Influence of remedial ground densification on seismic site amplification

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ABSTRACT

A methodology is presented in this paper to conduct "hazard-consistent" soil-foundation-structure interaction analyses and evaluate the influence of remedial ground densification on seismic site amplification. The pseudo-spectral accelerations (PSAs) predicted between one-dimensional (1-D) and two-dimensional (2-D) site response models are compared for various lateral extents of the improved zone. It is found that 1-D models can result in lower estimates of PSAs compared to 2-D models, and this mismatch is increased as the horizontal extent of ground improvement is reduced. Furthermore, a shallow densified crust underlain by soft soil layers tends to de-amplify the PSAs at the ground surface, with a greater reduction at shorter periods and little change in the PSAs at periods beyond the fundamental site period. The previous trends are reversed when considering the influence soil-foundation-structure interaction effects on the seismic demand of buildings founded on densified soils. In this case, the elastic base shear transmitted to the structures is amplified by up to a 1.55 ratio between the improved and unimproved site response predictions.

1 INTRODUCTION

Ground densification is the most common approach employed to improve the geotechnical performance of shallow foundations in the presence of loose granular soils. The rearrangement of soil particles to a denser configuration results in an increase in particle interlocking, lateral earth pressures, and soil shear stiffness, which in turn increases the soil bearing capacity and its resistance to liquefaction. While the ability of ground densification to improve the seismic performance of shallow foundations has been widely evaluated in recent decades (Karimi and Dashti, 2016), the relative changes in ground motion amplification within the improved zone and its impact on the overlying structures has received little attention. The necessity to adopt a holistic strategy between geotechnical and structural engineers for the design of ground improvement is well recognised in guidelines (MBIE and NZGS, 2021). However, a certain number of practical issues need to be addressed to enhance the incorporation of the entire soil-foundation-structure system within a unified framework suitable for a performance-base design approach (Kramer 2008).

In this study, a specific engineering routine is employed to perform "hazard-consistent" soil-foundation-structure interaction (SFSI) analysis using a nonlinear constitutive soil model for total stress conditions.

Parametric two-dimensional finite element models incorporating an improved zone with variable depths and lateral extents are implemented using the open-source platform OpenSees (McKenna, 2011). Results from a total of 3960 site response analyses are examined to quantify the influence of the level of ground densification on the spectral accelerations at the surface in free field conditions, and in terms of seismic base shear developed in overlying structures. The ratios between the improved and unimproved soil-foundation-structure responses are quantified for low-to-mid rise buildings.

2 METHODOLOGY

2.1 Soil profiles and improved ground conditions

In this study, we consider a set of five soil profiles comprised of a clean sand deposit, loose to medium-dense, underlain by a competent soil formation represented by a sharp shear-wave velocity (V_S) contrast at the interface with the overlying deposits. Figure 1 depicts the unimproved V_S profiles implemented for each site, plotted in solid black lines. The thickness of the loose to medium-dense sand (H_{soft}) varies, increasingly from Sites 1 to 5 between 10 and 22.5 m. Based on the site classification system defined in the NZS1170.5 standard, the unimproved sites fall into the subsoil Site Class D for deep or soft soil profiles, with a site period varying increasingly from Site 1 to Site 5 between 0.65 s and 1.00 s considering a bedrock condition at 50 m depth, with $V_{S,rock}$ = 700 m/s and ρ_{rock} = 2.5x10^3 kg/m^3. This approach is considered acceptable to capture the dynamic response of buildings which are expected to be excited around their resonant periods, with longer soil response harmonics associated with deep soil profiles not expected to contribute to the building response.

The loose sand layers on top of the soil profiles are improved to account for various levels of ground densification. For the sake of simplicity in this study, the effects of ground densification throughout the entire improved zone are characterised by an increase in soil density (ρ), elastic shear modulus (G) where $G = \rho V_S^2$, and soil shear strength represented by friction angle. As such, three improved soil conditions referred to as IC1, IC2, and IC3 are implemented using dense to very dense sands, with an increase in shear-wave velocity (ΔV_S) approximately equal to 40%, 60% and 80%, respectively (see Figure 1). The thickness of the improved zone H_i is gradually increased from 2.5 m to 22.5 m below ground level across all sites.

