DETERMINATION OF LIQUEFACTION IN TIME DOMAIN USING WAVELET ANALYSIS

I. E. Bal[1], E. Smyrou[2], P. Tasiopoulou[3] and G. Gazetas[4]

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A method is described for identifying ground motions containing large-period pulses caused by liquefaction. It is known that the liquefied soils exhibit a series of large-period waves at the end of the acceleration record. The period, starting time and the number of cycles of these waves are of engineering interest. There have been methods for identifying traces of liquefaction by using the acceleration records, however, a time-domain approach for the determination of liquefaction has not been examined enough in the existing literature because of lack of available data.

In this study, acceleration records from Superstition Hills (1987), Kobe (1995), and Christchurch (2011) events have been used as datasets. An approach, where pseudo-periods have been used for identification of a certain wave series appearing in the records at a certain time, has been proposed. The observations have also been validated by using nonlinear soil simulations where the pore pressure can be observed in time domain and the start of liquefaction can be correlated. Results are rather satisfactory and encouraging in terms of allowing engineers in automatically detecting the liquefaction traces in a given record.

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A method is described for identifying ground motions containing large-period pulses caused by liquefaction. It is known that the liquefied soils exhibit a series of large-period waves at the end of the acceleration record. The period, starting time and the number of cycles of these waves are of engineering interest. There have been methods for identifying traces of liquefaction by using the acceleration records, however, a time-domain approach for determination of liquefaction has not been examined enough in the existing literature because of lack of available data.

In this study, acceleration records from Superstition Hills (1987), Kobe (1995), and Christchurch (2011) events have been used as datasets. An approach, where pseudo-periods have been used for identification of a certain wave series appearing in the records at a certain time, has been proposed. The observations have also been validated by using nonlinear soil simulations where the pore pressure can be observed in time domain and the start of liquefaction can be correlated. Results are rather satisfactory and encouraging in terms of allowing engineers in automatically detecting the liquefaction traces in a given record.

Introduction

The effects of liquefaction on the frequency content of the recorded motions are known for long [1]. Fourier transformation is often not enough to capture the phenomenon since the information derived from time domain is lost. The time domain is an important parameter in liquefaction analyses because the pore pressure builds up as function of time, until a point where liquefaction actually initiates. Though the distinction between the duration of the records before and after the liquefaction starts is not that clear, still some insights can be obtained. One of the most powerful tools for doing so is the wavelet analysis.

Detecting the liquefaction in a record by using wavelet procedure can be extremely useful because a decision making can be made automatically (i.e. by a computer) in this way. This is because one of the new research areas is to estimate the losses during an earthquake by using the accelerometer data network, thus, the definition of liquefaction by using accelerometer outputs

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and correlating this to the estimated losses will certainly be of use in the future. There are acceleration time history-based procedures to define whether the liquefaction occurred or not, such as [2 to 4], but these procedures do not provide information about neither the time domain nor the dominant frequency, with the latter being a fundamental parameter in estimating the structural losses.

An existing method to correlate the liquefaction, though not fully compatible with the output of the wavelet approach explained hereinafter, was proposed by Bird et al. [5], encouraging the inclusion of liquefaction phenomena in urban-level loss estimation studies that could be useful in decision making in the immediate aftermath of a catastrophe.

As explained above, the wavelet analysis is a powerful tool to correlate the ground motion properties of the liquefaction-affected recorded motion with liquefaction. Wavelet analysis is a procedure similar to Fourier Transformation but with two main differences, which are i) the series can be opened in any wave format, ii) presence of waves is recorded in time domain. In other words, the wavelet procedure scans the entire record and tries to match the wavelet shape, and when found it registers the time.

There are several wavelets defined and used in the literature, however one of the wavelets compatible with earthquake engineering problems is the Morlet wavelet shown in Fig. 1. The Morlet wavelet contains 5 cycles, which start from low amplitude and go up, decreasing after the peak cycle. This shape is quite similar to that of a ground motion record.

