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Near fault effects on near fault ground motion on soil amplification and liquefaction

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ABSTRACT: In near-fault regions, fault rupture towards a site can generate one or two intense cycles in the velocity-time history called velocity pulse. Ground motions which contain a velocity pulse signature, typically most pronounced within the fault-normal component, may cause greater structural damage than those which do not. It is also recognised that velocity pulse signatures are characterised by short frequency ground motions which can induce to high cyclic demand on soil strata.

In this study, site response analyse using near-fault ground motions containing velocity pulse signatures were carried out to examine the effect on soil amplification and peak shear stress. A response spectrum characterising directivity effects of fault normal and fault parallel using Bayless and Somerville (PEER 2013/09) model has been developed. An appropriate proportion of pulse-containing ground motions with characteristics representative of a desired hazard level were used based on the extended method of Shahi and Baker (2011) described in Almufti et al. (2013).

The preliminary assessment suggests the pulse-containing ground motion would not induce larger soil amplification but may potentially induce larger peak shear stress ratio in soft soil. These effects are particularly pronounced for softer soil profiles. As such, the potential for the triggering of liquefaction may be higher in cases where pulse-containing ground motions occur and due consideration should be made of these effects.

1 INTRODUCTION

Near fault ground motion, also known as “directivity” has been studied including Somerville et al. (1997), Baker (2007), Shahi and Baker (2011) and recently been summarised in PEER (2013). Near fault ground motion contains a velocity pulse that exhibits a strong amplitude enhancement within a short amount of time relative to the full duration of shaking. The velocity pulse, generated by the propagation of the rupture front, is generally preserved in the fault-normal (FN) component. Ground motions containing velocity pulses affect the response of the structure (i.e. stresses, displacements, ductility demand, damage, etc.) as attributed to a large amount of energy being dissipated in a short time interval. Velocity pulse contribute disproportionately to large nonlinear response and greater level of demand to inelastic systems of structures.

The effect of near-fault ground motion on geotechnical aspects such as soil amplification and liquefaction analysis have not been widely investigated. In this study, the pulse-like ground motion was adopted to examine the effect on two major geotechnical parameters: soil amplification and peak shear stress. A site in Manila, Philippines has been selected as the case study. Several one-dimensional site response analyses have been carried out to investigate the ground response using the pulse-like ground motion.

2 STUDY AREA

Manila is within a seismic active region in the Philippines. A mapped active fault, the Marikina Valley

Fault System (MVFS), passes through Metro Manila. The MVFS is a 150 km long, trending NNE, right lateral fault. The fault has been recently studied by Nelson et al., (2000), Rimando and Knepfer (2006) and Allen et al., (2014). The studies suggested the fault is active with slip rate interpreted to be range from 2 to 10 mm/year with possible maximum earthquake magnitude from 6.4 to 7.7. As much Metro Manila is within 5 km from the MVFS, the near fault ground motion has to be considered in the design process.

For this study, a site located approximately 3 km from the MVFS is selected.

3 GROUND MOTION

For the purpose of this study, the pulse-containing ground motion (*hereafter* pulse ground motion) and ground motion without velocity pulse (*hereafter* non-pulse ground motion) have been developed for the site response analysis.

Arup conducted a Probabilistic Seismic Hazard Assessment (PSHA) in 2008 (Koo et al., 2008) and the PSHA model has been recently updated in 2013 and 2015 (Arup internal report). The ground motion of 2% probability of being exceeded in 50 years is used. The de-aggregation result shows that the majority of contribution to the seismic hazard is MVFS, and confirms that near fault ground motion should be considered in Metro Manila.

To develop the pulse-like ground motion, methods are briefly discussed below.

3.1 Velocity pulse calculation

To create a representative suit of pulse ground motions under a given hazard level, the methodology of probabilistic framework proposed by Shahi and Baker (2011) was adopted. This method calculates the probability of having ground motion with pulses from the MVFS and the likely pulse period (Tp) can be calculated. The detailed methodology can be found in Almufti (2013).

