8.0 FEASIBILITY OF PASSIVE SITE REMEDIATION

8.1 Introduction

The purpose of this chapter is to evaluate the feasibility of passive site remediation based on the results of strength testing of stabilized sands, groundwater modeling, and cost data. Four issues need to be addressed:

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?
4. How long will it take?

8.2 Will Colloidal Grout Adequately Stabilize the Soil?

In laboratory testing, treatment of loose sands (D_r = 22%) with colloidal silica at concentrations as low as 10 percent by weight significantly reduced deformations during cyclic loading and prevented collapse of the soils. Untreated loose sands were tested in cyclic triaxial tests at cyclic stress ratios (CSR's) between 0.19 and 0.27. As noted previously, the cyclic stress ratio is the ratio of the deviator stress to the initial effective confining stress. During testing, the untreated samples accumulated 1 percent double amplitude axial strain after 28, 18, 18 and 11 cycles at CSR's of 0.19, 0.21, 0.23, and 0.27, respectively. Each of these samples then collapsed within two additional cycles. In contrast, samples at the same relative density but treated with 10 percent Ludox-SM colloidal silica were tested at CSR's between 0.23 and 0.41 for up to 1000 cycles and never collapsed. At CSR's above 0.29, one percent double amplitude axial strain occurred after only a few cycles, but in most cases, no more than 2 or 3 percent strain accumulated in 100 cycles. For comparison, a magnitude 7.5 earthquake would be expected to generate 15 significant uniform stress cycles.

The majority of samples were made by pluviating dry sand into a mold containing grout, which insured complete coverage of the sand grains with grout. This method of preparation was used so samples would be reproducible. However, it is not representative of the way a formation will be grouted. In the field, the stabilizer will permeate through the formation. Two samples were made by permeation grouting. Under cyclic loading, the samples strained less than 2 percent in up to 1000 cycles.

When samples were made by permeation grouting, three pore volumes of grout were permeated through the sample. In practice, by the end of the treatment period it would be expected that at least three pore volumes of grout would pass through most of the treatment area, except near the down gradient edge. However, the liquefiable formation will likely be heterogeneous and more variable than the controlled samples made for testing. It is likely that not all the pores will be filled with grout when permeation grouting occurs in the field. There may be variability in the size of the pores and preferential flow through the formation. It is likely that the larger pores will fill with grout first. Grout will then make its way into smaller pores by dispersion and diffusion. Therefore, the coverage throughout the formation will probably not be uniform. However, if the majority of the pores are filled with grout, the silica bonds between the grains are likely to be enough to hold the particles together and prevent excessive deformation during seismic events.

It is also possible that treatment with smaller concentrations of colloidal silica may be adequate. Additional testing should be done at lower concentrations of colloidal silica to determine how much strain occurs during cyclic loading when smaller concentrations of colloidal silica are used.

To be able to stabilize the formation, the grout needs to be able to gel. Gel time is related to the concentration of colloidal silica, the pH, and the ionic strength of the grout solution. Gel times increase with increasing pH, decreasing silica content, or decreasing ionic strength. If the concentration of the colloidal silica or the ionic strength of the solution were to decrease at the edges of the delivery plume due to dilution, the gel time would increase and the grout could travel beyond the treatment area prior to gelling or be too dilute to gel. One way to deal with this problem would be to inject small amounts of sodium chloride solution into the formation at the fringe of the treatment area. This would cause the ionic strength to increase, resulting in a decreased gel time. Gelation of the grout at the edge of the treatment area would also cause a greatly decreased hydraulic conductivity at the edge of the site.

Based on the results of the strength testing, it appears that colloidal silica can adequately stabilize liquefiable formations if it can be delivered at a concentration of 10 percent. It will limit strain and prevent catastrophic collapse during seismic loading. It may be possible to stabilize the formation with lower concentrations, but additional testing will be required to determine if a lower concentration will be adequate for successful treatment.

8.3 Can the Stabilizer be Delivered to the Formation?

This question is the central feasibility issue with respect to passive site remediation and there are numerous issues associated with it. Initially, the most important issue is whether the groundwater flow would be adequate to deliver enough stabilizer to the formation during the induction period of the grout. If not, the next issue is whether the flow be augmented with delivery or extraction wells. If these issues can be addressed satisfactorily, there are more complex issues that will need to be addressed, including the effects of dispersion and the appropriate way to account for dispersion in the formation. The effects of heterogeneity within the formation and the issues associated with layered systems will also need to be considered. Additionally, there will likely be a difference in the concentration both laterally and longitudinally away from the source.