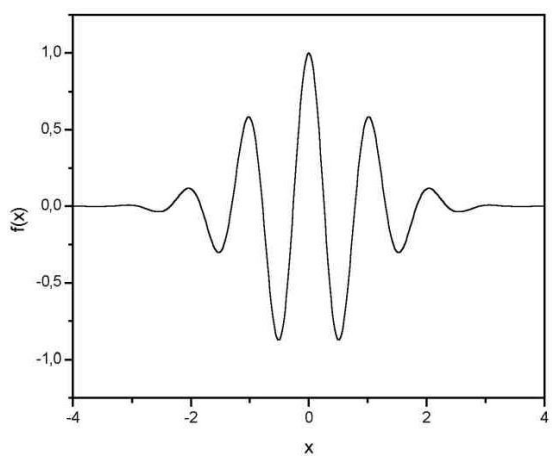

Figure 1. Morlet-type wavelet used in the analyses.

The wavelet analysis results are often presented with what is called “wavelet maps” where the wavelet content is defined with colors, meaning that the high values (from blue to red colors in this paper, for instance) represent higher match of the recorded motion with the pre-defined wave form.

The use of wavelets is common in earthquake engineering. Haigh et al. [6], for instance, show that the harmonic wavelet analysis is a versatile tool that can reveal information, especially for liquefaction, even if traditional time or frequency domain analysis is not available. Tezcan et al. [7] show the advantage of a wavelet-based approach over its Fourier-based counterpart, where

time domain information is lost. Their study concludes that the energy localization patterns observed in the wavelet spectra from different sites and events can be used to detect nonlinear effects and characterize soil damping. Kramer et al. [8] present a set of wavelets and come to the conclusion that there is a sudden drop of available frequencies after a certain time step. Rezai and Ventura [9] work on the applicability of wavelet transform for the analysis of strong and weak ground motions recorded on rock at Yerba Buena Island and on dredged sandfill at nearby (about 2 km away) Treasure Island during the 1989 Loma Prieta earthquake in California. The major important feature of this data set is that liquefaction occurred at the Treasure Island site during the strong shaking. The Daubechies 20-coefficient wavelet transform is utilized in their study. Results of the application show that there are some large peaks at the highest resolution in the wavelet transforms at the Treasure Island site, which can be attributed to a progressive change in the stiffness characteristics of the soil.

Wavelet Analysis of Real Accelerograms

The wavelet analyses presented hereinafter have been conducted by using Matlab software and by employing the Morlet (morl) wavelet. The minimum and maximum periods of interest are set to 0.01 and 10 sec, but the plots are limited to 4 sec period since there is no significant match after 4 sec period. The plots are shown with period in one axis, a parameter that is of more interest to the structural engineers, and time domain in the other axis. The colors represent the match of the record at the relevant time slice with the pre-defined wavelet.

Table 1. The acceleration records used in the analyses.

Event	Station	Site Class	PGA (g)	Liquefaction
Kobe, Japan, 1995, M=6.9	JMA	Soft Soil	0.85	No
Supertition Hills, 1987, M=6.5	Wildlife	Soft Soil	0.12	Yes
Christchurch, 2011, M_L=6.3	CBGS	Soft Soil	0.64	Yes
	CCCC	Soft Soil	0.49	Yes
	CHHC	Soft Soil	0.46	Yes
	HVSC	Hard Soil	1.50	No

As far as the wavelet analysis of the ground motions with liquefaction is concerned, the main problem in drawing concise conclusions is the lack of enough number of strong motion data with confirmed liquefaction traces. In 2011 there was a significant increase in the number of ground motion records with liquefaction due to the recent Canterbury Earthquakes in New Zealand in 2010 and 2011. This study tries to take advantage of the recently available Canterbury data in reaching conclusions. Though not presented here due to lack of space, the other liquefaction-affected records of the recent Canterbury Earthquakes exhibit similar results, in general, to that of the ones presented in this paper. The acceleration records used in this paper are listed in Table 1. Note that the dominant direction of each record is used, where the direction with the highest PGA occurs. For a detailed discussion on the use of dominant direction, the readers are referred to the work by Smyrou et al. [10]. The range of PGA of the records used is between 0.12 and 1.5g.