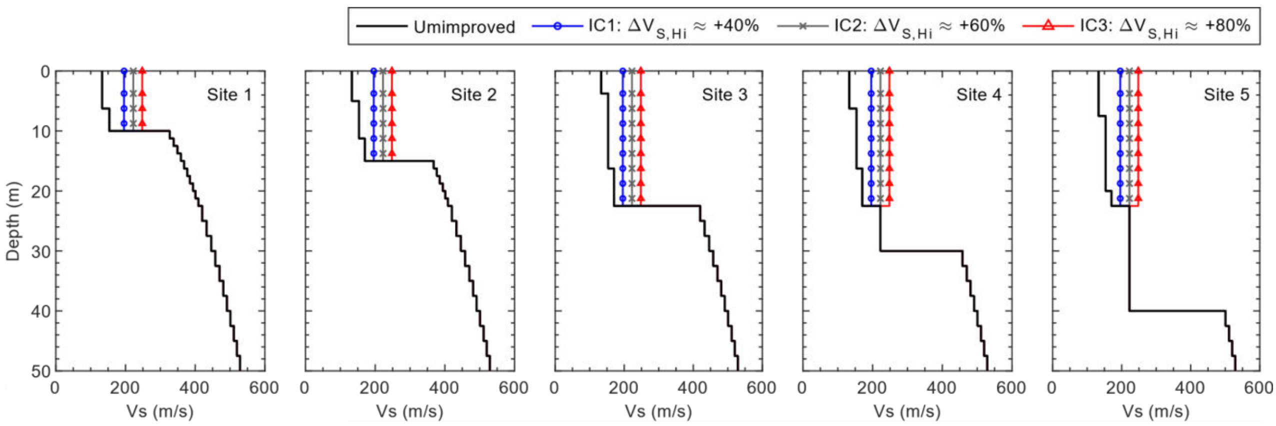

Figure 1: V_S profiles employed in this study considering five different soil profiles and modified using a range of ground densification conditions IC1, IC2 and IC3.

2.2 Moment resisting frames

The structures employed in this study consist of a three-bay archetype representative of a commercial building, 27.42 m total width, with a regular bay spacing in plan so that the torsional effects can be omitted when using a 2-D model. The archetypes for the 2-storey and 4-storey reinforced concrete moment resisting frames are depicted in Figure 2. Linear elastic structures are considered in this study so that the elastic base shears calculated are proportional to the elastic forces and bending moments developed in beams and columns prior to modification per design practice to account for ductility and the formation of plastic hinges. The fundamental periods ($T_{S,1}$) of the 2- and 4-storey frames are 0.68 s and 1.17 s, respectively. The gravity actions and seismic masses were defined at the ULS according to the AS/NZS1170.1 standard. The buildings are founded on a rigid mat as recommended in practice to mitigate the development of differential settlements due to compressible soil layers at greater depths.

