1. Grain size distribution of investigated silty soil

denoted as "NS") in the form of a colloid, type Levasil 200/30, was used. For comparison of the difference in particle size, the grain composition of the soil and the additive are shown as frequency curves in Fig. 2. In the case of the soil, a Mastersizer 2000 laser granulometer was used, while the size distribution of the colloid nanoparticles was determined based on tests in the Zetasizer Nano particle characterisation system. In addition, the specific surface area S_0 (in accordance with [42]) and the concentration of hydrogen ions pH (in accordance with [43]) were determined. Selected properties of the soil material and nanosilica admixture are shown in Table 1. The microstructure of the components has been investigated by a scanning electron microscope (SEM) for the soil and by a transmission electron microscope (TEM) for the nanosilica. The results are presented in Fig. 3.

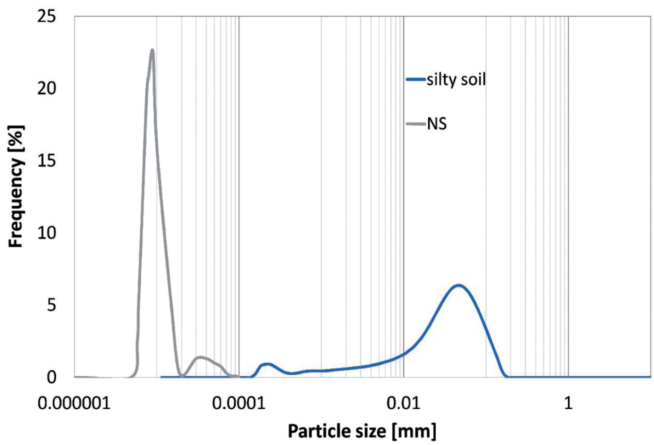

Fig. 2. Particle size distribution frequency curves of silty soil and NS

Table 1. Silty soil and NS characteristics

Property	Value	
	silty soil	NS
Sand %]	21.00	–
Silt [%]	67.00	–
Clay [%]	12.00	–
Specific surface area S_0 [$m^2 \cdot g^{-1}$]	35.70	196.49
Concentration of hydrogen ions pH [–]	8.68	9.00
Concentration of SiO_2 [%]	–	30.00

Strength tests were carried out in four variants: on soil alone and on specimens stabilised with 1, 3, 5% NS contents with respect to dry mass. It was not possible to prepare a mixture with a larger amount of the additive due to its colloidal form, which resulted

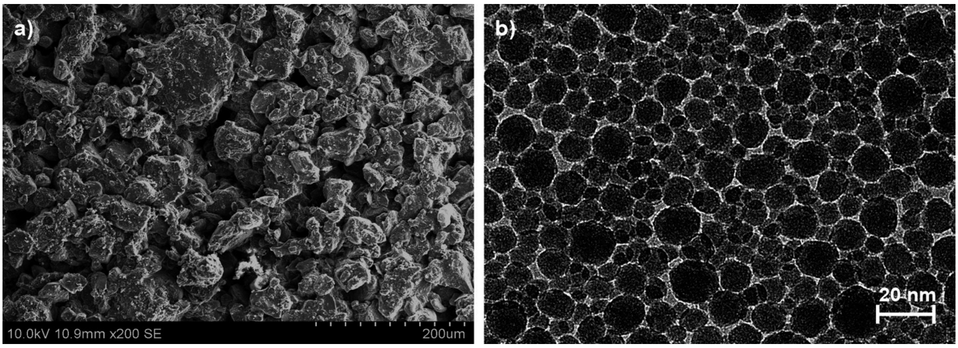

Fig. 3. Materials microstructure: a) silty soil, b) NS

in plastification of the soil mixture. However, only colloidal form is suitable for achieving uniform distribution in the soil. The use of another type (e.g. powder) is less effective in this respect [44]. The natural soil was initially sieved through a 2 mm sieve. Then, for samples with an admixture of nanosilica, the soil was thoroughly mixed with a specific amount of NS. All specimens were prepared using the Proctor method (rammer A and mould A) in accordance with [45] with the same compaction energy of 0.596 J/cm^3. The use of the optimum moisture content (OMC) and the corresponding maximum dry density (MDD) as reference values ensured the repeatability of the samples. Next, cores with a diameter of 38 mm and a height of 76 mm were cut out from the prepared mixtures for strength testing. After that, samples were cured at room temperature for 7 days. To prevent moisture loss, they were wrapped tightly in a plastic membrane and stored buried in sand.