First of all, can the grout be delivered to the formation? The preliminary groundwater modeling analysis was a “numerical experiment” that identified scenarios where the natural groundwater flow could be used to deliver the stabilizer to the formation. For a 200-foot by 200-foot treatment area, with single lines of injection and extraction wells, travel times 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. If the hydraulic conductivity of the formation is less than about 0.01 cm/s, the travel times through the formation will likely be too long for passive site remediation to be feasible for the size and shape of the treatment area assumed for this study. If the hydraulic conductivity of the formation is between 0.01 and 0.05 cm/s, travel times may be short enough for passive site remediation to be feasible, depending on the hydraulic gradient. The use of injection and extraction wells decreases travel times and may be especially helpful in delivering stabilizer to the treatment area when the hydraulic conductivity is between 0.01 and 0.05 cm/s.

The travel time through the formation also depends on the viscosity of the stabilizer. The viscosity of colloidal silica is expected to be about 2 cP for most of the induction period. This will cause a 50 percent decrease in the hydraulic conductivity of the formation as the colloidal silica progresses through the formation. The groundwater modeling software was not able to model a fluid with a variable viscosity. Therefore, the problem was bounded by calculating travel times for two cases: 1) the hydraulic conductivity in the treatment area equal to the hydraulic conductivity in the region, and 2) the hydraulic conductivity in the treatment area equal to half the regional hydraulic conductivity to account for the increased viscosity of the colloidal silica solution. These limits provided an upper and lower travel time estimate for advective flow. The actual travel time based on advective flow would be somewhere between these limits.

The estimation of travel time based on purely advective flow uses the average groundwater flow velocity to calculate travel time. The actual groundwater flow will vary within the formation and cause mixing and dilution at the front of the stabilizer plume. Solute transport modeling considers the effects of dispersion and is used to estimate the concentration distribution in an aquifer. The selection of a dispersion coefficient is difficult even in well-characterized aquifers, let alone a hypothetical liquefiable aquifer. Therefore, two approaches were used to bound the problem: an aquifer with a regional dispersion coefficient and a uniform hydraulic conductivity and an aquifer with a variable hydraulic conductivity and a local dispersion coefficient. For the aquifer with a variable hydraulic conductivity, a slightly different hydraulic conductivity value was used in each layer for a total variation across the aquifer of one order of magnitude. This process was discussed in Chapter 7.

When a uniform hydraulic conductivity is used in conjunction with a regional dispersion coefficient, the stabilizer moves through the formation predictably, but has a fairly wide coverage beyond the treatment area. Consequently, the concentration at the down gradient edge of the treatment is only about 50 to 60 percent of the source concentration at the travel time predicted by advective flow calculations. It takes about 1½ times the predicted travel time to reach about 70 to 80 percent of the source concentration throughout most of the treatment area. For example, consider a uniform aquifer with a regional dispersion coefficient (Case 1-1), as discussed in Chapter 7. Figure 7-3 (a) is a plot of the concentration field at a time of 103 days when a constant source concentration of 100 g/l of colloidal silica is used. The advective travel time through the treatment area is about 100 days for this case, assuming the hydraulic conductivity in the treatment area equals the regional hydraulic conductivity. The concentration at the down gradient edge after 103 days is about 60 g/l. After 150 days, the concentration at the down gradient edge is about 80 g/l. The implication of this analysis is that a longer delivery time would be needed to deliver the stabilizer if the desired concentration is injected at the source. Otherwise, a higher source concentration would be required to get the adequate concentration at the down gradient edge.

If extraction wells are added at the downgradient edge, the lateral extent of the plume is reduced somewhat and the concentration at the down gradient edge is slightly higher, but there is still a fairly wide coverage outside the treatment area. An added advantage of extraction wells is that they cause the travel time to decrease.