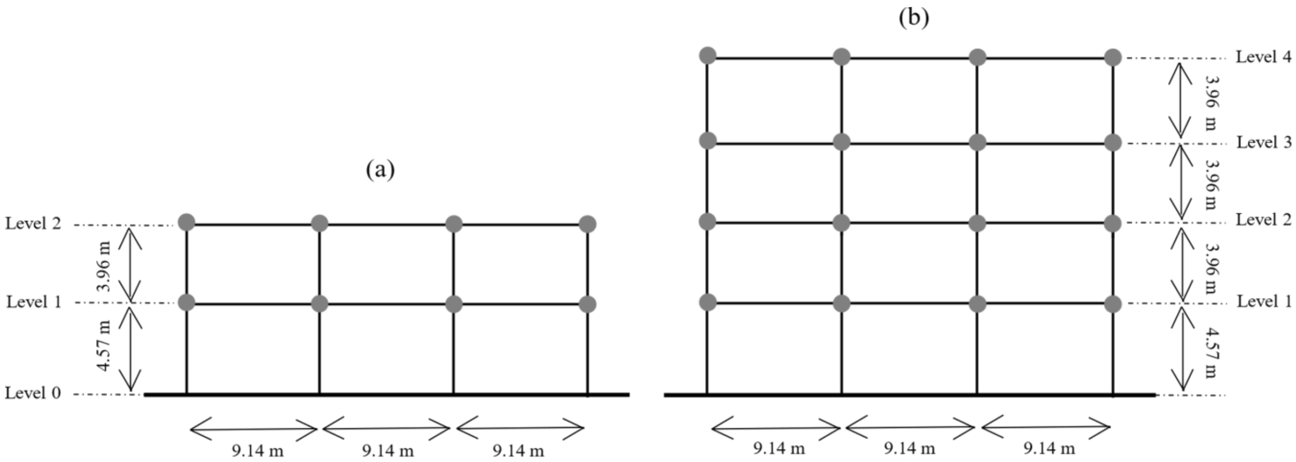

Figure 2: Archetypes for RC moment resisting frames: (a) 2-storey building and (b) 4-storey building.

2.3 Hazard-consistent SFSI analysis in the time domain

2.3.1 Design site response spectrum

In this study, the 5%-damped design spectrum ($\mathrm{PSA_{design}}$) at the free field defined as per the NZS1170.5 standard is used as a target spectrum for site response analysis. The design spectrum is defined such as:

$$PSA_{design} = \left(\frac{1+S_p}{2}\right) Z\ R\ N\ C_h(T) \tag{1}$$

where $\mathrm{C_h(T)}$ is the elastic spectral shape factor for Site Class D as a function of oscillator period T; N is a near-fault factor (herein N=1); R is a return period factor, which is associated with a 1/500 annual probability of exceedance for the ULS (R = 1); Z is a hazard factor depending on the location, herein using Z = 0.30g; and $\mathrm{S_p}$ is a structural performance factor (herein $\mathrm{S_p}$ = 0.7). As such, the design peak ground acceleration ($\mathrm{PGA_{design}}$) is 3.74 m/s^2 (≈ 0.38g).

2.3.2 Scaled surface motions

A suite of 16 horizontal ground motion acceleration records from major earthquakes dominated by shallow crustal earthquakes associated with a mixture of strike-slip and thrust/reverse faulting movements are selected for their goodness of fit with the design spectrum. The motions include 2 records from GeoNet compiled by GNS Science and 14 records from the Pacific Earthquake Engineering Research Center database (PEER, NGA-West2). In this study, the scaling approach adopted in the NZS1170.5 standard is slightly modified to ensure a better fit between the mean spectral accelerations ($\mathrm{PSA_{record}}$) of selected ground motions and the targeted design spectrum. The proposed procedure relies on a set of three constant scaling factors (namely $\mathrm{k_1}$, $\mathrm{k_2}$ and $\mathrm{k_3}$) determined for each record as follows:

1. Determine a best-fitting scale factor $\mathrm{k_1}$ for each horizontal component which minimizes the function $\log(\mathrm{k_1 PSA_{record}/PSA_{design}})$ in a least mean square sense over all periods considered for the design spectrum (herein T = [0.02-4] s), with $0.33 < \mathrm{k_1} < 3.0$.

2. Calculate a scaling factor k_2 for each horizontal component such as $k_1 k_2 PSA_{record} > PSA_{design}$ over the period range of interest of the structure T_{range}. The NZS1170.5 standard recommends T_{range}= [0.4-1.3]$T_{S,1}$, where $T_{S,1}$ is the fundament period of the structure.
3. Determine a group scale factor k_3 applied to all records so that geometric mean spectrum envelops PSA_{design} across all periods (herein T= [0.02-4] s). k_3 is obtained using an iterative procedure.
4. Compute the scaled records so that $PSA_{scaled} = k_1 k_2 k_3 PSA_{record}$.