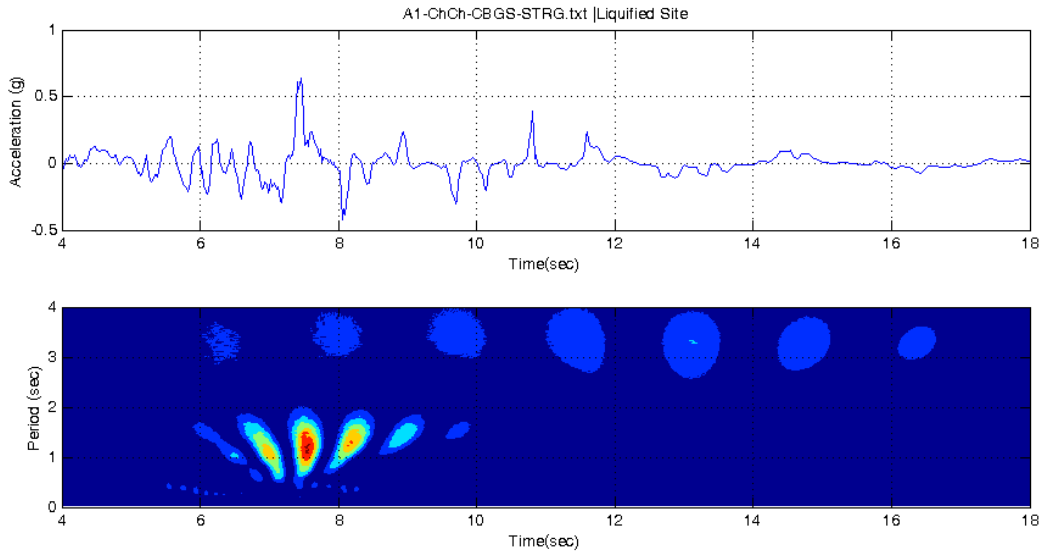

Figure 2. Time history and the wavelet map (the percentage of energy content) for the Christchurch, New Zealand (2012) Event, CBGS recorder with observed liquefaction.

The wavelet results in this paper are presented for liquefied sites, for a soft soil site without liquefaction and for a hard soil site. Figs 2 to 5 show the wavelet maps of the liquefied sites. The two common characteristics of these wavelet maps are that i) the concentration of the peak wavelet match is between 1.0 to 2.0 seconds period, ii) the long period waves exist until the very end of the significant part of the recorded motion. The long period waves, which are initiated with liquefaction, are also clearly separated from the rest of the peaks of the wavelet map, a property that could easily be used for software-based decision-making. This observation is valid, though not presented here due to lack of space, for all other liquefaction-affected records from the entire dataset from the earthquakes of Canterbury (2010 and 2011), Kobe (1995), Superstition (1987).

As far as the response of a hard soil example is concerned, a close look to HVSC record and its wavelet map could show that the wave content reaches a peak at around 0.3 sec period and then the period ranges with high energy-content fade with time (Fig. 6). Note that HVSC is recorded on hard soil, and the wavelet map of HVSC is characteristic of hard soils both in terms of the period range of the major waves and the reduction of high energy-content periods after the peak.

Soft soil response is presented by using the JMA record of Kobe (1995) event, as shown in Fig. 7. The soft soil response also provides peaks at around 1.0-1.5 sec periods, similarly to the records with liquefaction. Nevertheless, the main difference between the wavelet maps of liquefaction and soft soil sites is that the long period waves do not remain until the end of the significant duration of the record in the case of soft soil. The long period waves are possibly created by liquefaction at the time of onset of liquefaction and exist until the end, something that cannot be seen in case of soft soil wavelet maps.