The result for Metro Manila shows that there is 80% chance of having an earthquake with velocity pulses occurring at the site at the ground motion having 2% probability of exceedance (0.42 g at 3s of structural period). Hence, six pulse ground motions were selected out of seven time history events for this study. The PEER NGA WEST2 ground motion database was used to select time histories (Table 1).

To select an appropriate Tp of the ground motion, the cumulative frequency of Tp was plotted as shown in Figure 1. Table 1 also gives Tp calculated and the corresponding ground motion selected.

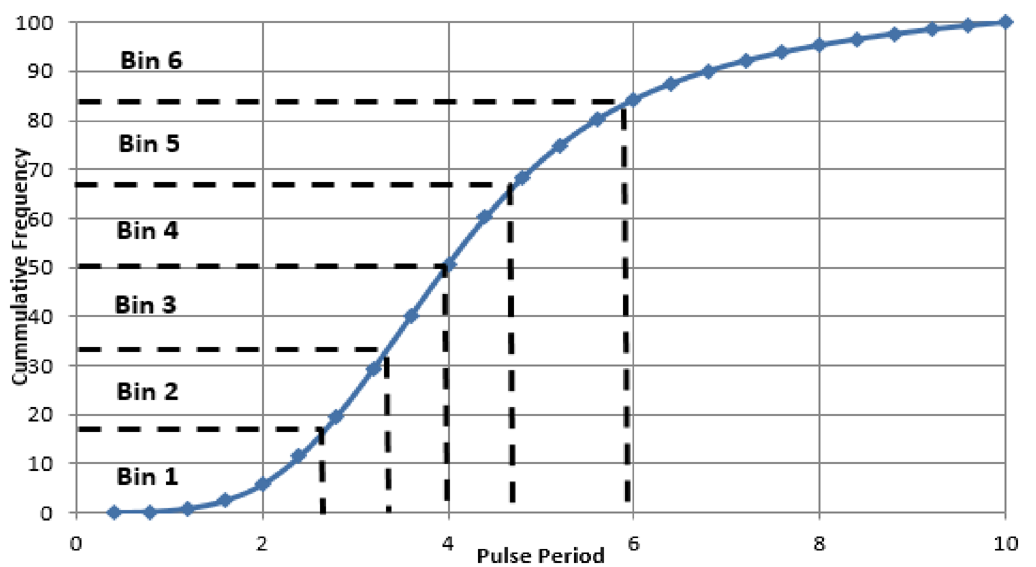

Figure 1. Normalized cumulative distribution function of pulse period for T=3 sec with equal contribution bins.

Table 1. Selected ground motion records from NGA WEST2 database

Tp required (s)	NGA	TH Record name	Magnitude	Mechanism	Pulse period, Tp (s)	PGV (cm/s)
0.00-2.66	**1182**	1999 Chi-Chi, Taiwan, CHY006	7.60	Reverse-Oblique	2.57	58.30
2.66-3.35	**828**	1992 Cape Mendocino, Petrolia	7.00	Reverse-Oblique	3.00	96.70
3.35-3.98	**171**	1979 Imperial Valley-06, El Centro - Meloland Geot. Array	6.50	Strike Slip	3.42	116.40
3.98-4.72	**802**	1989 Loma Prieta, Saratoga - Aloha Ave	6.90	Reverse-Oblique	4.57	53.50
4.72-5.92	**879**	1992 Landers, Lucerne	7.30	Strike Slip	5.12	132.30
5.92-10.00	**1148**	1999 Kocaeli, Turkey, Arcelik	7.50	Strike Slip	7.79	40.30

3.2 Target response spectrum

The response spectrum of selected ground motion varies with different earthquake event. For a direct comparison in this study, the time histories were spectrally matched with a target response spectrum.

