Effect of soil-cement reinforcement panels in seismic ground improvement of soft soil sites

Effet des panneaux de renforcement sol-ciment dans l'amélioration des sols sismiques des sols souples

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ABSTRACT: Soft soil sites are prone to high ground motion amplification during earthquake events. The objective of this study is to evaluate the effectiveness of thin and shallow soil-cement panels in reducing such ground motion amplifications. A soft clay profile was prepared in a Plexiglas container and instrumented with a number of accelerometers. Those profiles were shaken on a shake table with sinusoidal motions having amplitudes ranging from 0.1g to 0.3g and frequencies ranging from 1 to 3 Hz, in addition to a ground motion recorded at a station in Los Angeles after the 1994 Northridge Earthquake. In the second phase, all of those models were reinforced by replacing 16% and 30% plan area (separately) of the soil with floating compacted soil-cement panels and shaken with the same seismic motions. The ground acceleration amplification factors for the reinforced soil profile were normalized with that of the unreinforced profile and the effect of type, depth and area of soil reinforcement panels in reducing seismic ground amplification were evaluated. The study results show that there was up to 48% reduction in seismic ground amplification by introducing compacted soil-cement panels in soft clays when replaced for 30% of the plan area.

RÉSUMÉ: Les sites de sols souples sont sujets à une forte amplification au sol pendant les tremblements de terre. L'objectif de cette étude est d'évaluer l'efficacité des panneaux minces et peu profonds sol-ciment dans la réduction de telles amplifications au sol. Un profil en argile molle a été préparé dans un conteneur en plexiglas et équipé d'un certain nombre d'accéléromètres. Ces profils ont été secoués sur une table secouée avec des mouvements sinusoïdaux ayant des amplitudes allant de 0,1g à 0,3g et des fréquences allant de 1 à 3 Hz, en plus d'un mouvement au sol enregistré à une station de Los Angeles après le séisme de Northridge de 1994. Dans la deuxième phase, tous ces modèles ont été renforcés en remplaçant 16% et 30% de la surface de plan (séparément) du sol par des panneaux sol-ciment compacts flottants et secoués par les mêmes mouvements sismiques. Les facteurs d'amplification de l'accélération au sol pour le profil de sol renforcé ont été normalisés avec ceux du profil non renforcé et l'effet du type, de la profondeur et de l'aire des panneaux de renforcement du sol dans la réduction de l'amplification sismique au sol a été évalué. Les résultats de l'étude montrent qu'il y a eu jusqu'à 48% de réduction de l'amplification sismique terrestre en introduisant des panneaux de sol-ciment compacté dans des argiles molles lorsqu'ils ont été remplacés pour 30% de la surface du plan.

KEYWORDS: soil reinforcement panels, soft clay, ground motion amplification, ground acceleration, shaking table test.

1 INTRODUCTION

Soft clay sites are found to have very high seismic amplification potential and thus they have a tendency to amplify the effect of ground shaking on infrastructures built on them. Significant damage and loss of life has been reported during several earthquakes in soft clay sites (1985 Mexico City, 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe earthquakes among the others). Among all the potential factors contributing to the damage, such as topography, basin effects, liquefaction, and structural deficiencies, the amplification of ground motion plays an important role in increasing seismic damage (Rodriguez-Marek et al., 2001). This creates a need of better characterizing the soil properties and developing efficient and cost effective recommendations for mitigation of such soil sites.

As reported by various studies, ground improvement techniques such as stone columns, jet grouting and deep soil mixing have been found to be very effective in increasing the foundation support, excavation support, reducing earthquake induced deformations, and liquefaction mitigation (Inatomi et al., 1986; Porbaha et al., 1999; Durgunoglu et al., 2004; Hausler and Sitar, 2001; Ou et al., 2007; Guetif et al., 2007; Chen et al., 2013). However, the effect of such ground improvement techniques on seismic ground shaking has not been studied in detail. If reduction in ground shaking level can be achieved, it will be an added benefit. This could result in reduced seismic loads on superstructure and lesser design requirements, thus leading to economized construction. Moreover, the current NEHRP/IBC code does not have any site-class provision for improved ground. Thus, there is a need to study on the possible reduction of ground motion so that the current site classes can be modified for the improved ground conditions.