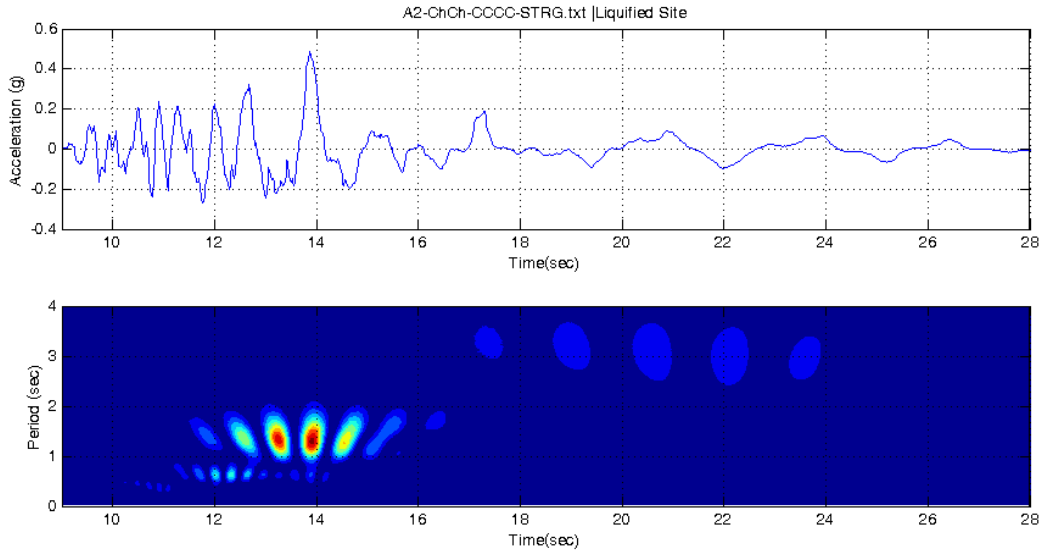

Figure 3. Time history and the wavelet map (the percentage of energy content) for the Christchurch, New Zealand (2011) Event, CCCC recorder with observed liquefaction.

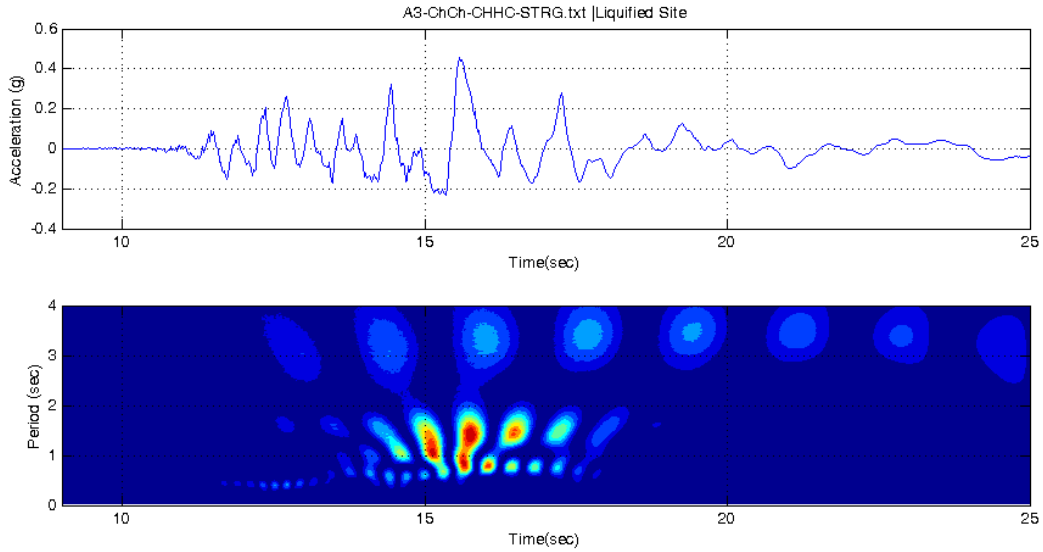

Figure 4. Time history and the wavelet map (the percentage of energy content) for the Christchurch, New Zealand (2012) Event, CHHS recorder with observed liquefaction.

