



POLYMER INJECTION AND ASSOCIATED SITE LIQUEFACTION REMEDIATION MECHANISMS

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Abstract

The results from a pilot study performed at the University of California, San Diego to assess potential of the polymer injection technique as a liquefaction countermeasure are presented. Three containers of dimensions about 1.1 m (length) by 0.9 m (width) by 1.0 m (height) are filled with saturated Ottawa F-65 sand at loose, medium-dense and dense relative densities. An expansive polymer is then injected into each container. Once the polymer material was cured, all three containers are placed on a shake table and subjected to strong dynamic excitation. Post shaking, all three containers are carefully dissected to observe the extent of permeation of the polymer within the saturated sand. On careful examination of the hardened composite polymer-sand inclusion, mechanisms contributing to improved liquefaction resistance including densification, cementation, and increase in lateral confinement are observed. The composite inclusions are characterized based on weight/volume relationships. Further, an initial guideline is proposed to relate amount of polymer to increased level of liquefaction resistance, in preparation for large-scale shake table testing. A recommendation is then made, in the context of an example, towards deploying the developed framework for field applications.

Keywords: Liquefaction Countermeasure, Polymer, Polyurethane, Settlement, Ground Improvement



1. Introduction

Seismically induced soil liquefaction is a documented mechanism that results in severe damage to structures and foundation systems. Liquefaction-induced loss of soil strength and stiffness and subsequent consequences have been well documented in several major earthquakes including events in Japan, Turkey, India and New Zealand [1-6]. For example, during the 2010-2011 Canterbury earthquake sequence, severe soil liquefaction affected 3,000 buildings within the Central Business District (CBD) of Christchurch, of which over 50% were to be demolished, being deemed economically unfit for further repairs [7]. Hence in high seismic regions, with loose saturated granular soils, it is vital that remediation measures be undertaken to minimize the consequences of soil liquefaction.

Various techniques currently exist to improve liquefaction susceptible soils, including strategies involving soil densification [8, 9], cementation [10], drainage, and replacement. Among the mitigation techniques [11], the injection of low viscosity polyurethane (polymer) using permeation grouting has proven to be an effective measure for remediation, at locations which might otherwise be difficult to treat with conventional techniques [12, 13]. Injection of expansive polymers into the ground has long been used to improve karsts in soil, reduce permeability, improve soil strength, particularly to prevent subsidence during excavation or tunneling, and relevel structures exhibiting differential settlement [14, 15].

In the context of liquefaction remediation, the technique offers two-fold benefit in terms of a reduction in the shear demand (cyclic shear stress ratio) and improvement in soil confinement and related liquefaction resistance (cyclic resistance ratio) of the insitu soil [13]. The injection methodology (Fig. 1) uses either low viscosity grouts injected under pressure to hydro-fracture the soil or high-viscosity grouts that densify soil through compaction. The polymer is injected through thin cold form steel tubes with either an opening at the tip or using sleeved tubes (*tube à manchette*) which offer a distributed surface [15]. The tubes are typically deployed at a spacing of 0.9 m-1.0 m on center and are easy to install in dense urban environments as it does not require an excavation [13]. The ability to tailor polymers with structural and rheological capabilities specific to the ground conditions is a considerable advantage to this technique. For example, such an improvement strategy could even be adopted in the presence of underground utilities whereby a low viscosity polymer would be injected to allow for permeation without damage to buried infrastructure.