The pseudo-spectral accelerations of each record obtained after scaling (PSA_{scaled}) along with the geometric mean across all records are compared to the design spectrum (PSA_{design}) in Figure 3-a. For the sake of simplicity, the choice was made to scale the ground motions over a period of interest compatible with both buildings, herein with T_{range} = [0.4-1.3] s. The scaled motions are in good agreement with SA_{design} across a wide range of periods and the geometric mean is an envelope of the design spectrum as intended.

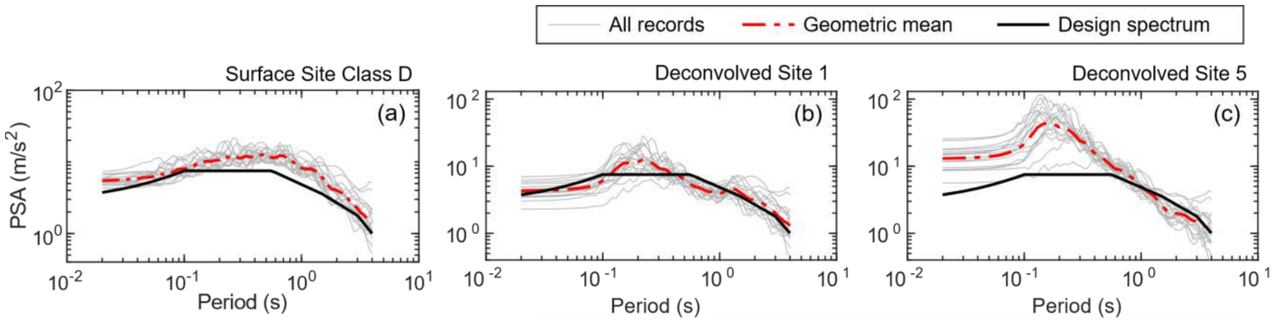

Figure 3: Comparison of pseudo-spectral accelerations (PSA) between the design spectrum (PSA_{target}) at the ground surface and: (a) PSA of selected ground motions obtained after scaling (PSA_{scaled}); (b)-(c) PSA of base motions obtained after deconvolution of scaled motions at Sites 1 and 5, respectively.

2.3.3 Deconvolved base motions

To quantify the influence of ground densification and SFSI effects on the seismic demand of buildings, the simulated surface ground motion accelerations outside of the improved zone should be compatible with the design spectrum (PSA_{design}). To achieve this, the surface ground motions obtained after scaling are deconvolved to an elastic bedrock condition at 50 m depth. The deconvolved time histories are obtained for each of the five unimproved soil profiles and used as input excitations to perform site response analysis.

The deconvolution of ground motions is commonly performed using one-dimensional visco-elastic transfer functions that relate the surface-to-base ground motion amplitudes through a spectral decomposition of site response harmonics. The equivalent linear (EL) procedure is the most widely used method to approximate soil nonlinearity effects in total stress condition, in which the elastic transfer functions are compatible with the "effective" strain amplitudes obtained after convergence of the solution. However, the EL procedure suffers from a number of shortcomings when considering soft soil layers where higher degrees of nonlinearity develop (Kaklamanos and Bradley, 2018). In this study, a recently developed frequency-dependent equivalent linear (FDEL) method (Meite et al., 2020) is employed to overcome the limitations of the EL method and provide more reliable predictions when performing deconvolution analysis. The FDEL model predictions are compatible with the nonlinear model implemented in this study for total stress site response analysis. Figure 3-b-c shows the spectral accelerations of the deconvolved ground motions for the unimproved Sites 1 and 5 (Figure 1), for example. The amplitudes of base ground motions are either reduced or amplified compared to the targeted design spectrum, with a site-specific spectral signature which depends on the V_S profile and the ground motion intensity simulated.