The main objective of this study is to evaluate the effectiveness of shallow soil-cement panels in reducing the seismic ground shaking intensity on soft clay sites utilizing 1-g Shake table tests. Preliminary study performed by Tiwari et al. (2014) has suggested that the use of annular stiff soil-cement panels as ground reinforcement could significantly reduce the seismic amplification potential on loose sand. These soil-cement reinforcement panels can be effectively applied to reduce base shear, which ultimately reduces the seismic force in building components. Such reduction in base shear can be attributed to the reduction in amplification factor, mainly due to the increased strength and modulus of elasticity of soil-cement mixture compared to the untreated soil.

Different researchers in the past have performed studies on the mitigation of seismic damage potential of weak soil sites. The effectiveness of various ground improvement methods in reducing the earthquake induced ground failures has been well documented. Durgunoglu et al. (2001, 2004) investigated the performance of ground improvement measures against liquefaction, at Carrefoursa Shopping Center in Izmit, Turkey, during the 1999 Kocaeli Earthquake. Soil improvement was performed at the shopping center site to reduce anticipated large settlements in soft cohesive soils and to mitigate liquefaction in loose sands. Parts of the site were preloaded with surcharge fills and wick drains were installed to expedite the consolidation of clayey soils. Jet grout columns were also installed across the site to provide extra bearing support and prevent liquefaction of the loose sandy soils. The Jet grout columns were prepared at a water/cement ratio of 1:1. Compressive strength values of the 7 day-old jet grout columns varied between 1.4 MPa and 6.7 MPa with an average value of 2.9 MPa. Following the earthquake, field reconnaissance indicated that no excessive settlement or liquefaction-related damage occurred at the improved site. However, significant liquefaction-related damages, including settlements, sand boils, and lateral spreading were observed in the adjacent areas that were not yet treated.

Guetif et al. (2007) demonstrated the significant improvement of the Young's modulus of soft clay subjected to vibrocompacted column installation. In their paper, they stated that the improvement of the soft soil was due to two factors. The first factor was the inclusion of stiffer column materials such as gravels, crushed stones, etc. and the second factor was the densification of the surrounding soft soil during the installation of the vibrocompacted soil column and subsequent consolidation process occurring in the soft soil before the actual loading.

A study was performed by Ou et al. (2008) on the analysis and design of partial ground improvement in deep excavations and found that the most common problems encountered during deep excavations in soft clay are excessive wall deflection and ground settlement. One of the methods for reducing the excavation induced lateral movement is to strengthen the soil in front of the excavation wall by jet grouting or mechanical deep mixing method. In this study, the ground columns were constructed with the deep mixing pile method and installed at the excavation site which resulted into significant reduction in ground settlements as well as wall deflection.

