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Sand stabilization with colloidal silica for protection from liquefaction caused by dynamic loads

Stabilisation du sable avec de la silice colloïdale pour la protection contre la liquéfaction causée par les charges dynamiques

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ABSTRACT: Dynamic loads may cause liquefaction of the saturated sandy soil. The colloidal silica grouting is the most advanced and effective sand stabilization method. Higher permeability of the colloidal silica gives the method an advantage over other soil stabilization methods. Due to its water-like density and viscosity, the highly dispersive colloidal silica with the particle size less than 15 nm (up to 15-30 nm) is capable to penetrate into sands of various grain size. It forms gel in soil pores after being mixed with activator, thereby stabilizing the soil. The paper presents results of the study on gel time, permeability properties and dynamic strength of sand against concentration of the colloidal silica and sand density. It has been obtained that with increasing colloidal silica content and activator concentration, as well as with increasing temperature, the gel time significantly reduces. The defined and therefore recommended for use colloidal silica concentration ranges from 5% to 10%, which provides gel hardening within 10 days at the activator concentration of 1-2%. It has been found that dynamic strength of sand increases by 1.5-5 times when sand is grouted with minimum concentration of 5%. The performed study has shown that the colloidal silica concentration of 5% is sufficient for stabilizing the soil subjected to earthquakes of the intensity up to 9 (on the base of MSK-64 scale). The dependency of gel time on concentration resulted from the study can be applied in design practice. Due to its permeability, colloidal silica is a promising material for strengthening clayey or silty sand.

RÉSUMÉ: Les charges dynamiques peuvent provoquer la liquéfaction du sol sableux saturé. Le jointoiement de silice colloïdale est la méthode de stabilisation du sable la plus avancée et la plus efficace. Une perméabilité plus élevée de la silice colloïdale confère à la méthode un avantage par rapport aux autres méthodes de stabilisation du sol. En raison de sa densité et de sa viscosité semblables à l'eau, la silice colloïdale hautement dispersive avec une granulométrie inférieure à 15 nm (jusqu'à 15-30 nm) est capable de pénétrer dans des sables de différentes granulométries. Il forme du gel dans les pores du sol après avoir été mélangé avec un activateur, stabilisant ainsi le sol. L'article présente les résultats de l'étude sur le temps de gel, les propriétés de perméabilité et la résistance dynamique du sable contre la concentration de la silice colloïdale et la densité du sable. Il a été obtenu qu'avec l'augmentation de la teneur en silice colloïdale et de la concentration de l'activateur, ainsi qu'avec l'augmentation de la température, le temps de gel diminue considérablement. La concentration de silice colloïdale définie et donc recommandée pour une utilisation varie de 5% à 10%, ce qui permet un durcissement du gel en 10 jours à la concentration d'activateur de 1-2%. Il a été constaté que la résistance dynamique du sable augmente de 1,5 à 5 fois lorsque le sable est jointoyé avec une concentration minimale de 5%. L'étude réalisée a montré que la concentration de silice colloïdale de 5% est suffisante pour stabiliser le sol soumis à des séismes d'intensité jusqu'à 9 (sur la base de l'échelle MSK-64). La dépendance du temps de gel sur la concentration résultant de l'étude peut être appliquée dans la pratique de la conception. En raison de sa perméabilité, la silice colloïdale est un matériau prometteur pour renforcer les sables argileux ou limoneux.

Keywords: Ground improvement; colloidal silica; gelling time; dynamic strength.

1 INTRODUCTION

The earthquake hazard of more than 25 % of the Russian territory is classified as high. Sandy water-saturated soil of these regions is most liable to liquefaction. The dynamic strength improvement of liquefiable sands is necessary to use these soils as base of structures. However, the traditional grout improvement techniques (such as cement, microfine cement, epoxy or silica grouting) are often not applicable due to poor penetrability of materials into the granular soils (Semkin and Ibragimov, 2016).

The colloidal silica can be used for stabilizing saturated sand and protecting it against liquefaction. The advantage of the method is high penetrability of colloidal silica. It is capable to penetrate into granular soil due to solution's finely dispersed particles of less than 15 nm in size and its density and viscosity are close to water. Soil stabilization is result of colloidal silica gelling caused by activator.

