Undrained Shearing Properties of Sand Permeated with a Bentonite Suspension for Static Liquefaction Mitigation

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ABSTRACT

The undrained shearing properties of sand permeated with bentonite suspensions are studied to investigate the use of bentonite suspensions for static liquefaction mitigation. Rheological tests are performed to evaluate the penetrability and the thixotropic strength recovery of the suspensions. The results show that the initial viscosity and the yield stress are reduced significantly by adding 2% sodium pyrophosphate (SPP) to 10% bentonite suspensions. Moreover, the yield stress and the viscosity gradually increase with time due to the thixotropic nature of the bentonite suspensions. The shearing response of the permeated soil is observed by consolidated undrained triaxial tests on loose Ottawa sand specimens permeated with bentonite suspensions. The stress-strain response of the permeated specimens shows no drop in stress after the undrained instability state as compared to the response of clean sand specimens. Additionally, the undrained shear response of the permeated sand specimens displays no cohesion and the same friction angle as clean sand. This indicates that the sand fabric is relatively unaffected by the pressures applied to permeate the bentonite suspension. It is concluded that the permeation of bentonite suspensions could be an effective method of soil improvement for static liquefaction prevention in loose saturated sands.

INTRODUCTION

Permeation grouting is an effective way to deliver fines into the ground, without disturbing the soil's structure, in order to mitigate liquefaction. With this technique, plastic fines are injected into the ground in the form of a suspension. Bentonite is an appropriate material for this type of ground improvement because of its thixotropic nature and environmental friendliness. However, the problem with the use of these concentrated bentonite suspensions for permeation grouting is the high initial yield stress and viscosity. Previous studies have shown that introducing sodium pyrophosphate (SPP) reduces the initial viscosity and yield stress of the bentonite suspensions (Abend and Lagaly 2000, Gonzales and Martin-Vivaldi 1963, and Jessen and Turan 1961), resulting in increased mobility. Moreover, it is found that sodium pyrophosphate allows clay particles to be flocculated with time, indicating thixotropic recovery of its microstructure as opposed to the lack of recovery observed using sodium hydroxide and sodium silicate (Tchillingarian 1952). This implies that bentonite suspensions treated with SPP will have low enough initial viscosity and yield stress to allow permeation but also high enough yield stress and viscosity after settling to prevent the flow of the suspension out of the desired deposit. Furthermore, the gel-like pore fluid formed by thixotropic recovery of the suspension will contribute to reducing the contractive behavior of the sand.

The presence of plastic fines in sand highly affects undrained behavior of the sand by providing "lubricated" contacts between sand particles and reducing the generation of pore water pressure (Carraro et al 2009). Previous studies show that plastic or non-plastic fines reduce the contact area of the sand particles so that the sand shows contractive behavior under undrained loading (Lade and Yamamuro 1997, Abedi and Yasrobi 2009, and El Mohtar 2008). Moreover, there is the general agreement that the presence of plastic fines such as bentonite reduces the generation of excess pore water pressures, resulting in an increase in the cyclic resistance of sands (Polito 1999 and El Mohtar et al. 2008). Based on these findings, it is hypothesized that, provided the plastic fines can be injected in the pore spaces without reducing the particle contacts of the sand, the fines will retard the generation of the positive pore water pressures, resulting in decreased strain softening without changing the shear strength of the sand. This paper shows the possible application of bentonite suspensions for static liquefaction mitigation by investigating the undrained shearing response of the sand permeated with bentonite suspension.

EXPERIMENTAL PROGRAM

Materials

Ottawa sand (ASTM graded sand C778) is utilized for this study. A summary of Ottawa sand properties can be seen in Table 1.

Table 1. Summary of Ottawa sand properties

Gs	2.65	Cu	1.61
e_{min}	0.50	Cc	1.07
e_{max}	0.76	D_{10} (mm)	0.23
USCS	SP	D_{60} (mm)	0.37

The bentonite used for this study is Wyoming sodium-bentonite grade CP-200. All of the bentonite utilized was screened with a No.200 sieve to remove impurities which may have an affect on the results of the rheological tests (Clarke 2008). A summary of the bentonite clay properties can be found in Table 2. The specific gravity of the bentonite was 2.7.

