Passive Site Remediation for Mitigation of Liquefaction Risk

by Patricia M. Gallagher and James K. Mitchell

Research Objectives

Passive site remediation is a new concept proposed for non-disruptive mitigation of liquefaction risk at developed sites susceptible to liquefaction. It is based on the concept of slow injection of stabilizing materials at the edge of a site and delivery of the stabilizer to the target location using the natural groundwater flow. Stabilizer candidates need to have long controllable gel times and low viscosities so they can flow into a liquefiable formation slowly over a fairly long period of time. Colloidal silica is a potential stabilizer for passive site remediation because at low concentrations it has a low viscosity and a wide range of controllable gel times of up to about 200 days. Loose sands treated with colloidal silica grout had significantly higher deformation resistance to cyclic loading than untreated sands. Groundwater and stabilizer transport modeling were done to determine the range of conditions where passive site remediation might be feasible. For a 200-foot by 200-foot treatment area with a single line of injection wells, it was found that passive site remediation could be feasible in formations with hydraulic conductivity values of 0.05 cm/s or more and hydraulic gradients of 0.005 and above.

At many sites susceptible to liquefaction, the simplest way to mitigate the liquefaction risk is to densify the soil. For large, open and undeveloped sites, the easiest and cheapest methods for densification are by "traditional" procedures such as deep dynamic compaction, explosive compaction, or vibrocompaction. However, at constrained or developed sites, ground improvement by densification may not be possible due to the presence of structures sensitive to deformation or vibration. Additionally, access to the site could be limited and normal site use activities could interfere with mitigation activities. At these sites, the most common methods for remediation are grouting or underpinning. Passive site remediation is a new concept proposed for non-disruptive improvement of developed sites susceptible to liquefaction. Passive site remediation is based on the concept of the slow injection of stabilizing materials at the up gradient edge of a site and delivery of the stabilizer to the target location using the

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Collaborative Partners

- ***Mr. Chris Gause*** *of Master Builders contributed materials for laboratory testing of microfine cement grouts and expertise on grouting technology.*
- ***Dupont*** *provided some of the colloidal silica used in the experimental program.*
- ***Dr. Ernst Ahrens****, Sandia National Laboratory and* ***Mr. Henry Pringer****, Blue Circle, contributed cement for testing.*

natural or augmented groundwater flow. The concept is illustrated in Figure 1.

The set time of the stabilizer would be controlled so there would be adequate time for it to reach the desired location beneath the site prior to gelling or setting. If the natural groundwater flow were inadequate to deliver the stabilizer to the right place at the right time, it could be augmented by use of low-head injection wells or downgradient extraction wells. Once the stabilizer reached the desired location beneath the site, it would gel or set to stabilize the formation.

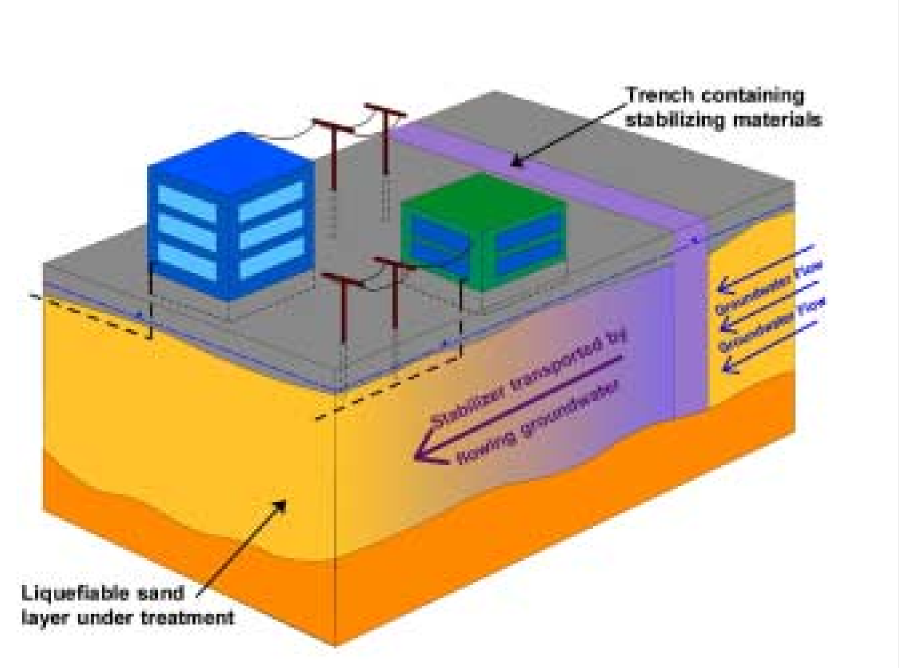
Passive site remediation techniques could have broad application for developed sites where more traditional methods of ground improvement are difficult or impossible to implement. It would be less disruptive to existing infrastructure and facilities than existing ground improvement methods. Additionally, access to the entire site would be unnecessary using this technology, and normal site use activities would probably not need to be disrupted. Finally, excessive deformation and disturbance of the ground around and beneath existing structures could be avoided.

