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IMPROVEMENT OF STATIC AND DYNAMIC PROPERTIES OF SOFT CLAY USING HIGH PRESSURE JET GROUT

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ABSTRACT

A proposed subway project is located in an area marked by a number of soft clay layers situated at depths from 60 ft to 100 ft below the ground surface. With unconfined compressive strength less than 0.6 tsf these natural soils are not strong enough to support on coming heavy loads and vibrations that the subway may be subject to in future. Hence the soil was trial grouted in-situ using high pressure jet grout technique to improve the engineering properties of the natural clay. A series of static and dynamic property tests were carried out on 18 samples selected from the site. Results show that the static and dynamic strength of the grouted clay improved significantly and the improvement depends on several parameters like confining pressure, cement content and water/cement ratio. The study provides a reasonable estimate of the extent of improvement (with respect to natural soil) and leads towards a better understanding of the static and dynamic properties of cement-treated clays and their behavior under various conditions.

INTRODUCTION

Although a number of studies have been made related to the behavior of cemented sand, there is little information available related to the engineering properties of cement-treated clay. The primary purpose of this study was to evaluate the influence of high pressure jet grout on clay.

Soils upon which a structure is founded quite often are subjected to vibrations which may result in inelastic deformation of the soil. Hence it is important that the dynamic properties of soil be considered in the design and construction activities involving such soils. A proposed subway project in Taiwan is located in an area marked by a number of soft clay layers situated at depths of around 60 ft below the ground surface. Exhibiting an unconfined compressive strength of less than 0.6 tsf, these natural soils are not strong enough to support the heavy loads and vibrations that the subway may induce during regular operations in the future. To provide useful and reliable information about the effectiveness of jet grouting for the design and construction of the subway system, the natural soil deposit was trial grouted using high pressure jet grouting techniques.

Three methods (i.e. single-tube method, double-tube method and triple-tube method) were used for grouting at various depths at a selected site near the proposed subway system.

The single-tube method cuts soils by injecting the cement grout (single-fluid system) with high pressure. The double-tube method uses two concentric tubes for cutting and mixing the soils with cement grout and air (two-fluid system) under high pressure. The triple-tube method uses three concentric tubes for cutting and mixing the soils with cement grout, water and air (three-fluid system) under high pressure, while extracting the rotary drill rod. This is how a grouted column is formed. The drilling fluid used was mostly water. The injected grout had a cement/water ratio of 1.1 and was injected at a rate ranging about 0.5 to 1.1 gallons per second (1.8 to 4.2 liters per second). The grouted columns extended from a depth of about 5 ft (1.5 m) from the ground surface to a maximum depth of about 20 ft (6 m) and were aligned vertically. Some columns were inclined at angles of 45° and 60°. Spacing between the grouted columns varied between about 5 ft to 11.5 ft (1.5m to 3.5m).

Results indicate that the static and dynamic strength of the soil depends on several parameters such as confining pressure, water content, cement content and water/cement ratio. Previous studies on artificially cemented soils justify this conclusion (*Clough et al., 1981; Chang, 1986; Acar et al., 1986; Saxena et al., 1988*). Results from this study provide a reasonable approximation of the extent of improvement of static and dynamic strength of the soil (with respect to natural soil) and leads towards a better understanding of the static and dynamic strength of cement-treated clays and their behavior under various conditions.

Case applications- a brief review

The ASCE, Geotechnical Engineering Division committee on Grouting defines jet grouting as a technique utilizing a special drill bit with horizontal and vertical high speed water jets to excavate alluvial soils and produce hard impervious columns by pumping grout through the horizontal nozzles that jets and mixes with foundation material as the drill bit is withdrawn (*Joseph Welsh, 1987*). In recent years jet grouting has been widely applied in different fields of geotechnical engineering and in a variety of subsurface materials. Most common applications of jet grouting to date have been underpinning of existing structures and waterproofing cutwalls for tunnels, open cuts, canals and dams. Some selected case applications are presented below in Table 1 (*Joseph Welsh, 1987*).