3 INFLUENCE OF GROUND DENSIFICATION ON FREE FIELD SITE RESPONSE

1-D site response analysis, which simulates remedial ground densification in the upper layers to an infinite lateral extent, are compared against 2-D models that account for the seismic interactions between the improved zone of finite lateral extent and the adjacent unimproved soil. The PSAs for the computed motions at the ground surface between the 1-D and 2-D models are compared in Figure 4, considering the geometric mean response across all sites (x5) and ground motions (x16). The improved condition IC2 (ΔV_S = 60%) with three lateral extents B= {10; 20; 35} m and two improved thickness ratios H_i/H_{soft} = {0.25; 0.75} are examined.

The ranges of PSA calculated at the ground surface within the improved zones for the 2-D models are plotted as grey shaded areas in Figure 4. As may be observed from this figure, the ranges of PSA developed within the improved zone are unchanged at periods greater than the natural site periods featured across all soil profiles, herein between 0.65 and 1.0 s, and tend to widen at lower periods as B increases. The mismatch between 1-D and 2-D model predictions is more pronounced as the width of the improved zone B reduces from 35 to 10 m. The 1-D PSAs calculated at periods ranging approximately from 0.4 to 1.0 s are underpredicted compared to 2-D model values, with PSAs for both models overlapping around 0.4 s. As compared to the design spectrum for Site Class D applicable for the unimproved sites, the PSAs predicted in the improved models tend to be reduced at periods ranging approximately from 0.08 to 0.4 s when forming a shallow densified crust with H_i/H_{soft} = 0.25. In contrast, as the extent of the improved zone increases both laterally and in depth with H_i/H_{soft} = 0.75, the PSAs within the improved zone are noticeably amplified compared to the design spectrum, with a plateau for the improved spectrum potentially increased by 20% (Figure 4-f).