The objective of this study was to establish the feasibility of passive site remediation. The work included identification of stabilizing materials, a study of how to adapt or design groundwater flow patterns to deliver the stabilizers to the right place at the right time, and an evaluation of potential time requirements and costs.

Performance Criteria and Identification of Potential Stabilizers

For a stabilizer to work in this application, it should have a low viscosity and a long induction period between mixing and the onset of gelation. Once gelation starts, it should proceed rapidly. The stabilizer should also be permanent, nontoxic and cost-effective. Materials evaluated as potential stabilizers included colloidal silica, microfine cement grouts, chemical grouts, zero-valent iron, and ultramicrobacteria. Colloidal silica was selected as a potentially suitable stabilizing material because it has a wide range of gel times and a low viscosity. Colloidal silica is an aqueous suspension of tiny silica particles that can be made to gel

Passive site remediation is a new technology for mitigation of liquefaction and ground failure risk at developed and inaccessible sites where more traditional methods for ground improvement are not suitable. Slow permeation of chemical soil stabilizer beneath and around foundations on and in potentially liquefiable soils should be especially attractive to owners, engineers, and planners who are charged with assuring seismic safety of existing infrastructure.



■ Figure 1. Passive treatment for mitigation of liquefaction risk.

by adjusting the pH or the salt concentration of the solution. Gel times of more than 200 days have been measured in laboratory tests. Additionally, the initial viscosities of dilute solutions of colloidal silica are about 2 centipoise (water=1 cP) and the viscosities remain very low for most of the induction period.

Microfine cement grout was eliminated because its viscosity is too high to meet the necessary requirements for passive site remediation. Additionally, since cement grouts are particulate suspensions, the particles tend to settle in the suspension and further increase the viscosity. Numerous chemical grouts were considered. All were eliminated as potentially suitable stabilizers, but for different reasons. Sodium silicate was eliminated because gel time is not well controlled at long gel times. Additionally, the chemical durability of sodium silicate formulations with long gel times is questionable. Acrylamide is a neurotoxin in powdered form, so it was eliminated due to environmental, safety, and handling concerns. Additionally, it is very expensive. Acrylate was eliminated due to durability concerns. Epoxy and polysiloxane were rejected because they are very expensive. Zero-valent iron is extremely sensitive to oxidation and reduction, so it would be difficult to treat a large area and the minerals precipitated would probably not be chemically durable. Ultramicrobacteria might be able to clog the pores of a formation with a biofilm, but biofilms can be dissolved by strong oxidants such as bleach, so there are durability concerns.

Feasibility

The feasibility of passive site remediation depends on the answers to the following questions:

Links to Current Research

Program 2: Seismic Retrofit of Hospitals

- *Task 2.3, Geotechnical Rehabilitation Site and Foundation Remediation*
- *Task 2.6, MEDAT-2 Workshop on Mitigation of Earthquake Disaster by Advanced Technologies*

1. Will the colloidal silica grout adequately stabilize the soil?
2. Can the stabilizer be delivered to the liquefiable formation and achieve adequate coverage within the induction period of the grout?
3. How much will it cost?

Strength testing of stabilized sands was done to address the first issue. Groundwater and stabilizer transport modeling were done to determine if the stabilizer could be delivered to the formation within the induction period of the grout. Finally, a preliminary cost analysis was done to address the final issue.

