Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-578

Evaluation of the stabilization of sand liquefaction using colloidal silica

Rafael Sharafutdinov, Darina Kuznetsova**,** Vladimir Morozov, Yuri Stolyarov
Gersevanov Research Institute of bases and underground structures (NIIOSP) JSC Research Center of Construction, Russian Federation; www.527515@ya.ru

ABSTRACT: Dynamic loads may cause the liquefaction of saturated sands. Colloidal silica grouting is the most advanced and effective method of sand stabilization. The practical advantage of colloidal silica is its excellent penetrability and similar to water density and viscosity. After mixing with an activator, colloidal silica gels in soil pores, thereby stabilizing the soil. The article describes gel time and ability of the colloidal silica to penetrate into different sands. The colloidal silica with the concentration of 5-10% and the activator of 1-2% are optimal to stabilize sands. The effectiveness of colloidal silica was assessed basing on cyclic resistance ratio (CRR) analysis of stabilized and unstabilized samples in a series of laboratory cyclic tests. The analysis showed that the colloidal silica concentration of 5% is sufficient to stabilize the soil subjected to earthquakes with the intensity of up to 9 points (MSK-64 scale). The optimal silica-grouted zone of the soil prone to liquefaction was obtained with FEM modelling.

KEYWORDS: Ground improvement, colloidal silica, gel time, dynamic strength.

1 INTRODUCTION

More than a quarter of Russia’s territory is prone to a significant seismic risk. Sandy water-saturated soil of these regions is most liable to liquefaction. To ensure the stability of structures built on such soils, it is essential to enhance their dynamic strength. However, the traditional grout improvement techniques (such as cement, microfine cement, epoxy or silica grouting) are often not applicable due to poor penetrability of grouting solutions into granular soils (Ibragimov et al. 2017; Sharafutdinov et al. 2024).

The colloidal silica can be used to stabilize saturated sand and protect it against liquefaction. The advantage of the method is high penetrability of colloidal silica. It is capable to penetrate into granular soil due to its finely dispersed particles of less than 15 nm in size and its density and viscosity, which are close to water. Soil stabilization is a result of colloidal silica gelation caused by an activator.

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

The article presents the results of laboratory analysis of gel time and penetrability of colloidal silica at the temperature ranging from 20 to 25°C and from 0 to 10°C, which is close to a natural temperature range. The results of dynamic strength analysis of soil grouted by colloidal silica are presented. The optimal colloidal silica concentration is determined based on the gel time, permeability and dynamic strength of the stabilized soil. The optimal grouted zone of liquefied soil for protection of structures was obtained using FEM modelling.

2 EXPERIMANTAL LABORATORY STUDIES ON COLLOIDAL SILICA

2.1 *Gel time in relation to the temperature*

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

A 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, and 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 happened, 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 tests on medium and fine sands were 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 sandy soils.

Each test was repeated at least three times.

Prior to testing, the components were kept at a given temperature in the refrigerator chamber for at least a day. 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 (Ishihara K., 1996) was used to assess strength of sandy soil grouted with colloidal silica. Strength characteristics under dynamic loading were estimated for both grouted and live soil. The test installation comprised a GDS ELDYN (Figure 1).

Figure 1. Dynamic triaxial test device GDS ELDYN.

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

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

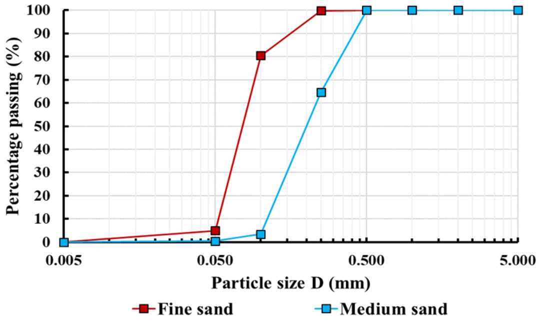

Figure 2. Cumulative curve of the grain size distribution.