However, well-known laboratory tests on colloidal silica application have been conducted at a room temperature ~20˚C which differs from the natural soil temperature of 0-10˚C.

The article presents results of laboratory analysis of gel time and permeability of colloidal silica at the temperature ranging from 20 to 25°C and close to a natural temperature range from 0 to 10°C. The results of dynamic strength analysis of soil grouted by colloidal silica are presented. The optimal colloidal silica concentration on the basis of gel time, permeability and dynamic strength of the stabilized soil is determined.

2 METHODS

2.1 Gel time in relation to the temperature

The dependency of gel time on colloidal silica content at different the temperatures was studied in laboratory. For the purpose, a colloidal silica sol was taken with initial concentration of $K_{initial}$ = 30%. Gel time was analyzed at the temperature range from 5 to 25 ˚C. To maintain the required temperature, colloidal silica mixtures were prepared in a refrigeration chamber equipped with temperature controllers.

Series of tests were performed with:

- Colloidal silica concentration of 2.5, 5, 10 and 15%;
- *NaCl* activator concentration of 0.25, 0.5 1 and 2%;
- The temperature of 5, 10 and 25˚C.

Each test was repeated at least three times.

Testing technique was as follows:

At the first stage, NaCl was introduced into a desired volume of distilled water, thoroughly mixed until the required concentration of the activator was reached.

At the second stage, the required volume of colloidal silica was introduced into the *NaCL* solution, thoroughly mixed, hermetically sealed in the glass container and left at rest until the gelation started.

At the third stage, the gel was visually examined. A stage of the hard gel formation, at which no deformations of gel surface were observed, was taken as a gel time.

2.2 Permeation of colloidal silica

Permeation of colloidal silica was studied in tests on filtration soil properties, when soil was saturated with distilled water or colloidal silica of various concentrations. A series of test on medium and fine sands was carried out at:

- Colloidal silica concentration of 0, 2.5, 5, 10 and 15%;
- The temperature of 5; 10 и 25˚C;
- Minimum (I_D=0), medium (I_D=0,5) and maximum (I_D=1) density degree of sands.

Each test was repeated at least three times.

The components were kept at a given temperature in the refrigerator chamber for at least a day for further experiments. Testing and processing of results were carried out in accordance with the stationary filtration mode scheme prescribed by GOST 25584-2016.

2.3 Dynamic strength of soils grouted with colloidal silica

Dynamic triaxial test (Voznesensky, 1997) was used for assessing strength of sandy soil grouted with colloidal silica. Strength characteristics under dynamic loading were estimated for both grouted and clean sand. The tests were performed via GDS ELDYN (Figure 1).

Figure 1. Dynamic triaxial test system GDS ELDYN.

Tests were performed on medium and fine sands (Figure 2) at:

- Initial void ratio e=0,7; 0,6 and 0,5;
- Colloidal silica concentration of 5, 10 and 15%.

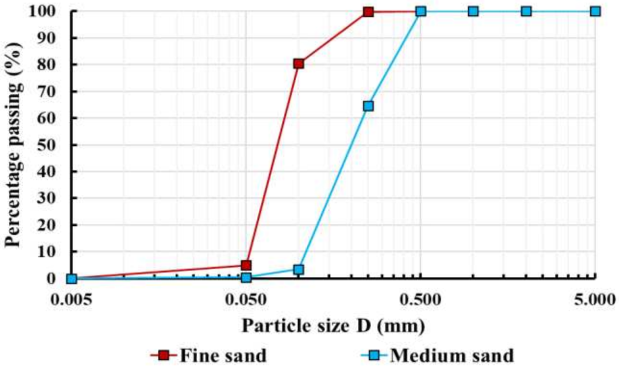

Figure 2. Cumulative curve of the grain size distribution.

Each test involved the following sequences:

At the first stage, a specimen was prepared in a special split mold by tamping dry soil in layers.

At the second stage, the specimen was grouted with colloidal silica through the bottom side (Figure 3) under the pressure of 10 kPa. When the specimens became saturated, the molds were removed and specimens were kept at rest until the gel stabilized.