Commercially available Sodium Pyrophosphate decahydrate was used as the dispersing agent for this study. Sodium Pyrophosphate has a specific gravity of 1.8. The chemical structure of the SPP is $Na_4P_2O_7{\cdot}10H_2O$ and the molecular weight is 446.06. The pH of a 5% solution was measured to be 9.5 using a JENCO 60 pH meter. De-stilled, de-aired water was used for the preparation of all bentonite suspensions and for all triaxial tests.

Table 2. Properties of bentonite (Modified from Mitchell and Soga 1976)

PL	35%	CEC	80 to 150 meq/100g
LL	190% to 1160%	Specific area	700 to 800 m^2/g
Initial water content	8.3%	Swelling capacity	8ml/g

Testing Methods

Rheological Tests

The bentonite was sieved through a No.200 sieve to remove impurities and the initial water content of the bentonite was taken into account during determination of the mass of bentonite. The target concentrations were achieved by calculating the mass of bentonite divided by the total mass of the suspension. The concentration of sodium pyrophosphate was determined as the ratio of the mass of SPP to the mass of bentonite. A 5% sodium pyrophosphate solution was utilized for suspension preparation. Bentonite suspensions were prepared with a high speed mixer. The suspensions were mixed in their proper ratios for three intervals of 5 minutes each in the mixer. The suspensions were hand mixed in between intervals to prevent flocs from sticking to the sides and bottom of the steel mixing cup. For samples rested for extended periods of time, the cups were tightly sealed and mineral oil was added at the top of the bentonite suspension to prevent any evaporation from the samples.

Yield stress and viscosity were measured using an Anton Paar MCR301 rheometer. Figure 1 shows the schematic of the rheometer and measuring system used in this study. Vane and cup geometry were utilized to measure the shear rate corresponding to the applied stepwise shear stress at a specific resting time in order to avoid severe disturbance in samples, which is usually caused by the cone and plate setup. The vane consists of six blades 1 mm in thickness and 16 mm in length. The radius of the vane is 11 mm and the bentonite suspension is placed in a cup with 3.46 mm gap between the blades and the cup. Room temperature of 22º was maintained throughout all rheological tests.

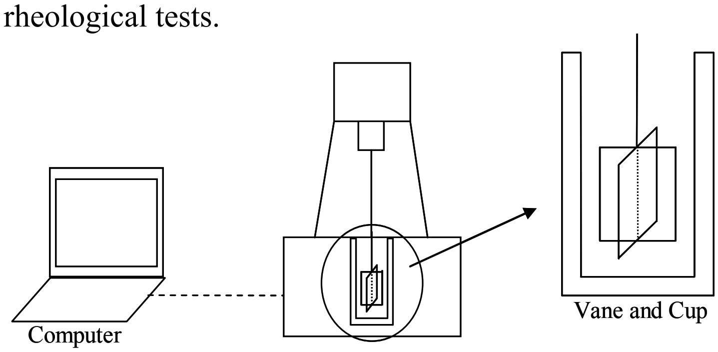


Figure 1. Schematic of Rheological test setup.

The stress ramp test, which is a stress controlled test, was conducted to measure yield stress and viscosity of the bentonite suspensions. The samples were rested for 2 min after inserting the vane to provide consistent initial conditions. Data was recorded at 12 sec intervals and a ramp rate of 3 Pa/step was applied. End effects of the vane were considered small enough to ignore for all practical purposes (Barnes and Carnali 1990).

Consolidated Undrained Triaxial Tests

Consolidated undrained triaxial tests with pore pressure measurements were performed on both clean and permeated Ottawa sand specimens. Tests were run on two different setups. The first system utilized a Wykeham Farrance mechanical loading frame (base loading frame) in conjunction with an upper air actuator piston to apply uplift compensation for isotropic consolidation conditions. This piston was locked during shearing. The second system utilized was the Geojac loading frame by Geotac (top loading frame). External regulators were used to control the cell and pore pressures and external load cells were utilized to measure deviatoric stresses for both setups. Pore pressures were monitored throughout the test from the base of the specimen.

