5ICEGE
5th International Conference on Earthquake Geotechnical Engineering
January 2011, 10-13 | Santiago, Chile
Paper No. REDMA

REDUCTION OF SEISMIC SHAKING INTENSITY USING SOIL-MIX GROUND REINFORCEMENT

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ABSTRACT

Ground reinforcement methods such as stone columns, jet grouting, and soil mixing are commonly used to improve soft soil sites for seismic mitigation. This improvement is typically designed to increase foundation support, limit deformations, and/or mitigate liquefaction. Additional seismic benefits, such as a possible reduction in ground motions, are not considered in conventional design practice or current building code provisions. Such reductions, if present, would have significant economic benefit due to lower construction costs. To investigate this effect, we performed parametric 3-D dynamic finite element analyses of soil-mix reinforced ground. Our results showed that soil-mix panels, installed in a lattice-type grid with typical replacement ratios, strengths, and stiffnesses, can significantly reduce ground surface motions at many soft-ground sites. This paper presents results from parametric analyses of soil-mix reinforced ground at a generic 30-m deep soft-ground site. For a wide range of input base motions, the predicted ground-surface spectral accelerations were up to 40% lower for soil-mix reinforced ground compared to unimproved ground. The reductions were most apparent for spectral periods less than 1.0 second. Of particular promise, the cost of such soil improvement may be more than offset by the lower construction cost resulting from lower design motions and a more favorable building code site classification.

Keywords: ground improvement, earthquake, soil mixing, numerical, seismic

INTRODUCTION

Mitigation of the seismic damage potential of sites underlain by soft soils remains one of the most difficult challenges in geotechnical earthquake engineering. There is a critical need to develop modeling procedures and predictive design tools for the seismic performance of improved soft soil sites. Ground reinforcement methods such as stone columns, jet grouting and soil mixing are commonly used, with the usual purpose of providing increased bearing support, deformation control, and/or liquefaction mitigation.

Additional seismic benefits of the ground improvement, such as a possible reduction in ground motions, are not accounted for in conventional design practice or explicitly considered in NEHRP/IBC code provisions for establishing site classification and seismic design motions. Such reduction of ground motions, if present, can have a large payoff. Reduced seismic design loads on the superstructure result in reduced construction costs. It is conceivable that in some cases the cost of ground improvement, typically about 5-15% of total construction costs, may be more than offset by lower project costs resulting from reduced seismic design motions.

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We performed a series of parametric finite element analyses to investigate these potentially beneficial effects. Our studies show that some soil improvement techniques using stiff reinforcement can indeed reduce the intensity of earthquake ground shaking beneath structures. In particular, we found that stiff soil-mix panels arranged in large lattice-type grids can reduce the amplification of motions up through the soil profile, resulting in lower ground surface motions. This means an improved NEHRP/IBC seismic site classification, corresponding to lower design motions, may be warranted for some soil-mix-reinforced sites. Soil-mix panels are commonly used for liquefaction mitigation, containment of liquefied soils, and reduction of permanent deformations. Their use for the specific purpose of reducing ground shaking intensity as discussed here is unprecedented. Thus, our study demonstrates a promising additional benefit that may be derived from this improvement technique.

This paper presents and summarizes results from preliminary dynamic three-dimensional (3-D) finite element analyses of soil-mix reinforced ground. Results are shown for a series of analyses where soil-mix panels are installed at a generic soft-ground site with typical replacement ratios of 24% and 36%. A wide range of ground motions were input at the base of the site and predicted spectral acceleration levels on top of improved ground were calculated and compared to motions on unimproved ground. Calculated ground surface spectral accelerations on reinforced ground were up to 40% lower than those on unimproved ground for structural periods less than 1.0 second. The effects of different replacement ratios, panel stiffnesses, and improvement depths are currently being studied to provide further insight into the governing behavioral mechanisms.

DYNAMIC FINITE ELEMENT ANALYSIS OF SOIL-MIX PANEL REINFORCED GROUND

A series of 3-D dynamic nonlinear finite element analyses were performed to investigate the effect of ground reinforcement with soil-mix panels on ground motions. The analyses utilized the dynamic finite element code DYNAFLOW (Prevost, 1981). To provide a benchmark for comparison, a series of runs were also performed where the soil-mix panels were removed from the model and the soil profile was assumed to be unimproved. The responses at the ground surface for the improved and unimproved cases were compared to show the effectiveness of the improvement.