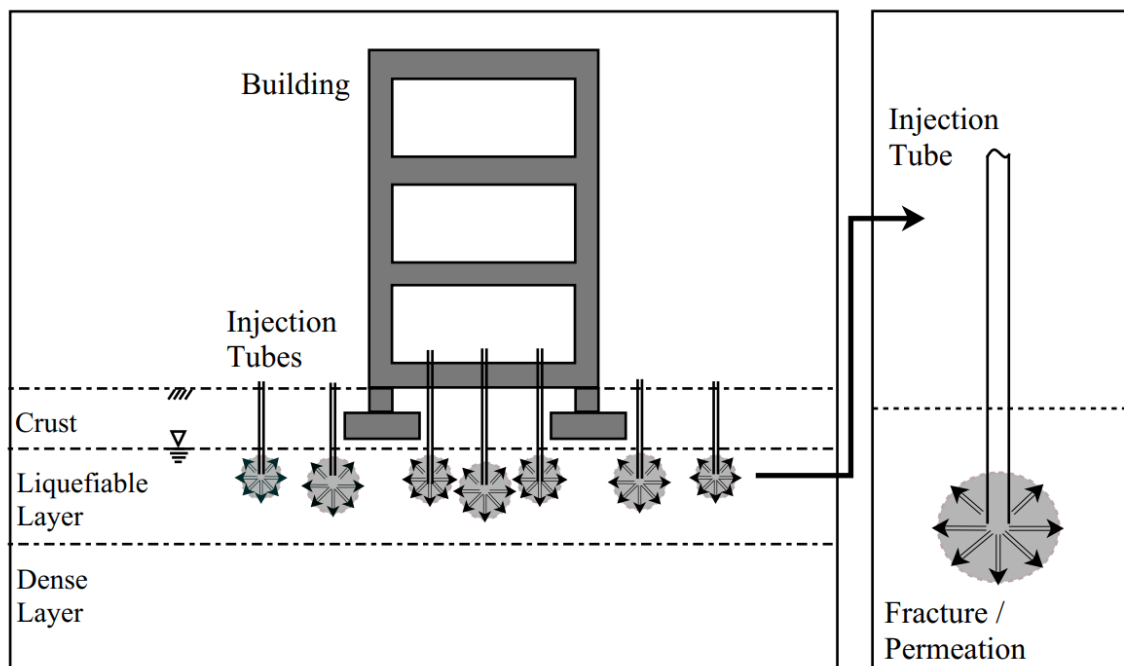


Fig. 1 – Typical Layout and mechanisms in polymer injection



In this paper, the authors discuss the results from a pilot experimental stage of a three-phase testing program. Overall, the aim is to study a number of ground improvement strategies to remediate liquefaction induced settlement of a shallow foundation on loose liquefiable soil through 1g-large scale shake table testing [17]. The pilot experiment is performed to provide insight into the mechanisms contributing towards improved liquefaction resistance of polymer remediated soils. The results from this phase are then used to develop a methodology to estimate the extent of remediation required in the subsequent large-scale shake table test, with an initial guideline chart for practical applications.

Within this pilot phase, three identical containers are filled with sand at different relative densities (D_r) and polymer is injected thereafter into the containers. The three containers are then subjected to base excitation on the shake table facility at the Powell Structural Engineering Laboratories at UC San Diego (UCSD). Further, the containers are carefully dissected to characterize the extent of polymer permeation and properties of the hardened sand-polymer matrix (composite inclusion). Associated ground improvement mechanisms contributing to the increased liquefaction resistance are explored. Recommendations made from this testing phase are provided to aid in the design of related large-scale testing and applications in practice.

2. Specimen Characterization and Polymer Injection

2.1. Specimen Preparation

Specimen construction involved the preparation of three containers (Fig. 2), each about 1.10 m (length) by 0.90 m (width) by 1.00 m (height), filled with Ottawa F-65 sand. Different deposition techniques were employed in order to build loose, medium-dense and dense specimens (in each container). Ottawa F-65 is a clean poorly graded fine sand with minimum and maximum dry densities of 14.02 kN/m^3 ($e_{\max} = 0.83$) and 17.3 kN/m^3 ($e_{\min} = 0.51$) [18].