Although several researches have indicated that such ground improvement methods are effective in mitigating earthquake induced deformation and potential liquefaction, the effect of ground improvement on the possible ground motion reduction has not been studied in detail. However, Porbaha et al. (1999) briefly reported that lattice type ground improvement using deep mixing performed well during strong shaking. Among others, Tiwari et al. (2014) utilized the strength and stiffness properties of soil-cement mixtures and investigated the effect of soil-cement mix panel reinforcement on ground motions using a shake table. Loose dry construction sand was mixed with various proportions of cement to identify the optimum proportion of cement for soil modification (Tiwari and Das, 2013). Square annular compacted soil cement panels were prepared in wooden molds corresponding to two different replacement ratios and cured for 14 days. A loose sand deposit of 1.2m x 1.2m x 0.6m size was modeled in a Plexiglas box and Tri-axial accelerometers were set at 4 different locations to measure the motions within the model which was shaken with different base motions with a) no soil replacement, b) 10% soil-cement panel replacement by surface area, and c) 25% soil-cement panel replacement by surface area. The applied motions included a recording from the Northridge Earthquake as well as a series of sinusoidal waves of different frequencies and amplitudes. The research result showed around 10% and 30% reduction in ground motion amplification factor for 10% and 25% soil-cement panel replacement ratio, respectively. Moreover, a 50cm tall 3 story building using 1 cm diameter steel bar columns at four corners and 0.4m by 0.4m Plexiglas slab, covered with walls made of poster boards, was modeled on top of the soil without any improvement and with the implementation of soil-cement panel at 25% RR. It was observed that the maximum acceleration on top of the building reduced from 1.16g at no replacement to 0.92g with a replacement ratio of 25%.

2 MATERIALS AND METHODS

Granular Kaolin clay, commercially available as Hydrite Flat DS, was used in the entire study. The cement used in the study was Ordinary Portland Cement Type II-V as per ASTM C150 with 7 day strength of 23 MPa. De-ionized water was used for all the laboratory tests performed for soil characterization and tap water was used for the shake table modeling. The geotechnical properties of Granular Kaolin Clay are presented in Table 1. The drained and undrained friction angles of the normally consolidated clay were found to be 20 and 12.4 degrees respectively. G_{max} of the NC material at the effective vertical stress of 100 kPa was 12 MPa.

Table 1. Geotechnical properties of the materials used in this study.

Liquid Limit	*Plasticity Index*	*Clay Fraction*	*Activity*	*USCS Classification*
46	17	25	0.68	ML

Different soil-cement mixtures were prepared by adding 2, 4, 6, 8, and 10% cement to the soil at water content equal to optimum moisture content of the parent soil i.e. 28%, as determined from the Standard Proctor Compaction test. Cylindrical soil samples for the untreated as well as the cement treated soil were prepared using the Harvard Miniature Compaction device. The samples were 33.02 mm in diameter and 71.12 mm tall. The Harvard Miniature Compaction Device was calibrated according to Harvard Procedure described in ASTM D4609-08. The soil-cement mix samples were wrapped with plastic wraps and cured for 7 and 14 days in an airtight container. After curing some of the samples were immersed in water for two days. The unconfined compressive strength tests were performed following ASTM D2166 on untreated soil samples, cement treated soil samples cured for 0, 7 and 14 days and cement treated soil samples cured and immersed in water for 2 days after curing. Utilizing the results from the unconfined compression test, the soil-cement mix that gave the highest strength and stiffness was used to prepare soil cement panels. The properties of soil-cement panel mix obtained after 14 days of curing are given in Table 2.

Table 2. Properties of the compacted soil-cement panel.

Proportion of cement (%)	*Moisture content (%)*	*Unconfined compressive. Stress (MPa)*	*Modulus of Elasticity (MPa)*	*Dry unit weight (kN/m^3)*
10	28	1.4	150	14

In order to prepare the compacted soil-cement panels, two wooden molds, both 30 cm in depth were prepared corresponding to two different area replacement ratios (RR). The mold for the 16% replacement ratio panel had a panel thickness of 6 cm and inside dimensions of 68 x 68 cm and the mold for the 30% replacement ratio panel had a panel thickness of 12 cm and inside dimensions of 74 x 74 cm (Figure 1). The inside of the panels were covered with plastic so as to preserve the moisture during curing process. The soil-cement mixing was performed in large trays using shovels until a homogeneous mixture was obtained. The mixing was done in less than 30 minutes. The soil-cement mixture was compacted inside the mold in 5 layers. For each mold, the mass of soil-cement mixture required to obtain the desired maximum dry density of 14 KN/m^3 was divided in 5 equal portions. The height of the mold was marked into 5 equal layers and each portion of the mix was compacted using the modified Proctor compaction hammer until the mark was reached. The compacted soil-cement panels were cured for 14 days to allow the cement to gain the desired strength (Figure 2). The panels were wrapped with plastic sheets and sealed completely. Moist towels were used to maintain constant humidity and temperature.