Table 1 Examples of Jet grouting application

Project	Location	Nature of problem	Soil type
British Rail Glasgow Tunnel	England	Track Settlement	Saturated Silt
Oldenburg Underpinning	Germany	Underpinning for Basement Construction	Silty and Clayey Sand and Fill
Porto Tolle Power Plant	Italy	Cutoff Wall for Seepage and Erosion Prevention	Silty Sand and Organics
New Wadell Dam	U.S.A	Eliminate Water Flow into Shaft	Sand, Gravel Cobbles and Boulders
Milan-Rome Railroad	Italy	Prevent Scouring of Bridge Piers	Alluvium
Halic Sewer Tunnel	Turkey	Eliminate Water Flow into Open Excavation	Alluvial Sands
Yokohana Highway	Japan	Trench Cutoff	Sand and Silt
Pump Lift Station	U.S.A	Minimize Subsidence	Saturated Clays
Porto Tolle Power Plant	Italy	Cutoff Wall for Seepage and Erosion Prvention	Silty Sand and Organics
Stockton on Trees New Tunnel	England	Shaft Excavation and Correction to Tunnel	Submerged Silty Sand
Nuclear Fuel Reprocessing Plant	Japan	Slope Protection Cutoff	Sand and Gravel
Singapore MRT Tunnels	Singapore	Increase Stand-Up Time	Marine Clay

These are some recent examples of jet grouting applications. Of these, the New Wadell Dam project was a experimental program to evaluate the feasibility of employing jet grouting to construct the permanent cutoff. The test was performed around a shaft to investigate the effectiveness of a jet grouted cutoff wall to eliminate water inflow. These case studies have led to a better understanding of the process and design rationale. However, more studies are required for a complete understanding on the effectiveness of jet grouting on different types of subsurface materials.

TESTING PROGRAM

A total of 18 samples were taken from the site and tested for their dynamic behavior and cement content. Of these, 12 were grouted samples and 6 were natural samples. The grouted samples were taken at different locations in reference to the drilling point (i.e. at various distances from the drilling point). The dynamic tests were performed at confining pressures of 5, 10, 20, 40, 60 and 90 psi, which represent the in-situ depth from near the ground surface up to about 200 ft below the ground surface.

A resonant column device was used to study the dynamic properties of the soil. The specimens were tested for their unconfined compressive strength (Q_U) in a triaxial testing machine. The cement content of grouted samples was determined by using the test procedures outlined in ASTM D806-89.

Single (S), double (D) and triple (T) fluid systems were used in the trial jet grouting operation. All three types, i.e. S, D and T samples, were selected and tested for their static and dynamic properties. Three S samples, two D samples and seven T samples were tested in the study.

RESULTS

Table 2 shows the range of test results in the testing program. The values of shear modulus and shear wave velocity are at an average confining pressure of 40psi which may represent a depth of about 60 ft where the subway is to be constructed. In general, results show that strength of clay is significantly improved. After jet grout was used, unconfined compressive strength, on the average, increased by up to about 15-20 times that of natural soils. The average increase in shear modulus is up by about 16 times and increase in shear wave velocity is up by about 5 times. Grouted samples were found to have much higher water content than natural samples. This is understandable because clay is impermeable and so water used during the grouting operation may have been retained by the clay particles thus, increasing the water content of grouted samples. Cement content (%, by weight of soil) in `D' samples ranged from 25.67 % to 39.67 %, in `S' samples it ranged from 40.11 % to 42.31 % and in `T' samples it ranged from 44.27 % to 45.22 %.

Table 2 Range of test results

PARAMETERS	NATURAL SAMPLES	GROUTED SAMPLES
1) Unconfined compressive strength, Q_u	0.55 - 4.5 tsf	15.9 - 61.91 tsf
2) Shear modulus, G	1140 - 14078 psi	18515 - 63848 psi
3) Shearwave velocity, Vs	204 - 728 ft/sec	903 - 1636 ft/sec
4) Water content, W_c (%)	23.8 % - 46.6 %	22.4 % - 81.4 %
5) Cement content (%)	-	25.7 % - 45.2 %
6) Liquid Limit, W_L (%)	31.5% - 38%	-
7) Plastic Limit, W_p (%)	23.2% - 28.6%	-
8) Plasticity Index, I_p	6.4% - 10.7%	-
6) Flow Index, F_i	-6.75 - -28.98	-

The above results for natural samples are representative of general properties of the clay in the zone where trial grouting was performed. The samples were taken from a depth ranging from about 16 ft to 65 ft (5 to 20m) from the ground surface. Figure 1 shows grain size distribution of the soil samples. All soil samples contained at least about 70% silt/clay particles. This curve only shows particle size finer than .075 mm (No. 200) in the samples.

DISCUSSION

The static and dynamic strength of grouted soil depends on parameters like confining pressure, cement content and water/cement ratio. The following sections discuss the effect of these parameters on the static and dynamic strength of natural and grouted clay on the basis of the test results.