Unconfined compression tests were performed on a series of 12 specimens (3 for each soil mixture) according to the [46] with the velocity of 1%/min. The undrained shear strength c_u is defined as half of the unconfined compressive strength q_u that corresponds to the vertical stress σ_v at failure:

$$c_u = 0.5 \cdot q_u \tag{2.1}$$

$$\sigma_v = \frac{P}{A_i/(1-\varepsilon_v)} \tag{2.2}$$

where: P is a vertical load, ε_v is a vertical strain and A_i is an initial cross-section area of the sample. In the study, the maximum vertical stress value was assumed as the q_u value. A stress-strain curve was plotted for each specimen and the compressive strength and undrained shear strength were established. The stiffness expressed by the undrained secant modulus E_{u50} was also calculated. The modulus is determined from formula:

$$E_{u50} = \frac{\sigma_{v50}}{\varepsilon_{50}} \tag{2.3}$$

where: σ_{v50} and ε_{v50} are the vertical stress and strain at 50% of the maximum stress level.

2.2. Results and discussion

The results from Proctor apparatus are presented in Fig. 4. Tests have shown that the addition of nanosilica increases the maximum dry density and slightly increases optimum moisture content. A dry density value of 1.883 g/cm^3 was obtained for the pure soil and 1.914 g/cm^3 for the sample with 5% NS content. The optimum moisture content for the soil was 11.6% and for the samples with nanosilica it varied in the range 11.8–11.9%.

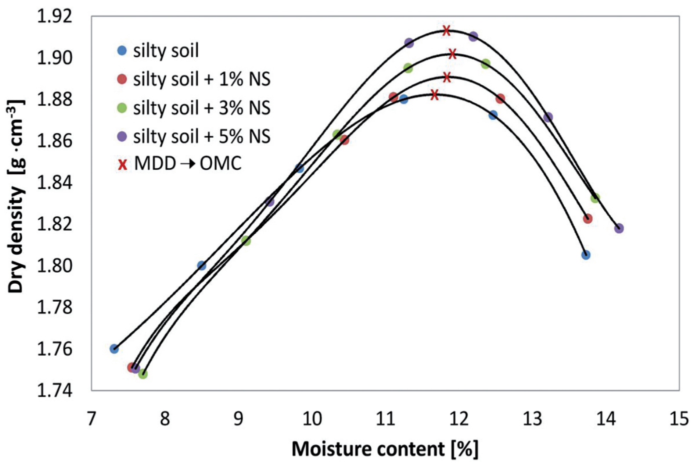

Fig. 4. Maximum dry density and optimum moisture content of the soil samples

The study confirmed an increase in soil strength with increasing nanosilica addition in unconfined compression tests. A summary of the outputs is presented in Table 2. The lowest undrained shear strength c_u value (46.37 kPa) was obtained for the pure soil and the highest (88.62 kPa) for the sample with 5% NS addition. Due to the similarity of the results of three samples obtained for each level of nanosilica content, in subsequent calculations mean values were used. For the soil, the mean undrained strength was 48.76 kPa and for the soil with 1, 3 and 5% NS it was 57.60 kPa, 75.54 kPa and 85.80 kPa, respectively. This represents an average strength improvement of 18.1%, 54.9% and 76.0% compared to the soil without the additive. This implies a quite regular increase in strength with increasing nanosilica content. The dependence of undrained shear strength on NS content is shown in Fig. 5.