Strength Testing of Stabilized Sands

Cyclic triaxial tests were done on Monterey No. 0/30 sand samples treated with colloidal silica grout to investigate the influence of colloidal silica grout on the deformation properties of loose sand (relative density, Dr = 22%). The grain size distribution of Monterey No. 0/30 sand is shown in Figure 2. Distinctly different deformation properties were observed between grouted and ungrouted samples. Untreated samples developed very little axial strain after a few cycles of loading and prior to the onset of liquefaction. However, once liquefaction was triggered, large strains occurred rapidly and the samples collapsed within a few additional cycles. In contrast, grouted sand samples experienced very little strain during cyclic loading. What strain accumulated did so uniformly throughout loading and the samples remained intact after cyclic loading.

An example is shown in Figure 3 for two samples at a relative density of 22 percent that were tested at a cyclic stress ratio of 0.27. The cyclic stress ratio is defined as the ratio of the maximum cyclic shear stress to the initial effective confining stress. The untreated sample strained 1 percent in 11 cycles and collapsed in 13 cycles. The sample treated with 10 weight percent colloidal silica was tested for 400 cycles. It strained less than about half a percent in 11 cycles, about 8 percent in 400 cycles, and never collapsed. Only the first 40 loading cycles are shown in Figure 3. These results are typical for samples treated with 10 percent colloidal silica by weight. For comparison, a magnitude 7.5 earthquake would be expected to generate about 15 uniform stress cycles.

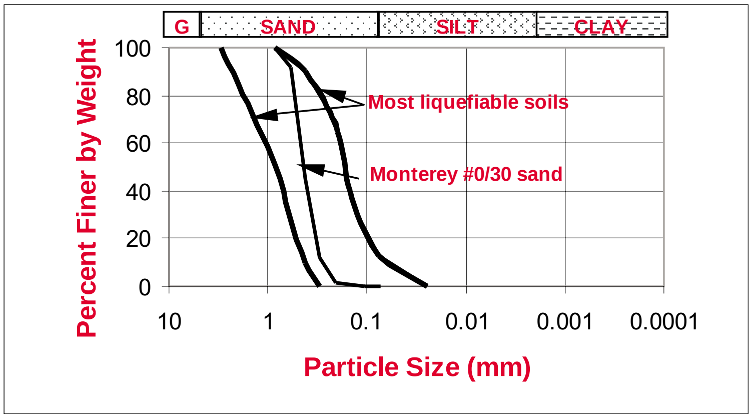
Samples stabilized with concentrations of 15 and 20 weight percent colloidal silica experienced very little (less than two percent) strain during cyclic loading. Sands stabilized with 10 weight percent colloidal silica resisted cyclic loading well, but experienced slightly more (up to eight percent) strain. Overall, treatment with colloidal silica grout significantly increased the deformation resistance of loose sand to cyclic loading.

Groundwater and Stabilizer Transport Modeling

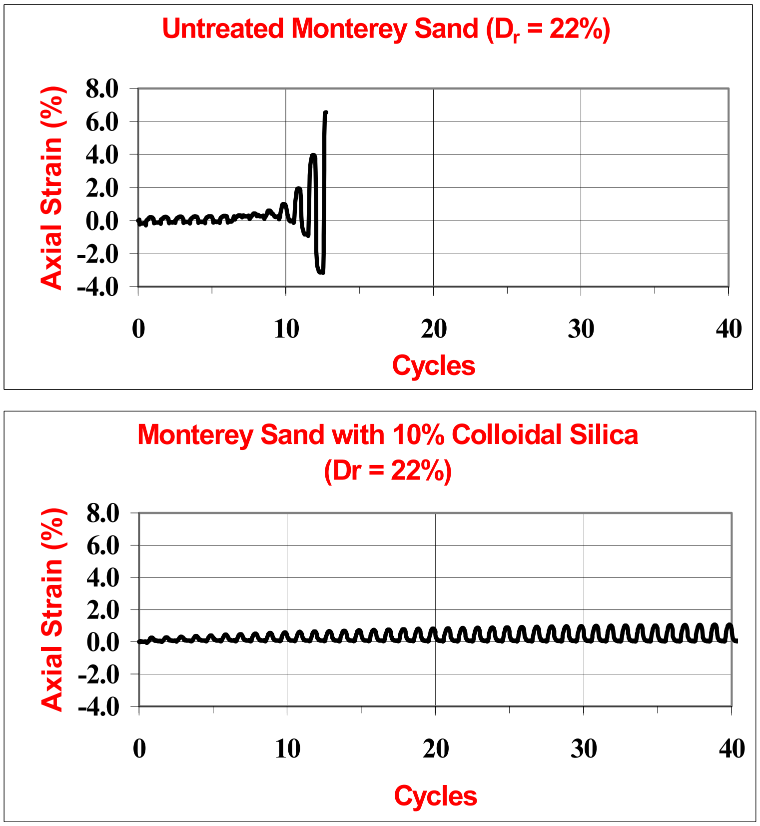
Stabilizer delivery is the main feasibility issue with respect to passive site remediation. Preliminary groundwater and solute transport modeling were done using the codes MODFLOW, MODPATH, and