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 into water to prevent contact with the air and they were left so to gain strength.

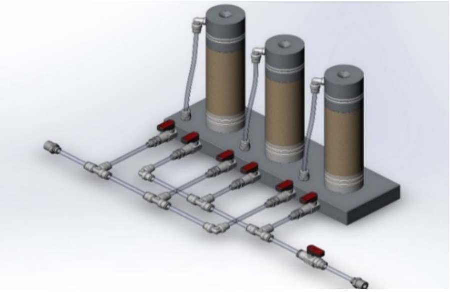

Figure 3. Saturation device.

At the fourth stage, after anisotropic consolidation at a given initial stress, the specimens 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 SiO2 concentration is 5%, inasmuch that with minimum temperature of 5 ˚C and minimum activator concentration of 1 % it is possible to fix moment of gelation within the optimum waiting period (Figure 4). At lower concentration, gel time increases significantly and in laboratory conditions gelation has not been fixed.

Concentration of colloidal silica has a significant effect on its penetrability. 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 $C_{SiO_2} \leq 5\%$ the difference in the rate of colloidal silica delivery and water infiltration was less than 10%. This indicated the high penetrability of low-concentrated grout (Figure 5).

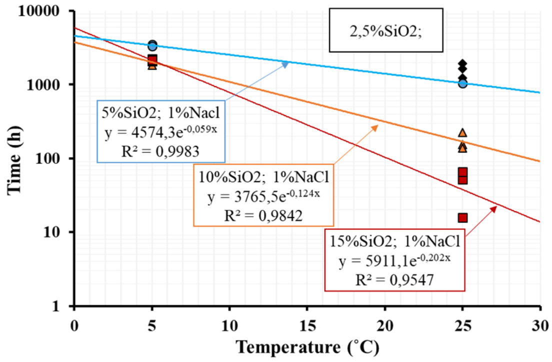

Figure 4. The relationship between gel time and temperature at activator concentration of 1%.

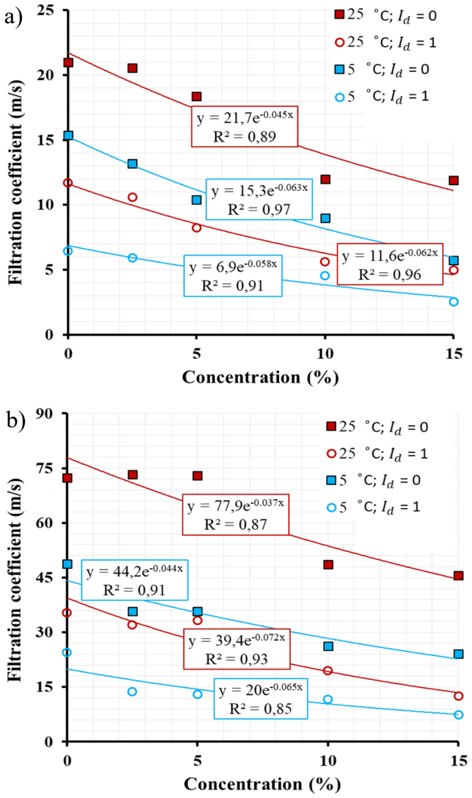

Figure 5. Installation scheme for filtration test on sandy soil at a constant pressure level, where: a – permeability of colloidal silica in fine sand versus concentration; b - permeability of colloidal silica in medium sand versus concentration.

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

The hydraulic conductivity of sand decreased by 1,8 – 3,6 times with the density degree ID increasing 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 strength 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.