A generic 30-m deep profile with constant Standard Penetration Test (SPT) blow counts of N = 10 blows/ft was used in the analyses. The shear wave velocity profile was inferred from the correlation proposed by Seed et al. (1986) relating mean effective confining pressure, SPT blow counts and maximum shear modulus. The shear wave velocity profile of the 30-m deep soil stack is shown in Figure 1. The average shear wave velocity of the 30 meter deep soil profile $Vs_{,30}$, is about 190 m/s, corresponding to a soft soil site which classifies as NEHRP/IBC Site Class E (IBC, 2006). The 30-m deep profile is underlain by soft rock with a shear wave velocity of V_s = 750 m/s.

In the initial set of analyses, a grid pattern of 1.8-m thick soil-mix panels with 9-m center-to-center spacing was selected as the improvement scheme for analysis. A plan view of this gemoetry for a single panel is shown in Figure 2. The replacement ratio for this panel-reinforced geometry is 36%. In these analyses, the soil-mix panels extended from the ground surface to a depth of 10 m. This improvement geometry was selected in part because the authors worked on a recent seismic mitigation project where this layout was used and prompted the initiation of this research.

The geometrical constraints of the analyzed improvement scenario necessitated a 3-D finite element model with about 25,000 nodes. The model was formed using a unit cell of the soil-mix panel system to encapsulate a square geometry (9 m by 9 m) through the centerline of the panels in both directions. The model was simultaneously shaken at the base in two horizontal directions.

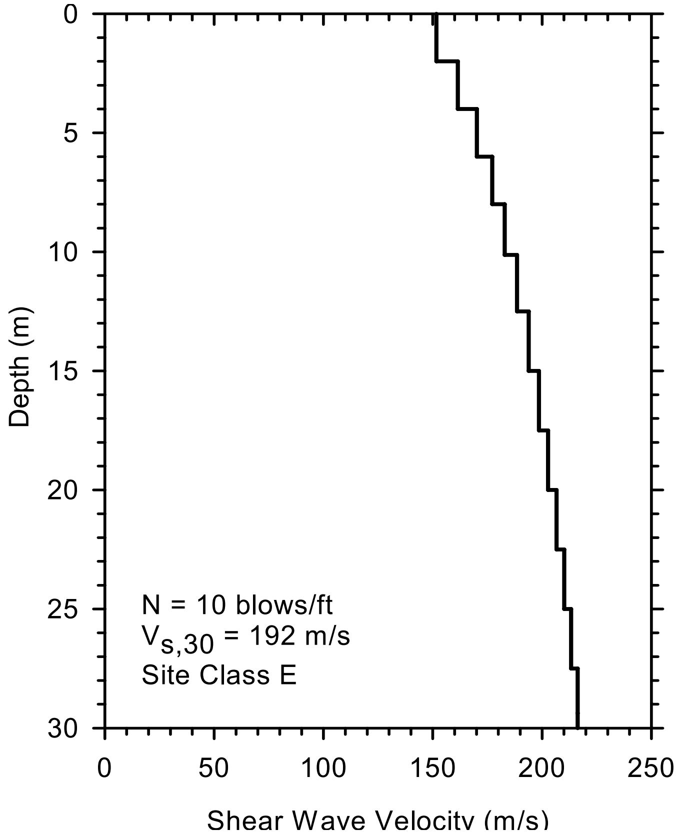

Fig. 1. Shear wave velocity profile of the generic site used in the numerical analyses.

In terms of boundary conditions along the sides, the 3-D model was assumed to be surrounded by an infinitely repeating sequence of identical reinforced soil sections in plan view. This symmetry condition was achieved by assigning the opposite nodes on each face of the model to be equivalent. By assigning nodal equivalency to nodes at the same elevation along opposite faces, the node couples share the same set of equations of motion, and therefore undergo the same motion. This nodal equivalency imposes dynamic symmetry along each vertical face of the model and therefore a repeating sequence of soil-mix panel reinforcement is defined.