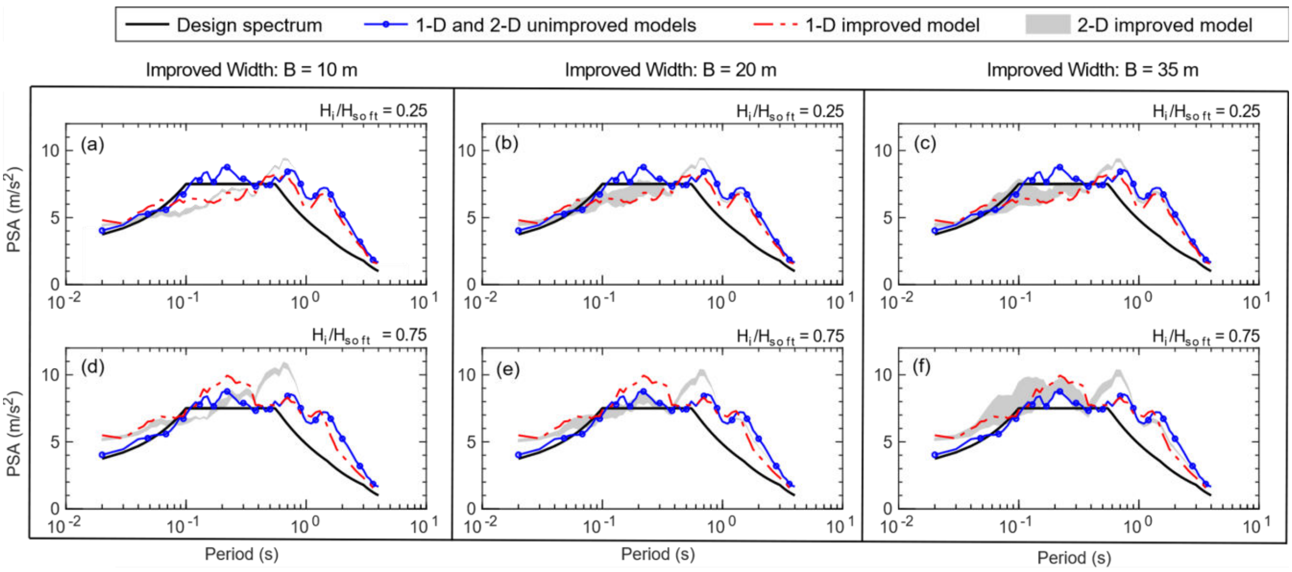

Figure 4: Comparison of mean PSAs for the computed motions at the ground surface between 1-D and 2-D models using the improved soil condition IC2 (ΔV_S= 60%) and various improved thickness ratios (H_i/H_{soft}) and lateral extents (B) of the improved zone: (a)-(d) B = 10 m with H_i/H_{soft} = {0.25; 0.75} ; (b)-(e) B = 20 m with H_i/H_{soft} = {0.25; 0.75}; (c)-(f) B = 35 m with H_i/H_{soft} = {0.25; 0.75}, respectively.

4 INFLUENCE OF GROUD DENSIFICATION ON BUILDING DEMAND

The influence of ground densification on the seismic demand of buildings is quantified in terms of settlement reduction ratio, spectral acceleration (SA_1) ratio calculated at the centre of the concrete raft around the building's natural period, and elastic shear base ratio between the improved and unimproved soil model predictions. The results were calculated using the geometric mean responses across all sites (x5) and ground motions (x16) to capture the general trends. The mean ratios of seismic responses for the 2-storey and 4-storey buildings are depicted in Figure 5 and Figure 6, respectively.

As anticipated, the shear-induced settlements gradually reduce with the increase in ΔV_S and improved thickness ratio H_i/H_{soft}, with similar settlement reduction ratios observed for both buildings. It should be noted that these trends are only valid for total stress conditions, i.e., the effect of liquefaction induced settlements are not captured in this study. The spectral accelerations SA_1 increase with the extent of ground densification considered for both buildings. When $H_i/H_{soft} \geq 0.25$, the mean spectral amplification ratios for SA_1 ranged approximately between 1.10–1.30 for the 2-storey building, while a lower spectral amplification is obtained for the 4-storey building with SA_1 ratios comprised between 1.05–1.15. These results are compatible with the PSAs previously observed in free field conditions around the buildings' natural periods, herein comprised between 0.68 and 1.17 s (Figure 4). Similar trends are observed for the seismic base shear except that the base shear amplification ratios are generally greater than the corresponding SA_1 ratios. Indeed, it was found that when $H_i/H_{soft} \geq 0.25$, the base shear amplification ratios ranged approximately between 1.15–1.55 for the 2-storey building and between 1.15–1.30 for the 4-storey building. These results suggest that the amplification of the seismic demand for improved sites is exacerbated depending on the building's natural period in relation to the site response. As such, when the overlying structure is rigid, with a low natural period, SFSI effects are particularly detrimental for the seismic demand as multiple modes of resonance may occur between a low-period structure and the improved soil response harmonics that are shifted towards lower periods as compared to the unimproved site response. Moreover, the presence of soft soil layers underneath the improved zone tends to dissipate the seismic energy transmitted to the ground surface, which in turn reduces the seismic forces developed in the overlying structures.