The uniform hazard response spectrum (UHRS) of 2% chance of being exceeded in 50 years ground motion calculated from Arup PSHA model is used as target response spectrum for non-pulse ground motion. As Metro Manila is underlain by Neogene volcanic rock of which the shear wave velocity is generally lower than 760m/s, a Class C as per NEHRP site classification UHRS is adopted.

For the target response spectrum of pulse ground motion, the coefficient developed in Bayless and Somerville (PEER 2013/09) is used to multiply the response spectrum of the non-pulse ground motion. Bayless and Somerville (PEER 2013/09) updated a directivity model from Somerville et al. (1997) and have developed coefficients to modify non-pulse ground-motion to account for directivity amplification.

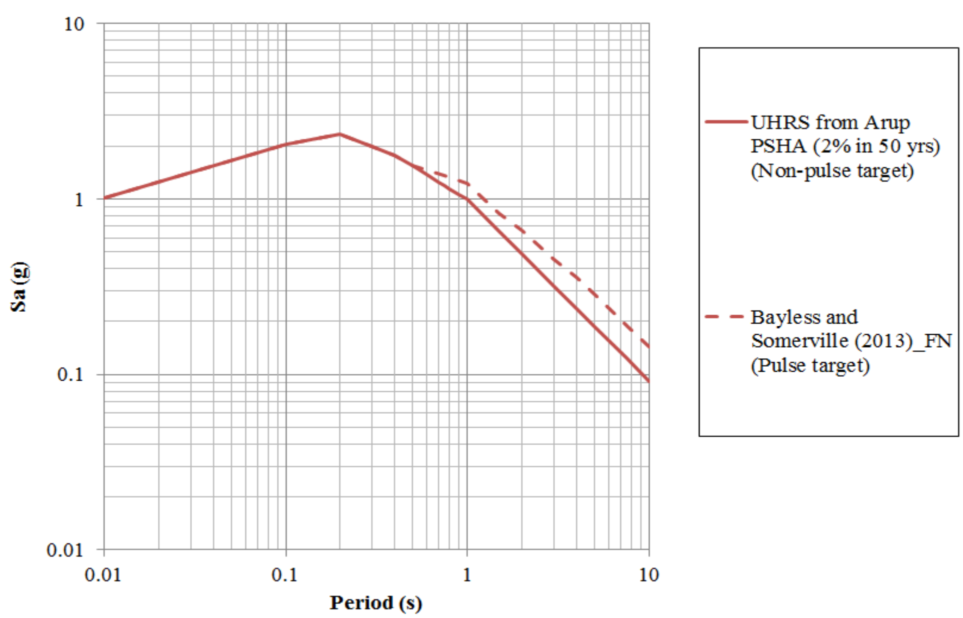

Figure 2 Target response spectrum

3.3 Matching Methodology

In order to keep the pulse components in the ground motion, the time histories is decomposed into "residual" and "pulse-like" portion. The residual ground motion is matched with the target spectrum and pulse motion is added in subsequently. This method was proposed in NIST (2011) and Grant (2012).

The decomposition of the ground motion was carried out by using the algorithm of Baker (2007). Baker (2007) can identify and check ground motions that contain dominant velocity pulses. The algorithm uses wavelet analysis to decompose the ground motion to several wavelets and extract the largest wavelet coefficient that is associated with the energy.

The residual time histories have been matched to the non-pulse target response spectrum using the RSPMatch code developed by Abrahamson (1992). This method creates the non-pulse ground motion.

Subsequently, the linearly pulse potion was added back to the matched residual portion to form the pulse ground motion. A check is made so as the time histories are close but do not exceed the pulse target spectra. Figure 3 shows the spectrally matched TH of pulse and non-pulse ground motion.