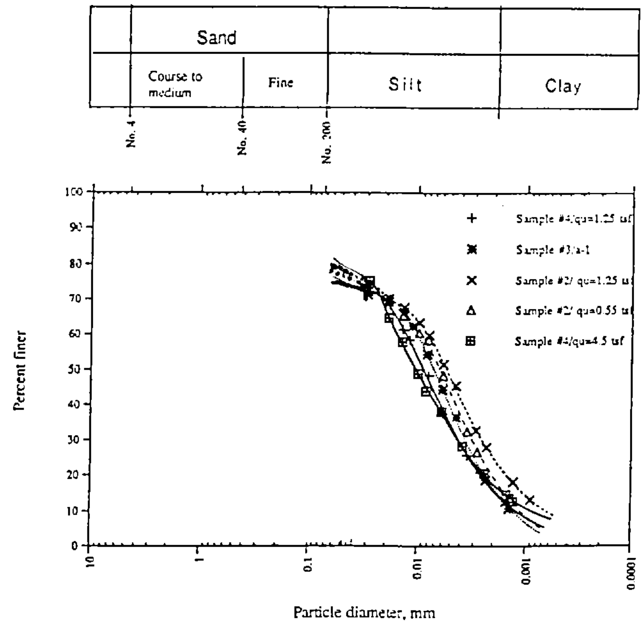

Figure 1 Grain Size Distribution Cutve of Natural Soil Samples

Effect of confining pressure

Shear modulus and shear wave velocity increase with an increase in confining pressure (*Chang et al., 1987*). Figure 2 shows the variation of shear modulus with confining pressure at different cement contents. `n' represents the effect of confining pressure on shear modulus/shear wave velocity. The value of `n' for the shear modulus of grouted samples ranged from 0.025 to 0.37, and those for natural samples ranged from .32 to .68.

Figure 3 shows the variation of shearwave velocity with confining pressure at different cement contents Comparing the value of `n' for natural and grouted samples, it is evident that confining pressure has little influence on grouted samples because grouted samples have been significantly stiffened in strength and have become much more incompressible.

At a given confining pressure, the increase in shear modulus is due to the stiffened soil skeleton by cement. The increment in shear modulus (with respect to natural soil) is maximum at lower confining pressure and it keeps decreasing with an increase in confining pressure. Hence, the influence of cement on increasing shear modulus/shear wave velocity decreases with increase in confining pressure. This implies that at greater depths (high confining pressure) confining pressure has a significant influence on the rigidity of the soil, and the further stiffening of soil skeleton by cement is limited.

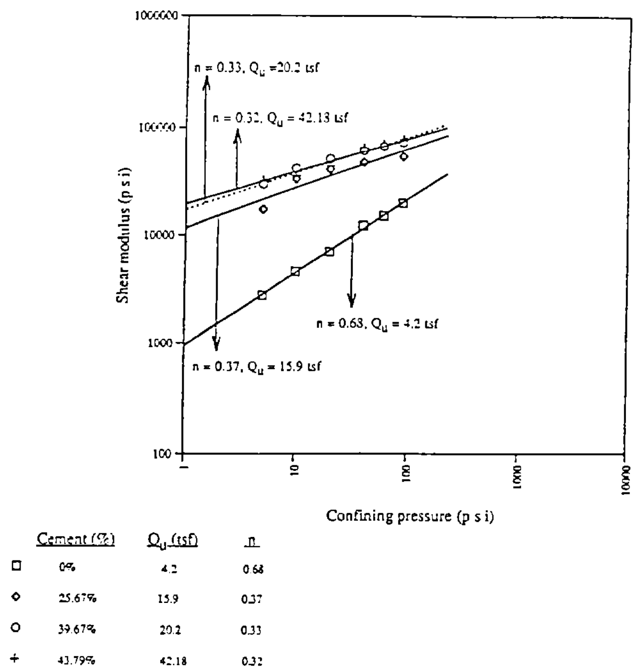

Figure 2 *Shear Modulus Vs Confining Pressure (at various Cement Contents and Unconfined Compressive Strengths)*

