Numerical modeling of the seismic response of soil-mixed reinforced ground

Modélisation numérique du comportement séismique de la terre renforcée

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ABSTRACT
Ground reinforcement methods such as stone columns, jet grouting, and soil mixing are commonly used to improve subsoil conditions for seismic mitigation. The purpose of this improvement is usually for foundation support and/or liquefaction mitigation. Additional benefits, such as a possible reduction in seismic ground motions, are not considered in NEHRP/IBC code provisions. This paper summarizes results from parametric dynamic 3-D finite element analyses of soil-mix reinforced ground. The results suggest that stiff ground reinforcements arranged in lattice-type soil-mix panels may significantly reduce ground motions and improve NEHRP/IBC Site Classification. Moreover, the cost of the soil improvement may be more than offset by the lower construction cost resulting from lower design motions and a more favorable site classification. Additional research is needed to provide detailed insight.

RÉSUMÉ
Les méthodes au sol de renfort telles que les colonnes en pierre, jet grouting, et soil mixing sont utilisées généralement pour améliorer des conditions de sous-sol pour la réduction séismique. Le but de cette amélioration est habituellement pour l'appui de base et/ou la réduction de liquéfaction. Des avantages accessoires, tels qu'une réduction possible des mouvements de terrain séismiques, ne sont pas considérés dans des dispositions de code de NEHRP/IBC. Ce document récapitule des résultats des analyses par éléments finis à trois dimensions dynamiques paramétriques de sol-mélangent la terre renforcée. Les résultats suggèrent que les renforts au sol raides disposés dans le trellis-type sol-mélangent des panneaux puissent de manière significative réduire des mouvements de terrain et améliorer la classification d'emplacement de NEHRP/IBC. D'ailleurs, le coût de l'aménagement de sols peut plus qu'être compensé par le coût de construction inférieur résultant des mouvements inférieurs de conception et d'une classification plus favorable d'emplacement. La recherche additionnelle est nécessaire pour fournir la perspicacité détaillée.

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

1 INTRODUCTION

Ground reinforcement methods such as stone columns, jet grouting, and soil mixing are commonly used to improve subsoil conditions for seismic mitigation. In most cases, the purpose of this improvement is for foundation support and/or liquefaction mitigation. Additional benefits of the improvement, such as a possible reduction in seismic ground motions, are not explicitly considered in NEHRP/IBC code provisions for establishing site classification and seismic design motions. Such reductions, if present, can have significant payoff. Reduced seismic loads on the super structure result in lower seismic design levels and reduced construction costs. It is conceivable that the cost of ground improvement, typically 5-15% of total construction costs, may be more than offset by lower overall costs resulting from reduced design ground motions.

Ongoing research suggests that some soil improvement techniques using stiff reinforcement may reduce the intensity of earthquake ground shaking beneath structures. Of particular interest, our dynamic finite element modeling suggests that stiff ground reinforcements arranged in lattice-type panels (i.e. soil-mix panels) has great promise. Such panels may significantly reduce ground motions and improve NEHRP/IBC site classification.

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 typical soil-mix panels are installed at replacement ratios of 24% and 36%. The improvement was found to cause reductions in spectral acceleration of up to 40%, especially for structural periods less than 1.0 second. Other ground improvement schemes, such as different replacement ratios and panel stiffnesses are currently being studied by the authors to provide further insight into the phenomenon.

2 DYNAMIC FE ANALYSIS OF SOIL-MIX PANEL REINFORCED GROUND

A series of 3-D dynamic nonlinear finite element analyses was performed to investigate the effect of 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 response at the ground surface for the improved and unimproved cases was compared to show the effectiveness of the improvement.

A 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. Prevost's (1981) multi-yield plasticity constitutive model was used for the soil with $\phi' = 36$ degrees. The unit weight of the soil was selected 18 kN/m^3. The shear wave velocity profile is shown in Figure 1. The average shear wave velocity of the 30 m soil profile, $V_{s,30}$, is 190 m/s, corresponding to a soft soil site which classifies as NEHRP/IBC Site Class E (IBC 2006). The 30-m profile is underlain by soft rock with $V_s = 750$ m/s.

A grid pattern of 1.8-m thick soil-mix panels with 9-m center-to-center spacing was selected as the improvement

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scheme for analysis. A plan view of this arrangement is shown in Figure 2. The replacement ratio for this geometry is 36%. The soil-mix panels extended to a depth of 10 m. These geometries were selected in part because the authors worked on a recent seismic mitigation project where this layout was used.