At the third stage, after gel stabilization, the specimens were placed under water to prevent contact with the air and they were left so to gain strength.

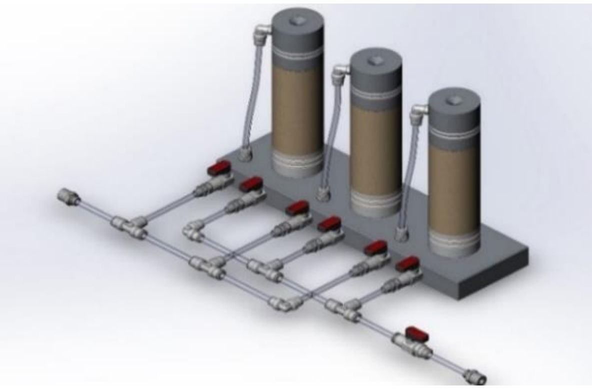

Figure 3. Saturation device.

At the fourth stage, the specimens were loaded under anisotropic consolidation at a given initial stress and then were subjected to dynamic loading. The tests were repeated at least six times with a shear stress taken depending on soil strength. The dynamic load was applied until the specimens failed.

Changes in cyclic resistance ration *CRR* of specimens were assessed with a method of equivalent cycles. A critical number of cycles N_{cr}, at which the specimens failed, was determined for each test and a relation $CRR = f(N_{cr})$ was then generated.

3 RESULTS

Gel time. It has been defined that minimum colloidal silica SiO_2 concentration is 5%, inasmuch that with minimum temperature of 5 ˚C and minimum activator concentration of 1 % it was possible to fix moment of gelation within the optimum waiting period (Figure 4). At lower concentration, gel time increases significantly and gelation in laboratory conditions has not fixed.

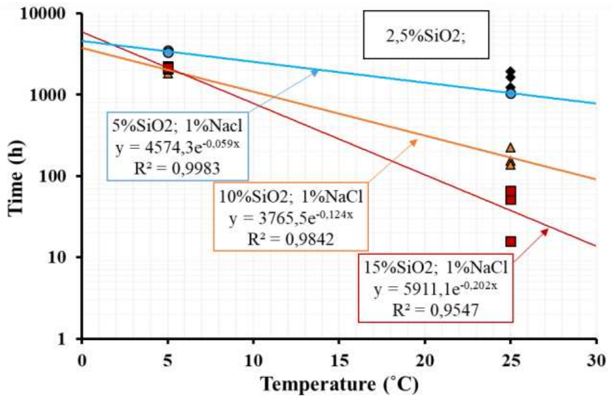

Figure 4. The relationship between gel time and temperature at activator concentration of 1%

Concentration of colloidal silica has a significant effect on its permeability. As the concentration increases from 0 to 15%, the hydraulic conductivity of sands decreases by average 2 times regardless of sands density, particles distribution and temperature conditions. It was observed, that for the concentration of colloidal silica $C_{SiO2} \leq 5\%$ the difference in the rate of colloidal silica delivery and water infiltration was less than 10%. This indicated the high permeability of low-concentrated grout (Figure 5).

The temperature drop by *5* times lowered the rate of grout delivery by 1,2 – 2,2 times, whatever density and particle distribution of sand were.

The hydraulic conductivity of sand decreased by 1,8 – 3,6 times with the increasing density degree I_D from 0 to 1. In this case, the influence of the density degree of medium sand was more significant than that of fine sand due to the pore size and the roundness of the particles of the soils considered (Figure 5).

Dynamic strenght of soils grouted with colloidal silica. Figure 6 shows the results of dynamic triaxial tests on fine sand (6a, 6b) and medium sand (6c, 6d) at different concentration of colloidal silica. It was observed that strength properties of fine sand increased significantly as compared to medium sand. Grouting smaller fractions was approximately 55% more effective.