Unconfined compressive strength for cement- or lime-mixed soils can vary considerably under different field conditions such as soil type, cement dosage, water content, and mixing method (dry or wet). Strength and stiffness properties of the soil-mix panels in the analyses were selected as typical values based on experience and the literature (Ekstrom 1994, CDIT 2002). An unconfined compressive strength of 1,500 kPa was used for the soil-mix in the analyses. The stress-strain behavior of the soil-mix material was modeled to simulate that the full compressive strength was reached at an axial strain of about 1%. Higher strength and stiffness values may be achieved with other technologies, such as jet-grouting. Modeling the effects of stronger and stiffer panels are outside the scope of this initial study.

As mentioned above, the response of the unimproved profile was also investigated where the soil-mix panels were removed from the finite element model. Both the improved and unimproved profiles were shaken with the same base motions and the ground motions on top of both profiles were computed.

Figure 3 shows a set of three acceleration time histories, including one of the base motions used in the analyses and two calculated surface motions in response to this base motion. The bottom-most record shows the input motion applied on rock at the base of the improved and unimproved profiles. This motion is from the 1999 Kocaeli Earthquake (IZT Station East-West component) and has a peak acceleration of about 0.2g.

The middle record shows the ground surface response calculated on top of the unimproved profile. The peak acceleration for the unimproved case is about 0.5g. As can be seen, the soft soil profile considerably amplifies the peak acceleration of base motion, typical for such profiles. This kind of amplification potential is addressed in the NEHRP/IBC building codes via site amplification coefficients (F_a and F_v) which are based on seismic Site Classification.

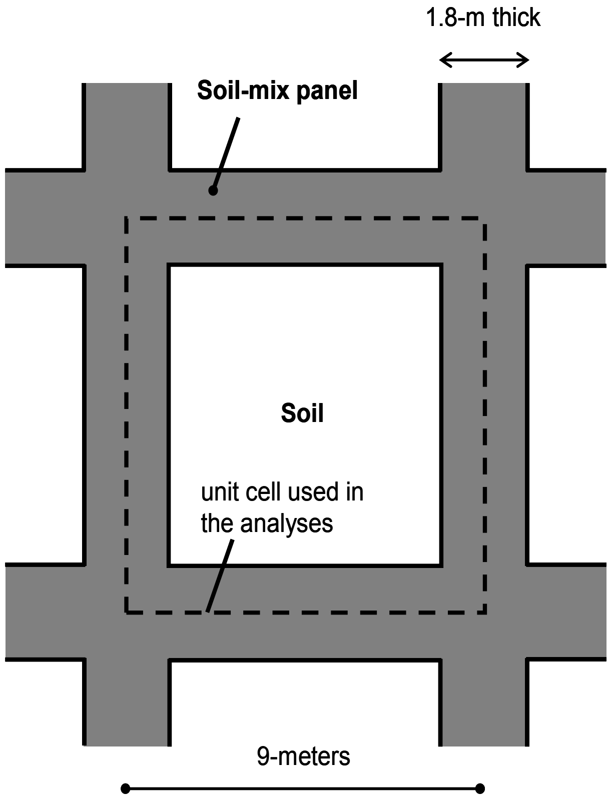

Fig. 2. Plan view of soil-mix panel improvement, 1.8-m thick soil-mix panels at 9 m center-to-center spacing (Rep. Ratio = 36%).