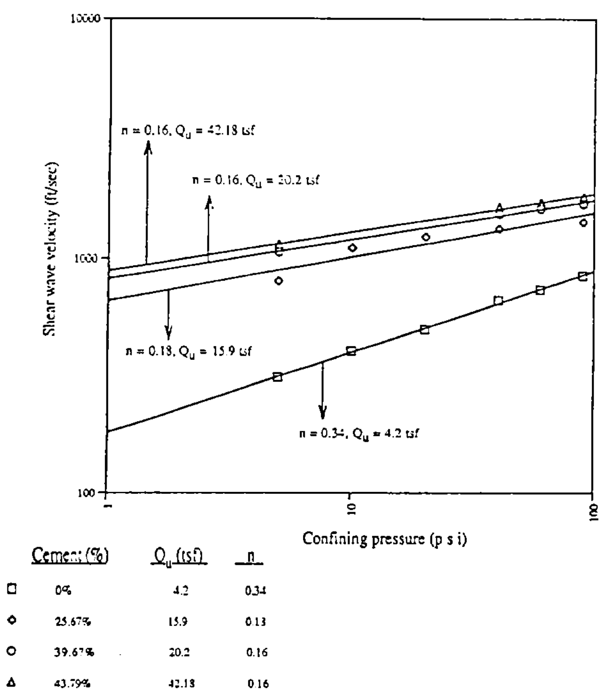

Figure 3 *Shearwave Velocity Vs Confining Pressure (at various Cement Contents and Unconfined Compressive Strengths)*

Figure 4 shows the variation of percentage increase in shear modulus and shear wave velocity (Percentage increase with respect to natural soil) with confining pressure.

Increase in shear modulus or shear wave velocity decreases with increase in confining pressure. In between 20 and 40 psi, the increment of shear modulus is about 380% and the increment of shear wave velocity is about 200%. Confining pressures between 20 and 40 psi approximately represent the depths at which the samples were taken.

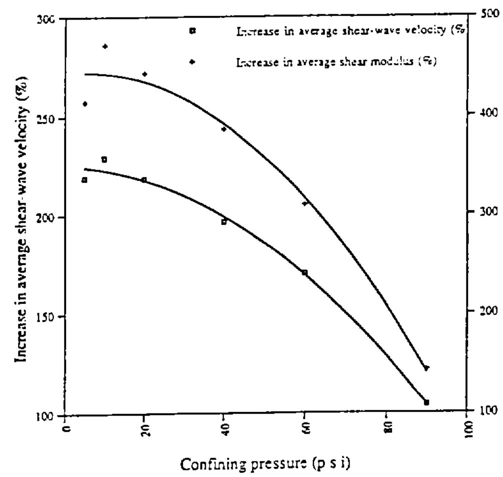

Figure 4 *Increase in Average Shear Modulus(%),Increase in Average Shearwave Velocity(%) Vs Confining Pressure*

Variation of shear modulus with depth

Figure 5 shows the variation of increase in shear modulus (with respect to natural soil) with depth. The increase in shear modulus becomes less significant with an increase in depth. At depths greater than about 100 ft, the increment becomes less significant. Up to about 50 ft the increase is about 4 to 11 times, depending on the cement content. At higher cement contents, as expected, the increase in shear modulus (at a given depth) is more than that at lower cement contents. Therefore, for the applied nozzle pressure and the water/cement ratio used, grouting was very effective in improving the soil properties up to a depth of about 100 ft. Shear wave velocity also showed a similar relationship.

Effect of cement content

Unconfined compressive strength.

Unconfined compressive strength increases with an increase in cement content (%). Cement with water tends to fill in voids present in the natural soil and improves particle-particle contact by bonding, thereby increasing the strength of the soil. An increase in cement content would lead to more voids being effectively filled and would result in a better particle bonding and so, it would significantly increase the strength. As Figure 6 indicates, a small increase in cement content results in a significant increase in unconfined compressive strength.

Shear modulus/Shear wave velocity.

Shear modulus/shear wave velocity also increases as cement content increases (Figure 7). Shear modulus tends to increase more at higher cement content (*Chang, 1986*).

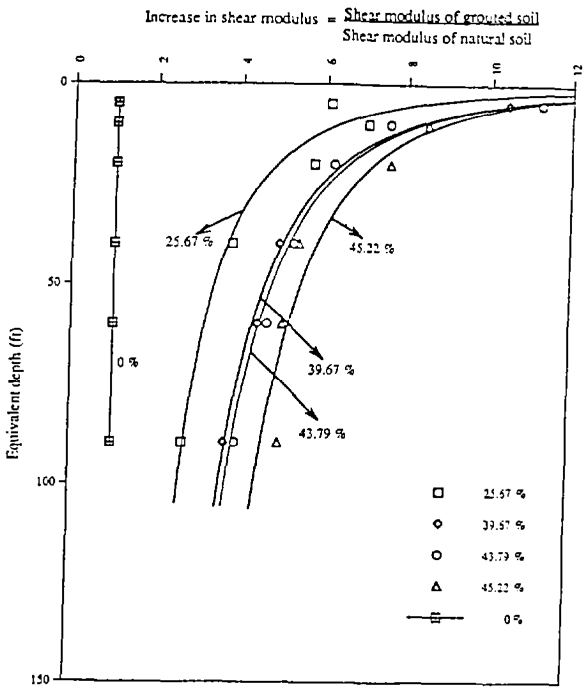

Figure 5 *Increase in Shear Modulus Vs Equivalent Depth (at different Cement Contents)*

The effect of cement content on shear modulus seems to be more pronounced at lower confining pressures (comparing percentage increase in shear modulus at lower and higher confining pressures).