When a variable hydraulic conductivity is used in conjunction with a local dispersion coefficient, there is much more variation in stabilizer concentration from layer to layer, as expected, but much less lateral dispersion. Consequently, the shape of the concentration plume at the down gradient edge of the treatment is much closer to the shape that would be expected from plug flow in each layer. The travel times in each layer vary according to the hydraulic conductivity assigned to the layer, but the shapes of the plumes are very similar. When Case 1 is analyzed using a variable hydraulic conductivity and a local dispersion coefficient, the concentration at the down gradient edge of the site is quite variable vertically, as shown in Figure 7-7, but the overall concentration after 100 days is about 70 to 80 percent of the source concentration. The drawback with this scenario is that the layers with the lowest hydraulic conductivity values have much lower concentrations, i.e. on the order of 20 to 40 percent of the source concentration after 100 days. However, when extraction wells are added to this analysis, the concentration profile becomes much more uniform. Figure 7-10 is a profile through the treatment area shown in Figure 7-7 when extraction wells are added. The implication of this analysis is that adequate concentrations might be able to be delivered in a shorter period of time than shown by the analysis using a regional dispersivity. Additionally, when extraction wells are added to the case where hydraulic conductivity is variable, the variation in concentration between layers decreases. However, one drawback of extraction wells is that the lateral extent of treatment decreases somewhat.

Stabilizer delivery will vary laterally away from the source and longitudinally down gradient from the source. The best coverage will be achieved close to the source of the stabilizer. Concentrations will decrease laterally away from the source and down gradient of the source.

When wells are used to augment the natural flow regime, the delivery width of the well must be balanced with the volume injected through the well to get adequate coverage. The delivery width is a function of the volume of stabilizer injected through the well, the hydraulic conductivity of the aquifer, and the average linear groundwater flow velocity. Examples were done for two cases: delivery via 7 wells at 1000 cubic feet per day and delivery via 3 wells at 2500 cubic feet per day. Both of these scenarios provided concentration profiles across the site that were similar to Case 1 when a constant source concentration was used. These injection rates should be achieved with wells that have less than 3 feet of head.

Heterogeneity in the formation will actually control how well the stabilizer can be delivered. If the formation is highly variable, then the travel times will vary from point to point within the formation. If there are layers or seams with high hydraulic conductivity, more grout will travel through those layers and seams than through regions of lower hydraulic conductivity. The seams that are grouted first will presumably have a higher concentration of grout and be more stable than the regions of lower hydraulic conductivity. 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. If the layer with more treatment is above a layer with less treatment, it could provide an improved crust over the layer with less treatment. If the highly treated layer is thick enough, it could prevent surface manifestations of liquefaction even if the underlying soil does liquefy (Ishihara 1985).

For cases where the hydraulic conductivity and hydraulic gradient are in the range where passive site remediation is feasible, the heterogeneity in the aquifer will control the delivery of the stabilizer. There will probably be non-uniform coverage from the up gradient to the down gradient edge of the site, as well as non-uniform coverage laterally. However, if the minimum amount of stabilizer required for adequate stabilization is delivered to the majority of the treatment area, it is likely that the formation would be stable enough to withstand seismic loading. 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 in order to get an adequate concentration at the down gradient edge. This will make it more expensive.

8.4 How Much Will it Cost?

The cost of materials depends on the concentration of colloidal silica used in the grout. Table 8-1 lists the cost per cubic foot for different concentrations. In bulk, colloidal silica costs about $0.44 per pound. Depending on the grade, one gallon of colloidal silica weighs about 10 pounds. Ludox-SM is supplied as a 30-weight-percent solution, so it must be diluted with water to obtain the desired concentration. The ratio of Ludox-SM to water for different concentrations is shown in Table 8-1. For a 15 percent solution, 10 parts of Ludox-SM must be diluted with 12 parts of water. Therefore, 10 gallons of Ludox-SM will make 22 gallons of 15 percent solution.

Table 8-1 Cost of Ludox-SM Based on Concentration

Concentration, %	15%	10%	5%
Dilution, Ludox-SM/Water	10:12	10:24	10:60
Cost per cubic foot of stabilizer ($)	14.94	9.66	4.75
Cost per cubic meter of soil treated, assuming n=0.35	185	120	59

If the pores of the formation could be filled perfectly without wasting any grout, the cost per cubic meter of treated soil would be that shown in Table 8-1, assuming a porosity of 0.35. However, it is likely that higher source concentrations would be required because of the effects of dispersion. Based on the results of the strength testing, treatment with 10 percent colloidal silica should be adequate. However, it is likely that a 15 percent solution will need to be delivered to the treatment area to get adequate coverage in a period of 100 days. Therefore, the cost for treating a formation to get 10 percent stabilizer in the pores will be closer to the cost of shown in Table 8-1 for a 15 percent solution.

These costs are comparable to other forms of chemical grouting. If dilutions of 5 percent could provide adequate stabilization, passive site remediation would be less costly than chemical grouting.