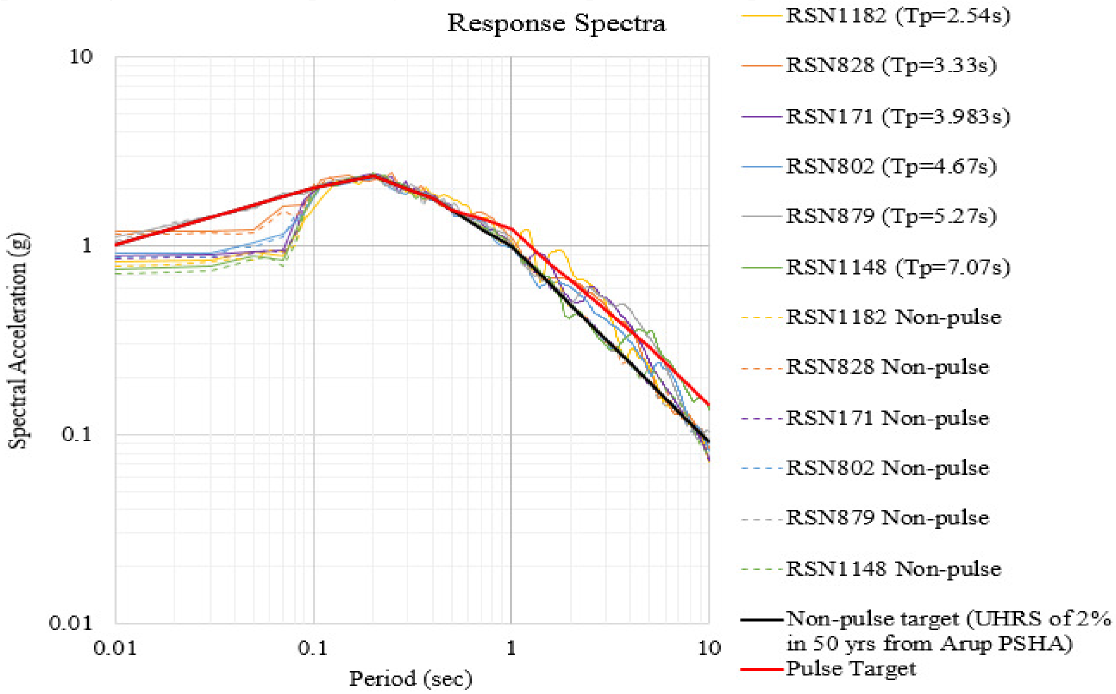

Figure 3. Response spectra plots of pulse and non-pulse ground motion.

3.4 Check of pulse preserved after match

To ensure the processed pulse ground motion containing the pulse that is suitable for the study, the pulse ground motion were reassessed to be "pulse-like". The re-assessment includes checking of pulse period, pulse time occurrence, waveform of pulse, energy content, and significant duration which were possibly introduced by spectral matching. The method of Baker (2007) is adopted to verify if the non-stationary characteristics of the record like pulse velocity were preserved. Below are the criteria for this verification process:

1. The change in pulse period should not exceed the range of the pulse bin in the cumulative frequency curve or not greater than plus minus twenty percent compared to the original pulse period of the unmodified time history.
2. The arrival of pulse should be in the start of the record and late occurring pulse was rejected.
3. Energy content and significant duration of the record was investigated to classify whether the record has been greatly altered.

Table 2 is a summary of the records pulse period before and after matching and shown the pulse is preserved.

Table 2 Summary of pulse period before and after match.

NGA RSN#	Event Name	Initial Scaling Factor	Pre-match Tp Sec.	Post-match Tp Sec.	Percent Difference
1182	Chi Chi Taiwan	1.90	2.57	2.54	-1.17%
828	Cape Mendocino	1.67	3.00	3.33	+11.00%
171	Imperial Valley-06	0.67	3.42	3.98	+16.37%
802	Loma Prieta	2.20	4.57	4.67	+2.19%
879	Landers	1.07	5.12	5.34	+4.30%
1148	Kocaeli	2.75	7.79	7.07	-9.24%

4 SITE RESPONSE ANALYSIS

4.1 Methodology

A series of three fictitious soil profiles displaying a range of fundamental site periods were generated based on local experience and published micro-tremor surveys performed in Metro Manila (Abeki et al., 1996). Site response analysis was then performed with the 1D analysis program DEEPSOIL v6.0 (Hashash et al., 2015) applying non-linear time domain analysis with non-Masing hysteretic behaviour. The material properties were calibrated for reasonable small strain shear stiffness and shear strength.