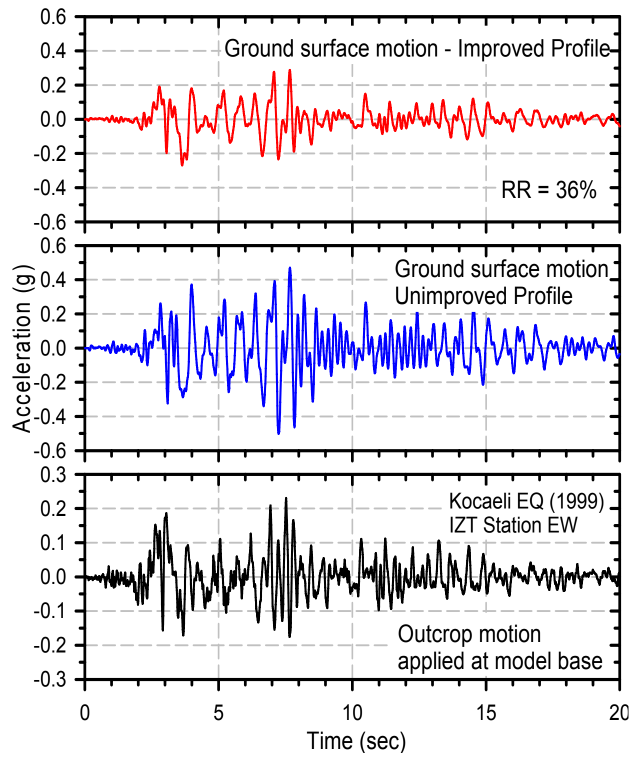

Fig. 3. Computed ground surface acceleration time histories of improved and unimproved soil profiles and input base motion.

The upper-most record shows the ground surface motion of the improved soil profile reinforced with soil-mix panels. As can be seen, the peak acceleration is about 0.3g, considerably less than the 0.5g for the unimproved profile. This reduced shaking level on top of the improved profile can be attributed to the stiffening effect of the panel reinforcements. Presumably, the fundamental frequency of the site, and thus the amplification potential of the site, is modified by the stiffening effect of the panles in the upper 10 meters of the soft soil profile.

The amplification function of a soil profile can be calculated in the frequency domain from the ratio of Fourier amplitude spectra of ground surface motion and the outcrop base motion. Accordingly, the transfer functions for the unimproved and improved profiles calculated from the motions computed from both analyses are shown in Figure 4. It can be seen that the unimproved profile exhibits the largest amplification potential at its fundamental frequency of f = 1.6 Hz (predominant period T ~ 0.63 second). Fundamental frequency of the improved profile shifts to the right to f = 2.1 Hz (T ~ 0.47 sec) apparently from the lateral resistance provided by the panels and the resulting stiffening at the top 10 m of the profile. In addition it can also be seen that the overall amplification has come down which can again be attributed to the overall stiffening of the profile. Even though the base of the soil profile remains unimproved the impedance contrast at that elevation remains unchanged, the overall velocity increase of the improved profile apparently reduces the effective impedance contrast between the soil profile and the underlain soft rock thus reducing the amplification potential of the profile.

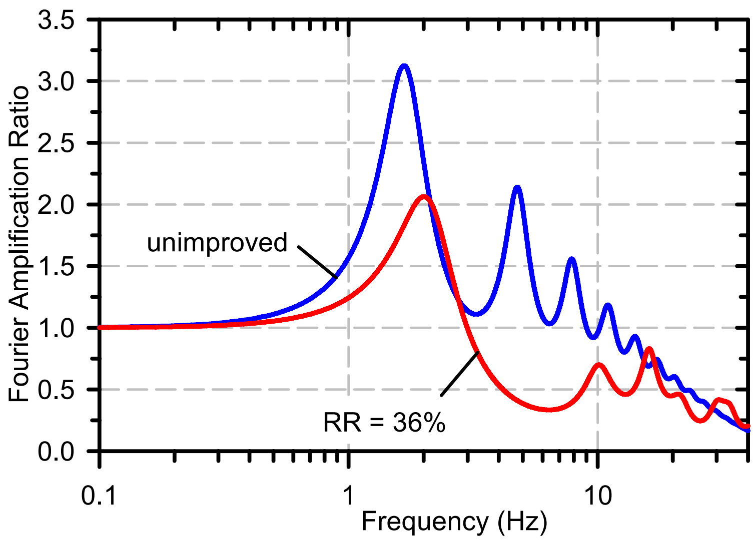

Fig 4. Transfer functions (amplification potential) of improved & unimproved profiles; Fourier amplitude ratios of the surface motion to outcrop input motion

In addition to comparison of the peak accelerations on top of the improved and unimproved profiles, spectral accelerations were also calculated and compared. The computed response spectrum for the top of the improved profile is shown in the upper panel of Figure 5, along with that for the unimproved profile. As shown, the spectral motions are much lower for periods less than 1 second. The ratio of the spectral accelerations for the improved-to-unimproved profiles is shown in the lower part of the figure.