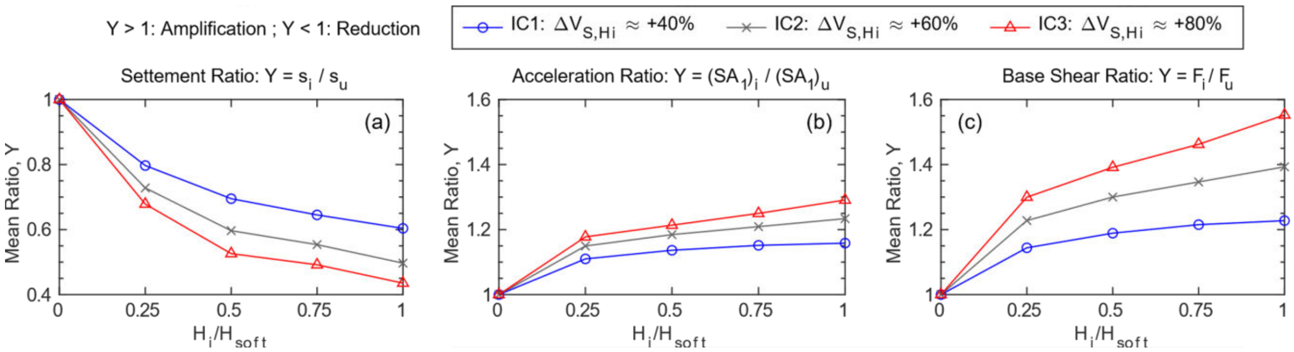

Figure 5: Mean ratios of seismic responses for the 2-storey building between the improved and unimproved soil model predictions as a function of the extent of ground densification: (a) settlement ratio; (b) spectral acceleration ratio; (c) elastic shear base ratio.

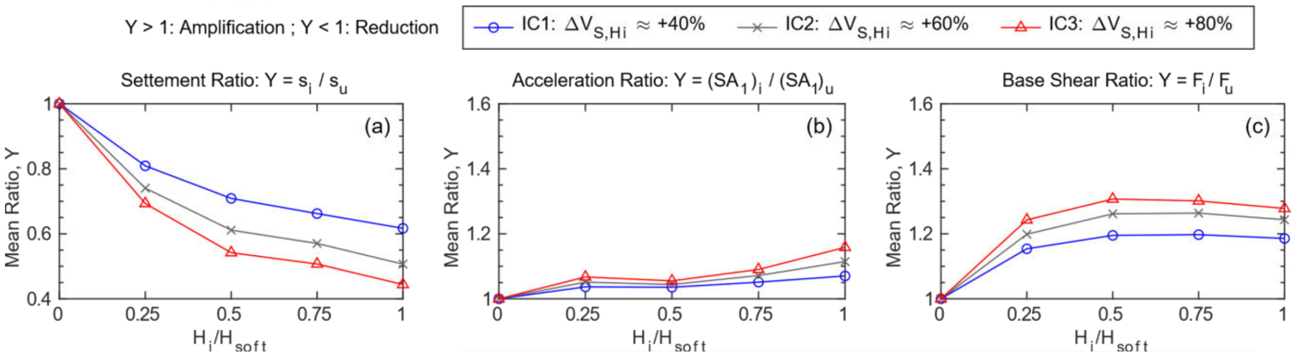

Figure 6: Mean ratios of seismic responses for the 4-storey building between the improved and unimproved soil model predictions as a function of the extent of ground densification: (a) settlement ratio; (b) spectral acceleration ratio; (c) elastic shear base ratio.

5 CONCLUSIONS

A series of 1-D and 2-D total stress site response analyses were conducted to evaluate the influence of remedial ground densification on the seismic demand. A methodology was presented to conduct "hazard-consistent" soil-foundation-structure interaction analyses, for which the ground motion accelerations developed at the surface are compatible with the design spectrum defined as per the NZS1170.5 standard.

It was found that as the lateral extent of the improved zone is reduced, the spectral accelerations obtained at the ground surface using 1-D models are under-predicted at periods ranging from 0.4 to 1.0 s compared to 2-D model predictions. While a densified crust underlain by softer soils can potentially reduce the spectral accelerations below the site period in free field conditions, the seismic shear base developed in the overlying buildings is substantially amplified compared to the unimproved soil model predictions due to SFSI effects. The relative increase in the seismic demand of buildings is magnified as the extent of ground densification increases, with an elastic shear base ratio up to 1.55 between the improved and unimproved sites. The amplification of the seismic demand is also exacerbated for low-period buildings subject to multiple seismic resonances with the soil-foundation system whose natural period is lowered after ground densification.

Finally, it should be noted that the trends presented in this study are highly correlated to the input ground motion intensities and soil nonlinearity effects simulated. The use of advanced constitutive soil models in engineering practice is a critical step forward to better capture nonlinear SFSI effects, especially in areas where high ground motion intensities are required for the ULS design.

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