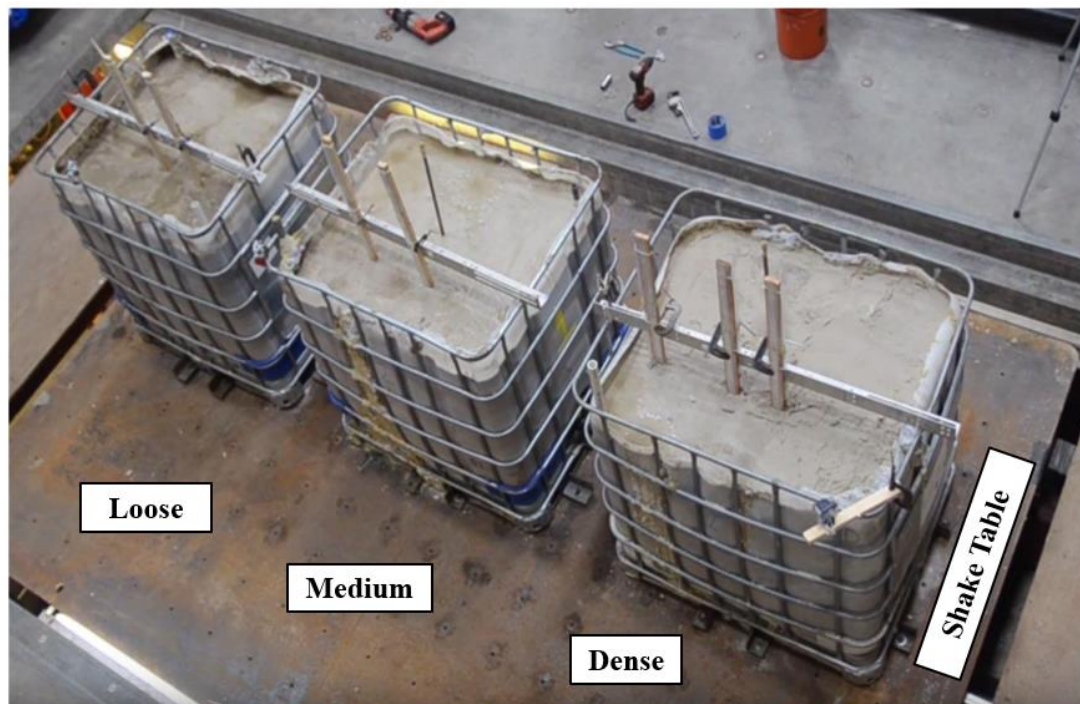


Fig. 2 – Containers placed on the shake table platform

Each container is equipped with a u-shaped perforated piping system at its base to saturate the soil specimen. Further, three flexible acrylic tubes of diameter 12 mm are embedded at different depths to monitor the dissipation of excess pore pressure within the specimen (i.e., serving as piezometers). The weight of the



dry sand and water deposited into each specimen is noted during each lift. Each container is filled with sand up to a specimen height of 0.95 m as follows:

2.1.1. Loose Sand

The container with loose sand is prepared using the hydraulic fill approach, whereby Ottawa sand is first pluviated into the model while maintaining a clear water head of 125 mm resulting in a specimen relative density (D_r) of about 30%.

2.1.2. Medium-Dense Sand

The container with medium-dense sand is prepared using the hydraulic fill approach, whereby Ottawa sand is deposited into the soil model while maintaining a clear water head of 75 mm, resulting in a specimen D_r of about 55%.

2.1.3. Dense Sand

The container with dense sand is prepared moist in 5 lifts. Each lift consisted of sand deposition up to a height of 200 mm with further compaction using 10 blows of a 23 kg hammer. The process is repeated till the specimen height is achieved and saturated by adding water slowly through the perforated piping system installed at the base of the container. A specimen D_r of about 80% was achieved using this method approach.

Table 1 summarizes the achieved relative densities and equivalent corrected standard penetration test (N_1)₆₀ blow count based on Eq. (1) as proposed by Idriss and Boulanger in 2008 [19].

$$D_r = \sqrt{\frac{(N_1)_{60}}{46}} \quad (1)$$

Table 1 – Summary of specimen properties

Specimen	Weight of Sand (kN)	D_r (%)	Equivalent (N_1) ₆₀
Loose Sand	14.3	30	4
Medium-Dense Sand	15	55	14
Dense Sand	15.98	80	29

2.2. Polymer Injection

Post sample preparation, each container is injected with 18.15 kg of a two-component expansive polymer (designated EagleLIFT™ EL077), as shown in Fig. 3. The amount of polymer injected is based on the typical scenario to level-correct buildings on incompetent soil, as a first estimate in this preliminary test.