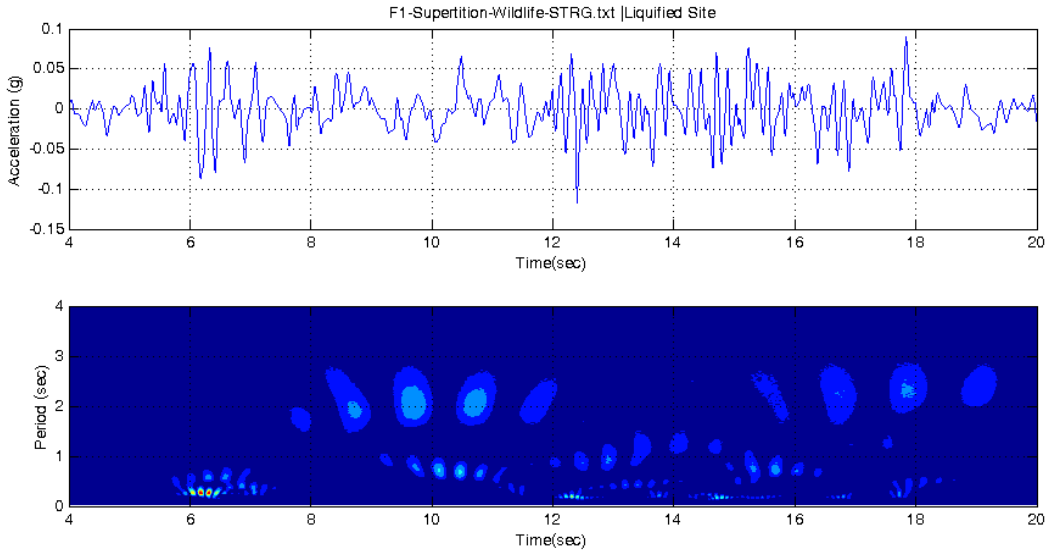

Figure 5. Time history and the wavelet map (the percentage of energy content) for the Superstition Hills, US (1987) Event, Wildlife recorder with observed liquefaction.

The main outcome of the wavelet analysis to be highlighted by the results presented here is that the long period waves exist until the end of the significant duration of the record. These long period waves are possibly created by liquefaction. In order to better understand this issue, the results of a liquefaction analysis have been used in this paper, as presented afterwards.

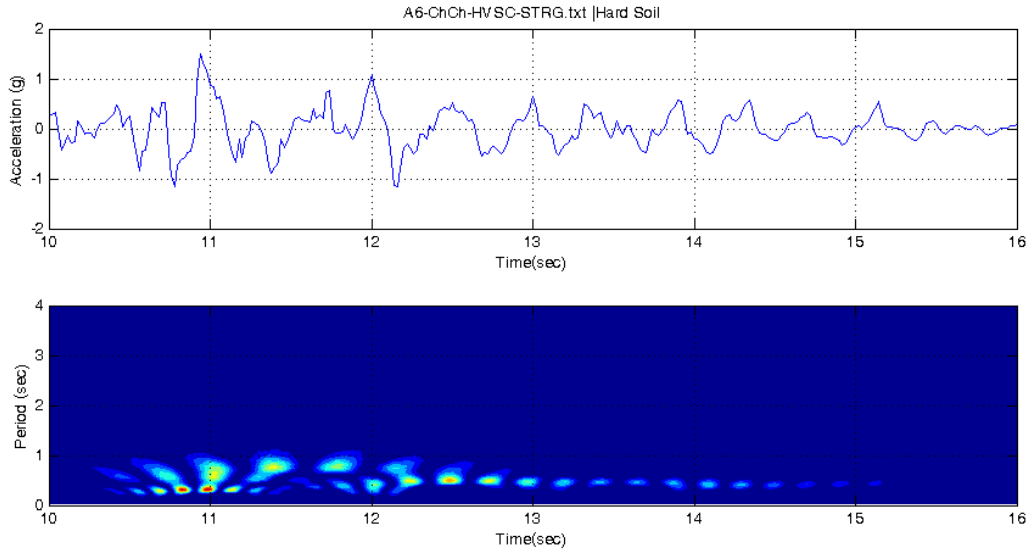

Figure 6. Time history and the wavelet map (the percentage of energy content) for the Christchurch, New Zealand (2012) Event, HVSC recorder laying on hard soil.

