Research Report

I. Abstract:

My purpose was to mitigate liquefaction through the use of iron nanoparticles in a zeolite structure. This would increase the shear strength causing the soil to not liquefy. To do this, I calculated saturation of soil and densities. Next, I conducted penetrometer tests with all combinations of sand, zeolite and ferrofluid, with and without the use of a magnetic field. My penetrometer results show ferrofluid with the magnet increased the shear strength of the soil by about 25%. Adding zeolite did not improve the strength of the soil; it decreased it. The results showed that zeolite does not improve strength of soil, and it won't be used for dynamic shear strength testing. The test samples included sand as a control and different concentrations of ferrofluid in sand for mitigation. The shaker table was used to measure shear resistance against liquefaction. The results show that 100% ferrofluid loses the least amount of shear resistance and has the highest amount of residual resistance. I conclude that 100% ferrofluid with a magnet creates the highest shear strength in liquefiable soils.

2. Introduction and Purpose:

It is the purpose of this project to find a mitigating solution to the challenge of groundwater during seismic liquefaction. During seismic liquefaction, water saturated, non-cohesive soils build excess pore water pressure that force the soil grains apart and reduce shear resistance. This project proposes to mitigate against liquefaction by displacing the ground water in liquefiable soils with ferrofluid. The ferrofluid contains nanoparticle sized grains of magnetite (2.8% -3.5% by volume) in a solution of a surfactant (2.0%-4.0% by volume), such as ammonium chloride and distilled water (92.5% -95.5% by volume) at a pH of 10. The concentration of this surfactant is reported to be a slight skin irritant in the manufacturer's MSDS for its ferrofluid product. Over a relatively short period of time, depending upon groundwater flow rates, the surfactant will dilute, lowering the pH to below 8. This will cause the nanoparticles to consolidate in the pore spaces between the soil particles, and when subjected to a magnetic field, increase the inter-granular forces. The benefit of this process is that the shear resistance of the soil can be increased, reducing the potential for damage to the built environment during a seismic event from liquefaction.

3. Discussion:

Geotechnical and structural engineers currently utilize various methods to mitigate seismic liquefaction from soil replacements or amendments to the addition of structural reinforcements. This investigation looked at the potential of how magnetized iron nanoparticles could be used to mitigate the effects of liquefaction. As originally planned, the project was to perform a cation exchange between Zeolite and iron nanoparticles. The manufactured form of the ferrofluid (magnetite nanoparticles) was produced as an anion suspension with a surfactant that had a pH of 10 and was not suitable for the cation exchange process. With additional research, I found a collection of papers that converted the pH of ferrofluid from 10 to 2.5 and transformed the magnetite to maghemite through a dilution and magnetic decanting and heating process. Though Ferrotec, a ferrofluid distributer, was doubtful that I could perform this transformation, I was able to successfully obtain maghemite suspended in a low pH solution. The uncertainty of this new anion to cation conversion procedure required a revision to my original research plan that had included various combinations of sand, Zeolite, and ferrofluid to be evaluated in a simple penetration procedure before dynamic testing. The results of the soil indices and testing process were to develop the quantities for the penetrometer tests as indicated in the following table:

Components Tested

Test No.	Description	Dry Sand (g)	Water (ml)	pH	Ferrofluid (ml)	Zeolite (g)	Magnet
0	Control	105	31.6	7	0	0	off
1	Magnet	105	31.6	7	0	0	on
2	Zeolite	94.5	34.0	7	0	10.5	off
3	Zeolite & Magnet	94.5	34.0	7	0	10.5	on
4	Ferrofluid @ pH 10	105	12.3	10	20.0	0	off
5	Ferrofluid @ pH 10 & Magnet	105	12.3	10	20.0	0	on
6	Zeolite & Ferrofluid @ pH 10	94.5	14.7	10	20.0	10.5	off
7	Zeolite, Ferrofluid @ pH 10 & Magnet	94.5	14.7	10	20.0	10.5	on
8	Zeolite & Ferrofluid @ pH 2.5	94.5	14.7	2.5	20.0	10.5	off
9	Zeolite, Ferrofluid @ pH 2.5 & Magnet	94.5	14.7	2.5	20.0	10.5	on

During the Penetrometer testing I discovered that in all cases when ferrofluid and a magnetic force was applied the test with magnetic force had less penetration than the test without magnetic force. Test 9, from my hypothesis, had an average penetration depth of 16.6 mm with a fractional error of 6%. Test 5, with the shallowest penetration, had an average penetration depth of 15.4 mm with a fractional error of 6.5%. Any time zeolite was added to the sample, the penetration depth increased, suggesting that Zeolite reduces shear resistance in soil. This could be because when added to water it feels slick to the touch. This was supported by the Zeolite having an average penetration of 27.5 mm, which is 8.0 mm higher penetration than the average control.