The resulting amplification ratio and peak shear stress ratio at the ground surface were compared for pulse and non-pulse ground motion containing different Tp.

4.2 Soil Profile

On the basis of parametric analysis, a 30m thick, uniform layer of soft fine-grained soil with a constant normalised shear wave velocity, V_{s1}, was modelled. A lower bound limit of 40m/s was applied to shear wave velocity on the basis of local experience in soft alluvium. Under this assumption, the soil represents a material wholly deposited under the same conditions whereby shear wave velocity increases with confining pressure. It is acknowledged this assumption is non-representative of actual variability in real soil deposits, however, this provides a simplistic platform upon which to compare the impact of low frequency ground motions attributed to directivity effects.

The analysed soil profiles display natural site periods of 0.75s, 1.25s and 2.0s. Shear stiffness degradation and damping for the soil were calibrated against the curves proposed by Vucetic and Dobry (1991) for a clay soil with plasticity index = 20%. A typical soil density of 1.8t/m^3 was adopted. As the Metro Manila is underlain by Neogene volcanic rock, bedrock was taken as an NEHRP Class C rock with density of 2.4t/m^3 and shear wave velocity of 500m/s.

The determined shear wave velocity, shear stiffness and shear strength for the various soil profiles are presented in Figure 4.

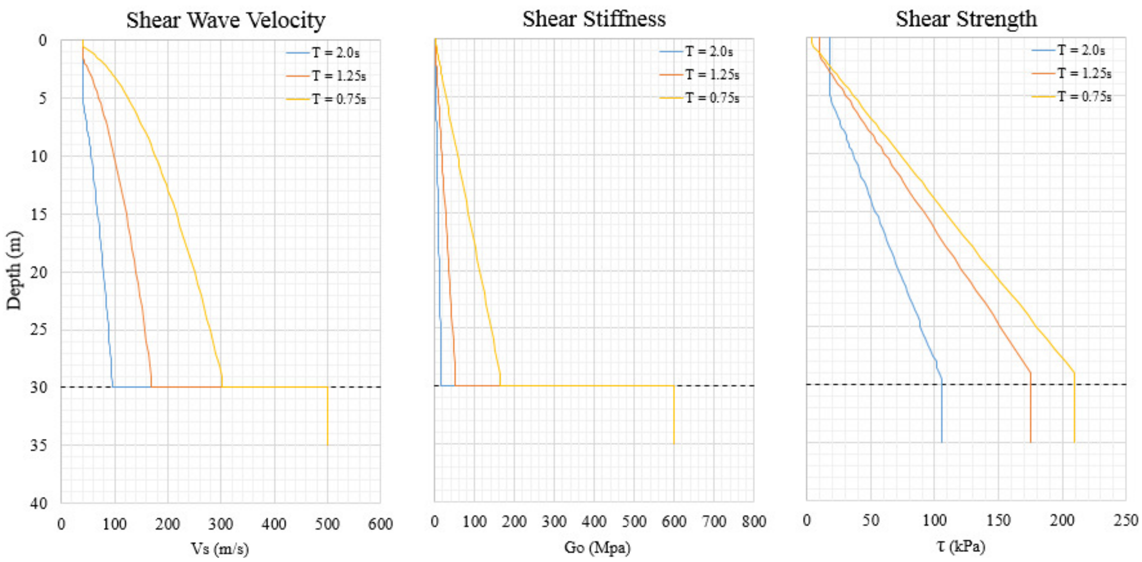

Figure 4. Shear wave velocity, shear stiffness and shear strength material properties for modelled soil profiles

5 RESULT

The soil amplification using pulse and non-pulse ground motions are compared and the results are shown in Figure 5 (a) to (c). The comparison is expressed in the ratio of

$$\frac{Soil\ amplifcation\ using\ pulse\ ground\ motion}{Soil\ amplfication\ using\ the\ non-pulse\ ground\ motion}$$

The ratio larger than unity indicates the soil amplification using pulse ground motion is higher than non-pulse, and vice versa. The ratio are calculated for the three soil profiles, having site natural period of 0.75s (Figure 5a), 1.25s (Figure 5b) and 2s (Figure 5c).