It can be seen that the ground reinforcement resulted in about a 40% reduction in motions for periods less than 0.6 seconds. Less reduction occurred from 0.6 to 1.0 second. This again shows the frequency dependent nature of the site stiffening obtained by the soil-mix panel reinforcement. As discussed above, the peak base motion acceleration of 0.2g is amplified by the unimproved soil to about 0.5g, and amplified to about 0.3g by the improved profile. Although the improved profile still amplifies the base rock motion, the degree of amplification is much less. Similar trends occur in the response spectra for periods less than 1 second.

The significance of the reductions caused by the soil improvement can be further understood by comparison of NEHRP/IBC Site Classification. As mentioned above, the unimproved profile classifies as Site Class E, whereas the response of the improved profile corresponds roughly to a Site Class D soil profile. Therefore, the use of a more favorable seismic site classification may be appropriate for many sites treated with stiff panel reinforcements. Current building code procedures do not consider this possibility and it should be further investigated.

To demonstrate the sensitivity of the results to the base input motions, additional runs were made using a total of 10 different ground motions, representing a wide range of shaking intensities, durations, and frequency contents. Results are shown in Figure 6. The ratios of the spectral accelerations on the improved profiles to those on the unimproved profiles are plotted, along with the average trend. As shown, the results were similar for all 10 input motions, as the average trend is narrowly-banded. This is an indication that the main response characteristics of this ground improvement scheme are not very sensitive to the input base rock motions.

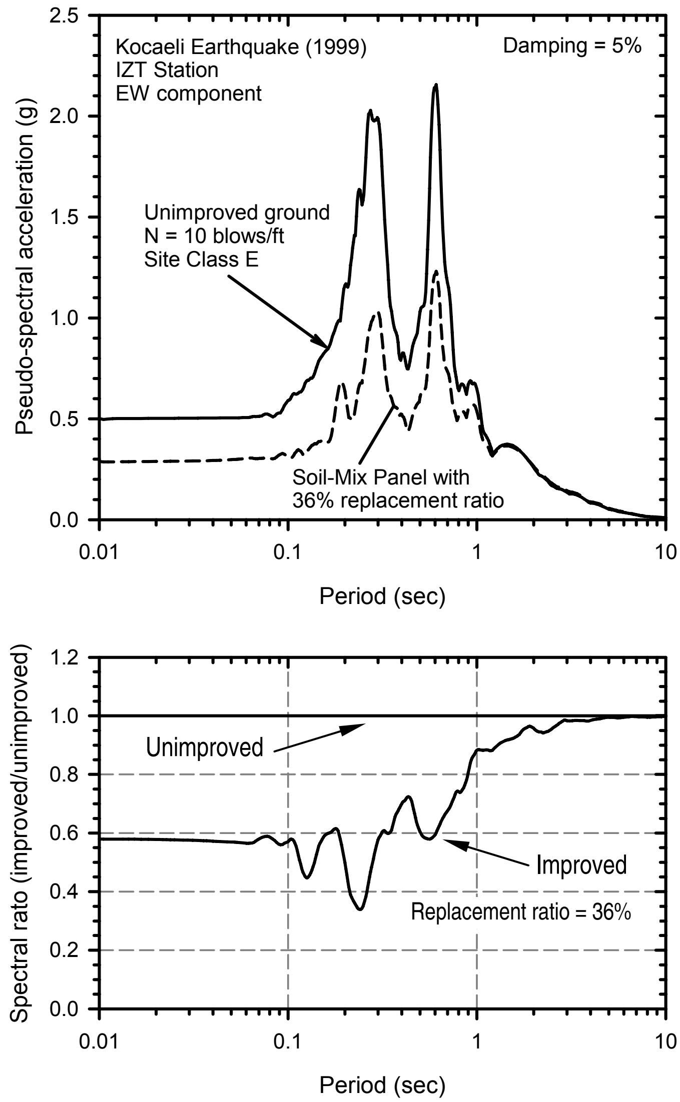

Fig. 5. Response spectra at the ground surface of improved and unimproved profiles (top fig.); ratio of ground surface spectral accelerations for improved and unimproved profiles (bottom fig.)