The stress-strain relationship (σ_v–ε_v) was analysed for each sample. Again, the similarity of the curves for each level of nanosilica content was noted. In Fig. 6 the comparison of the graphs of selected samples for the 4 investigated variants of soil composition are presented. As the NS content increases, the peak becomes more pronounced and the strain level at which it occurs decreases. For the pure soil alone, the maximum vertical strain was found at approximately 6% of vertical strain. For the sample with 1% NS addition, the peak occurred at ε_v around 5% and for the 5% NS mixture – around 3%. Only for the soil with 3% NS content such clear results wasn't found and the maximum value for deformation

Table 2. Unconfined compression test results

Sample	Bulk density ρ	Unconfined compressive strength q_u	Vertical strain at failure ε_v	Undrained shear strength c_u	Undrained secant modulus E_{u50}
[–]	[g/cm^3]	[kPa]	[%]	[kPa]	[MPa]
silty soil	2.097	92.73	5.70	46.37	2.81
	2.099	96.16	6.01	48.08	3.10
	2.101	103.66	5.98	51.83	4.71
silty soil + 1% NS	2.111	109.54	4.87	54.77	4.82
	2.113	117.40	5.28	58.70	4.15
	2.114	118.67	4.97	59.33	4.50
silty soil + 3% NS	2.127	154.53	5.27	77.27	8.79
	2.125	143.27	3.85	71.63	8.37
	2.127	155.47	5.88	77.73	5.26
silty soil + 5% NS	2.139	177.23	3.14	88,62	6.90
	2.134	168.48	2.95	84.24	7.91
	2.135	169.08	3.15	84.54	8.55

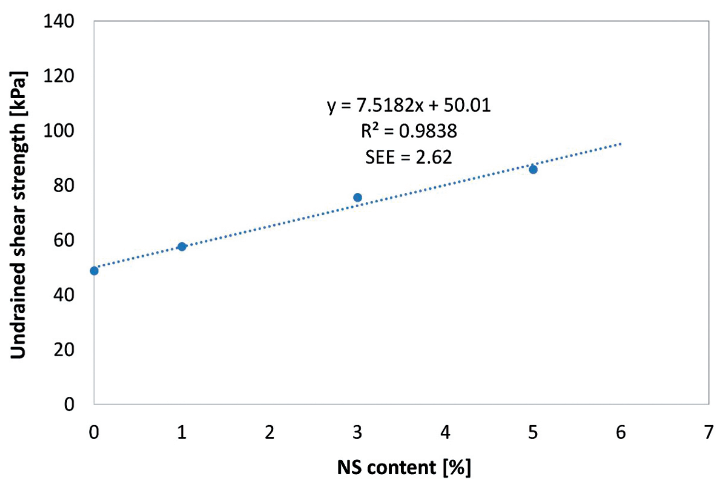

Fig. 5. The dependence of undrained shear strength on nanosilica content

were reached from 3.14% to 5.88% of strain. As a result, not only the strength but also the stiffness of the soil has increased. The values of the E_{u50} modules are also shown in

Table 2. The average modulus was 3.54 MPa for the pure soil and for the mixture with 1, 3 and 5% NS it was 4.59 MPa, 7.47 MPa and 7.79 MPa, respectively. Which means an increase in mean stiffness of 29.7%, 111.0% and 120.1%. A steep value rise was observed for 3% NS content and for 5% the further growth was not so significant. However, a high scattering of results was also observed, which is a consequence of the test type. Thus, it is difficult to draw strong conclusions about the dependence of stiffness on the nanosilica content.