Grouted samples also have higher shear modulus at high confining pressures. However, at high confining pressures, an increase (%) in shear modulus (with respect to natural soil) is less significant compared to the increase at lower confining pressures. This means that at high confining pressures even with the addition of cement, an increase (%) in shear modulus is not significant. Thus cement content influences the shear modulus more significantly at low confining pressures. The shear wave velocity also shows a similar relationship (Figure 8).

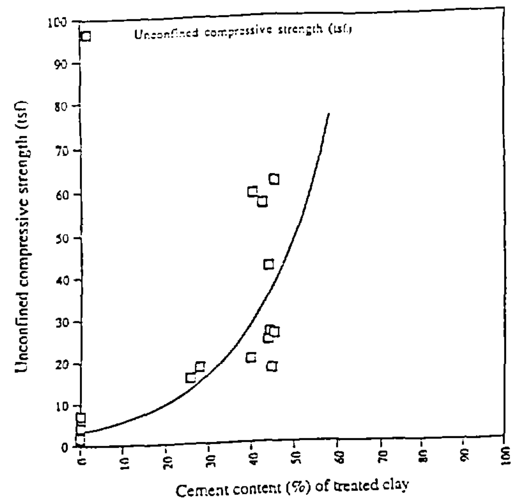

Figure 6 *Unconfined Compressive Strength Vs Cement Content of Treated Clay*

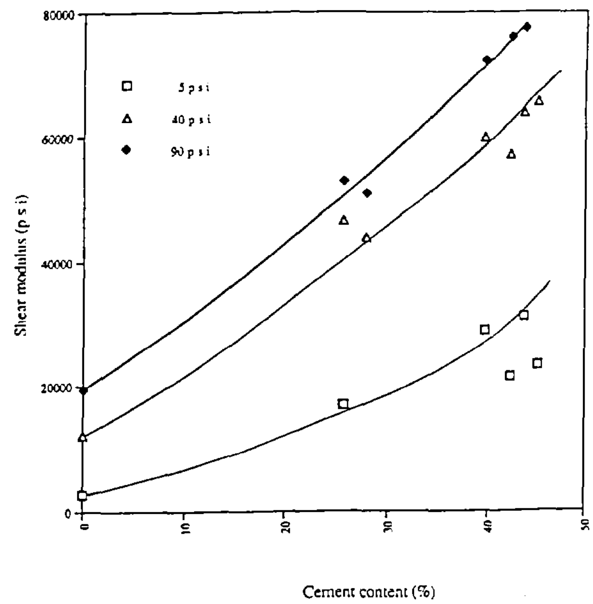

Figure 7 *Shear Modulus Vs Cement Content (at different Confining Pressures)*

Damping ratio.

The damping ratio increases with an increase in cement content (Figure 9), the clay particles become closely packed and hence more energy is required for the wave to propagate through, thereby increasing the damping ratio (*Saxena et al., 1988*). At an average pressure of 40 psi, the damping ratio of natural soil is about 1% and that of grouted soil is about 12% (at 40 psi). This is a significant improvement in the dynamic property of the soil which is useful for dynamic design.

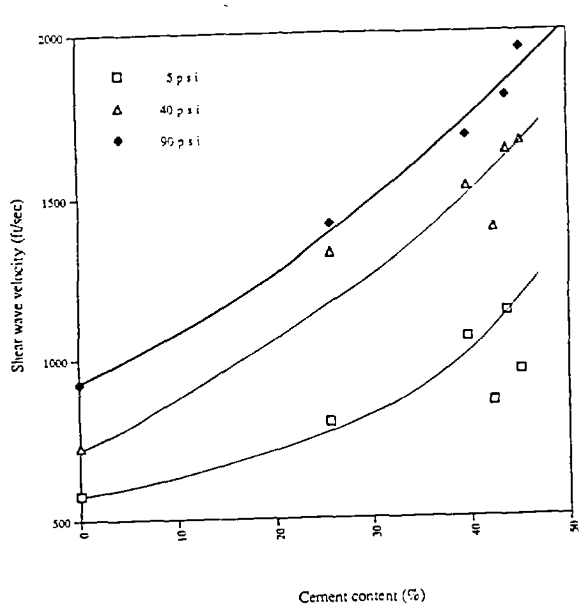

Figure 8 *Shearwave Velocity Vs Cement Content (at different Confining Pressures)*

Effect of water/cement ratio of treated clay

Unconfined compressive strength depends on the water/cement ratio in the slurry that is being injected and the amount of water lost in the following weeks of operation. In other words the strength attained greatly depends on the final water/cement ratio of the grouted soil (*Gallavresi, 1992*). After more than 30 days, when more than 90% strength is achieved, the water/cement ratio is below 1.8. As Figure 10 shows, unconfined compressive strength increases as water/cement ratio decreases.