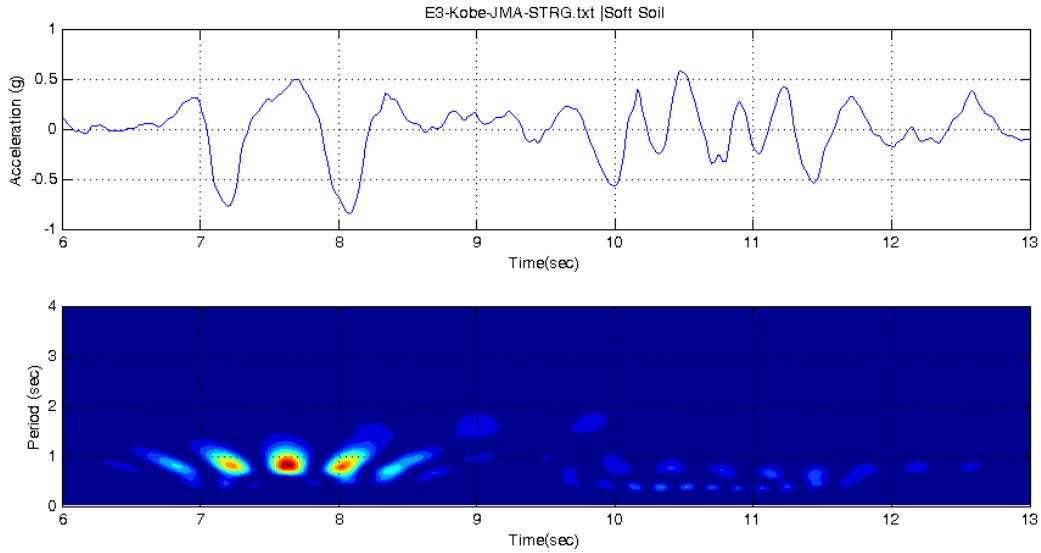

Figure 7. Time history and the wavelet map (the percentage of energy content) for the Kobe, Japan (1995) Event, JMA recorder laying on soft soil.

Wavelet Analysis of a Liquefaction Simulation

In order to better understand the onset of liquefaction in time domain and its effects on the wavelet map, results of a numerical simulation have been used, as shown in Fig. 8. If the development of the pore pressure ratio is observed, it will be seen that the pore pressure ratio at 5 m depth reaches unit value at around 5 seconds, and thus the pore pressure ratio at lower depths reaches saturation though it exhibits values below 1.0 (Fig. 9). It can be said, based only on Fig. 9 and with some level of uncertainty, that the peak energy in long periods, which are in the range of 1.0 to 1.2 sec in this example, develop when the pore pressure ratio at the mid-height of the liquefiable soil layer reaches saturation.

The details of the analyses and the assumptions used can be found in [10], and not mentioned here due to lack of space. Note that in Fig. 6, the pore pressure ratio that corresponds to the mid-height of the liquefiable layer is at 12.5 m, a parameter that is not shown here.

Moreover, it can be observed that the pore pressure reaches its peak at around the peak values of the wavelet map. This coincidence is surely the sign of the initiation of liquefaction. Interestingly, the long period waves with periods of 3.0 to 4.0 seconds start to appear after the pore pressure reaches its peak, and they exist until the end. Thus, it can now be said that the statements above are valid.

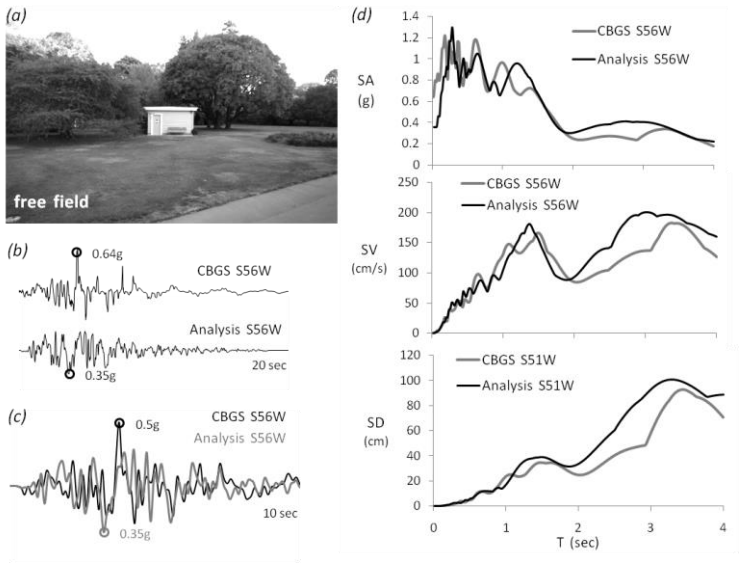

Figure 8. (a) The CBGS seismic station, with the remnants of liquefaction sandboils seen; (b) acceleration time histories of CBGS: record and analysis; (c) Comparison of (the about) acceleration time histories after filtering them at 4 Hz; (d) Comparison of acceleration 5%–damped spectra between CBGS record and analysis [10].