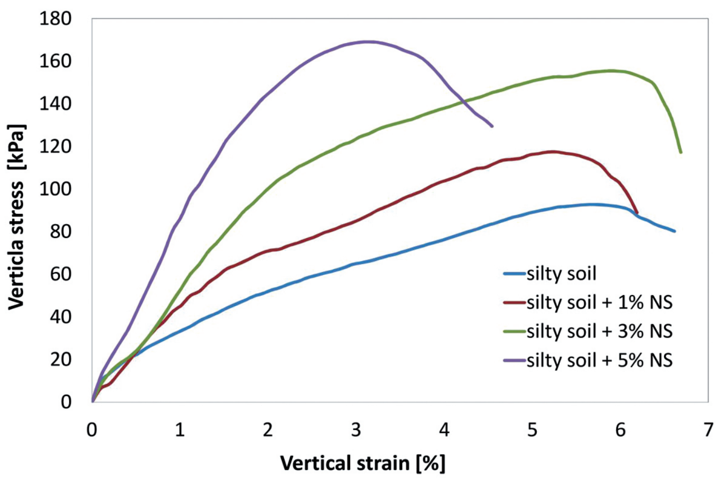

Fig. 6. Stress-strain curves for selected samples without and with nanosilica admixture

The results obtained were compared with those available in the literature. In [28] the influence of nanosilica up to 1% was determined for low plasticity clay. The study reported not only an increase in dry density, but also a noticeable increase in optimum moisture content. In the unconfined compression test, a 50% increase in undrained shear strength and 84% increase in secant modulus was obtained for the sample with 1% NS content, which is not consistent with the results obtained. In [47] the unconfined compression test results were presented for lacustrine classified as high plasticity silt and clays with NS 1% and 3% addition. The increase in c_u for the 1% additive was between 20% and 60% and for the 3% additive between 30% and 95%, which is again higher than that determined in this research. Another investigation [48] of soil with similar grain composition to that in the paper showed an increase in strength of more than 300% and relatively small differences between the samples with 3 and 5% additives (curing of 3, 14 and 28 days). As can be seen, the results established for nanosilica stabilised soil are extremely varied. Obviously, outcomes are highly influenced by different factors like: type of soil, the curing time, the characteristics and form of the additive properties. Therefore, when planning the application of chemical stabilisation with nanosilica, estimating the increase in soil strength should be based on experimental tests.

3. Bearing capacity calculations

3.1. Case study

The results of the unconfined compression tests were used to calculate the bearing capacity of the subsoil under the strip footing in the undrained condition. In the paper, 4 variants of homogeneous subsoil were analysed – without or with the addition of selected amounts of nanosilica. The average values of the determined undrained shear strength and bulk density were used (see Table 3). A number of factors influence the undrained bearing capacity. Not only the strength of the soil, but also the shape of the foundation, the slope of the base, foundation depth, and the load inclination and eccentricity. Due to the complexity of the issue, the analysis focuses on selected tasks.

Table 3. Unconfined compression test results

Sample	Bulk density ρ	Unit weight γ	Undrained shear strength c_u
[–]	[g/cm^3]	[kN/m^3]	[kPa]
silty soil	2.099	20.59	48.76
silty soil +1% NS	2.113	20.73	57.60
silty soil +3% NS	2.126	20.86	75.54
silty soil +5% NS	2.136	20.95	85.80

The calculations were carried out for a footing with a horizontal base. The main emphasis was on the effect of load and load eccentricity on bearing capacity, so also a fixed foundation depth was assumed. A scheme of the task is shown in Fig. 7. A total of 9