While the clean sand specimens were prepared directly on the triaxial cell's base, the bentonite permeated specimens had to be prepared in a separate permeation mold. A schematic and photograph of this three-way split mold can be seen in Figure 2. The mold was assembled with a latex membrane wrapped around the interior of the central split mold with rubber O-rings just outside the extents of the latex membrane. The membrane took the shape of the central split mold with the aid of a vacuum between the membrane and mold. The O-rings provide an adequate seal between the central split mold and the upper and lower portions of the three-way mold. First, filter materials were placed at the base of the bottom split mold. These materials consisted of approximately 2.54 cm of pea gravel (D>4.75 mm) and 2.54 cm of coarse sand (1.2 mm<D<1.75 mm) on top of the pea gravel. The top of the filter materials is 1 – 2 cm below the base of the central split mold to ensure that the filter materials will not be part of the final specimen. Next the Ottawa sand was air-pluviated into the base of the mold through the central mold and into the upper portion of the mold. The sand was pluviated at a relative density of approximately 35% ($\pm$ 5%). Finally the mold was topped with filter materials and capped.

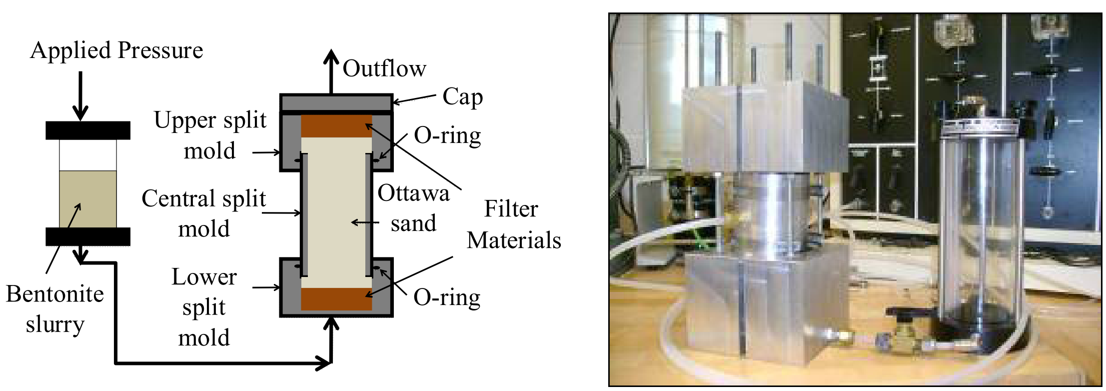


Figure 2. Schematic and photograph of permeation set up.

After assembling the split mold and pluviating the sand, the specimen was flushed from bottom to top with carbon dioxide to help achieve saturation at lower back pressures. Next the specimen was flushed with de-aired water at a rate of 6 ml/minute to prevent the disturbance of the sand structure during flushing. After flushing with water, a bentonite suspension was prepared and permeated through the specimen from bottom to top. The bentonite suspension was permeated from a separate bath as shown in Figure 2 and a pressure was applied to assist in permeation. This pressure was limited to 200 kPa in order to allow for sufficient permeation while attempting to limit changes to the sand fabric during permeation. Following successful permeation, the drainage lines to the split mold were shut and the specimen was allowed a 48 hour curing period.

Next the split mold was disassembled and the specimen was trimmed around the central mold and then placed on the base of the triaxial cell (See Figure 3). At this point, the vacuum between the membrane and the central split mold was released. A vacuum of 25 kPa was then applied to the top of the specimen and the split mold remained around the specimen for an additional 48 hours. Finally, the central split mold was removed, the triaxial cell was assembled, and a cell pressure was applied while removing the vacuum to maintain an effective stress of 25 kPa. After removal of the vacuum, the specimen was allowed a final 24 hours of rest and swell under the seating effective stress of 25 kPa.