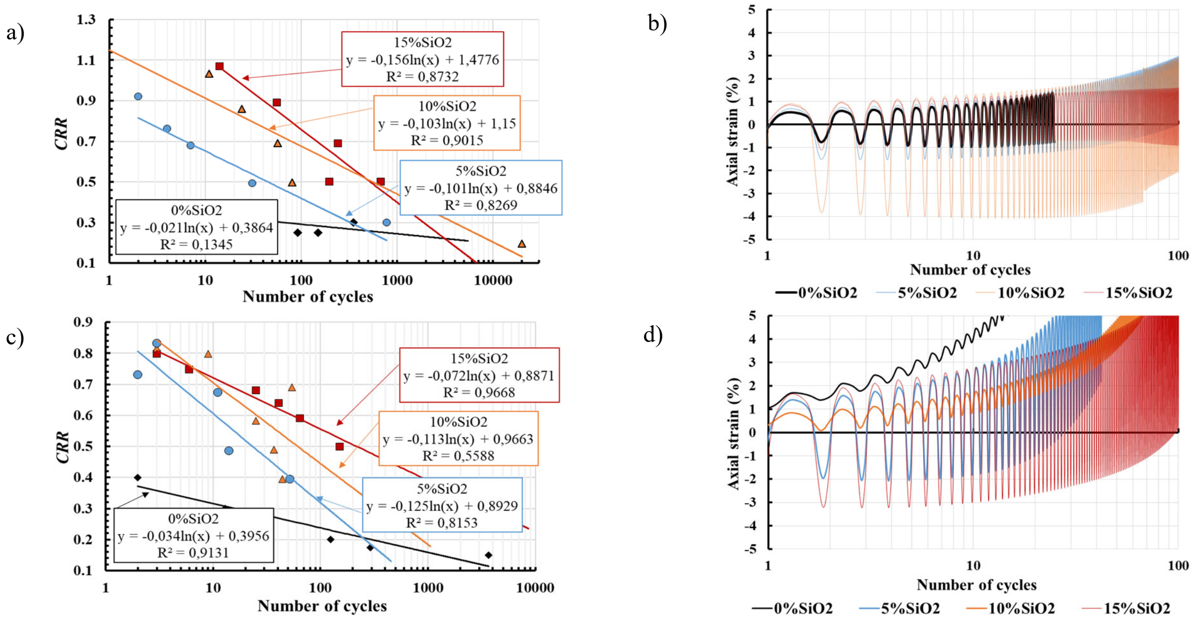

Figure 6. Dynamic testing results: a - cyclic resistance ration of fine sand (e=0,7) versus number of loading cycles; b – axial strain of fine sand versus number of loading cycles for different C_{SiO_2} (*CRR*=0,6); c - cyclic resistance ration of medium sand (e=0,7) versus number of loading cycles; d – axial strain of versus number of loading cycles for different C_{SiO_2} (*CRR*=0,6).

Overall, based on the total results published (Gallagher, 2002, 2009; Sharafutdinov & Kuznetsova, 2023), it can be noted that 5% colloidal silica content is enough to protect sandy soil from earthquakes with intensity up to 9. 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).

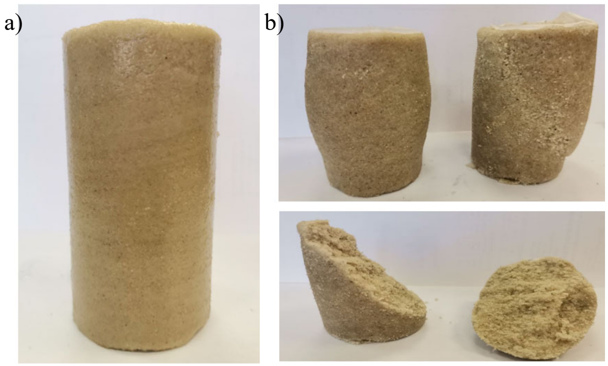

Figure 7. Specimens of sand grouted with colloidal silica: before (a) and after (b) dynamic failure.

Moreover, most existing publications deal with laboratory assessment of the influence of colloidal silica content on stiffness and deformation of manmade soil specimens. The benefits of colloidal silica grouting needs to be more thoroughly studied in-situ.