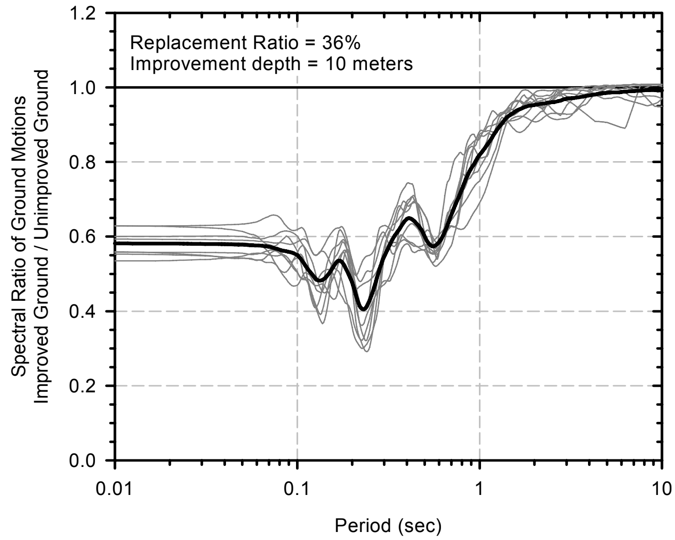

Fig. 6. Summary of results – Spectral ratio of improved and unimproved ground surface motions for 10 different base motions for the improvement geometry (Rep. Ratio = 36% and Improvement Depth = 10 m)

PARAMETRIC ANALYSES WITH DIFFERENT IMPROVEMENT GEOMETRIES

Additional parametric analyses were performed to study the effect of different improvement geometries such as different replacement ratios and treatment depths on the seismic response and ground motion reduction potential of soil-mix- panel reinforced ground. For this purpose, analyses of the model described above were performed using the 10 different input ground motions with: 1.) a lower soil-mix panel replacement ratio of 24%; and, 2.) the above-mentioned soil-mix panel replacement ratio = 36%, but with deeper soil-mix panels that extended to 15 and 20 meters, respectively, within the soil profile. The results of these analyses are summarized and discussed below.

The analyses focused on a replacement ratio of 24% with 1.8-m thick soil-mix panels spaced at 14 meters center-to-center. As in the earlier analyses, the panels extended to a depth of 10 m. The results from these analyses, shown in Figure 7, are compared to the results obtained with the 36% replacement ratio. It can be seen that the lower replacement ratio results in smaller reductions in ground motions. A replacement ratio of 24% results in about 30% lower spectral accelerations for periods up to 0.6 seconds, compared to a 40% reduction for the 36% replacement ratio.

As expected, this suggests that higher replacement ratios result in lower ground shaking, presumably due to increased shear stiffness of the profile. This demonstrates how the degree of stiffening affects the ground motions on top of the improved soil profile. Even though the results of such analyses are not presented herein, these results provide some indication of the potential benefits using stiffer reinforcing elements such as jet-grouted panels. Such analyses are ongoing and trends similar to that shown for increased replacement ratios are observed in cases where stiffer panel reinforcements are used.

Additional analyses were also performed to investigate the effect of improvement depth on seismic response. The results for different improvement depths (all for 36% replacement ratio) are shown in Figure 8. In this figure the average trend of ground motion reduction is plotted for three different improvement depths, 10 m, 15 m and 20 m. It can be seen that treatment depth has some effect; however, the benefit is marginal, as similar reduction characteristics are exhibited for all treatment depths. For example, increasing treatment depth from 10 m to 20 m only reduces the ground motions an additional 10% or so. Therefore, it may not be as cost-beneficial to increase the depth of improvement relative to taking other measures such as increasing the replacement ratio.

The analyses presented above are preliminary, and are being extended as of this writing to develop a more complete set of results that illustrate the effects of factors such as panel stiffness, replacement ratios, and treatment depths.