8.5 How Long Will it Take?

The delivery time is the key consideration in terms of successful treatment by passive site remediation. However, the time required for passive site remediation will also include the setting and curing time. One of the advantages of colloidal silica as a stabilizer is that it has a wide range of gel times and the viscosity remains low for most of the induction period. Once the grout begins to gel, it rapidly increases in viscosity. However, colloidal silica gels continue to gain strength for many times the gel time. At lower concentrations, the amount of strain that occurs during cyclic loading decreases as the curing time increases (Figure 6-19).

The samples tested in this study were cured for a minimum of 10 times the gel time. For a 100-day gel time, this would correspond to a curing time of 1000 days. Shorter curing times may be possible, but additional testing would have to be done to determine the minimum curing time. In cases where the grout is diluted, gel times and curing times could increase.

Once the grout is in place, gelation could be induced by injecting sodium chloride solution into the formation through the delivery and extraction wells. Increasing the ionic strength of the grout would cause the gel time to decrease. This would start the process of gelation at the outer edges of the treatment area. If there was a large sodium concentration gradient, there could be diffusion of ions into the treatment area, which would cause gelation to progress into the treatment area. This would decrease the curing time requirements.

8.6 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 Ludox-SM appears to be suitable for stabilizing liquefiable sands. Additional testing should be done with concentrations as low as 5 percent to determine if the level of strain during cyclic loading would be acceptable.

Delivery of the stabilizer is the central feasibility issue. It is very difficult to accurately characterize the hydraulic conductivity and dispersivity in an aquifer. Although liquefaction tends to occur in fairly uniform formations, it is expected that there would be a fair amount of heterogeneity in any formation that might be a candidate for passive site remediation. It is likely that the delivery of colloidal silica to a formation would be non-uniform. The use of extraction wells can help to control stabilizer delivery and remove some of the non-uniformity of grout delivery in the concentration profile in layers with variable hydraulic conductivity. An added benefit of extraction wells is that they would help control the down gradient extent of stabilizer delivery. The water from the extraction wells might be able to be used for mixing the grout, depending on the concentration of silica that is present in the effluent.

The distribution of colloidal silica after treatment is likely to vary across the site. The area surrounding the source delivery wells is likely to be extremely well grouted with a high and uniform concentration of grout. The concentration will gradually decrease away from the delivery wells, both down gradient and laterally away from the delivery wells. As long as the minimum concentration required reaches the fringes of the site, this should not present too much difficulty. The highly treated areas will probably experience less strain during earthquake loading than areas with less treatment. However, even when samples strained during cyclic loading, they regained their original height after loading stopped. There was little observable permanent axial deformation due to cyclic loading. The residual strengths of samples that strained more were lower than residual strengths of samples that strained very little, but the shape of the specimens appeared to be the same.

9.0 SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

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 a stabilizing material at the edge of a site and delivery of the stabilizer to the treatment area using the natural groundwater flow. The set time of the stabilizer would be controlled so there would be adequate time for it to reach the treatment area prior to setting. If the natural groundwater flow were inadequate to deliver the stabilizer to the right place at the right time, it could be augmented with low-head delivery wells or down gradient extraction wells. Passive site remediation techniques could have broad application for developed sites where more traditional methods of ground improvement are difficult or impossible to implement.

The purpose of this research was to establish the feasibility of passive site remediation by identifying stabilizing materials, studying how to design or adapt groundwater flow patterns to deliver the stabilizers to the right place at the right time, and an evaluation of time and cost requirements.

9.1 Key Findings

For a given liquefiable formation and flow regime, the time required for a stabilizer to travel through a formation depends primarily on the viscosity and the unit weight of the stabilizer. The unit weight of the stabilizer will likely not vary much from the unit weight of water, so viscosity is the primary variable that will control how fast a stabilizer can travel through a formation. The hydraulic conductivity of a formation is inversely proportional to the viscosity of the permeant. When compared to water, every order of magnitude increase in the viscosity of a stabilizer will result in an order of magnitude decrease in the hydraulic conductivity of the formation. Therefore, to minimize the travel time through the formation, it is important that the viscosity of the stabilizer be as close to the viscosity of water as possible.

Performance criteria for potential stabilizers were established to aid in evaluation of materials for passive site remediation. Desirable stabilizer characteristics include a low initial viscosity and a long induction period between mixing and the start of gelation; rapid setting or gelation at the end of the induction period; chemical and mechanical stability; minimal safety, handling, mixing and environmental concerns; and, cost-competitive materials and installation process.