MT3DMS for a generic liquefiable formation. A "numerical experiment" was done to determine the ranges of hydraulic conductivity and hydraulic gradient where passive site remediation might be feasible. For a 200-foot by 200-foot treatment area, with single lines of injection and extraction wells, travel times through the treatment area will be about 100 days or less if a formation has a hydraulic conductivity greater than about 0.05 cm/s and a hydraulic gradient higher than about 0.005. Based on the possible gel times, this time frame is considered feasible. Extraction wells will increase the speed of delivery and help control the down gradient extent of stabilizer movement.

The results of solute transport modeling indicate that stabilizer delivery will vary throughout the treatment area. A typical stabilizer contour plot for a hypothetical formation with a uniform hydraulic conductivity of 0.05 cm/s and a hydraulic gradient of 0.005 is shown in Figure 4. A stabilizer concentration of 100 g/l would be delivered through an infiltration trench for 100 days. The best coverage would be achieved close to the source of the stabilizer. Concentrations would decrease laterally away from the source and down gradient of the source. If the minimum amount of stabilizer required for adequate stabilization could be delivered to the majority of the treatment area, it is likely that the formation would be stable enough to withstand seismic loading. However, there could be some differential or variable response across the site. It may be necessary to deliver a higher concentration at the up gradient edge of the treatment area



■ Figure 2. Gradation curve for Monterey No. 0/30 sand.

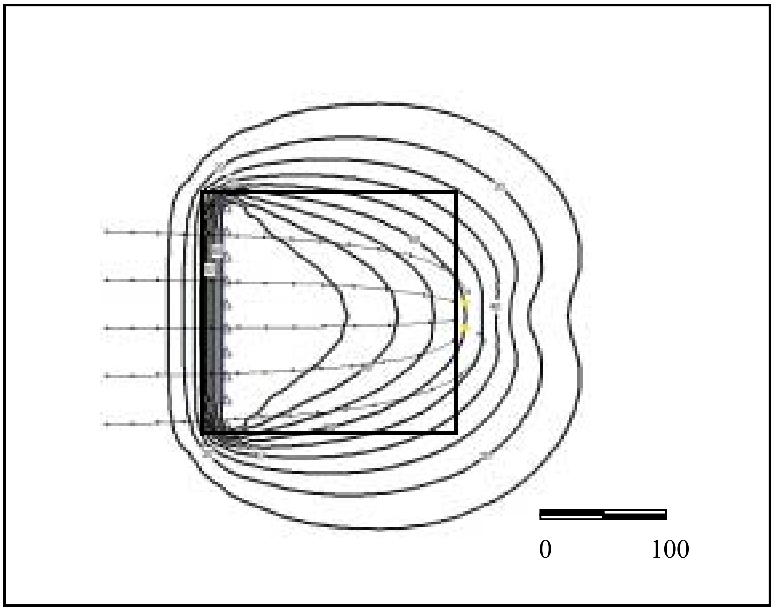

Untreated Monterey Sand (D_r = 22%)

Monterey Sand with 10% Colloidal Silica (Dr = 22%)