The structural polyurethane (polymer) used in this study is a two-component chemically blown foam consisting of a curative phase (poly-isocyanate) and a resin phase (including polyol). The two components are mixed in equal parts to produce the expanding foam at a nominal temperature of 43°C. The resulting structural foam has a free rise density of 64 kg/m³. On injection, the polymer used in this study has a low viscosity and a cream time of 7 s and expands in volume depending on its surrounding state of confinement (thereby increasing in viscosity). In this experiment, the injection is performed only at a single point in each container, at a height of 300 mm from the base of each container. After injection, the polymer was allowed to cure for 72 hours.

3. Shake table testing and results

Post injection, all three specimens are carefully lifted and placed on the uniaxial shake table facility at the Powell Structural Engineering Laboratories, University of California, San Diego. The uniaxial shake table platform has dimensions of 4.9 m by 3.1m and is designed for models that weigh up to 350 kN. Further details



concerning the shake and its performance characteristics are reported by Trautner et al. [20]. All specimens are subjected to a test protocol that consisted of two base motions (Fig. 4), allowing for excess pore pressure dissipation between, as observed through the embedded thin flexible acrylic tubes.



Fig. 3 – Polymer injection in each container

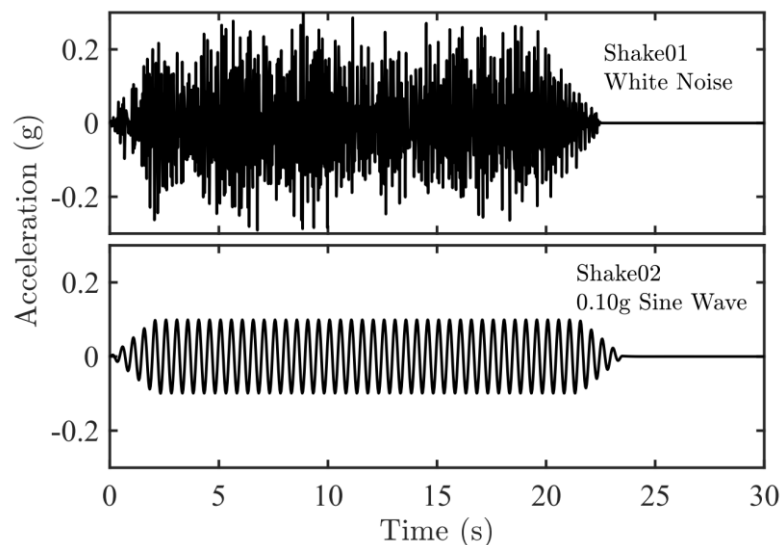


Fig. 4 – Base excitation imparted to the specimen

Significant rise in pore water pressure and consequent volumetric settlement were observed in the loose and medium-dense specimens during shake01. Loss of effective confinement was evident with ground surface oscillation and subsequent tilting of the injection tube in the loose specimen. As such, the amount of polymer that remained within the loose specimen after injection could not prevent liquefaction. Relatively moderate ground oscillation of the pipe was seen in the medium-dense specimen, and no movement was observed in the dense specimen, indicating an adequately sustained level of effective confinement during the shaking phase. Following each shaking event, the volumetric (settlement) strains developed in each specimen are presented in Fig. 5.

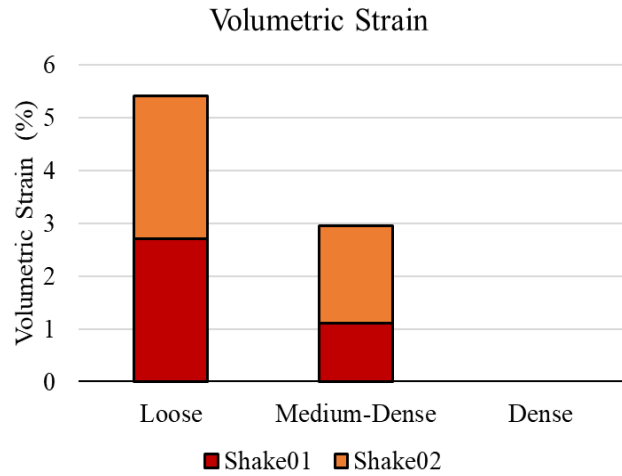


Fig. 5 – Volumetric (settlement) strains developed after each shaking event in the three specimens

4. Excavation and results

4.1. Model Excavation

After shaking, the containers were dissected, and the sand was excavated to see the formation of the composite inclusion within each specimen (Fig. 6). Emphasis is based on the distribution of the polymer around the point of injection. As seen in Fig. 6, due to the low initial viscosity and high mobility, the orientation of the inclusion is irregular in all three specimens.