Figure 3. Bentonite permeated specimen under vacuum and after bulging failure.

After specimen preparation (and curing) was complete all specimens were back pressure saturated to achieve a B-value of at least 0.95. The back pressure stage was performed rather quickly for the clean sand specimens (2 to 3 hours) and significantly longer for the bentonite permeated specimens (up to 2 to 3 days), but targeted B-values were generally reached at back pressures of 200 to 250 kPa for all specimens. Next, the specimens were consolidated to the desired effective stress (50 to 200 kPa). The clean sand specimens were allowed to consolidate under each increment for 10 to 20 minutes, while the permeated specimens were allowed to consolidate 24 hours under each consolidation stress. Finally, the drainage lines were closed and the specimens were sheared undrained. The clean sand specimens were sheared at a rate of 0.254 mm/min (0.2%/min) and the permeated specimens were sheared at 0.0356 mm/min (0.025%/min). All specimens, both clean and permeated, displayed bulging failures as seen in Figure 3 and as is expected for loose sands with no adjustments for end friction.

The clean sand specimens were air-pluviated directly on the triaxial cell's base to achieve a relative density of approximately 35% (± 5%). All specimens were approximately 70 mm in diameter and 140 mm in height. The clean sand specimens were then subject to a vacuum of 25 kPa while the triaxial cell was assembled. Next the vacuum was removed while simultaneously increasing the cell pressure to maintain an effective stress of 25 kPa. Under this seating cell pressure, the specimen was flushed with carbon dioxide. Next the specimen was flushed with water at a rate of 6 ml/minute. After this saturation stage the $\overline{CU}$ triaxial test was conducted in a similar manner as described for the bentonite permeated specimens.

After shearing was complete, the permeated specimens were sliced into three pieces: top, middle, and bottom. The water content was determined for each section and the final void ratio was calculated assuming saturation. This is a reasonable assumption since all specimens achieved B-values of 0.95 or greater. Skeletal void ratios were determined for the permeated specimens and the bentonite content was then determined for the top, middle, and bottom of each specimen using a specific gravity hydrometer and a calibration curve determined by El Mohtar (2008).

RESULTS AND ANALYSIS

Rheological Tests

Yield stress and viscosity is used to estimate the penetrability of the suspensions. The log γ-log τ method (Zhu et al. 2001) was utilized to determine yield stress, which is defined as a shear stress to initiate flow of fluid. The intersection between the initial linear portion and the plateau is determined as the yield stress. If a suspension has no yield stress, the plateau does not exist. Figure 4 shows a log γ-log τ plot for treated and untreated 10% suspensions. For the untreated suspensions, a yield stress of approximately 140 Pa was found. This yield stress was reduced to approximately 0 Pa with the addition of 2% SPP.

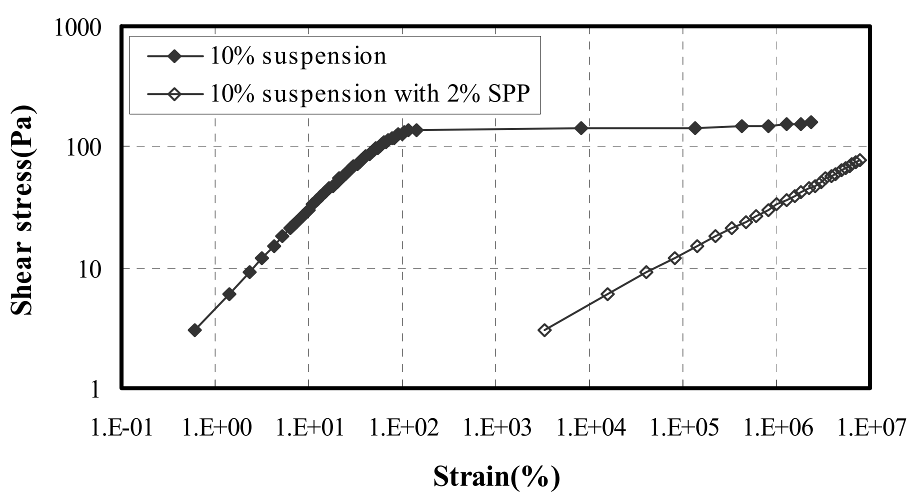


Figure 4. Shear stress-strain curves for 10% suspension and 10% suspension with 2% SPP.