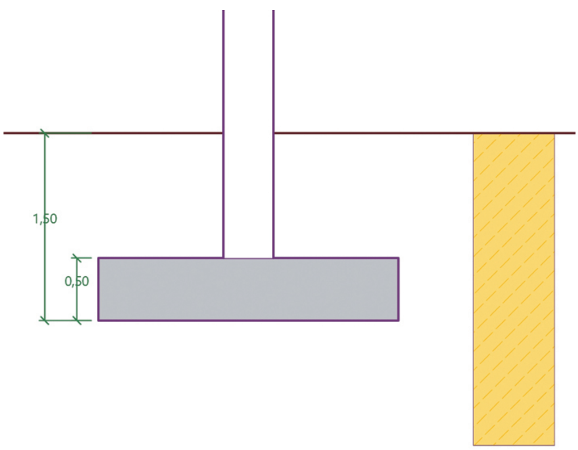

Fig. 7. Foundation scheme from GEO5

load cases were considered – with three different vertical force values and three different eccentricity variants. A summary of the load variants is shown in Table 4. In each case, the optimum foundation width was determined, assuming the symmetry of the solution. If an asymmetrical foundation was used, the widths could be reduced, but for the clarity of the example it was decided not to include this in the calculations. Next, in order to compare the increase in bearing capacity for a given case, the analysis was performed for the fixed dimension for axial load scheme 2a. All calculations were carried out in accordance with Eurocode 7 with a second design approach (DA2) and executed with GEO5 software. According to the software, the calculations were made for the worse case – taking into account the weight of the foundation or not – and default settings for concrete.

Table 4. Load combinations

Type of load	Load 1a	Load 1b	Load 1c	Load 2a	Load 2b	Load 2c	Load 3a	Load 3b	Load 3c
Vertical force [kN]	250	250	250	500	500	500	750	750	750
Bending moment [kN·m]	0	100	200	0	100	200	0	100	200

3.2. Calculation results and discussion

The results of the minimum foundation widths obtained on the basis of selected load variants are shown in Table 5 as a metric quantity and in Table 6 as a percentage of the foundation width on soil without nanosilica. In the case of axial loading with no eccentricity, the use of stabilisation allowed the width of the projected foundation to be reduced by approximately 20% (1% NS), 40% (3% NS) or up to 50% (5% NS), respectively. Changing the value of the axial force has a minor effect on the strengthening result (expressed in terms of minimum foundation width) on the bearing capacity of the subsoil. However, if a bending moment occurs, the impact of the improvement is reduced. The larger the eccentricity, the lower this strengthening effect. Despite this, for higher loads (e.g. scheme 3), the use of the

Table 5. Optimum foundation width determined from calculations

Sample	Width [m]								
	Load 1a	Load 1b	Load 1c	Load 2a	Load 2b	Load 2c	Load 3a	Load 3b	Load 3c
silty soil	1.30	2.10	2.80	2.90	3.30	3.70	4.50	4.75	5.00
silty soil + 1% NS	1.05	1.85	2.50	2.35	2.80	3.15	3.70	3.95	4.20
silty soil + 3% NS	0.80	1.55	2.20	1.70	2.10	2.50	2.70	2.95	3.25
silty soil + 5% NS	0.75	1.45	2.10	1.45	1.90	2.25	2.35	2.60	2.85

nanosilica additive under the footing allows for shallow foundation to be made, whereas unreasonable dimensions were obtained for natural soil.

Table 6. Optimum foundation width in relation to the untreated soil

Sample	Width [%]								
	Load 1a	Load 1b	Load 1c	Load 2a	Load 2b	Load 2c	Load 3a	Load 3b	Load 3c
silty soil	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
silty soil + 1% NS	80.8	88.1	89.3	81.0	84.5	85.1	82.2	83.2	84.0
silty soil + 3% NS	61.5	73.8	78.6	58.6	63.6	67.6	60.0	62.1	65.0
silty soil + 5% NS	57.7	69.0	75.0	50.0	57.6	60.8	52.2	54.7	57.0

In order to better illustrate the increase in bearing capacity, a recalculation was made for selected load 2a with a fixed foundation dimension. The maximum width obtained for this variant, i.e. 2.9 m, has been adopted. The results in terms of numeric and percentage values are shown in Fig. 8. As can be seen, the increase in bearing capacity is linear with respect to the nanosilica content. In the considered case, it was 16.3% (1% NS), 49.4% (3% NS) and 68.3% (5% NS), respectively. As can be noted, these values are slightly lower than those for compressive strength and undrained shear strength alone. Of course, each construction must be considered on its own merits, with different dimensions and load schemes, and the results obtained will be quite different. However, it should be noted that an increase in parameters of soil should not be considered the same as an increase in bearing capacity, but rather as its upper limit.

