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Ground response at liquefied sites: seismic isolation or amplification?

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ABSTRACT

The seismic response of liquefied ground is parametrically investigated via analytical visco-elastic wave propagation theory, as well as nonlinear, effective stress, numerical analyses. It is found that a minimum liquefied layer thickness is required in order to ensure seismic isolation effects, i.e. significant attenuation of the seismic motion at the ground surface relative to that at the base, while for thinner layers attenuation of the seismic motion becomes marginal and may even turn into amplification. For harmonic excitations, the limiting thickness for seismic isolation and for seismic amplification are expressed as fractions of the corresponding wave length in the liquefied layer, and are also correlated to the thickness of the non-liquefiable soil crust reduced relative to that of the underlying liquefied layer. For a given soil profile, the above criteria may be inversely utilized in order to identify the harmonic excitation components that will be eventually filtered out and those that will be amplified. Application examples verify the validity of the proposed criteria for site and excitation conditions of engineering interest.

1. Introduction

Among the various design issues related to earthquake-induced liquefaction, the free-field response is probably the least considered by the research community today. One possible reason is that the current practice is overwhelmingly in favor of pile foundations, which transfer the structure loads to deeper non-liquefiable strata, combined with soil improvement over the entire liquefaction depth aimed to minimize the lateral loads applied upon the piles. However, this practice has been challenged in recent years (e.g. [1–6]), in the light of new evidence that the existence of a shear resistant non-liquefiable crust, either natural (e.g. clay or dense gravel) or artificial (e.g. stone-column densified sand), on top of the liquefied soil layers may moderate liquefaction effects so that performance criteria for the structures are satisfied even for shallow foundations (e.g. [7–10]). An additional benefit from this alternative design approach may result from the liquefaction-induced reduction of the inertia loads on the superstructure, since it is widely acknowledged that liquefaction may soften the site characteristics and consequently act as a form of “natural seismic isolation”. In that sense, liquefaction of the subsoil may also provide an extra protection shield to the superstructure in the accidental case when the design seismic intensity is exceeded. Kokusho [11] provides a comprehensive review of cases studies from past earthquakes where damage reduction was observed to structures resting on liquefied ground, due to the afore-mentioned base-isolation effect.

Within the above research and design initiatives, this paper refers to the capacity of liquefied soil layers to effectively attenuate the seismic motion, providing thus natural isolation of the seismic ground motion, as well as to the conditions which may lead to opposite results, i.e. detrimental amplification effects. These tasks are first explored analytically, with the aid of visco-elastic harmonic wave propagation theory in a stratified soil column. Nonlinear, effective stress, numerical analyses are used in the sequel in order to verify the analytical findings and provide quantitative criteria for the liquefied ground response.

It is important to clarify that this study refers to the site response at a liquefied state, i.e. after complete over depth liquefaction of a given subsoil layer. Furthermore, the emphasis is given to the soil and excitation conditions required in order to obtain significant attenuation of the seismic ground motion and those required in order to avoid its amplification. The exact amount of the anticipated attenuation and/or amplification of the seismic motion should be assessed independently, from site-specific response analyses which have been specifically developed for liquefiable ground conditions and take consistently into account the initial (pre-liquefaction) segment of the seismic excitation [12]. It is fortunate that, apart from advanced numerical methodologies, such as those that are used in the following, this task may be also accomplished approximately by a number of practice-oriented simplified methodologies, such as those proposed by Miwa and Ikeda [13],

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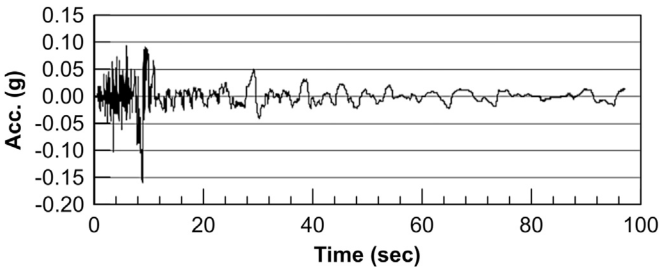

Fig. 1. Kawagishi-cho (E-W) seismic recordings of the Niigata, 1964 earthquake [15].

Kramer et al. [14], Kokusho [11] and Bouckovalas et al. [12].

2. Overview of liquefied ground response

Based on a number of seismic motion recordings at liquefied sites, such as the ones from Niigata, Japan M_w = 7.5 earthquake shown in Fig. 1 [15], it is a widespread belief among geotechnical and earthquake engineers today that the only beneficial effect of soil liquefaction is the drastic attenuation of the seismic motion of the free ground surface. Nevertheless, more recent studies suggest that this belief may not be unconditionally true. For instance, observe the seismic recordings in Figs. 2 and 3, obtained at the Port Island downhole array (PIDA) in Japan and at the Wildlife Liquefaction Array (WLA) in USA, during the Kobe (1995, M_w = 6.9) and the Superstition Hills (1987, M_w = 6.6) earthquakes respectively [16,17]. Each figure summarizes recorded acceleration time-histories and elastic response spectra at the ground surface and at the base of the liquefied layer.