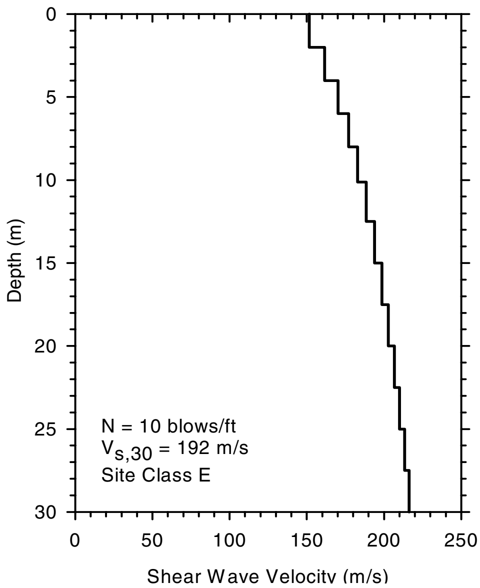

Figure 1- Shear wave velocity profile used in analyses.

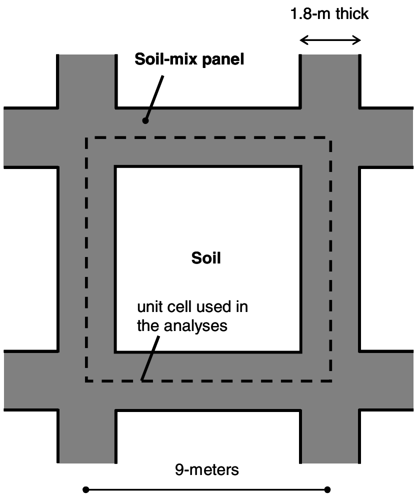

Figure 2. Plan view of soil-mix panel improvement, 1.8-m thick soil-mix panels at 9 m center-to-center spacing (Replacement Ratio = 36%)

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 1500 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 achieved 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 study.

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 shaken at the base in two horizontal directions simultaneously.

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 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.

The response of the unimproved profile was also investigated where the soil-mix panels were removed from the model. The ground motion on top of both improved and unimproved profiles were computed in response to the same base shaking.

Figure 3 shows a set of three time histories, including the base motion and two calculated surface motions. 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 soil profile considerably amplifies the peak acceleration of base motion, as typical for soft soil profiles. Such amplification potential is addressed in the NEHRP/IBC building codes via site amplification coefficients (F_a and F_v) which are based on Site Class.

The upper-most record shows the ground surface motion of the improved soil profile reinforced to a depth of 10 m 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 can be attributed to the shear stiffening effect of the panel reinforcements.

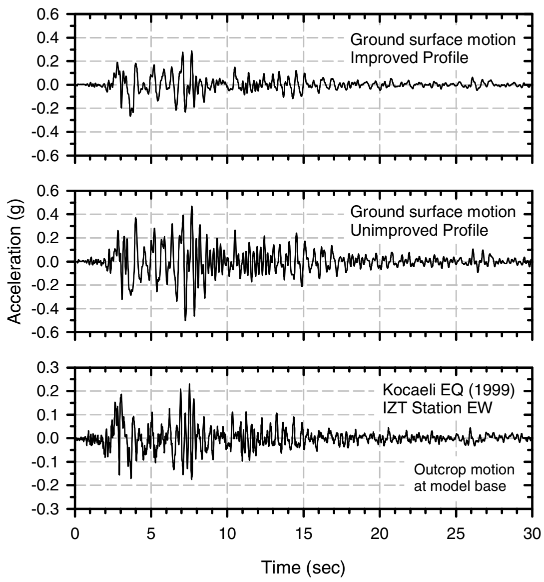

Figure 3. Ground surface acceleration time histories of improved and unimproved profiles and the input base motion

In addition to comparison of the peak accelerations, spectral accelerations at different periods were also calculated and compared. The response spectrum on top of the improved profile is shown in Figure 4, 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 also shown in the lower part of the figure. It can be seen that the panel reinforcement resulted in a 40% reduction in motions for periods 0.6 seconds, and much less reduction for periods up to 1 second.

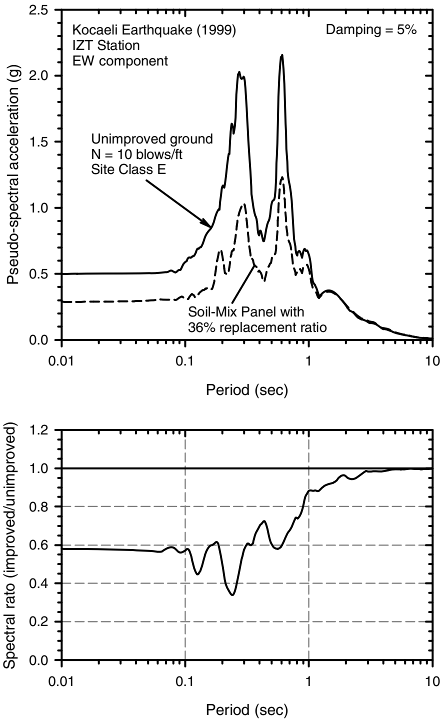

Figure 4. Response spectra at the ground surface of improved and unimproved profiles and the ratio of the spectral accelera-tion of ground motions for both cases (improved/unimproved)

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 site classification may be appropriate for sites treated with stiff panel reinforcements. Current building code procedures do not consider this possibility and it should be further investigated.