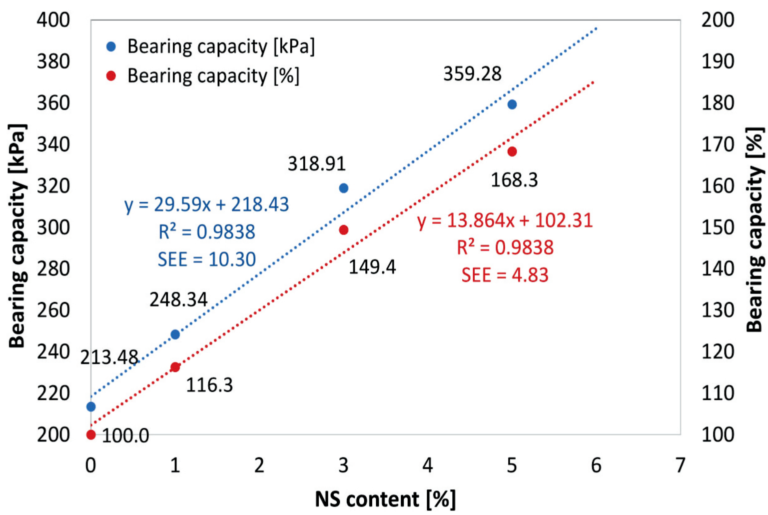

Fig. 8. Bearing capacity for a foundation 2.9 m wide in respect to the NS content

4. Conclusions

The paper presents the findings of an analysis of the effect of nanosilica admixture on undrained soil bearing capacity. The results of unconfined compression tests on silty soil and soil stabilised with 1%, 3% or 5% of nanosilica addition are presented. The tests showed an average improvement of 18.1%, 54.9% and 76.0% in undrained shear strength compared to soil without the additive. A significant increase in the stiffness was also observed i.e. 29.7%, 111.0% and 120.1%, respectively. In the case of strength, a linear dependence of strength on nanosilica content was identified. For stiffness, this relationship was completely different. However, due to the large scatter of results, further research is needed to establish the dependence. The outputs received differ significantly from those presented in the literature for similar soil types, which is probably caused by other factors influencing the test results. Therefore, the estimated increase in strength with nanosilica stabilisation should always be investigated.

The undrained shear strength values from laboratory tests were used to determine the undrained bearing capacity under the strip footing. A total of 9 load cases were considered, for 3 vertical axial loads and 3 eccentric load variants. The minimum foundation widths were determined for the selected loads and the percentage reduction in width relative to the soil without additive was determined. In the case of axial loading, the reduction was approximately 20% (1% NS), 40% (3% NS) or up to 50% (5% NS). Increasing the eccentricity resulted in less effectiveness in subsoil stabilisation. When estimating the bearing capacity for the fixed dimensions, the percentage increase in capacity was 16.3%, 49.4% and 68.3%, respectively. These values are lower than those for laboratory values of strength. This effect will be different for different structure, but the increase in strength can be considered the upper limit of the increase in bearing capacity that can be achieved in practice.

Nanosilica is one of the nano-additives used for chemical soil stabilisation. Due to its universality and effectiveness, it can be used as an alternative to traditional solutions. As demonstrated, small amounts of the additive can significantly affect the target dimensions of the foundation and contribute to a more rational design, even for soils with poor strength parameters.