The increase in unconfined strength due to a decrease of the water/cement ratio is more significant when the water/cement ratio is less than about 1.0, i.e., the cement proportion is more than water.

Although the water content of grouted samples is more than that of natural samples, the presence of cement in the grouted sample has a strong effect toward increasing the static and dynamic strength of the soil.

Figure 11 indicates that shear modulus versus water/cement ratio follows a similar trend like that of shear modulus versus water content of grouted soil (i.e. erratic behavior). As the water/cement ratio goes beyond about 1.0, shear modulus seems to show a decreasing pattern. Shear Modulus appears to increase as the water/cement ratio increases from 0.5 to 1.0 but a clear trend cannot be shown with the available data.

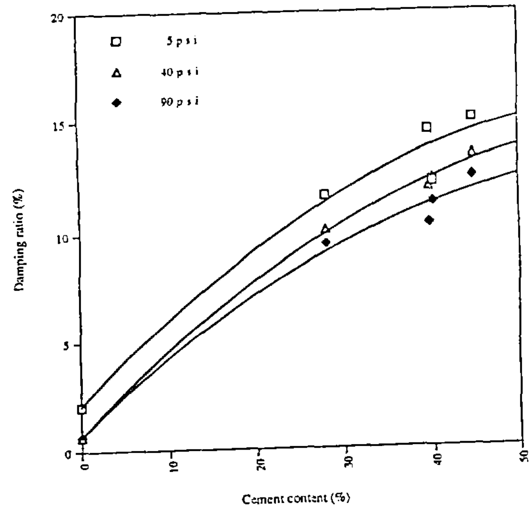

Figure 9 *Damping Ratio Vs Cement Content (at different Confining Pressures)*

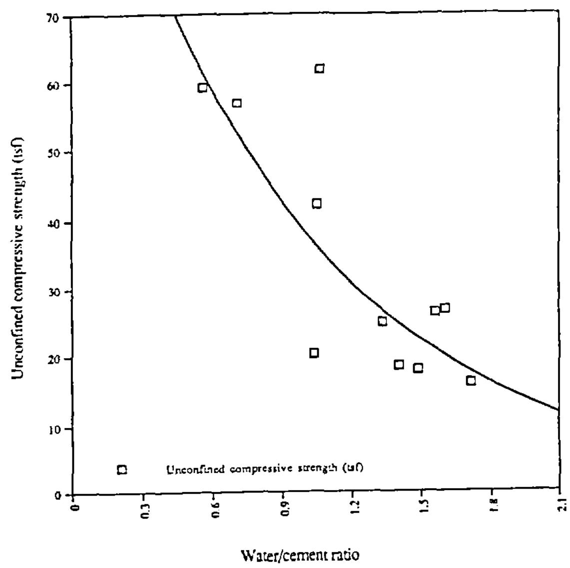

Figure 10 *Unconfined Compressive Strength Vs Water/Cement Ratio*

Relationship between unconfined compressive strength and shear modulus / shear wave velocity

Shear modulus and shear wave velocity increase as unconfined strength increases for both natural and grouted clay (Figure 12). The shear modulus /shear wave velocity of natural sample (Q_u < 6 t s f) seems to be more sensitive to a change in unconfined compressive strength (i.e., a small change in unconfined strength leading to a pronounced change in shear modulus /shear wave velocity) than grouted samples. A clear relationship can be seen between the unconfined compressive strength, shear modulus and shear wave velocity at all pressures used in the tests.