However, several salient features of the formation of the inclusion can be delineated (Fig. 7). In the loose and medium-dense specimens, the polymer is first seen to permeate laterally around the injection point, creating a grout bulb. Veins are then seen to emanate from this bulb, particularly at locations closer to the injection tube. The dense specimen is able to retain more of the polymer within its soil mass and hence the composite inclusion is not localized around the injection tube.

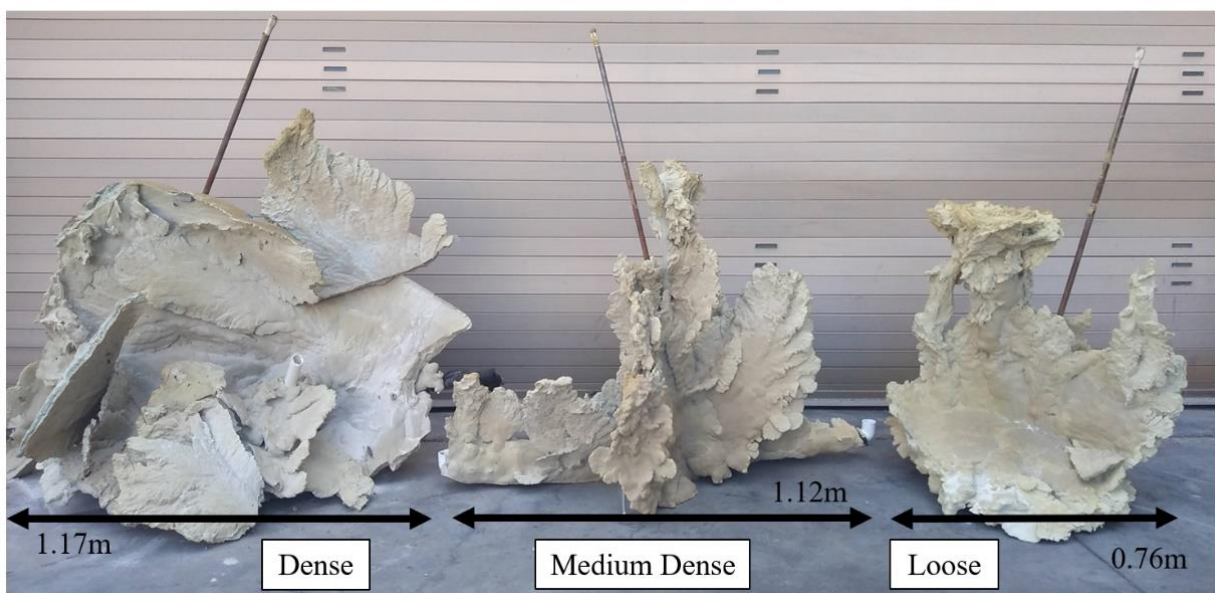


Fig. 6 – Hardened composite inclusions obtained post excavation



Fig. 7 – Observed composite inclusions (veins) after excavation in the dense and medium-dense specimens

Fig. 8 presents a cross-section of the composite excavated from the medium dense specimen, where several zones can be observed including a cemented polymer-sand surficial zone and a pure polymer inner zone. The extent of each of these zones can be attributed partially to the variation in fluid viscosity, extent of permeation, and the polymer expansion post injection. The polymer initially fractures through the soil deposit and then permeates into the sand. With cementation a portion of this sand mixes with the polymer and contributes to the cemented interface sand zone. Polymer expansion leads to further separation of surfaces where zones of the pure polymer are sandwiched between layers of cemented sand.