There are at least two distinct differences with respect to the recordings in Figs. 2 and 3, which should be considered for interpreting the observed trends. The first difference is that the liquefied layer is 13 m thick at PIDA and only 4.5 m thick at WLA. The second difference is that the average factor of safety against liquefaction was much lower during the Kobe (FS_L = 0.4) than during the Superstition Hills (FS_L = 0.8) earthquake and consequently the onset of liquefaction occurred very early during shaking in the first case and late during shaking in the second one. This is demonstrated in Fig. 2a and b, where recorded acceleration time-histories at the base of the liquefied layers and at the ground surface are plotted in parallel using a common time origin. It is thus observed that the incoherence between the two motions, indicating soil softening due to excess pore pressure buildup, becomes significant after about 8.3 s in the PIDA recording and after about 13.6 s in the WLA recording [18].

To isolate the effects of the pre-liquefaction seismic shaking, and focus upon the response of the liquefied ground, Fig. 3a and b compare the elastic response spectra corresponding to the segments of excitation and ground surface recordings that follow the onset of excess pore pressure induced soil softening. Observe that spectral accelerations for the PIDA recordings are drastically attenuated for periods up to $T \approx 1.0$ s, while they are marginally affected thereafter. On the contrary, spectral accelerations for the WLA recordings are practically amplified over the entire period range, except for medium periods between 0.2 s and 0.5 s, where the site effects are marginal. The ratio of surface to base elastic response spectra, shown in the second row of Fig. 3a and b, suggests that the average attenuation factor in the PIDA recordings and the respective amplification factor in the WLA recordings is of the order of two. The distinctly different response demonstrated in Figs. 2 and 3 may be attributed to the aforementioned difference in liquefied soil thickness at the PIDA (13 m) and the WLA (4.5 m) sites, suggesting that thick liquefied layers tend to attenuate the seismic motion, while relatively thin layers may amplify it. Furthermore, the results from the PIDA recordings show that, apart from the liquefied soil thickness, the excitation period may also affect the associated ground response.

Similar conclusions with regard to the conditional attenuation or amplification effects of liquefied soil layers are drawn from the results of centrifuge tests T3-30 and T3-50-SILT of Dashti et al. [19], presented in Fig. 4a. These tests were performed for a relatively thin (3 m thick) liquefiable sand layer at two relative densities D_r = 30% and D_r = 50%. In the second test, a very thin silica flower layer was placed on top of the liquefiable sand layer in order to delay excess pore pressure drainage to the free ground surface. The base of the test models was subjected to the N-S Kobe (1995) PIDA recording scaled down to peak acceleration equal to about 0.18g. Reported excess pore pressure time-histories indicate that soil softening and liquefaction in both tests were triggered very early during shaking, and hence it may be safely assumed that, except possibly from the low period range T < 0.5 s, the presented response spectra reflect the liquefied soil response. Observe that the seismic motion is moderately attenuated for the very loose liquefiable layer (D_r = 30%) and considerably amplified for the medium dense (D_r = 50%) layer, identifying the relative density as one more factor affecting the liquefied ground response. It is further noteworthy that the amplification response of the medium dense sand layer is overall consistent with that obtained from the Superstition Hills recording at WLA (Fig. 3b), where the liquefied layer was also thin (4.5 m thick) and the estimated in situ relative density varied between $D_r \approx$ 40% and 60%.

The effect of excitation period T_{exc} on the liquefied ground response seen in Fig. 3a is also indirectly suggested by the study of Kramer et al. [14], which is based on results from a very large number of numerical seismic response analyses of liquefiable sites, for nine soil profiles with different liquefiable layer thickness and density, as well as 139 input motions with different frequency content and intensity. Each analysis was performed once using nonlinear, effective stress analysis with excess pore pressure buildup and once using nonlinear, total stress analysis. The resulting spectral accelerations were then divided in order to compute the response spectral ratio $RSR(T)$ which is a measure of excess pore pressure effects on seismic ground motion. Fig. 4b shows the variation of RSR with excitation period for cases of intense liquefaction, with average factors of safety FS_L = 0.50–0.55. The Authors admit that the large scatter of the data points masks the identification of any detailed effects of soil liquefaction on seismic ground motion. It is still of interest to observe that, similar to the PIDA

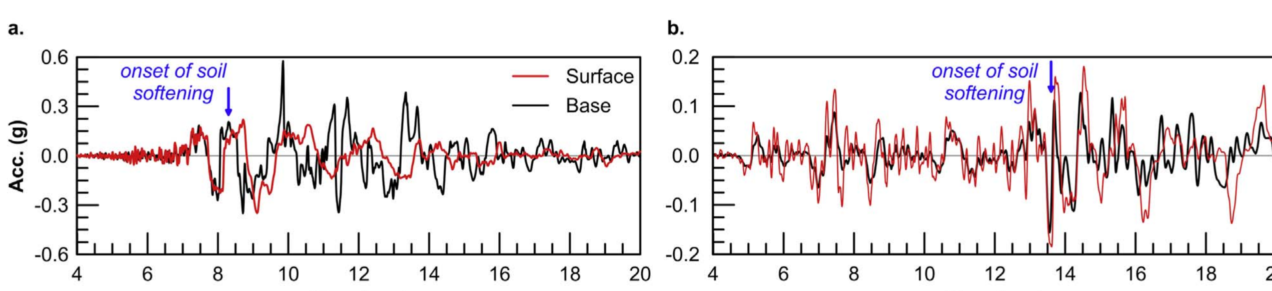

Fig. 2. Acceleration time-histories recorded at the ground surface and at the base of the liquefied layer (a) at Port Island seismic array during the Kobe, 1995 earthquake and (b) at Wildlife Liquefaction Array during the Superstition Hills, 1987 earthquake.