To show the sensitivity of the results to the base input motions, additional analyses were performed using a total of 10 different ground motions, representing a range of shaking intensities, durations, and frequency contents. Results are shown in Figure 5. 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.

3 PARAMETRIC ANALYSES WITH DIFFERENT IMPROVEMENT GEOMETRIES

Additional parametric analyses were performed to study the effect of different improvement geometries (i.e., treatment depths, replacement ratios) 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.) the above-mentioned soil-mix panel replacement ratio = 36%, but with deeper soil-mix panels that extended to 15 m and 20 m within the soil profile; and, 2.) a lower soil-mix panel replacement ratio of 24%.

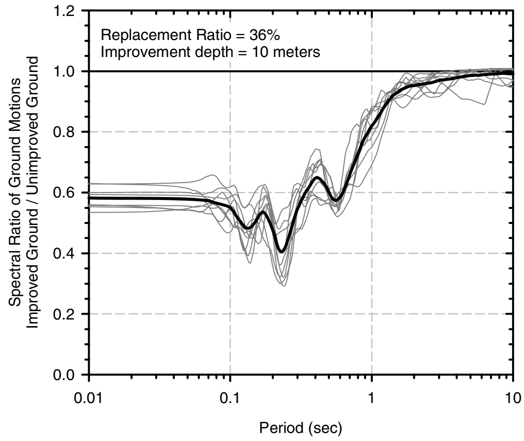

Figure 5. Summary of results – Spectral ratio of improved and unimproved ground surface motions for 10 different base motions for the improvement geometry (Replacement Ratio = 36% and Improvement Depth = 10 m)

The results for different improvement depths (all for 36% replacement ratio) are shown in Figure 6. 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 replacement ratio. The effect of replacement ratio is presented below.

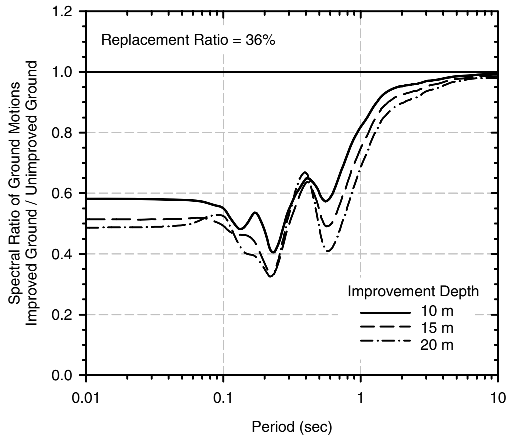

Figure 6. The effect of the depth of improvement – Spectral ratios for improvement depths 10, 15, and 20 m.

Additional analyses were performed with 1.8-m thick soil-mix panels spaced at 14 meters center-to-center, corresponding to a replacement ratio of 24%. 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.

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.

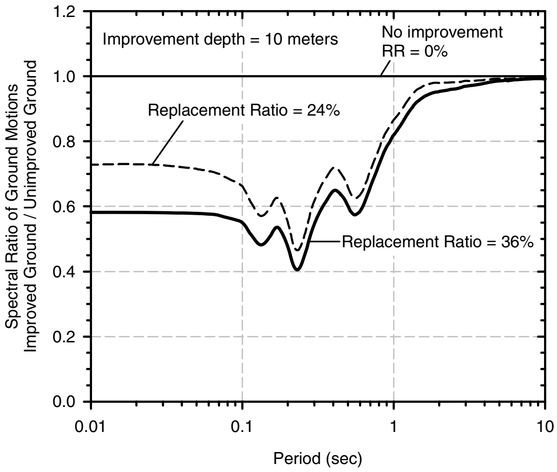

Figure 7. The effect of the replacement ratio – Spectral ratios for replacement ratios 24% and 36% in comparison to the un-improved case

4 CONCLUSIONS

Potential benefits of ground improvement in terms of reduction of seismic ground motions are not currently considered in NEHRP/IBC building code procedures. Preliminary 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 set 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 acheived 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.

REFERENCES

Coastal Development Institute of Technology (2002) "The deep mixing method: principle, design, and construction." Edited by Coastal Development Institute of Technology (CDIT), Japan. Swets & Zeitlinger Publishers.

Ekstrom, J.C., 1994. "Checking of Lime and Lime/Cement Columns: A Method Under Development." Swedish Geotechnical Society, Stockholm, Sweden.

International Building Code (2006). "IBC 2006, International Building Code," Whittier, CA.

Prevost, J.H. (1981) "DYNAFLOW: A nonlinear transient finite element analysis program," Technical report, Department of Civil Engineering and Operations Research, Princeton University, Princeton, New Jersey.

Seed, H.B., Wong, R.T., Idriss, I.M. and Tokimatsu, K. (1986). "Moduli and damping factors for dynamic analyses of cohesionless soils." Journal of Geotechnical Engineering, ASCE, Vol. 112, No. 11, pp. 1016-1032.