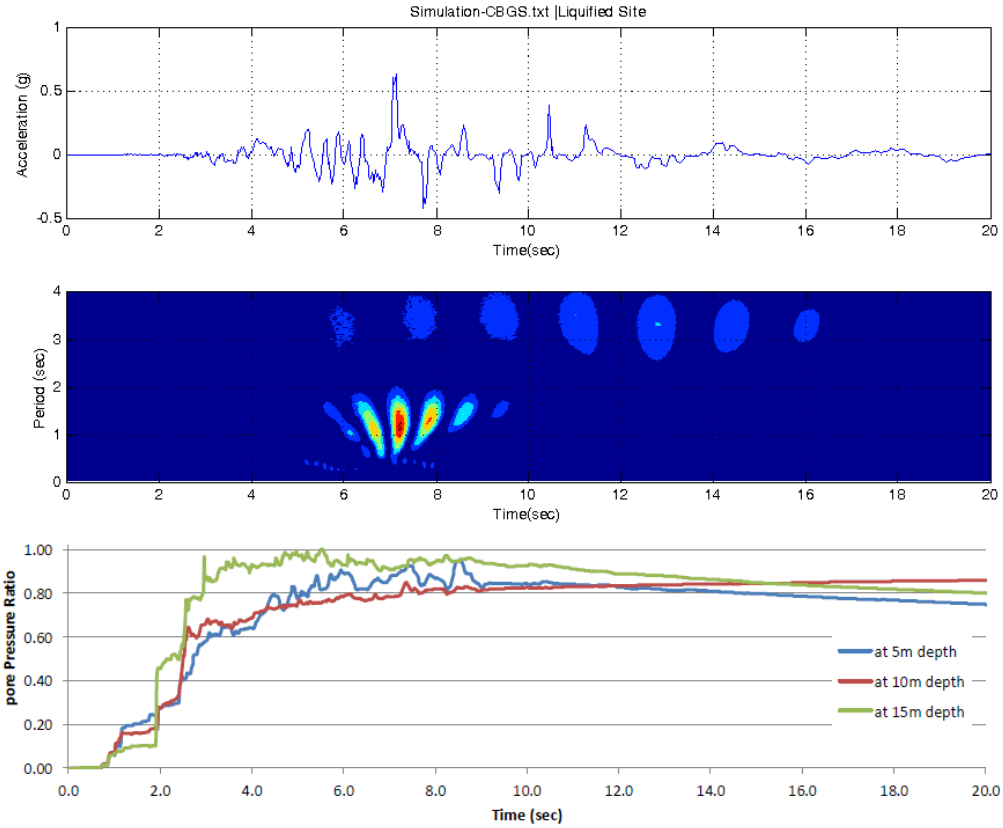

Figure 9. Time history, the wavelet map (the percentage of energy content) and the variation of pore pressure ratio at different heights for the simulated CBGS record of the Christchurch, New Zealand (2012) Event.

Conclusions

In this paper, an approach is explained for identifying ground motions containing large-period pulses caused by liquefaction. Acceleration records from Superstition Hills (1987), Kobe (1995), and Christchurch (2011) events have been used as datasets. The results of the methods used in this paper can be used in defining i) whether if the liquefaction occurred at the relevant site or not, ii) the approximate time of initiation of liquefaction, and, most importantly, iii) the frequency content of the liquefaction-affected record. These parameters can then be used in automatized (i.e. software-based) procedures in urban-level loss estimation studies that could be useful in decision making in the immediate aftermath of a catastrophe.

The two common characteristics of the wavelet maps of the liquefied sites, as presented above, are that i) the concentration of the peak wavelet match is between 1.0 to 2.0 seconds period, ii) the long period waves exist until the very end of the significant part of the recorded motion, iii) the long-period wave groups, which start to appear at the time of initiation of liquefaction, distinctly appear on the wavelet map easing thus the computer-based calculations. It was also confirmed by using the results of numerical analyses that the long period waves appear first with the initiation of the liquefaction and remain until the end.

As far as the response of a hard soil example is concerned, the wavelet map shows that the wave content reaches a peak at around 0.3 sec period and then the available periods decrease by time.

Soft soil response is presented by using the JMA record of Kobe (1995) event. The soft soil response also provides peaks at around 1.0-1.5 sec periods, similarly to the records with liquefaction. However the main difference between the wavelet maps of liquefaction and soft soil sites is that the long period waves do not remain until the end of the significant duration of the record in the case of soft soil. The long period waves are possibly created by liquefaction at the time of initiation of liquefaction and they exist until the end, something that cannot be seen in case of soft soil wavelet maps.

Acknowledgments

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