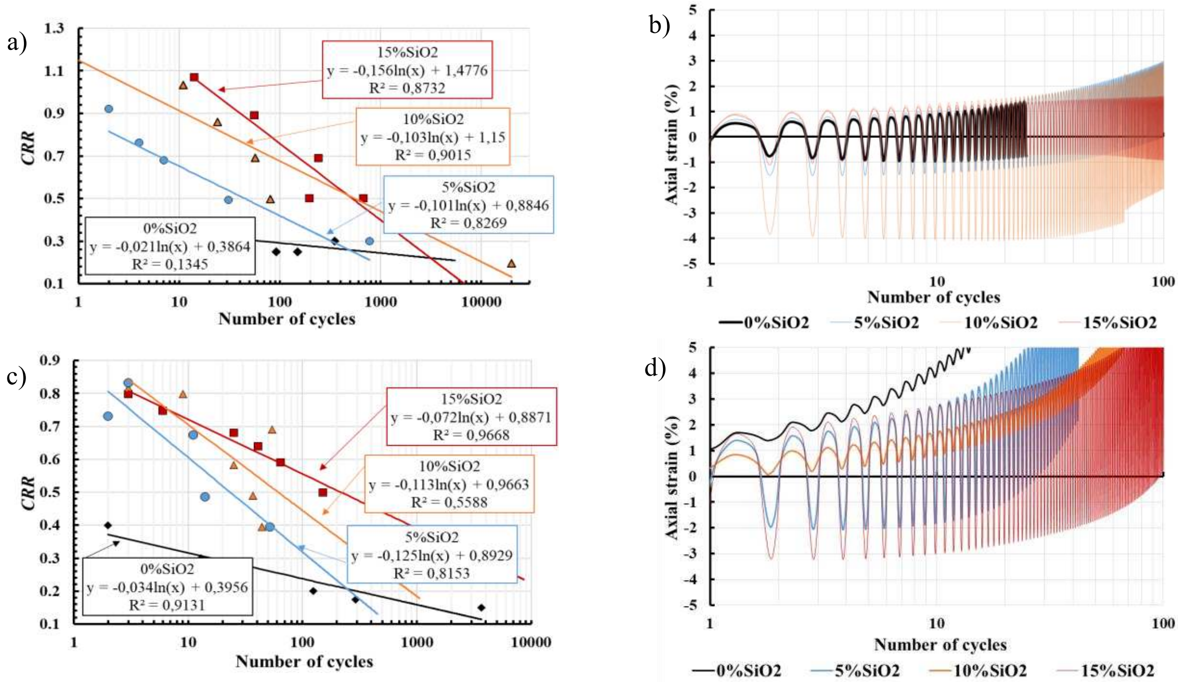

Figure 6. Results of dynamic triaxial tests: a - cyclic resistant ration (CRR=0,6) of fine sand (e=0,7) versus a number of loading cycles; b – fine sand axial strain under cyclic loading for different concentration of colloidal silica SiO_2 ; c- cyclic resistant ration (CRR=0,6) of medium sand (e=0,7) versus a number of loading cycles; d - medium sand axial strain under cyclic loading for different concentration of colloidal silica SiO_2.

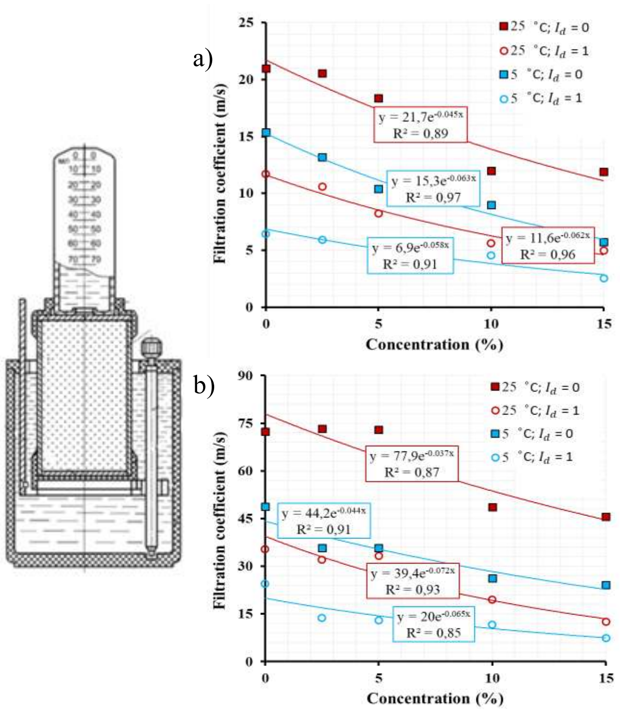

Figure 5. Installation scheme for testing filtration of sand at a constant pressure level: permeability of colloidal silica versus concentration in fine sand (a) and in medium sand (b).