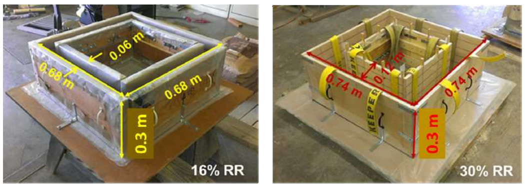

Figure 1. Wooden molds for soil-cement panel construction at 16% and 30% area replacement ratios.

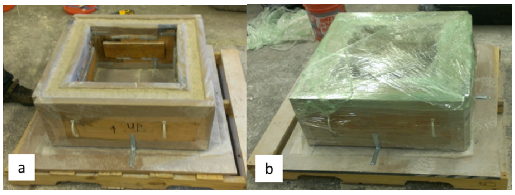

Figure 2. (a) Compacted soil-cement mix; (b) Curing (16% RR).

The shake table having a dimension of 1.5m x 2m and a hydraulic actuator of 25KN force capacity was utilized to apply seismic shaking. A Plexiglas container of internal dimension of 1.08m x 1.02m x 0.92m was used for the preparation of model. In order to facilitate the drainage during the consolidation process of the slurried Kaolin clay sample, a drainage system comprising of bottom drainage and side drainage was installed. The drainage at the sides of the box consisted of a 3.8 cm layer of sand separated from the kaolin clay by a barrier of Geo-grid and Geo-textile. The side drainage was installed to facilitate the radial drainage and expedite the consolidation process. The slurried soil sample was prepared by mixing Kaolin clay with water content equal to the liquid limit, i.e. 46% in large trays until a homogeneous mixture was obtained. The slurried clay was poured into the Plexiglas box in several lifts to a depth of 61 cm. The initial void ratio and dry density of the poured clay slurry without any consolidation pressure were 1.169 and 12.2 kN/m^3 respectively. Sand for the side drain was poured simultaneously and lightly compacted as the clay was poured in, to prevent the bulging out of clay. Moreover, inclusion of sand layer provided transition from Plexiglas container wall to the clay and helped in reducing the boundary effect to some extent. The slurried clay sample was allowed to consolidate at the normal stress of 10 kPa to simulate soft clay conditions. A layer of geotextile was used to cover the soil sample on the top and a wood plate was placed on top of it. Heavy metal bricks were used to apply the vertical loading. These bricks were placed evenly on the wooden plate to ensure the uniform distribution of load. The loading was applied gradually in steps until the desired stress level of 10 kPa was achieved. The drainage valve was kept open during the consolidation process to allow the pore pressure to dissipate. The clay sample was allowed to consolidate for 10 days and then loads were removed slowly.

To measure the response acceleration during shaking, three triaxial accelerometers (A1, A2 and A3) were set at different locations on the clay surface (Figure 3). The accelerometers were aligned such that the z-axis was along the horizontal direction of shaking. Shaking was performed at a series of sinusoidal waves for 20 cycles at combinations of frequencies of 1Hz, 2Hz, 3Hz and amplitudes of 0.1g, 0.2g and 0.3g.