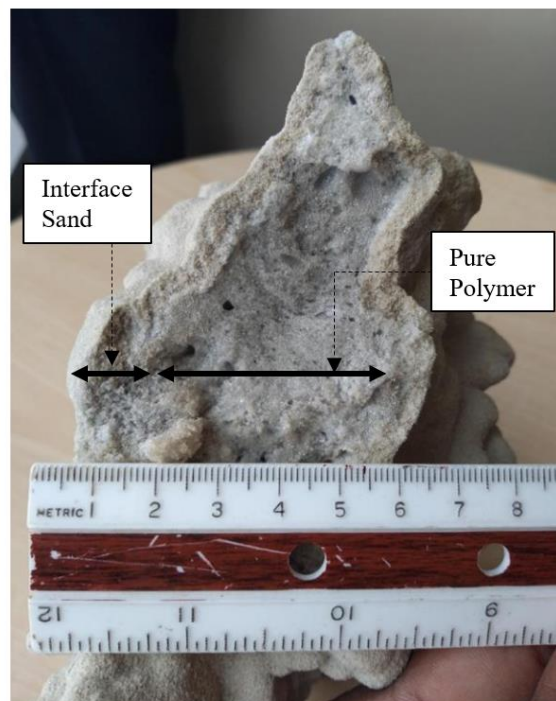


Fig. 8 – Cross section of the hardened polymer sand matrix obtained from the medium-dense specimen

After the dissection process, the three composite inclusions are weighed. Volume of each is estimated by immersion into a prismatic container filled with water and measuring the change in the water level pre and



post immersion. Table 2 presents a comparison of the mass densities of the three composite inclusions, where volume of the inclusion is normalized by volume of the soil in each container (0.93 m^3).

As the range of mass densities of pure polymer (80 kg/m^3 - 240 kg/m^3) and deposited sand in each specimen is known beforehand, it is possible to approximately estimate the amount of pure polymer and cemented sand within each composite inclusion from a mass balance calculation. Once obtained, an expansion ratio (volume of expanded soilified polymer compared to its liquid volume) can be established. On this basis, it is seen that on an average, pure polymer encompasses about 60% (by volume) of each composite inclusion (interface sand occupying 40%) in all three specimens. In addition, an average polymer expansion ratio of 2.7 is noted.

Table 2 – Mass and Volume of composite inclusions

Specimen	Mass of composite (kg)	Normalized Volume of Composite (%)	Mass Density (kg/m^3)	Estimated pure polymer in composite (%)	Estimated expansion ratio
Loose	25.9	3.64	741	(60 - 67)	2.5
Medium-Dense	33.75	4.26	825	(55 - 62)	2.2
Dense	61.1	7.79	816	(56 - 62)	3.5

4.2. Degree of soil improvement

As the volumes of pure polymer and cemented sand zones within the composite inclusion are now reasonably obtained, it is possible to estimate the D_r of the remaining sand which surrounds this inclusion (based on replacement assuming constant volume conditions). In the conducted experiment, this assumption is acceptable, as no significant visible heave was observed in the soil surface during injection.

Post injection, a fraction of granular phase of the sand is assumed to be cemented (obtained from Table 2) within the composite inclusion. The volume available for the granular phase uncemented sand (surrounding the inclusion) is hence reduced, assuming the injection occurs at constant volume. Since volume of the inclusion and the cemented sand in each container have been reasonably estimated, the D_r of the uncemented sand surrounding the inclusions can be obtained. As such, Fig. 9 presents the estimated improvement in the D_r of the surrounding uncemented sand. It is noted that a D_r greater than 100% in the dense specimen represents that a larger portion of the sand had been cemented in comparison with the estimate.