4 MODELING THE GROUND IMPROVEMENT

The initial evaluation of the effectiveness of colloidal silica can be conducted using analytical solutions (Sharafutdinov & Kuznetsova, 2023). However, the analytical solution does not consider the stress-strain of soil during an earthquake in different zones of basement.

The liquefaction risk is usually estimated based on the liquefaction bearing capacity factor of safety (*FS*) as an important index of seismic performance (Seed & Idriss, 1971):

$$FS = \frac{CRR}{CSR} \qquad (2)$$

The *FS* ratio is an important factor in the design of an anti-seismic base in geotechnical engineering (Bray & Sancio, 2009; Bray et al. 2014; Bray et al. 2017; Stavnitser, 2010). The Russian codes prescribe that if the *FS*-ratio is less than 1.15, the water-saturated soil is liquefiable.

Liquefaction zones can be evaluated using numerical simulation. In this regard the UBC3D soil model, which is implemented in Plaxis 3D, is useful (Makra, 2013). This model allows simulating the process of sand liquefaction under dynamic loading.

A 10-story residential building in Anapa city was used as an example for the calculations. The building foundation comprised dense, water-saturated sand. The seismic intensity of construction site was 8 on the MSK-64 scale. To ensure the accuracy of the results of the UBC3D geomechanical model, the values of the input parameters were verified based on dynamic triaxial tests.

It is well known that liquefaction of soils occurs when the pore pressure equals to effective stress. In this regard the pore pressure ratio (*PPR*) is used to evaluate liquefaction. The limited PPR-ratio value can be assessed using the following equation:

$$PPR_{lim} = \frac{1}{FS}\left(\frac{u}{p'}\right) \qquad (3)$$

where u – is the excess pore pressure as a result of seismic activity; p' – mean effective stresses in the soil.

Based on equations (2) and (3), sand can be assessed as liquefiable if the $PPR \geq 0.85$.

In Figure 8, the *PPR* exceeded the permitted value of 0.85 in some areas around the building, particularly in the corners of the foundation. As a result, liquefaction occurred in the unloaded area of the base.

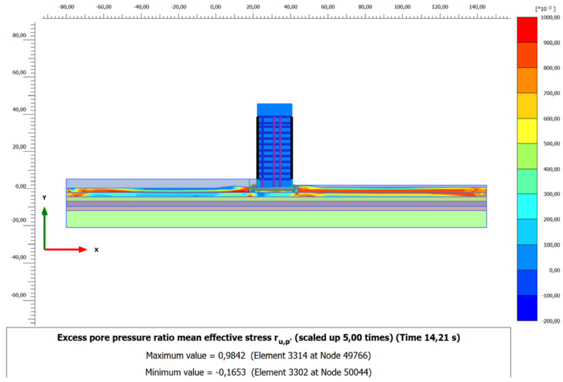

Figure 8. *PPR*-ratio results.

Numerical analysis with colloidal silica grouting included the following assumptions:

- a concentration of 5% colloidal silica and 2% activator was used for the grouting process;
- the grouting width was set of 2 m;
- injectors were arranged in a single row, with a spacing of 1 meter, and were inserted to a depth between 5 and 5.5 meters.

Numerical modeling was carried out in three stages:

Stage 1: Simulating the building's operation process by applying a load.

Stage 2: Modeling the process of stabilizing the sandy foundation.

Stage 3: Simulating seismic activity using accelerograms (full dynamic analysis).

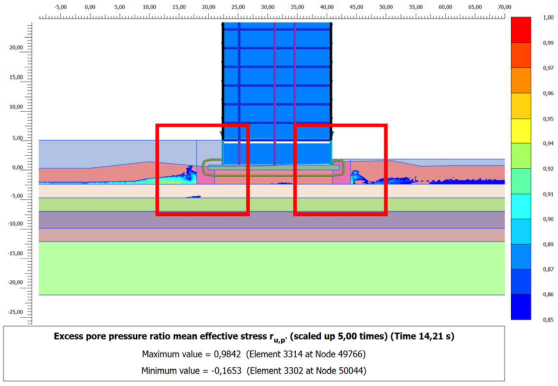

Figure 9. Zones to fix the base with colloidal silica.