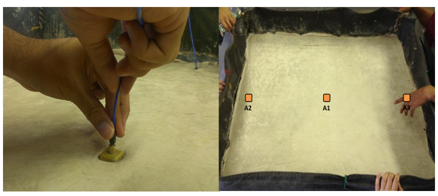

Figure 3. Picture showing the locations of accelerometers

In order to replace the center of the soil with soil-cement panels, excavation was performed. To prevent the collapse of soil during the excavation process, a support system was created. Two metal frames, both 35 cm in height; one 1 cm larger than the outer dimensions of the panel and the other 1 cm smaller than the inner dimensions of panel, were prepared. The metal frames were driven into the center of the clay and the soil between the metal frames was excavated to a depth of 30 cm as shown in Figure 4. The soil-cement panel was removed from the wooden mold after 14 days and placed into the excavation such that the panel flushed with the clay surface (Figure 4 a,b). Once the panel was in, the metal frames were pulled out. Same intensities and modes of shaking were repeated in the model after the replacement of soil-cement panels. Accelerometers were set at the same locations as before. Shaking was performed with the smaller panel corresponding to 16% RR and the panel was removed and the testing was conducted with the larger panel corresponding to a RR of 30%.

Figure 4. Left: Excavation process, Right: After soil-cement panel replacement (a) 16% RR (b) 30% RR

3 RESULTS OF THE STUDY

On applying the input motions of varying frequencies (1Hz, 2Hz and 3 Hz) and amplitudes (0.1g, 0.2g, and 0.3g) at 20 cycles, an amplification in base motion was observed at the ground surface as the waves travelled through the soft Kaolin clay deposit. Amplification factors (AF) were calculated for different input motions. AF is defined as the ratio of maximum acceleration at the ground surface with the maximum acceleration on the base of the shake table. In average, the base motions amplified by a factor of 1.134.

The accelerations on ground surface were compared with the base accelerations and the AF was calculated for no replacement (Figure 5), 16% (Figure 6) and 30% (Figure 7) replacement ratios. In general, the use of soil-cement panels led to the reduction in AF. It can be seen that, the AF reduced from 1.17 at no replacement to 0.88 at 16% RR and further reduced to 0.82 at 30% RR. Furthermore, the AFs after soil-cement panel replacement were less than 1, which indicates that the base motion deamplified as it travelled through the soil to the ground surface.

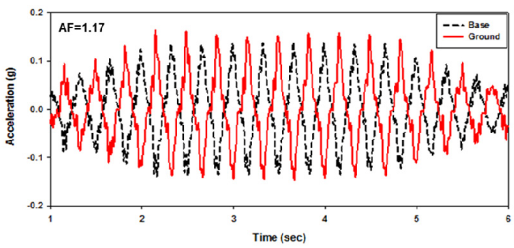

Figure 5. Comparison of ground acceleration with base acceleration for sinusoidal motion of amplitude 0.1g and frequency 3Hz without replacement

To summarize the results from input motions with various amplitudes and frequencies, normalized amplification factors were plotted against the replacement ratios. The normalized amplification factors (NAF) were found by dividing the AFs of the improved profile by the corresponding AFs of the unimproved profile. At 16% RR, the reduction in AF ranged from 24% to 33% and at 30% RR, the range of reduction was 30% to 55%. The average reductions in AF at 16% and 30% RR were 28% and 48% respectively. Figure 8 shows the reduction in the NAF due to the soil-cement panel replacement. It can be seen that NAF, in average, reduced from 1 to 0.7 at 16% RR, and further reduced to 0.5 at 30% RR.

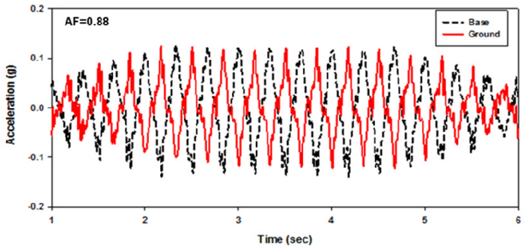

Figure 6. Comparison of ground acceleration with base acceleration for sinusoidal motion of amplitude 0.1g and frequency 3Hz at 16% RR.

