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PROPOSAL OF METHOD TO CHARACTERIZE PULSE-LIKE GROUND MOTIONS CONSIDERING PHASE

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Abstract

Pulse-like ground motions observed near the fault (e.g. the 1995 Kobe Earthquake) have caused severe damage to buildings. In addition, pulse-like ground motions with several predominant periods, such as the 2016 Kumamoto earthquake, have been observed. In order to understand the response of buildings due to pulse-like ground motions, research has been conducted to mathematically and simply characterize observation records. By characterizing the physical parameters (e.g. amplitude and predominant period) of observation records into variables, the effects on the building can be easily grasped.

A previous paper proposed a method for characterizing pulse-like ground motions into Gabor wave [1]. With this method, characteristic pulses can be easily created by specifying the velocity amplitude, period, and wave number as the pulse characteristic parameters. Furthermore, a method has been proposed to easily extract these pulse characteristic parameters from observation records.

Where, no calculation method is defined for the phase. For ground motions with several predominant periods, the phase may affect the response. Therefore, it is necessary to appropriately evaluate the pulse generation time and the pulse phase. In this report, we propose a method to characterize the pulse generation time and pulse phase.

First, the proposed waveform is as follows. A wave obtained by multiplying a cosine wave as a harmonic wave by a Gaussian function is a Gabor wave. The proposed wave considers the phase in the harmonic wave. When there are a plurality of predominant periods, a characteristic wave is created for each of the predominant periods, and the proposed wave is created by combining them in consideration of the time difference.

Next, a method of extracting the pulse generation time and the pulse phase from the observation record is as follows. Regarding the time difference of the maximum amplitude, the complex envelope is calculated for the wave that has been subjected to the band filter near the predominant period, and the time difference of the maximum amplitude is calculated. Subsequently, the phase is obtained from the phase spectrum around the calculated maximum amplitude of the complex envelope.

Finally, the validity of the proposed method was confirmed by the fact that the shape of the observation record and the characteristic pulse were almost the same.

The following are considered future issues. (1) Confirmation of applicability of this characterization to many observation records. (2) Formulation of estimation formula of pulse characteristic parameters and its variation using many observation records.

Keywords: pulse-like ground motion; characterization; pulse period; phase

1. Introduction

The pulse-like ground motions observed near the fault have caused severe damage to buildings. For example, the 1994 Northridge earthquake and the 1995 Kobe earthquake.

In order to understand the response of buildings due to pulse-like ground motions, research has been conducted to mathematically and simply characterize observation records. By characterizing the physical parameters (e.g. amplitude and pulse period) of the observation record into variables, the effects on the building can be easily grasped.

Among the characterization methods, there is a Gabor wave as a characterization method that can reproduce many observation records with as few input parameters as possible and can easily perform calculus. Gabor wave can be represented by the product of harmonic oscillation and Gaussian function, and can be represented by four input parameters (amplitude, pulse period, phase, and wave number). Sugino et al. (2018) [1] proposed a method to easily calculate the amplitude, pulse period, and wave number without arbitrariness in order to characterize from observation records to Gabor wave.

Where, no calculation method has been proposed for the phase, but it is considered that the phase does not significantly affect the building response in pulse-like ground motions having one predominant period. However, in recent years, pulse-like ground motions having several predominant periods have been observed. For example, the observation record of Nishihara Village Komori of the 2016 Kumamoto Earthquake.

Regarding the ground motion having a plurality of predominantperiods, there is a possibility that there is a difference in the time that affects the response depending on each predominant period. If the structure becomes longer due to the non-linearity, or if the influence of higher-order modes is considered, it is possible that the pulse generation time or phase may affect the building response. Therefore, it is necessary to appropriately evaluate the pulse generation time and the pulse phase.

In this paper, we first propose a characteristic pulse that takes into account several predominant periods using Gabor wave. Next, we propose a method to calculate the time difference and phase of pulse generation in order to characterize it from observation records. Finally, the validity of the calculation method of pulse characteristic parameters is confirmed by comparing the observed waveform with the velocity waveform of the characterizing pulse and confirming the difference in pulse generation time and the reproducibility of the phase.