The area where the sandy base was fixed with colloidal silica is shown in Figure 9. Based on the calculations, the *PPR* didn't exceed 0.85 in this area, so there was no liquefaction recorded. This ensures the reliability and operability of the building.

5 CONCLUSION

Minimum concentration of silica dioxide needed to stabilize soils was defined as 5%, since with this concentration gel formed at minimum temperature of 5 ˚C and minimum activator concentration of 1%.

The penetrability 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 penetrability 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 silica dioxide $C_{SiO_2} \leq 5\%$ the difference in the rate of 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 have been derived. Overall, based on the total results received, it can be noted that 5% colloidal silica content is enough to stabilize sandy soils, and protect 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. Dynamic stiffness 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, penetrability 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.

The study found that a concentration of 5% was sufficient to prevent liquefaction in a water-saturated sand in an area with seismic activity up to 9 on the MSK-64 scale. Numerical analysis was used to determine the size of the area that would need to be impregnated.

6 REFERENCES

Bray, J.D., Sancio, R.B., 2009. Performance of Buildings in Adapazari during the 1999 Kocaeli, Turkey Earthquake, in Earthquake Geotechnical Case Histories for Performance Based Design, ISSMFE, The Netherlands, pp.325-340.

Bray, J.D., Dashti, S., 2014. Liquefaction-Induced Building Movements. Bulletin of Earthquake Engineering, Springer, Vol. 12(3), 1129-1156, DOI: 10.1007/s10518-014-9619-8.

Bray, J.D., Markham, C.S., Cubrinovski, M., 2017. Liquefaction assessments at shallow foundation building sites in the Central Business District of Christchurch, New Zealand. Soil Dynamics and Earthquake Engineering J.

Gallagher, P.M., Conlee, C.T., Rollins, K.M., 2007. Full-scale field-testing of colloidal silica grouting formitigation of liquefaction risk. J. Geotech. Geoenviron. Eng. 133(2), 186–196. https://doi.org/10.1061(ASCE)1090-0241(2007)133:2(186)

Gallagher, P.M., Lin,Y., 2009. Colloidal silica transport through liquefiable porous media. J. Geotech. Geoenviron. Eng. 135(11), 1702–1712. https://doi.org/10.1061/(ASCE) GT.1943-5606.000012

Ibragimov, M.N., Semkin, V.V., Shaposhnikov, A.V., 2017. Soil Solidification by Micro-Cements. Soil Mech Found Eng 53, 412–419. https://doi.org/10.1007/s11204-017-9421-0

Ishihara, K., 1996. Soil behaviour in earthquake geotechnic. Oxford University Press, USA.

Seed, H., Idriss, I., 1971. Simplified Procedure for Evaluating Soil Liquefaction Potential. J. of the Soil Mechanics and Foundations Division, 97, 1249–1273.

Sharafutdinov, R.F., Kuznetsova, D.P., 2023. Colloidal silica as a medium for increasing sandy soil resistance to dynamic loading. Foundations, No 3, pp 74-76 (in Russian).

Sharafutdinov, R.F., Kuznetsova, D.P., Morozov, V.S., Stolyarov, Y.I., 2024. Sand stabilization with colloidal silica for protection from liquefaction caused by dynamic loads. Proceedings of the xviii european conference on soil mechanics and geotechnical engineering, Portugal, 1330–1335. DOI: 10.1201/9781003431749.

Stavnitser, L.R., 2010. Seismic resistance of bases and foundations. ASV. Moscow. (in Russian).

Makra, A., 2013. Evaluation of the UBC3D-PLM constitutive model for prediction of earthquake induced liquefaction on embankment dams. MscGraduation Thesis.