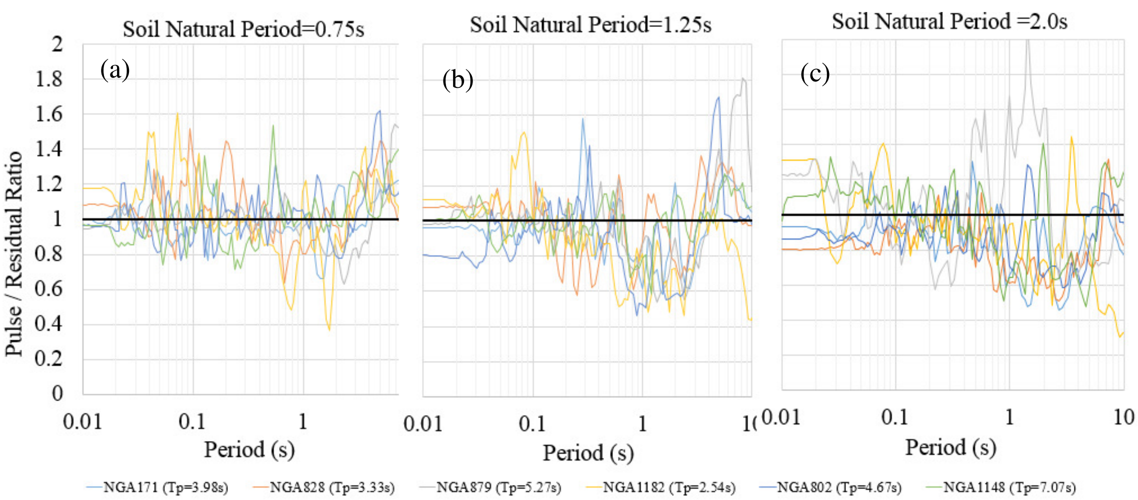

Figure 5 Ratio of soil amplification using pulse to non-pulse ground motion for the three soil profiles

Figure 5(a) shows that the soil amplification of the stiffer soil profile (natural site period=0.7s and 1.25s) has no significant difference between using pulse and non-pulse ground motion. However, the softer soil profile (natural site period=1.25s and 2s) in Figure 5 (b) and (c) suggest the soil amplification using the pulse ground motion is lower than using non-pulse ground motion.

Similarly, the comparison of peak shear stress ratio has been examined by adopting the following the ratio:

$$\frac{Peak\ Shear\ Stress\ using\ pulse\ ground\ motion}{Peak\ Shear\ Stress\ using\ the\ non-pulse\ ground\ motion}$$

The results are presented in Figure 6 (a) to (c)