2. Proposal formula

This section describes the proposed characterization pulse. First, Eq. (1) to (3) show the velocity waveforms of the proposed characteristic pulse. In the proposed formula, several pulses to be created by multiplying the envelope shape and the harmonic wave are added. Assuming that the envelope shape is symmetric, the envelope shape is a Gaussian function. In addition, the envelope shape considers the maximum time shift of the envelope state for each wave before synthesis. The harmonic wave is given as a cosine function in consideration of a phase shift from the envelope shape maximum value time.

$$\dot{y}(t)=\sum_{j=1}^{N}\left\{V_j\cdot\exp\left[-\left(\frac{2\pi}{T_{Hj}}\cdot\frac{t'_j}{\sigma_j}\right)^2\right]\cdot\cos\left(\frac{2\pi}{T_{Hj}}t'_j-\theta_j\right)\right\} \tag{1}$$

$$t'_j=t-t_{Mj} \tag{2}$$

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$$\sigma_j = \frac{k_j \pi}{3} \tag{3}$$

Where the t is time, the V_j is velocity amplitude, the T_{Hj} is the harmonic wave period, the k_j is the wave number, the t_{Mj} is the time when the envelope maximum value of the velocity occurs, the θ_j is the harmonic wave phase (phase from t_{Mj}), and the N is the number of pulse periods. That is, variables given as pulse characteristic parameters are V_j, T_{Hj}, k_j, t_{Mj}, θ_j, N (j = 1 to N). Fig. 1 shows a schematic diagram of the proposed velocity waveform (when $N = 1$ as an example).

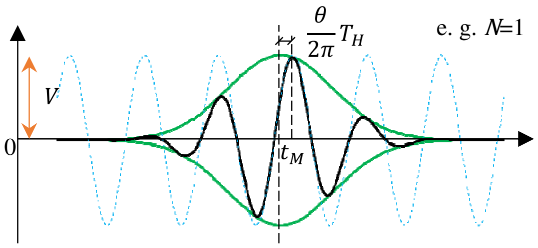


Fig. 1 – Proposed velocity waveform

3. Characterization procedure

This chapter describes how to calculate the pulse characteristic parameters in Chapter 2 from pulse-like ground motions. Fig. 2 shows the characterization flow. The V_j, T_{Hj}, and k_j are calculated by applying Sugino et al. (2018). The N is visually read from a pseudo-velocity response spectrum (damping ratio $h = 0.05$).

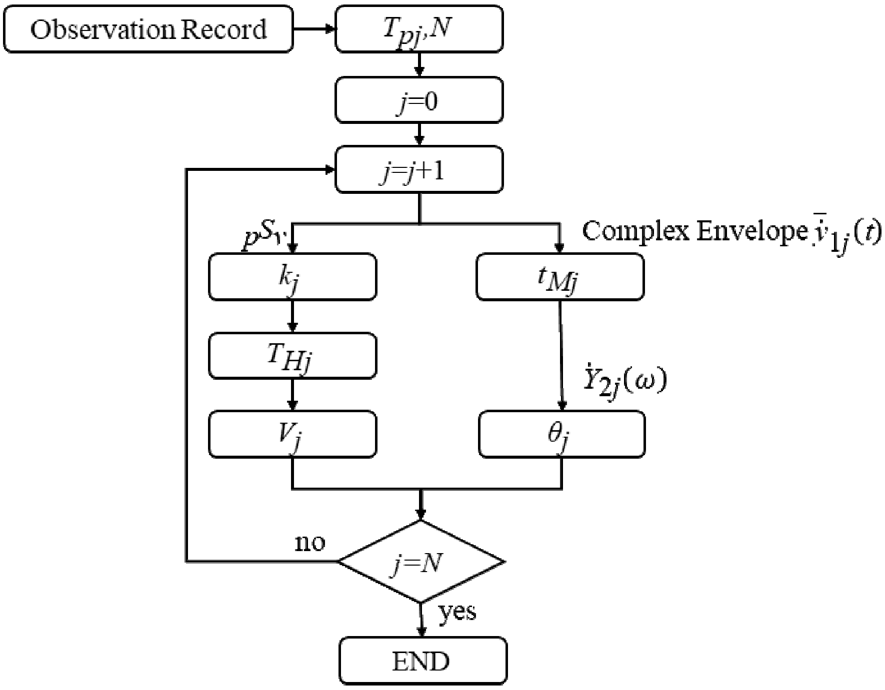


Fig. 2 – Flow diagram

3.1 Calculation of T_{pj}

A pseudo velocity response spectrum ${}_pS_v$ (damping ratio h = 0.05) is calculated from the observation record $\ddot{y}(t)$, and the cycle of the maximum value ${}_pS_{v\max}$ is defined as T_{pj}.

3.2 Calculation of k_j

The k_j is calculated by Eq. (4) from the ratio of ${}_pS_{v\max}$ (h = 0.10) and ${}_pS_{v\max}$ (h = 0.01). Where, the numerical calculation of the Gabor wave determines that α = 3.05 and β = -0.696 by regression.

$$k_j = \frac{1-\left\{{}_pS_v\left(h=0.10,T_{pj}\right)\Big/\left({}_pS_v\left(h=0.01,T_{pj}\right)\right)\right\}^{1/\beta}}{\alpha\left[0.10\left\{{}_pS_v\left(h=0.10,T_{pj}\right)\Big/\left({}_pS_v\left(h=0.01,T_{pj}\right)\right)\right\}^{1/\beta}-0.01\right]} \tag{4}$$