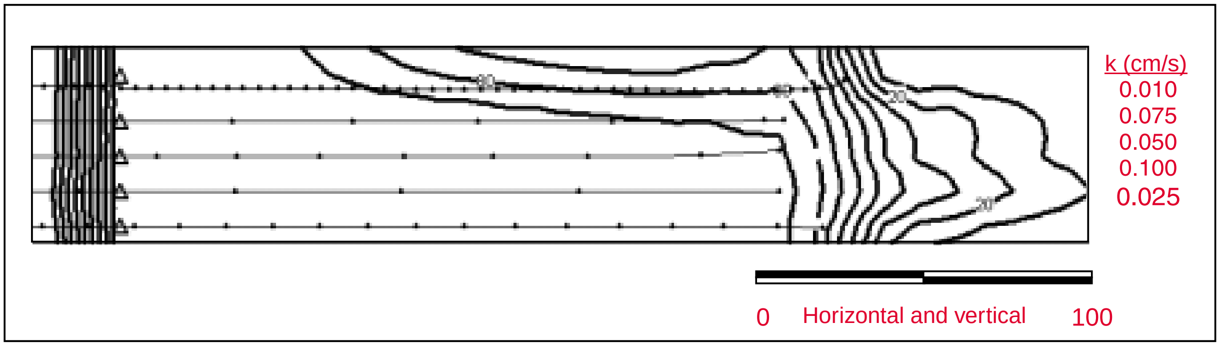
■ Figure 3. Axial deformation during cyclic loading (CSR=0.27) for treated and untreated sand.

in order to get an adequate concentration at the down gradient edge.

Heterogeneity in the formation will actually control how well the stabilizer can be delivered. If the formation is highly variable, then the stabilizer concentration will vary from point to point within the formation. An example stabilizer contour profile through a treatment area with a variable hydraulic conductivity is shown in Figure 5. In this case, the hydraulic conductivity was varied slightly in each layer as shown for a total variation throughout the layer of about one order of magnitude. The remainder of the simulation is the same as the previous case. The layers with higher hydraulic conductivity have a higher concentration at the down gradient edge. These layers would probably be more stable than layers with lower hydraulic conductivity that receive a lower concentration of grout during the treatment period. However, even if the regions of lower hydraulic conductivity liquefy, the presence of very stable seams will likely lessen the severity of the overall deformation. Accurate characterization of the hydraulic conductivity throughout the treatment area will be essential for successful treatment by passive site remediation.



■ Figure 4. Stabilizer contours for 200 ft. by 200 ft. treatment area (outlined in black) after 100 days of treatment. Stabilizer delivered through infiltration trench at concentration of 100 g/l. Two extraction wells at the down gradient edge withdraw a total of 7500 cfd. Contour intervals are 10 g/l. Concentration at extraction wells is 60 g/l. Travel paths for individual water particles are superimposed over the treatment area in 10-day increments. Particle travel times are about 75 to 80 days.



■ Figure 5. Stabilizer profile through centerline of 200 ft. by 200 ft. treatment area after 100 days of treatment. Stabilizer delivered through infiltration trench at concentration of 100 g/l. Extraction wells at the down gradient edge withdraw a total of 7500 cfd. Contour intervals are 10 g/l. Concentration at extraction wells is about 70 g/l in lower 30 ft. Travel paths for individual water particles are superimposed over the treatment area in 10-day increments. Particle travel times range from about 40 to 420 days.

Cost

The cost of passive site remediation is expected to be comparable to other methods of chemical grouting. It is likely that a 10 weight percent concentration of colloidal silica will be adequate to stabilize a liquefiable formation. It is possible that lower concentrations could be used. Based on a 10 percent concentration, it is expected that materials costs would be in the range of $120 to $180 per cubic meter of treated soil. These costs are competitive with other methods of chemical grouting.

Conclusion

Based on the feasibility analysis, passive site remediation appears to be a promising new concept for mitigation of liquefaction risk. At this time, a minimum concentration of 10 percent colloidal silica appears to be suitable for stabilizing liquefiable sands. Additional testing is being done with concentrations of 5 weight percent to determine if the level of strain during cyclic loading would be acceptable.

Delivery of the stabilizer is the central feasibility issue with respect to passive site remediation. For a 200-foot by 200-foot treatment area with a single line of injection wells, it was found that passive site remediation could be feasible in formations with hydraulic conductivity values of 0.05 cm/s or more and hydraulic gradients of 0.005 and above. However, the actual concentration profile across the site will depend on the variation in hydraulic conductivity throughout the formation.

The anticipated final outcome of this work is a new technology for mitigation of liquefaction and ground failure risk. Passive site remediation technology will be less disruptive to existing infrastructure and facilities than existing methods. It is expected that passive site remediation will be cost-competitive with other methods of chemical grouting. Model testing of both the injection method and the performance of grouted ground is planned as the next step in the evaluation of this new technology. It will be done using a geotechnical centrifuge equipped with a shake table.