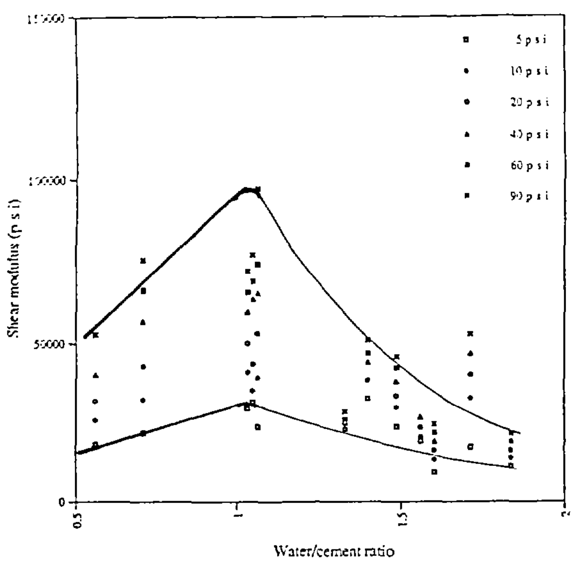

Figure 11 *Shear Modulus Vs Water/Cement Ratio*

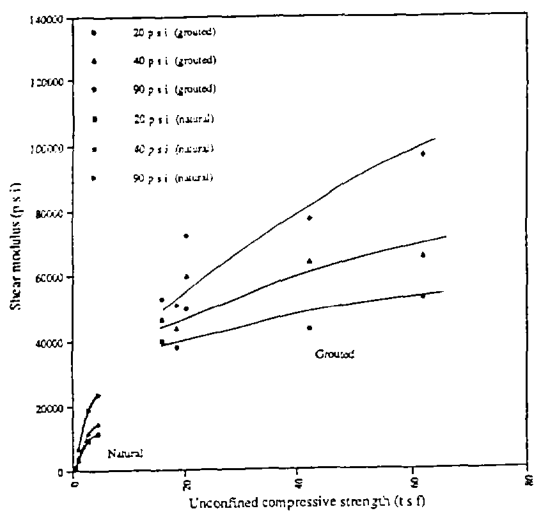

Figure 12 *Shear Modulus Vs Unconfined Compressive Strength (for Natural and Grouted Samples at three different Confining Pressures)*

Further test results are required to derive empirical equations for estimating shear wave velocity/shear modulus from a known confined compressive strength of soils or vice-versa.

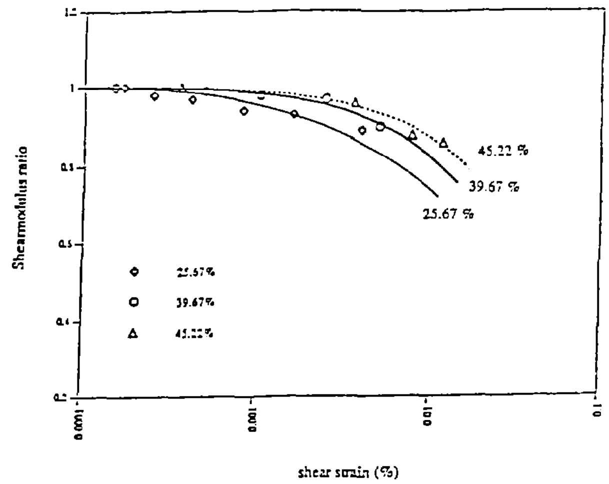

Figure 13 *Shear Modulus Ratio Vs Shear Strain at 20 psi (at different Cement Contents)*

High strain characteristics

As cement content increases the soil becomes more rigid and the modulus versus strain curve tends to flatten with an increase in cement content (Figure 13). Hence at higher cement contents, grouted clays have an elastic strain threshold at much higher strain. Figure 14 compares the behavior of natural and grouted samples at different confining pressures. At higher pressures, grouted samples follow a flat curve implying that they act like a rigid body at high confining pressures. This is useful information for analyzing the seismic response of a site with grouted clay layers when the site is subjected to dynamic loading.

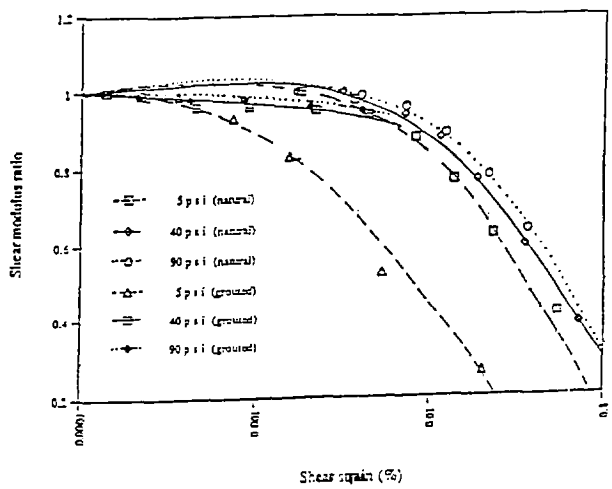

Figure 14 *Shear Modulus Ratio Vs Shear Strain (for Natural and Grouted Samples at different Confining Pressures)*