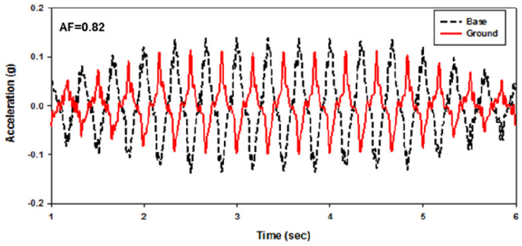

Figure 7. Comparison of ground acceleration with base acceleration for sinusoidal motion of amplitude 0.1g and frequency 3Hz at 30% RR.

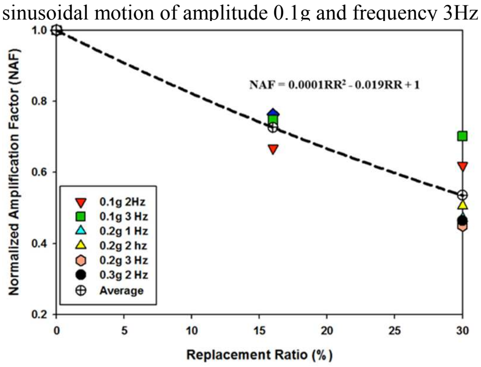

Figure 8. Overall reduction in normalized amplification factor at different replacement ratios and various input motions.

The reduction in AF observed in this study were compared to those from the study performed on loose sand by Tiwari et al. (2014), as shown in Figure 9. It can be seen that the reduction in NAF for the improved profiles for soft Kaolin clay was considerably higher compared to loose sand. By using soil-cement panels at 10% and 25% RRs in sand, the reduction in AF was 10% and 30% respectively. Whereas, in soft clay, 28% and 48% reduction in AF was observed for 16% and 30% RRs respectively. This suggests that soil-cement panels could be more effective in reducing the seismic shaking intensity in soft clay profiles compared to loose sand sites.

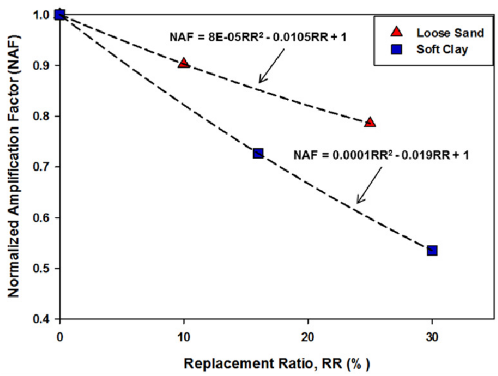

Figure 9. Reduction in NAF with RR in loose sand and soft clays.

4 SUMMARY AND CONCLUSION

Shake table tests were conducted to evaluate the effectiveness of stiff soil-cement ground reinforcement panels in reducing the seismic ground shaking intensities on soft soil sites. Granular Kaolin clay was used to prepare a deposit of soft clay in a Plexiglas container having dimensions of 1.03 x 1.08 x 0.91 m. Compacted soil-cement panels corresponding to area replacement ratios of 16% and 30% were prepared by adding 10% cement and were cured for 14 days. A series of small-scale shake table tests were conducted for a range of input motions on unimproved and panel reinforced soil profiles. Following conclusions can be drawn from the results of this study,

- Amplification of input motion, with an average AF of 1.13, was observed as the seismic waves travelled through the soft clay deposit from the base to the ground.
- Use of shallow soil-cement panels can reduce the seismic amplification potential significantly, as high as 28% for the RR of 16% and 48% for the RR of 30%.
- Soil-cement panels are effective in reducing the AF on both loose sand and soft clay profiles. However, the reduction is higher in soft clay compared to loose sand. The reduction in AF in both types of soils could have been due to increase in stiffness of the improved soils.
- These findings suggest that use of stiff soil-cement panels can have a beneficial influence in ground motion reduction, on both new and existing infrastructures.

The results of this study could also be explaied using the fundamental site period of the unimproved and improved sections as improved soil has different natural frequency compared to the unimproved soil. However, those results could not be presented here due to space limitation.

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