3.3 Calculation of T_{Hj}

The T_{Hj} is calculated by Eq. (5) because the maximum value of the Fourier amplitude of the Gabor wave (acceleration waveform) and the undamped pseudo-velocity response spectrum almost match near the maximum value.

$$T_{Hj} = T_{pj}\left(1+\sqrt{1+8/\sigma_j^2}\right)\Big/2 \tag{5}$$

3.4 Calculation of V_j

Similarly, since the maximum value of the Fourier amplitude of the Gabor wave (acceleration waveform) and the undamped pseudo-velocity response spectrum almost coincide with each other near the maximum value, the V_j is calculated by Eq. (6) to (9).

$$V_j = \frac{{}_pS_v\left(h=0.05,T_{pj}\right)}{p_j(k_j,h=0.05)\cdot\gamma} \tag{6}$$

$$p_j(k_j,h=0.05) = \left(1+\alpha k_j h\right)^{\beta} \tag{7}$$

$$\gamma_j = \frac{\sqrt{\pi}\sigma_j\bar{T}_j}{2}\cdot\left[\exp\left\{-\left(\left(\bar{T}_j+1\right)\sigma_j\right)^2/4\right\}+\exp\left\{-\left(\left(\bar{T}_j-1\right)\sigma_j\right)^2/4\right\}\right] \tag{8}$$

$$\bar{T}_j = T_{Hj}/T_{pj} \tag{9}$$

3.5 Calculation of t_{Mj}

In calculating t_{Mj}, the acceleration $\ddot{y}_0(t)$ of the observation record is Fourier-transformed into $\ddot{Y}_0(\omega)$. The velocity $\dot{Y}_0(\omega)$ is $\ddot{Y}_0(\omega)$ divided by $i\omega$. The $\dot{Y}_{1j}(\omega)$ is calculated by applying a band-pass filter around $\omega_{pj} = 2\pi / T_{pj}$ of the velocity $\dot{Y}_0(\omega)$.

$\bar{\dot{Y}}_{1j}(\omega)$ calculated from the EQ. (10) from the velocity $\dot{Y}_{1j}(\omega)$ is subjected to an inverse Fourier transform to Complex Envelope $\bar{y}_{1j}(t)$.

$$\bar{\dot{Y}}_{1j}(\omega) = \begin{cases} 0, & \omega < 0 \\ 2\dot{Y}_{1j}(\omega) & \omega > 0 \end{cases} \tag{10}$$

t_{Mj} is the maximum value of $\bar{y}_{1j}(t)$

3.6 Calculation of θ_j

To calculate θ_j, first, an inverse Fourier transform of $\dot{Y}_{1j}(\omega)$ into velocity $\dot{y}_{1j}(t)$. Next, the velocity $\dot{y}_{1j}(t)$ is shifted by t_{Mj} to $\dot{y}_{2j}(t)$ (Eq. (11)). Then, Fourier transform $\dot{y}_{2j}(t)$ into a phase Fourier spectrum $\dot{Y}_{2j}(\omega)$. The θ_j is $\dot{Y}_{2j}(\omega_{pj})$.

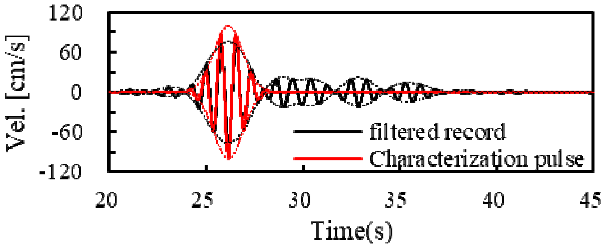
$$\dot{y}_{2j}(t) = \dot{y}_{1j}(t + t_{Mj}) \tag{11}$$

$$\dot{Y}_{2j}(\omega) = \int_{-\infty}^{\infty} \dot{y}_{1j}(t) e^{-i\omega t} dt \tag{12}$$

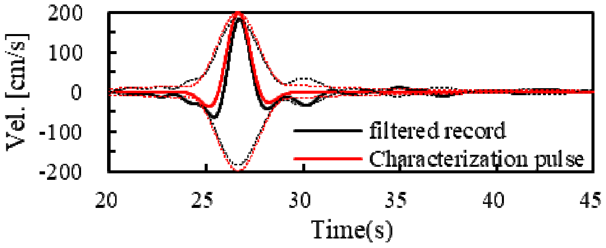
$$\theta_j = \mathrm{atan}\left[\frac{\mathrm{Re}\{\dot{Y}_{2j}(\omega_{pj})\}}{\mathrm{Im}\{\dot{Y}_{2j}(\omega_{pj})\}} \right] \tag{13}$$