CONCLUSION

The study demonstrates the significant influence of confining pressure, water content, cement content and water/cement ratio on the static and dynamic strength of soils. The conclusions of the study can be summarized as follows:

1) Grouting improves the static and dynamic strength of the soil to a significant effect, and the improvement is significant up to a depth of about 120 ft for the applied nozzle pressure. Static strength increases from about 0.55 tsf (least unconfined strength of natural soil) to a maximum of 61.91 tsf (highest unconfined strength of grouted soil). In general, the static strength of grouted soil increased by about 15-20 times (with respect to natural soil). At a confining pressure of 40 psi which represents a depth of about 60 ft from the ground surface, the average shear modulus/shear wave velocity increased by about 5-12 times

2) Damping ratio increased from about 2% (for natural soil) to about 13% for grouted soil under a pressure of 40 psi. This implies a significant improvement of dynamic properties as far as resistance to dynamic loading is concerned.

3) Increase of shear modulus due to cement content is more significant at shallow depths than at greater depths. At pressures greater than 40 psi, the increase of shear modulus due to cement content is less significant than at lower confining pressure.

4) The water/cement ratio is a very important parameter that controls the static and dynamic strength of grouted soil. It has a complex relationship with shear modulus. With the present data a relationship or a clear trend could not be established between shear modulus and water/cement ratio. Further studies are required to establish any relationship between these parameters.

5) Unconfined compressive strength and shear modulus/shear wave velocity show a clear relationship for both natural and grouted clay. The shear modulus/shear wave velocity increases with an increase in unconfined compressive strength. This increase is less significant for grouted clay than for natural clay.

6) The high strain characteristics of grouted clay have been significantly improved. At higher cement contents, grouted clays have an elastic threshold at a much higher strain implying higher rigidity with an increase in cement content.

REFERENCES

Acar, Y.B., and El-Tahir, E.A. (1986)."Low Strain Dynamic Properties of Artificially Cemented Sand." Journal of Geotechnical Engineering, Vol. 112, No.11, 1001-1015.

ASTM standards "Standard Test Method for Cement Content of Soil-Cement Mixtures." D 806-89.

Bowles, E.J. (1992) "Engineering properties of soils and their measurement."

Chang, T.S. (1986)."Dynamic behavior of Cemented Sand." Ph.D. thesis.

Chang, T.S. and Woods, R.D. (1987)." Effect of Confining Pressure on Shear Modulus of Cemented Soils." Soil Structure Interaction. Development in Geotechnical Engineering 43. Computational Mechanics Publications. International Conference on Soil Dynamics and Earthquake Engineering, Princeton University, 193-208.

Chang, T.S. and Woods, R.D. (1992)."Effect of Particle Contact Bond on Shear Modulus." Journal of Geotechnical Engineering, ASCE, Vol. 118, No. 8, 1216-1233.

Chang, T.S., Teh, L.K., and Zhang, Y. (1992)."Seismic Characteristics of Sediments in the New Madrid Seismic Zone" CERI Technical Report submitted to NSF, Memphis State University, Memphis.

Clough, G.W., Sitar, N., and Bachus, R.C. (1981)."Cemented Sand under Static Loading." Journal of Geotechnical Engineering, ASCE, Vol. 107, No. 6, 799-817.

Domone, P.L. (1990)."The Properties of Low Strength Silicates/Portland Cement Grouts." Cement and Concrete Research, Vol. 20, 25-35.

Drnevich, V.P., Hall J.R., Jr., and Richart, F.E., Jr. (1967)."Effects of Amplitude of Vibration on the Shear Modulus of Sand." Proceedings of International Symposium on Wave Propogation and Dynamic Properties of Earth Materials, 189-200.

Drnevich Long-Tor resonant column appartus operating manual. Soil Dynamics Instruments, Inc., Lexington, Kentucky.

Gallavresi, F. (1992)."Grouting Improvement of Foundation Soils." Grouting, Soil Improvement and Geosynthetics, Vol. 1, 1-38

Joseph P. Welsh, editor (1987). "Soil Improvement - A Ten Year Update." Geotechnical Special Publication No. 12, 43-55.

Richart, F.E., Jr. , Woods, R.D., and Hall J.R., Jr. (1970)."Vibrations of Soils and Foundations."

Saxena, K.S., Avramidis, S.A., and Reddy, R.K. (1988)."Dynamic Moduli and Damping ratio for Cemented Sands at Low Strains." Canada Geotechnical Journal, Vol. 25, 353-368.