On the base of regression analysis the following empirical dependence was proposed:

$$CRR = a_1 \lg N + a_2 \lg C_{SiO_2} + a_3 \quad (1)$$

where, N – a number of dynamic triaxial loading cycles; C_{SiO_2} – concentration of the colloidal silica; a_1, a_2, a_3 – empirical coefficients derived from tests.

Overall, based on the total results published (Gallagher, 2002, 2009; Sharafutdinov and Kuznetsova, 2023), it can be noted that 5% colloidal silica content is enough to protect sandy soil from earthquakes with intensity up to 9 (on MSK intensity scale). However, most existing studies do not make a direct correlation between soil density and minimum colloidal silica concentration required. A content of 5% colloidal silica was defined for particular sands (including particle roundness, mineralogy etc.) and, therefore, could not be recommended for practical application (Figure 7).

Moreover, most existing publications assess the influence of colloidal silica content on stiffness and deformation of soil specimens prepared in laboratories. The benefits of colloidal silica grouting needs to be studied more thoroughly in-situ.

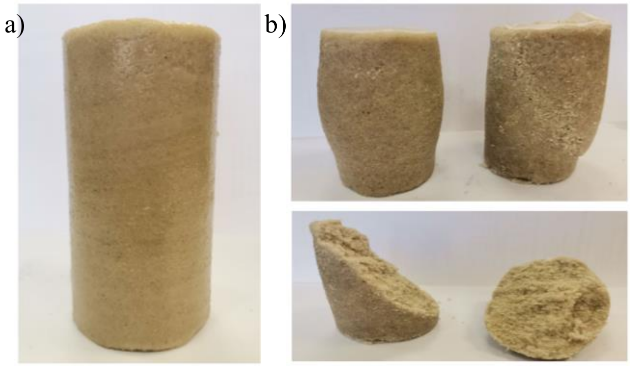

Figure 7. Specimens of sand grouted with colloidal silica: before (a) and after (b) dynamic testing.

4 CONCLUSIONS

Minimum concentration of colloidal silica needed to stabilize soils was defined as 5%, since with this concentration gel formed at minimum temperature of 5 $^{\circ}C$ and minimum activator concentration of 1%.

The permeability of colloidal silica has a significant influence on stabilization process. The research performed by the authors shows that with concentration of colloidal silica increasing from 0 to 15% its permeability reduces by 2 times. It is obvious that activator influences the results. While permeating, the colloidal silica forms gel and a real size of the grouted area is changing (Gallagher, 2007). Nevertheless, for the concentration of colloidal silica $C_{SiO2} \leq 5\%$ the difference in the rate of colloidal silica delivery and water infiltration is less than 10%. This indicates the high permeability of low-concentrated grout.

Temperature conditions are also of great importance. Notwithstanding the density degree of sand, hydraulic conductivity reduces by average 1,2-2,2 times when temperature falls by 5 times (from 25 ˚C to 5 ˚C). This factor should be taken into account when soil massive is grouted with colloidal silica in-situ.

On the base of the study performed, relations for estimating soil stiffness with regard to the concentration of colloidal silica, sand density and particle size distribution has been derived. Overall, based on the total results received, it can be noted that 5% colloidal silica content is enough to stabilize sandy soils, protecting them from dynamic impact. Strength properties of grouted fine sands are better if compared with medium sands. Grouting of fine fractions gives approximately 55% more effective results. The cyclic resistance ration can be estimated with relation (1), depending on concentration of the colloidal silica. However, the resulting empirical coefficients may be subjective, which requires additional research.

The performed study on gel time, permeability of colloidal silica and dynamic stiffness of sandy soil allows authors to conclude with carefulness that 5% concentration of colloidal silica may be recommended for grouting soils subjected to dynamic loading including seismic impact. According to the authors, benefits of colloidal silica grouting needs to be studied more thoroughly in-situ.

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