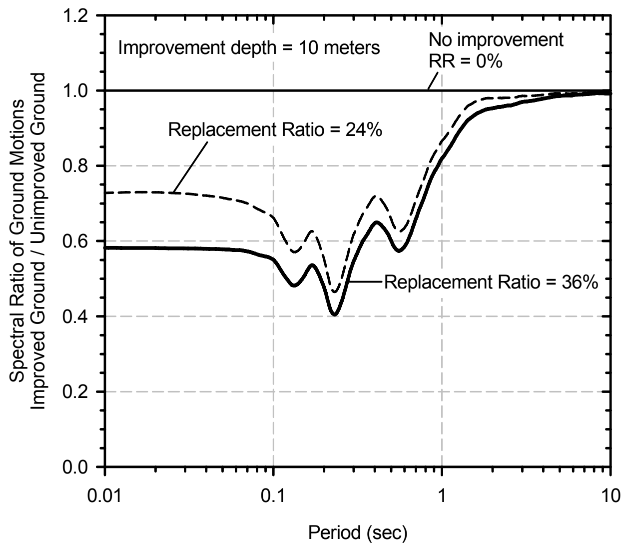

Fig. 7. The effect of the replacement ratio – Spectral ratios for replacement ratios 24% and 36% in comparison to the unimproved case.

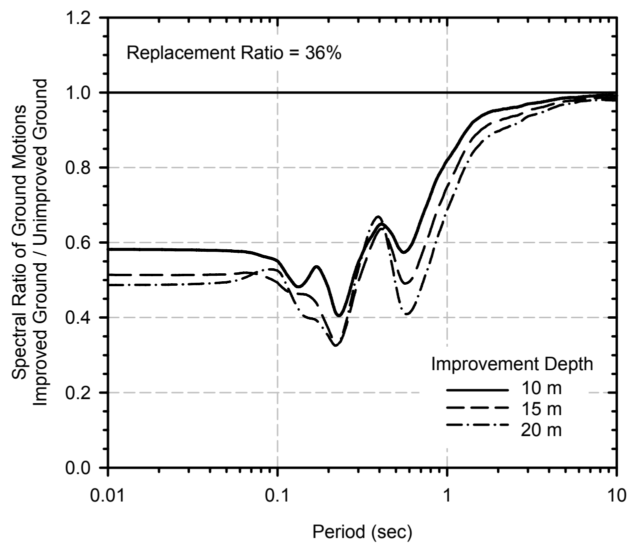

Fig. 8. The effect of the depth of improvement; spectral ratios shown for improvement depths 10, 15, and 20 m.

CONCLUSIONS

Potential benefits of ground improvement in terms of reduction of seismic ground motions are not currently considered in NEHRP/IBC building code procedures. Three-dimensional dynamic finite element analyses were performed to investigate this issue. Parametric analyses were run to study the potential for stiff soil-mix panels to reduce seismic motions. A series of 3-D dynamic finite element analyses were run using DYNAFLOW. A 30-m deep profile with constant SPT N values = 10 blows/ft was selected for analysis. For the soil improvement scheme, a grid pattern of 180-cm thick soil-mix panels with 9 m center-to-center spacings was used. The replacement ratio for this geometry is 36%. Panels were assigned an unconfined compressive strength of 1500 kPa, a typical value.

The results indicate that soil-mix panel reinforcement can significantly reduce ground motions. Compared to the unimproved soil profile, which classifies as NEHRP Site Class E, spectral accelerations on the improved profile are 40% lower for periods less than 0.6 seconds. The response of the improved profile roughly corresponds to a Site Class D soil profile. Less reduction is achieved for lower replacement ratios. A replacement ratio of 24% reduced the motions by only 20 - 25%. Extending the depth of treatment beyond 10 m had only marginal benefits for reducing ground motions.

The results suggest that lower seismic design motions and a more favorable NEHRP/IBC Site Class may be achieved using such ground treatment. This could lead to significant overall cost savings in many cases. Additional analyses are being conducted to better understand the effects of key factors, such as panel strength, stiffness and replacement ratio.

AKNOWLEDGEMENTS

This work was supported by the National Science Foundation Award No. 0085281 and funding from the World Institute for Disaster Risk Management at Virginia Tech (DRM-VT).

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