Figure 5 demonstrates reduction in viscosity with the addition of SPP. Although the variation of viscosity is different at each shear rate, it is reduced by approximately one order of magnitude. This reduction in yield stress combined with the reduction in viscosity allows for the successful permeation of sand specimens with treated bentonite suspensions.

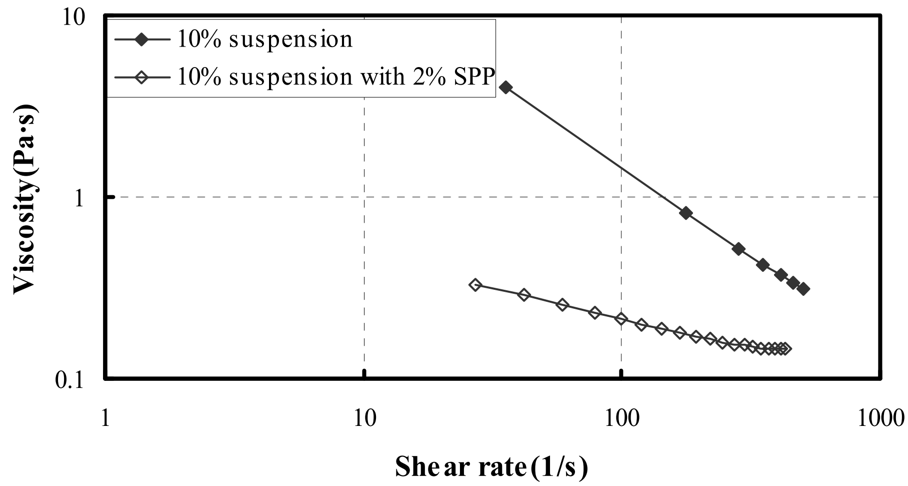


Figure 5. Viscosity-shear rate curves for 10% suspension and 10% suspension with 2% SPP.

Figure 6 presents the increase of yield stress with time due to the thixotropic nature of the bentonite suspensions for the treated (2% SPP) and untreated 10% suspension. Initially, the yield stress is significantly reduced with the addition of 2% SPP; however, over time, the yield stress of the treated suspension converges with that of the untreated suspension. The bentonite permeated sand specimens were sheared after approximately 6 to 9 days from permeation, depending on the consolidation pressure (the specimens were allowed 24 hours for each consolidation stage). During this time, the suspension will be subjected to different levels of strains, but a significant portion of the yield stress and viscosity will still be recovered. The difference in times is not expected to have a significant effect on the results since the thixotropic increase in yield stress between 6 and 9 days is minor.

For this study, eight consolidated undrained triaxial tests were run on clean Ottawa sand and nine tests were run on Ottawa sand permeated with 10% bentonite and 2% sodium pyrophosphate suspensions. Figure 7 shows (a) excess pore pressure versus strain and (b) stress strain response for clean and permeated specimens consolidated to 200 kPa effective stress. The permeated specimens tend to show more of a dilative behavior as compared with the clean sand specimens. This phenomenon is observed due to the presence of the thixotropic bentonite pore fluid, which reduces the ability for the sand grains to contract into a denser configuration and thus generate positive pore pressures. The reduced excess pore pressures generated in the permeated specimens, as seen in Figure 7 (a), cause these specimens to reach critical state at higher deviatoric stresses than the clean sand specimens.