The following grouts were evaluated for use in passive site remediation: microfine cement, colloidal silica, sodium silicate, acylamide, acrylate, iron precipitation, epoxy and polysiloxane. Additionally, materials used in permeable reactive barrier technology and biological materials such as ultramicrobacteria were considered. Candidates selected for laboratory testing included microfine cement and colloidal silica grout.

Microfine cement grout was considered because it should be able to penetrate most liquefiable formations and it would likely be the least expensive of all potential stabilizers. New set-retarding admixtures are available that are capable of extending the set time of cement grout for up to 3 days. Higher doses of these admixtures can extend the set time even longer. The goal was to develop a stable grout with a low viscosity and an extended set time of at least 50 days. Although set times were extended to more than 50 days, the goal was not met in terms of stability and viscosity. Therefore, microfine cement grouts were eliminated from further consideration.

Colloidal silica is an aqueous suspension of microscopic silica particles. In low dilutions it has a viscosity and density similar to water. A wide range of gel times are possible. Gelation is controlled by adjusting the pH or ionic strength of a solution. The results of laboratory testing indicated that gel times in the range of 50 to 100 days were possible and that the viscosity remained fairly low (about 2 cP) for the induction period and then increased rapidly.

Strength testing of stabilized sands was done to examine the effects of colloidal silica grout on the liquefaction resistance of loose sands. Loose sand samples (D_r = 22%) were made either by pluviating dry sand into molds containing colloidal silica grout or by gravity permeation. Grout concentrations ranged from 10 to 20 percent silica by weight. After gelation, the samples were cured for at least 10 times the gel time prior to testing under cyclic loading.

Cyclic triaxial tests were performed to investigate the influence of colloidal silica grout on the deformation properties of loose sand. Distinctly different deformation properties were observed between grouted and ungrouted samples. Untreated samples developed very little axial strain prior to the onset of liquefaction. However, once liquefaction was triggered, large strains occurred rapidly and the samples collapsed within a few additional cycles. An untreated sample tested at a cyclic stress ratio (ratio of maximum cyclic shear stress to initial effective confining stress) of 0.27 reached 1, 2, and 5 percent double amplitude (DA) axial strain in 11, 11, and 12 cycles, respectively, and collapsed after 13 cycles. In contrast, grouted sand samples experienced very little strain during cyclic loading. What strain accumulated did so uniformly throughout loading rather than rapidly prior to collapse. A sample treated with 10 percent colloidal silica by weight and tested at a cyclic stress ratio of 0.27 required 35, 159, and 276 cycles to reach 1, 2, and 5 percent DA strain, respectively. The sample never collapsed. For comparison, a magnitude 7.5 earthquake would be expected to generate 15 significant uniform stress cycles. Thus, treatment with colloidal silica grout significantly increased the deformation resistance of loose sand to cyclic loading

In general, samples stabilized with higher concentrations of colloidal silica experienced very little (less than two percent) strain during cyclic loading. Sands stabilized with lower concentrations tolerated cyclic loading well, but experienced slightly more (up to eight percent) strain. All of the stabilized sands remained intact during cyclic loading.

Unconfined compression tests and unconsolidated undrained tests were done to determine baseline strengths for samples stabilized with different concentrations of colloidal silica grout. UC and UU tests were also done on samples that had been cyclically loaded to determine residual strength. The degree of strain experienced during cyclic loading affected the residual strength of the stabilized sands. Samples that experienced the most strain had the lowest residual strengths. Samples that experienced more than two percent retained from half to two-thirds of the baseline strength. Samples that experienced less than about two percent strain show very little strength degradation.

A preliminary groundwater modeling study was done using the computer codes MODFLOW, MODPATH, and MT3DMS, which were run through the Groundwater Modeling System platform. The purpose of the modeling study was to do a “numerical experiment” to determine the conditions under which the stabilizer could be delivered to a formation using the natural groundwater flow as a delivery system. Augmentation of the groundwater flow regime was also considered for scenarios where the natural flow was inadequate to deliver the stabilizers within the induction period of the grout. Solute transport modeling was also done to estimate the concentration of stabilizer that would be required at the up gradient edge of the treatment area to deliver an adequate amount of stabilizer to the down gradient edge of the treatment area.