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Wpływ stabilizacji nanokrzemionką na nośność podłoża gruntowego w warunkach bez odpływu

Słowa kluczowe: nanokrzemionka, wytrzymałość na ścinanie bez odpływu, jednoosiowe ściskanie, nośność podłoża, ława fundamentowa

Streszczenie:

Ze względu na coraz powszechniejszą konieczność posadawienia obiektów na gruntach o niewystarczającej nośności, rozwój metod ulepszania i stabilizacji podłoża gruntowego jest aktualnym wyzwaniem inżynierii geotechnicznej. Jedną z innowacyjnych metod stabilizacji gruntu jest wykorzystanie nanododatków jako materiału stabilizującego. Zaletami tego rozwiązania są mniejsza ilość dodatku wymagana do uzyskania określonej poprawy właściwości mechanicznych gruntu względem tradycyjnych metod oraz mniejszy negatywny wpływ na środowisko. W kontekście ulepszenia podłoża gruntowego nanododatkami wybór nanokrzemionki (nano SiO_2) stanowi optymalne rozwiązanie z punktu widzenia skuteczności i kosztów.

W pracy przedstawiono wpływ zawartości nanokrzemionki na nośność podłoża pod ławą fundamentową w warunkach bez odpływu. W praktyce warunki te występują przede wszystkim w sytuacjach przejściowych, gdy następuje szybki przyrost obciążeń. W pierwszej kolejności wykonano badania laboratoryjne mające na celu określenie parametrów wytrzymałości wybranego gruntu bez dodatku oraz stabilizowanego nanokrzemionką. W tym celu wykorzystano prosty i szybki test jednoosiowego ściskania pozwalający na ocenę wytrzymałości gruntu w warunkach bez odpływu. Badania laboratoryjne wykonano dla wybranego gruntu pylastego. Testy przeprowadzono dla czystego materiału gruntowego oraz z dodatkiem nanokrzemionki 1, 3 i 5%. Wszystkie próbki zostały zagęszczone do maksymalnej gęstości objętościowej szkieletu gruntowego w aparacie Proctora a testy wytrzymałościowe przeprowadzono po 7 dniach dojrzewania próbek. Badania wykazały średni wzrost wytrzymałości na ścinanie bez odpływu c_u odpowiednio o 18.1%, 54.9% i 76.0% w porównaniu do gruntu bez dodatku. Zaobserwowano również znaczny wzrost modułu siecznego E_{u50} tj. odpowiednio 29.7%, 111.0% i 120.1%. W przypadku wytrzymałości stwierdzono liniową zależność wytrzymałości od zawartości nanokrzemionki. Dla sztywności ta zależność była inna, jednak ze względu na duży rozrzut wyników nie można było sformułować jednoznacznych wniosków. Otrzymane dane znacznie odbiegają od tych prezentowanych w literaturze dla podobnych typów gruntów i zawartości nanokrzemionki, co prawdopodobnie spowodowane jest innymi czynnikami wpływającymi na wyniki badań.

W oparciu o wyniki wytrzymałości wykonano analizę nośności podłoża dla 4 wariantów zawartości nanokrzemionki oraz dla 9 przypadków obciążenia – dla 3 wariantów obciążenia osiowego oraz dla 3 wariantów mimośrodu. Na tej podstawie określono nośność graniczną podłoża pod fundamentem oraz optymalną szerokość fundamentu dla każdego przypadku. Dodatkowo, dla wybranego przypadku obciążenia, wykonano szacowanie nośności dla stałego wymiaru fundamentu. Obliczenia

wykonano zgodnie z Eurokodem 7 (podejście obliczeniowe 2) z wykorzystaniem oprogramowania GEO5. W przypadku obciążenia osiowego redukcja szerokości ławy wyniosła około 20% (1% dodatku), 40% (3% dodatku) lub do 50% (5% dodatku). Zwiększanie mimośrodu powodowało mniejszą skuteczność wzmocnienia podłoża w kontekście redukcji wymiaru fundamentu. W przypadku szacowania nośności dla wybranego przypadku procentowy wzrost nośności wyniósłodpowiednio 16.3%, 49.4% i 68.3%. Wartości te są niższe niż w przypadku przyrostów wytrzymałości w badaniach laboratoryjnych. Co prawda efekt ten będzie inny dla każdej konstrukcji w zależności od wielu czynników, ale wzrost wytrzymałości można uznać za górną granicę wzrostu nośności, jaki można osiągnąć w praktyce.

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