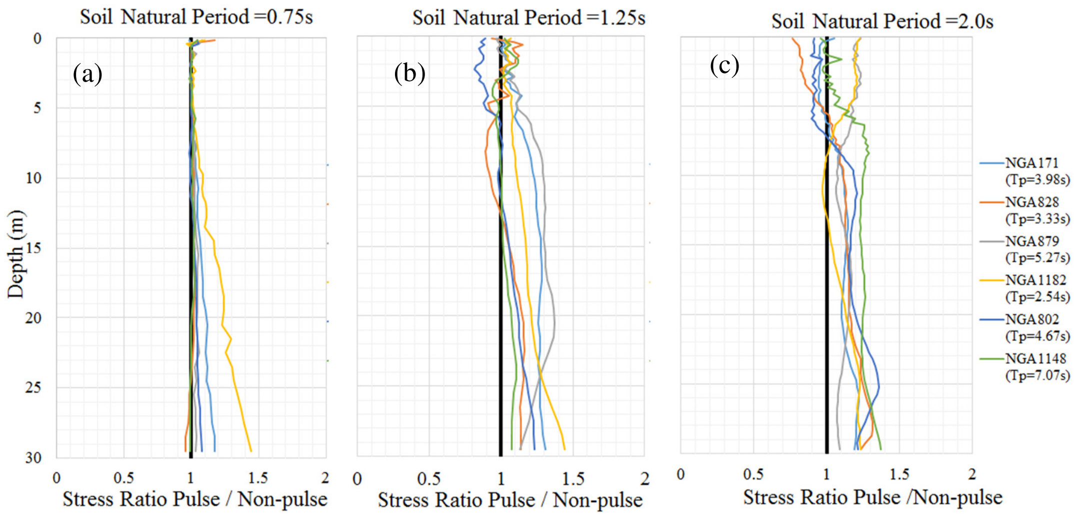

Figure 6 Ratio of peak shear stress ratio using pulse to non-pulse ground motion for the three soil profiles

In contrast to the soil amplification, the effect of pulse ground motion on the peak shear stress is relatively insignificant (the ratio ~1) for the stiff soil profile (soil natural period =0.75s in Figure 6a). However, the peak shear stress using the pulse ground motion is higher than non-pulse motion in the softer ground (soil natural period =1.25s and 2s in Figure 6 (b) to (c)) as indicated by ratio of larger than 1.

6 CONCLUSION AND DICUSSION

The velocity pulse effect on soil amplification and peak shear stress ratio has been investigated in this study. An area in Metro Manila near the MVFS, the Philippines has been chosen and typical soil profiles analysed.

To facilitate the study, the pulse ground motion has been developed using one of the methodology suggested in Grant (2012). The target response spectrum of the pulse motion was developed by using the response from PSHA model with a directivity model from Bayless and Somerville (2013). Six pulse ground motions were developed with the pulse period (Tp) estimated by using method of Almufti (2013), which is using the framework proposed by Shahi and Baker (2011). The pulse ground motion were also checked by Baker (2007) to ensure the velocity pulse is included in the ground motion.

In brief, the original pulse ground motions were decomposed into residual component and pulse ground component. The residual components were matched to the pulse target response spectrum (UHRS of 2% probability of exceeded in 50 years in Arup PSHA). Subsequently, the pulse components were added back to the matched residual components. The reason of using this method is to ensure the only difference the pulse and non-pulse ground motion is purely due to the “velocity pulse”. In addition, all the ground motions have been spectrally matched with the same target response spectrum.

The results suggest that pulse ground motions do not have significant effect on soil amplification in stiffer soil profiles (Figure 5, natural site period = 0.75s). It is also noted that peak shear stress ratios are comparable for pulse and non-pulse ground motions in stiffer soil profiles.

In contrast, it was observed that pulse ground motions in softer soils resulted in attenuation of low frequency ground motions and larger peak shear stress ratios (Figure 5, natural site period >1.25s). This may be explained as a result of soil non-linearity, where larger soil damping occurs in response to larger soil strain, induced by larger ground motions present in the velocity pulse. If this is the case, the pulse ground motion would potentially lead to higher chance of liquefaction in softer soils. This pulse effect cannot be reflected in the simplified conventional liquefaction assessment which only requires Peak Ground Acceleration (PGA) as the input ground motion for the assessment.

It is noted that this study is only a preliminary assessment and more rigorous studies are recommended to consolidate the findings. For way forward, the conditional mean spectrum (CMS) can be used instead of uniform hazard response spectrum (UHRS) to have better representation of a single earthquake scenario. Also, different types of soil can also be used by adopting other soil stiffness degradation and damping behaviour to investigate the pulse effect on variable soil.

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