A conceptual model was developed that assumed a one-acre treatment area in a liquefiable formation 50-feet-thick. MODFLOW does not have the capability to account for a permeant with a variable viscosity. Therefore, the increased viscosity was accounted for by assuming that the hydraulic conductivity in the treatment area was half of the hydraulic conductivity in the rest of the model. This assumption provided an upper bound estimate for travel times. A lower bound was calculated by assuming the hydraulic conductivity in the treatment area was based on water as the permeant. Travel times were estimated for purely advective flow using MODPATH. Travel times of 100 days or less were considered feasible given the wide range of gel times for colloidal silica grouts.

For a one-acre treatment area with a single line of injection wells, it appears that passive site remediation could be feasible for scenarios where the hydraulic conductivity is above about 0.05 cm/s and hydraulic gradients are above 0.005. For this case, travel times will likely be too long for passive site remediation to be feasible if the hydraulic conductivity is below about 0.01 cm/s and hydraulic gradients are up to 0.02, even if the flow regime is augmented with delivery wells. For hydraulic conductivity values between 0.01 cm/s and 0.05 cm/s, passive site remediation may be feasible for a one-acre treatment area with a single line of injection wells, but only if the hydraulic gradients are high.

The concentration of stabilizer delivered to the treatment area will depend on the concentration injected in the delivery wells. The concentration field will vary both laterally away from the source and down gradient of the source. Concentrations will be highest near the source and lowest at the down gradient edge of the treatment area. As long as the minimum concentration required is delivered to the down gradient edge of the site, variable concentrations of stabilizer across the treatment area should be acceptable. Areas with higher concentrations will probably experience less strain during seismic loading events.

The values chosen for dispersion have a large impact in determining if an appropriate amount of stabilizer can be delivered to the formation. Two methods were used to consider the effects of dispersion. First, a regional dispersion coefficient was used in conjunction with a uniform hydraulic conductivity. Second, the hydraulic conductivity was varied in each layer of the model and a local dispersion coefficient was used. When a regional dispersion coefficient is used in conjunction with a uniform hydraulic conductivity, both the lateral and the down gradient extents of the stabilizer plume are fairly large. It also takes longer to achieve adequate coverage in the treatment area. When dispersivity is considered by varying the hydraulic conductivity and using a local dispersion coefficient, the stabilizer plume moves as a non-uniform front. There is less lateral and down gradient dispersion. The actual behavior in the field would be expected to be between these limits. In practice, field tests will be needed to quantify dispersion for design of passive site remediation.

The cost of passive site remediation is expected to be comparable to other methods of chemical grouting. The cost will depend on both the concentration of colloidal silica grout that is used for treatment and the duration of treatment. A concentration of 10 percent Ludox-SM was found to stabilize the soil adequately in laboratory testing. For sands treated with 10 percent of Ludox-SM that is delivered using a 15 percent solution, the cost is expected to be about $185 per cubic meter of treated soil. It is possible that lower concentrations can be used, but additional testing will need to be done to determine the minimum concentration of colloidal silica that will adequately stabilize liquefiable soil.

9.2 Recommendations for Future Work

It is recommended that additional testing of stabilized sands be done to determine if concentrations of 7½ and 5 percent Ludox-SM will provide sufficient stabilization. It is also recommended that additional samples made by permeation grouting be tested. The effects of curing time on strength should be investigated to determine the minimum curing time necessary to develop adequate strength in a stabilized sample. It would also be interesting to test partially treated samples. For example, if samples were made using permeation grouting techniques and then the grout was allowed to drain out of the pore spaces in the samples after treatment, only the grout surrounding the sand grains would remain in the samples. In this way, the effects of limited treatment could be investigated.

It is also recommended that additional groundwater modeling be done using a code that can account for a stabilizer with a variable viscosity. If no available codes can do these computations, a module could be written for MODFLOW to account for the introduction of a material with a variable viscosity. Multiphase numerical simulators such as TOUGH2 could also be investigated for use in this application.

It is also recommended that a box model be constructed for bench-scale tests of passive site remediation. Flow predictions could be made using computer modeling and compared with actual results from the box model. The prediction of travel times using the upper and lower bound assumptions on viscosity could be compared with actual travel times. After treatment, samples from different parts of the treatment area could be tested to investigate the differences in variable treatment. A box model would provide a useful extension to the preliminary feasibility analysis. Shaking table tests could be done to determine how well a stabilized mass would behave during dynamic loading. An alternative would be to do centrifuge testing on liquefiable soils improved with passive site remediation.