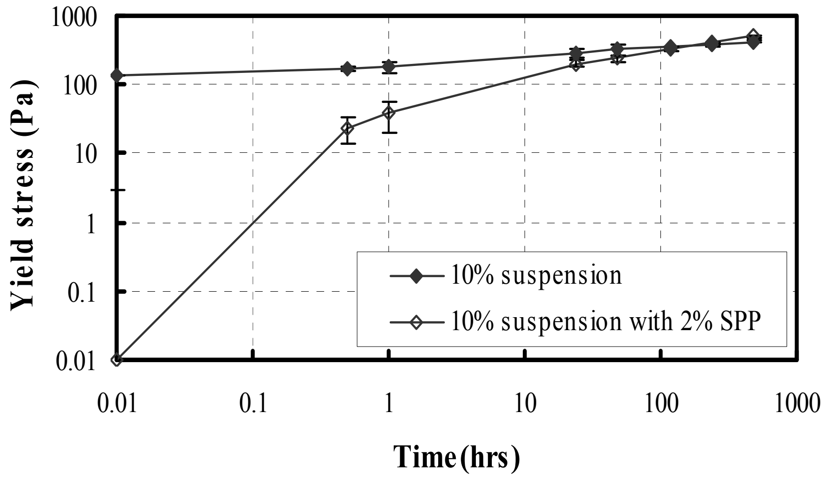
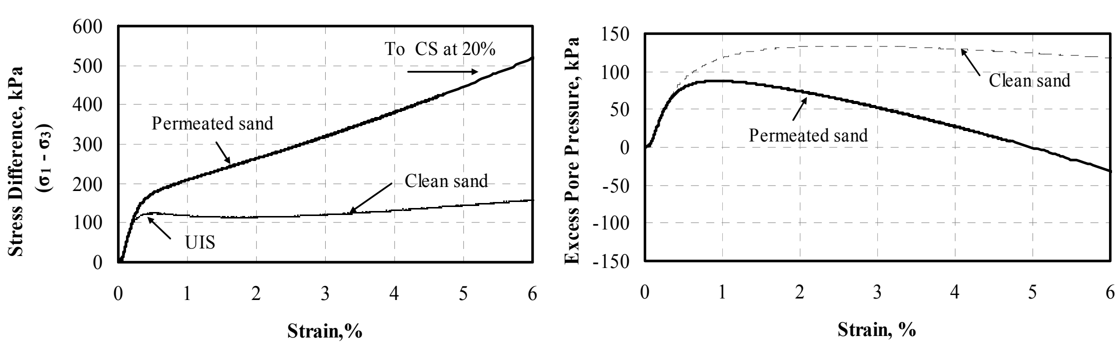


Figure 6. Thixotropy of 10% suspension and 10% suspension with 2% SPP.

Consolidated Undrained Shear Strength

Two friction angles were reported for each type of specimen. The first friction angle reported corresponds to the undrained instability state (UIS) for clean sands. The UIS is the point at which a loose or medium loose sand will first begin to show a tendency to liquefy and flow, as indicated in Figure 7 (a). This state is important to engineers because it corresponds to the peak undrained shear strength at small strains (Murthy et al. 2007). For the permeated sands, since there is no true "undrained instability state," the location of the initial change in slope on the stress-strain plots was used to compare this small strain friction angle. Furthermore, the permeated specimens display no UIS and thus show no tendency to flow. This concept is further illustrated in Figure 8, where it can clearly be seen that the permeated specimens show only a very slight tendency toward the left before the phase transformation state is reached, and dilation begins. The phase transformation state demarks the change in response from contractive to dilative behavior (Murthy et al 2007). This change in response under static loading indicates a higher resistance to static liquefaction due to the reduction in the generation of positive pore pressures.



(a) (b)

Figure 7. Stress difference (a) and excess pore pressure (b) versus strain for clean and permeated specimens.