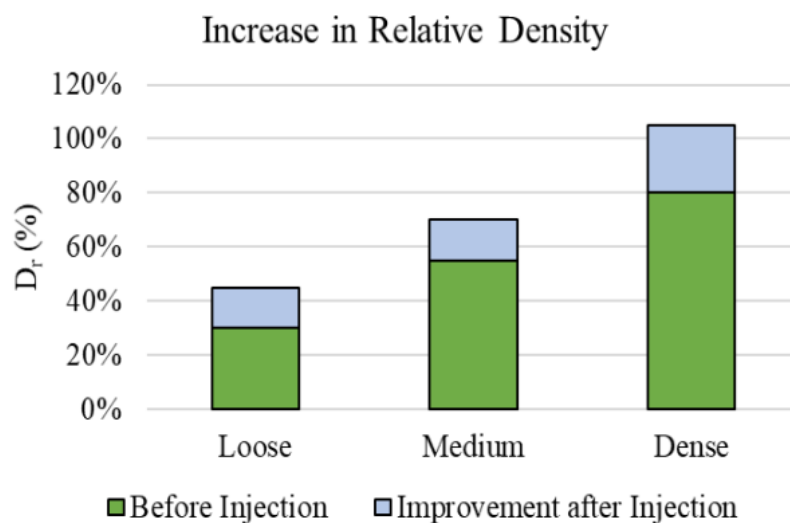


Fig. 9– Estimated Improvement in relative density (D_r) assuming constant volume conditions



5. Application to large scale testing

A framework is developed to derive a family of curves relating the final relative density of the uncemented sand to the volume of polymer injected in its liquid (Fig. 10), keeping in mind the following assumptions (per the earlier sections):

1. The deposit consists of granular soil
2. Injection takes place under constant volume (no heave or polymer escape through ground surface)
3. Expansion ratio of 2.7 is assumed (average value from the three specimens)
4. 40% of the composite inclusion consists of cemented sand.

The set of curves in Fig. 10, specifically address the change in $(N_1)_{60}$ within the uncemented sand of the improved layer. Through injection, the polymer expands (estimated at 2.7 times in this experiment) and a portion of the soil is cemented (therefore non-liquefiable). Due to this expansion, the remaining uncemented soil occupies less space and the new D_r can be obtained. In a field setting, the assumption of constant volume might be difficult to achieve. Thus, it would be a solution that a perimeter grout curtain could be created to help containment and prevent polymer escape.

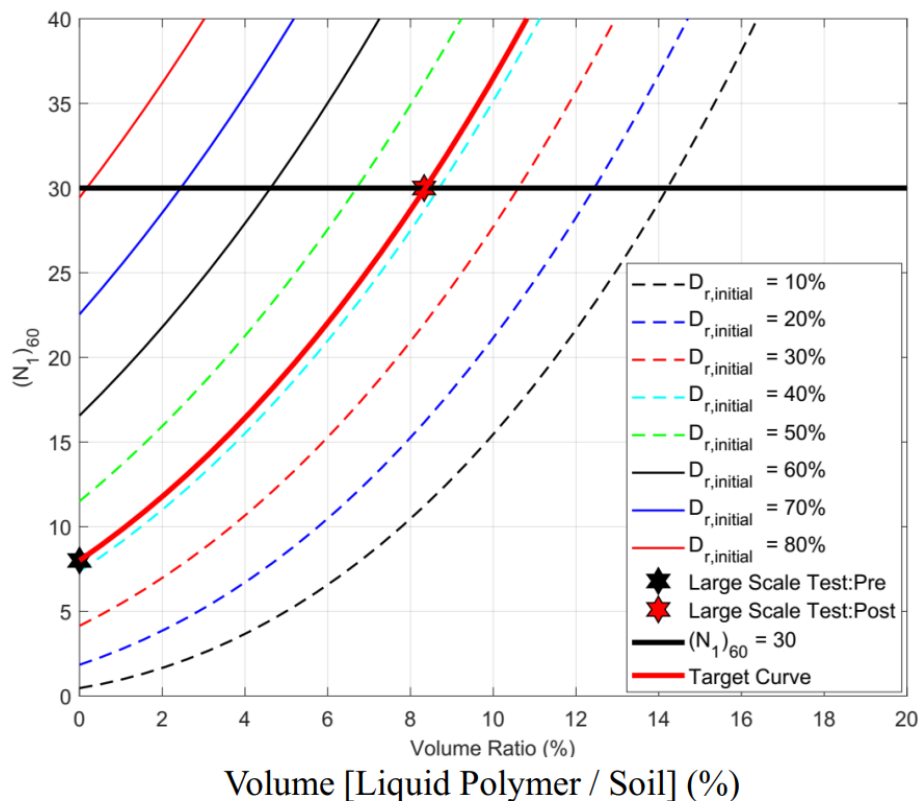


Fig. 10 – Family of curves developed to relate $(N_1)_{60}$ to the volume of injection

