ONE-DIMENSIONAL SEISMIC RESPONSE OF LIQUEFIABLE SOFT SOILS DUE TO MULTIPLE EARTHQUAKES

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Earthquake-induced liquefaction generates two major concerns: a) liquefaction may cause excessive ground deformation or ground failure, and b) modification of seismic wave due to ground softening may adversely affect seismic site response (Youd and Carter, 2005). In recent years, studies for practicing engineers have been developed on the effect of soil softening and pore water pressure build-up on seismic ground response. On the other hand, the recent experience after Chile, Tohoku (Japan) and Christchurch earthquakes, researchers have started paying attention to implement a new methodology to design and assess structures to resist more than one earthquake (Multiple Earthquakes), especially since current seismic codes do not account for their effects (Takewaki et al., 2013). Repeated or multiple earthquakes occur in many regions around the world where a complex fault system exists. The sequential ruptures along the fault segments lead to multiple earthquakes, which are often hard to distinguish them as fore main and aftershocks, or a sequence of earthquakes from proximate fault segments. In this regard, the main purpose of this study is to evaluate the seismic ground response for soft soils with liquefiable potential due to multiple earthquakes. Energy of hysteresis loop (EHL) was defined for evaluate the effects of earthquake's energy of liquefiable layer on seismic amplification patterns. Furthermore, in order to use the compatible constitutive model in numerical analysis, multi-yield surface's model developed by Elgamal et al. (2002) was utilized. They applied this constitutive model in Cyclic1D software that is including nonlinear effective and total stress analysis based on finite-element method. This code is a seismic analysis tool for conducting simulations of nonlinear seismic ground response including liquefaction. On the other hand, VELACS project includes a series of laboratory tests and centrifuge experiments, which offers a good database to verify the accuracy of analytical procedures. Recorded measurements in the centrifuge experiments are in terms of excess pore water pressure, acceleration, and displacement time histories. In this study, level-ground centrifuge experiment (model No. 1) was considered for verification of the numerical model based on prototype scale (Soil layer with a thickness of 10 m).

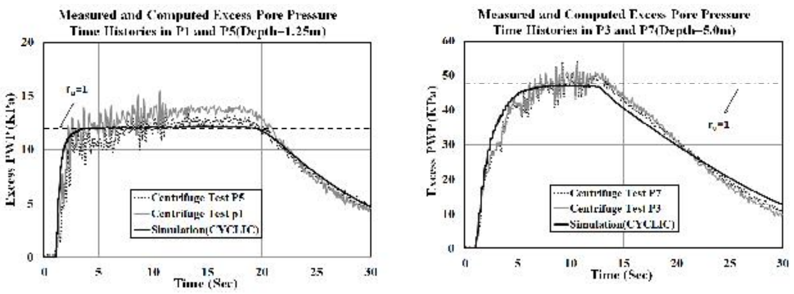

Figure 1. Comparison of predicted and measured pore water pressures at points P5–P7 from VELACS centrifuge tests No.1

Based on Table 1, thirty multiple earthquakes were applied to model by using CYCLIC1D software (validated model). In this paper in order to compare the results of amplification pattern, two types of effective and total stress analysis in time-domain were performed.

Table 1. Examples of strong ground-motions with multiple acceleration sequences

No.	Name	Year	Station	Epi dist	Mw	Comp	PGA(g)	EHL
1	Imperial Valley	1940	El Centro, Array Sta 9	12.2	6.90	S00E S90W	0.341 0.21	6.097 3.995
2	Coast of Honshu	1997	Katsurao, Japan	73.1	5.30	EW NS	0.116 0.117	0.551 0.47
3	Niigata-ken Chuetsu	2004	Koide, Japan	27.8	6.30	EW	0.524	5.127

According to analysis and obtained results, EHL is divided into three groups (i.e., EHL<1, 1≤EHL<10, and EHL≥10). Based on Figure 2, high levels of EHL with pore pressure build-up, caused decreased levels of seismic ground response amplification in liquefiable soft soils. Although these multiple earthquakes contain low energy content, but repeating sequence and long significant time duration will cause damage and soil liquefaction.

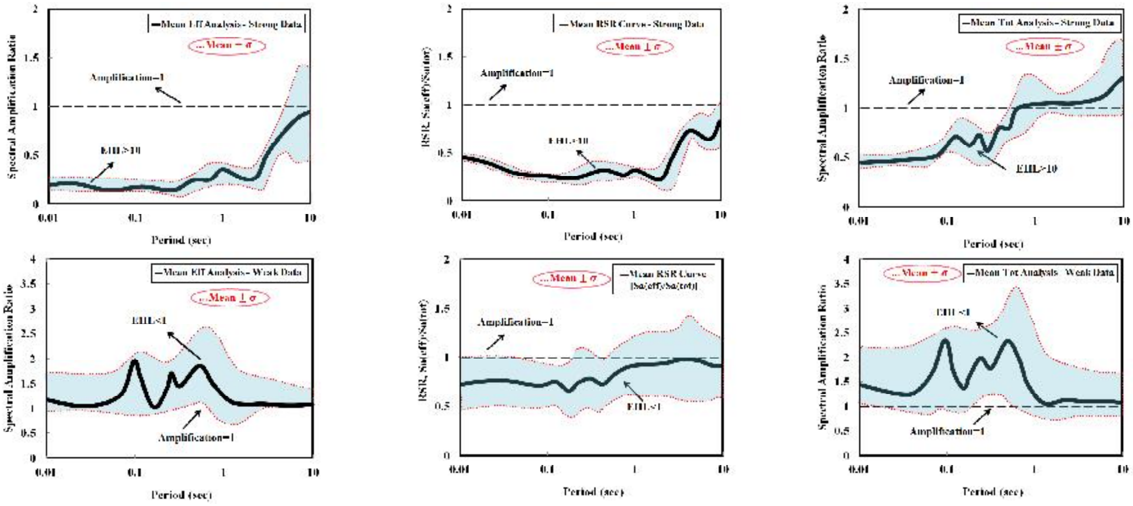

Figure 2. Amplification pattern curve based on total and effective stress analysis with average spectral ratios curves for different ranges of EHL values

Moreover, response spectral ratio [$Sa_{(effective)}/Sa_{(total)}$] was developed for demonstrating the effects of pore pressure build-up and its relation to the frequency (period) of motions. In addition, response spectral ratio varies from 0.4 (for EHL≥10 and period of 0.5s) to 1 (for EHL<1 and period≥1s) which shows the type of analysis has a great influence on spectral ratio curves, because of excess pore pressure build-up is not considered in total stress analysis method.

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