Figure 9 shows a modified Mohr-Coulomb plot for the clean and permeated specimens. For the clean sand, the friction angle corresponding to the undrained instability state (φ'_{uis}) is equal to 21˚. For the permeated specimens, this small strain friction angle is equal to 22˚. The second friction angle reported for each specimen is the Critical State friction angle (φ'_{cs}). The critical state friction angles for clean and permeated sands are calculated as 29˚ and 31˚ respectively. Since the small strain and critical state friction angles for the clean and permeated specimens are similar, it is safe to say that the addition of a small amount of highly plastic clay to a soil deposit via permeation grouting does not have a detrimental affect on the shear strength of the soil. Also, the coincidence of φ'_{uis} for both types of specimens tends to indicate that there must not be a significant disturbance to the soil fabric during permeation.

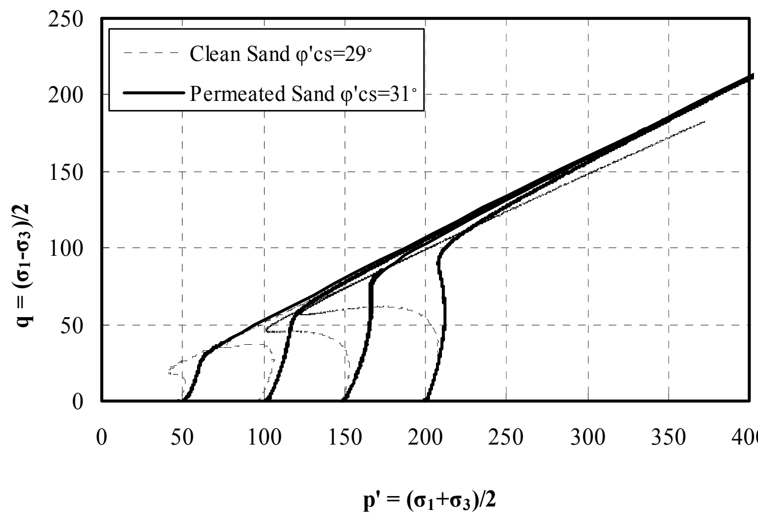


Figure 8. q-p' plots for clean and permeated specimens.

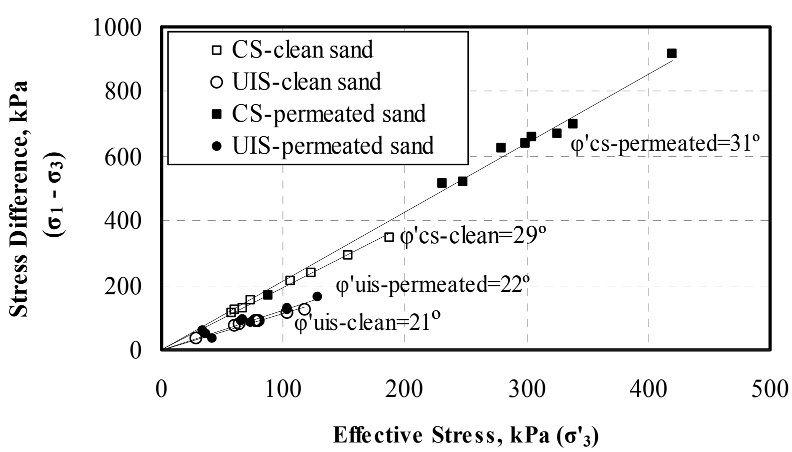


Figure 9. Modified Mohr-Coulomb plot for sand and permeated specimens.

CONCLUSIONS

Yield stress and viscosity were measured to investigate the penetrability of bentonite suspensions into sand. The addition of Sodium Pyrophosphate reduced the initial viscosity and yield stress, indicating an increase in mobility of the bentonite suspensions. With the addition of SPP, high concentration bentonite grout (10% by dry mass) was flushed through uniform fine sand without changing the structure of the sand.

Consolidated-Undrained behavior of clean sand and permeated sand was investigated. The permeated sand showed more dilative behavior than clean sand with reduced generation of excess pore water pressures. Moreover, the permeated sand did not display an undrained instability state, indicating that strain softening was not induced during the static loading. Based on these findings, it is concluded that permeation grouting with SPP treated bentonite suspensions can be an effective way to mitigate static liquefaction.

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