- Considering the results of the Penetrometer testing, it was decided that a combination of sand and ferrofluid at various concentrations with a pH of 10 would be dynamically tested in a magnetic field and compared to sand only, without a magnetic field as a control. The results for sand saturated with 100% ferrofluid (as provided by the manufacturer and used in lieu of water for saturation of the test sample) were consistent with the results of the Penetrometer tests.
- In the analysis of the Dynamic Testing results, the Shear Modulus of Rigidity (G) during any one cycle of oscillation of the shear strain time history was defined as a measure of shear resistance against liquefaction. The maximum loss of shear resistance was defined as the difference between maximum and minimum shear resistance divided by the maximum shear resistance and expressed as a percentage. An average of the shear resistance over several cycles, excluding the cycle with maximum loss and divided by the maximum shear resistance expressed as a percentage, was defined as residual shear resistance. The average of the dynamic testing for the sand only control test was a loss of 95% of its maximum shear resistance from liquefaction. As the water drained off to the top of the sample, reducing inter-granular pore pressure, it regained an average of only 24% of its maximum shear resistance as residual shear resistance. The average of the sand and 100% ferrofluid in a magnetic field was a loss of 91% of its maximum shear resistance from liquefaction and it regained an average of 41% of its shear resistance. Although the addition of 100% ferrofluid only reduced the loss of maximum shear resistance by 4% (95%-91%), it was able to increase the average residual shear resistance by 172% (41%/24%).
- The average of the sand and 75% ferrofluid and 50% ferrofluid in a magnetic field was a loss of 95% and 98% of their maximum shear resistances and they regained an average of 37% and only 23% of their shear resistance respectively. The use of 50% ferrofluid indicates that at that level of dilution with water at a pH of 10, ferrofluid is not effective at mitigating against liquefaction in sandy soils. The use of 50% ferrofluid did nothing to reduce the loss of shear resistance, but was able to increase the average residual shear resistance by 155%.

There were a number of possible sources of error within this project:

Procedure 1: Soil indices/densities and Penetrometer Testing

- A pH meter was in need of frequent recalibration. A pH of 7 buffer was used to calibrate and not the Vernier provided 4 pH solution. This may have led to inaccuracies in pH measurements.
- Penetrometer tests were conducted with a metal millimeter scale ruler. I was only able to read to the nearest 1 mm because I could not obtain a commercial penetrometer. This results in a higher fractional error that ranged from 3.6% to 6.3%.

Procedure 2: Dynamic Testing

- Rolling the wire for the electromagnet was tedious and a decision was made to change the gauge size of the wire from 28 Ga to 24 Ga, to reduce the number of turns required. As a result the current in one electro magnet was greater, while the number of turns in the other was less with a subsequent difference in the strength of their magnetic fields.
- The shaker table was operated by a drill where the speed was controlled by hand. It was difficult to control the speed and keep steady pressure on the trigger of the hand drill to meet the required acceleration for the specified time intervals.
- Measuring large masses accurately was difficult. I could not find a scale that would measure large masses up to ≈10,000 grams (100 N) yet measure to an accuracy to the nearest hundredth of a Newton. I had to construct a scale using two Vernier force meters, each with a capacity of 50 Newton each. Reference the picture of “Weighing Sand” in Procedure 2: Dynamic Shear Testing to view arrangement.
- Accelerometers were not able to sample and record data fast enough when the frequencies increased at the 10 second mark and, therefore, anything after

10 seconds could not be used for analysis.

- At higher rotation speeds the Pneumatic Door Closer mechanism in the shaker table produced higher frequencies, but not corresponding higher accelerations as in an actual earthquake. This can be accounted for in the previous source of error.
- The position graphs showed that the bottom accelerometer had moved 5 meters, when in reality it only moved several centimeters. A baseline correction to the acceleration time history was needed to reduce this discrepancy.

1. Conclusions:

In procedure 1, for the penetrometer tests, I hypothesized that the Zeolite with the maghemite cation at pH 2.5 while magnetized with an electro magnet (test 9) would yield the shallowest penetrations. I reject this hypothesis because the shallowest penetration occurred with ferrofluid at pH 10 with a magnet (test number 5). I concluded that the ferrofluid at a pH of 10 with an electromagnetic field had the highest shear resistance and therefore was used for the dynamic testing.

In procedure 2, for the dynamic testing, I hypothesized that a 100% ferrofluid saturated sand mixture would maintain the highest amount shear resistance. I accept my hypothesis for this second procedure because the 100% ferrofluid only lost 91% of its shear resistance and then regained 41% of its maximum shear resistance for an increase of 172% of the average amount of residual shear resistance gained in control tests without ferrofluid. This means that sand saturated with 100% ferrofluid loses less shear resistance and can regain significantly more of this resistance during shaking.

This project indicates that adding a soil amendment of ferrofluid in a magnetic field can increase the resistance of soil and also help it regain more of its lost resistance. Although additional testing is required by professional soil laboratories with more sophisticated equipment, the addition of ferrofluid to a liquefiable soil is useful in mitigating soil liquefaction in places susceptible to damage. This method allows for the fortification of soils under preexisting buildings at designated liquefaction sites that might be too expensive to mitigate any other way. As a realistic example, the ferrofluid could be pumped into the ground under pressure, displacing the groundwater. Electromagnets would be deployed within the ferrofluid and when seismic shaking begins, the electromagnet would be triggered by ground motion sensors and turned on from an electric energy storage system. This would magnetize the magnetite in the ferrofluid and result in mitigation of liquefaction.