4. Validity of the characterization method

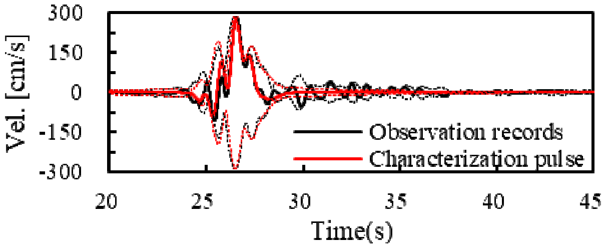
This chapter shows the validity of the characterization method in the previous chapter. Fig. 3 shows the velocity waveforms that characterize the 2016 Kumamoto earthquake (Nishiharamura Komori) using the method described in the previous section. In this paper, as an example of the characterization method, calculation is performed for the maximum velocity direction of recording. Fig. 3 (a, b) compares the characterization pulse with the bandpass filtered waveform of the observation record. From Fig. 3 (a, b), it can be seen that the phase and the time of occurrence of the maximum value of the envelope shape can be largely reproduced. However, because of the filtered waveform, the amplitude and duration could not be reproduced. To confirm the overall reproducibility, including the amplitude and duration, Fig. 3 (c) compares the characterization pulse with the original observation record. The velocity waveform of the observation record is baseline-corrected according to Boore (2001) [2]. From Fig. 3 (c), it can be seen that the waveform can be almost reproduced, including the amplitude and duration.



(a) Filtered record (*j*=1, High frequency)



(b) Filtered record (*j*=2, Low frequency)



(c) Observation record

Fig. 3 – Velocity waveforms of charactertization pulse

(The dashed line is complex envelope)

Next, Table 1 shows pulse characteristic parameters calculated from the observation records. The azimuth of the maximum velocity direction is a clockwise value from the north. The pulse on the long cycle side is generated late, and this difference in generation time can be attributed to the difference in the position of the strong ground motion generation area and the rupture velocity. In the future, it may be possible to analyze the relationship between faults and characteristic values.

Table 1 – Characterization results

Earthquake	**Year**	**M_w**	**Station**	**Azimuth [degree]**	***j***	**T_{pj} [s]**	**T_{Hj} [s]**	**V_j [cm/s]**	**k_j**	**θ_j [π]**	**t_{Mj} [s]**
Kumamoto	2016	7.0	Komori, Nishihara-mura	67	1	0.8	0.8	100	7.9	1.0	26.1
					2	3.1	4.3	199	1.8	0.0	26.6

Fig. 4 shows the observation record and the pseudo-velocity response spectrum by the characteristic pulse. It can be seen that the responses are also about the same near the pulse period.

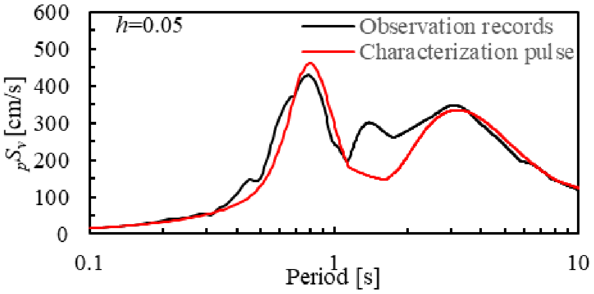


Fig. 4 – Pseudo velocity response spectrum

5. Conclusion

By adding Gabor wave considering the maximum envelope time and phase, we propose a characteristic pulse that can consider several predominant periods. Among the input parameters of the proposed characterizing pulse, a method of calculating the pulse generation time difference and phase is proposed. The amplitude, pulse period and wave number are calculated by applying Sugino et al. (2018).

1) Propose a method to characterize the difference in the time of occurrence of pulses with different predominant periods from the Complex Envelope of the waveform filtered near the predominant period
2) Propose a method to characterize the phase from the phase spectrum around the time when the maximum value of the envelope shape occurs

By comparing the characterization pulse created from the pulse characteristic value obtained from the proposed method with the velocity waveform of the observation record, it can be confirmed that the pulse waveform can be largely reproduced. The following are for future study.

1) Confirmation of applicability of this characterization to many observation records.
2) Estimation of pulse characteristic value and its variation using many observation records.

From these, it is important in the future to use the characteristic pulse based on the estimated pulse characteristic value to understand the influence of the building response in consideration of the fluctuation of the ground motion.

6. Acknowledgements

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7. References

[1] M.Sugino, S.Murase, S.Ohmura, Y.Hayashi : Simplified Characterization of Pulse-like Ground Motions in the 2016 Kumamoto Earthquake, Proc. of 16th ECEE, paper No.10605, June, 2018.

[2] Boore, D. M., : Effect of Baseline Corrections on Displacements and Response Spectra for Several Recordings of the 1999 Chi-Chi, Taiwan, Earthquake, Bulletin of the Seismological Society of America, 91, 5, pp. 1199-1211, October 2001