In the second phase of this experimental effort, a large-scale shake table test is conducted to study the response of a shallow foundation overlain on surficial liquefiable soils. The soil model in the experiment consisted of a three-layered deposit, consisting of a saturated 1.00 m dense bottom layer underlying a 1.25 m thick saturated liquefiable deposit, overlain by a moist 0.64 m crust. The loose liquefiable layer is constructed at D_r in the range of 35 %-44 %, corresponding to an $(N_1)_{60}$ of 5-9. The model is subjected to cyclic base excitation and large liquefaction induced settlements are observed as shown in Fig. 11. Full details of this testing program can be found in [17]. To remediate liquefaction induced foundation settlement in this baseline



experiment, an identical model is constructed with the EagleLift EL077 polymer injected into the loose liquefiable stratum. The methodology is applied specifically to strengthen the loose sand stratum within this large-scale shake table test.



Fig. 11 – Observed soil-foundation system response [17]

In the polymer remediated experiment, a corrected blow count $(N_1)_{60}$ of 30 (corresponding to a volume ratio of 8.4%) is selected as the target (Fig. 10), conceptually to preclude liquefaction. The remediated model post shaking response is presented in Fig 12, where the actual achieved volume ratio is about 7.9% is achieved. Full details may be found in Prabhakaran et al. [21].



Fig. 12 – Observed soil-foundation system response after injection [21]



6. Conclusions

A testing program was conducted to evaluate the mechanisms associated with improved liquefaction resistance in granular soils remediated with the polymer injection technique. Three containers were filled with sand at loose, medium-dense and dense relative densities, injected with polymer, with base excitation imparted. The specimens were then carefully dissected to examine the composite inclusion within the surrounding sand. Within all three composite inclusions, around 60% by volume of each was estimated as pure polymer. Across the three inclusions, the polymer was seen to expand about 2.7 times as compared to its liquid volume. This ratio could be used to estimate the degree of polymer expansion under similar confinement scenarios.

A number of mechanisms are noted to contribute to the observed improved liquefaction resistance. These mechanisms are illustrated via a representative scenario where deposit of clean sand at $D_r = 30\%$ (corresponding to $(N_1)_{60} = 5$) is improved by 6% volume polymer (in its liquid state).

1. The polymer forms a composite inclusion at relatively constant volume. This inclusion cements a portion of the liquefiable sand and reduces the shear demand on the surrounding soil due to the improved cemented composite stiffness. The 6% by volume injection will result in about 27 % of the total volume being occupied by the non-liquefiable composite inclusion.
2. Expansion of the polymer provides for an increase of D_r in the surrounding uncemented sand. This mechanism contributes to the increase in liquefaction resistance. Within the context of this representative scenario, an improvement in D_r will take place from 30 % (corresponding $(N_1)_{60}$ of 5) to about 57% (corresponding $(N_1)_{60}$ of 15). However, we must be mindful of considerations such as uneven distribution of volumetric strain reductions, and the potential for an extent of lateral expansion and/or subsurface heave as briefly discussed by Boulanger and Hayden [22]. These mechanisms can be further accounted for on a case by case basis.
3. Furthermore, expansion of the polymer offers additional lateral confinement (increasing the lateral pressure).

The weight volume relationships established from the test are then used to construct a family of curves relating the increase in corrected SPT blow count $(N_1)_{60}$ to the volume of polymer injected in its liquid form. Such a family of curves is specific to the polymer used in this experiment and can be extended for deployment in actual in situ remediation scenarios (by adjusting the polymer expansion ratio as a function of ambient confinement). Based on this family of curves, a large-scale shake table experiment was designed, where significant improvement was observed in the performance of the initially soft liquefiable ground. A similar approach can be taken for any prescribed site condition, in order to estimate the appropriate amount of polymer to be injected into the ground so as to mitigate the susceptibility and the consequences of soil liquefaction.

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