The effect of rupture propagation on predominant direction of pulse-like ground motions and landslides

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Abstract. Based on coupled analysis and energy approach, this study investigates the relationship between the direction of rupture propagation and the predominant direction of pulse-like ground motions and landslides during Chi-Chi earthquake and Hualien earthquake. 46 pulse-like ground motions are selected to study. The results show that pulse ground motions containing high-energy pulse tend to be perpendicular to the direction of fault rupture propagation in thrust events. In contrast, it occurred along the direction of fault rupture propagation in strike-slip events. The predominant direction of landslides is stronger directionality of rupture propagation in thrust events. It can provide research foundation for the risk zoning of regional earthquake landslides.

1. Introduction

In the near-field region, the fault mechanism has a significant influence on the predominant direction of pulse-like ground motions and landslides. The relationship is essential for engineering design.

Many researchers have studied the predominant direction of landslides. Chigira et al. (2010) studied distribution of landslides caused by Wenchuan earthquake. It shows that preferred orientations of landslide moving is perpendicular to the fault ruptures, indicating the effect of the directivity of the ground motions. Based on GIS and remote sensing technologies, the relationship of the landslide occurrence with seismic parameters, geologic and topographic conditions is analyzed by Xu et al. (2013). The results shows that the preferred orientations of landslides are eastern, southeastern and southern. Chen et al. (2014) used the simplified orientation model to analyze the relationship between the direction of fault rupture and initial slope of landslides in Wenchuan earthquake. It indicated that the moving direction of the fault is closely related to the original slope of the large-scale landslides, and the slope consistent with the moving direction of fault is more likely to slide. The findings of these researches not only provided the significant information about distribution of landslides in near-field region, but they also raised some questions on the relationship of the predominant direction of landslides in different events.

A pulse is indicated for more than one-half of range of angles, suggesting that near-fault pulses can affect structures in a variety of directions (Baker 2007). Shahi (2011) proposed a new method to identify pulses in any possible directions. 179 ground motions were classified as pulses. Xie (2019) studied the predominant direction of fling-step pulses and directivity pulses. The results showed that predominant direction of fling-step pulses consistent with the direction of horizontal coseismic displacement. The predominant direction of directivity pulses is related to the period. It is more likely to along the direction of horizontal coseismic displacement when the period is smaller, while around the normal direction of coseismic displacement. One question arose from the findings that there was
no research about preferred orientation of pulse-like ground motion with different fault rupture propagation.

Therefore, this study aims to investigate the relationship between the direction of rupture propagation and dominant orientation of pulse and preferred orientation of landslides in thrust fault and strike-slip events using the energy-based approach (Chang 2016) and coupled analysis (Rathje 1999).

2. Velocity pulse-like ground motions

2.1. Earthquake
The September 21, 1999, Mw 7.6 Chi-Chi earthquake is a typical earthquake caused by thrust fault in the past century in Taiwan. It occurred along the Chelungpu fault. The February 6, 2018, Mw 6.4 Hualien earthquake occurred in eastern Taiwan, in which a fault-to-fault jumping rupture was found. This fault-to-fault rupture process implied that slip on the Milun and Lingding faults was triggered by the N-S–striking west-dipping fault plane where the initial rupture originated (Lee 2018). These two earthquakes contain the abundant dataset of pulse-like recordings.

This study aims to investigate the relationship between the direction of rupture propagation and dominant orientation of pulse and preferred orientation of landslides. A total of 46 recordings are identified as pulse-like ground motions using energy-based approach proposed by Chang (2016). These ground motions are distributed within 30km with the fault rupture as the central axis (Figure 1). All pulse indicators of ground motions are calculated according to Equation (1):

\[ E_p = \frac{\int_{t_s}^{t_e} v^2(t) dt}{\int_0^{\infty} v^2(t) dt} \]  

where \( t_s \) and \( t_e \) represent the pulse-starting and pulse-ending points in the time axis, respectively, and \( v(t) \) indicates the velocity time history.

2.2. Pulse Orientation
Many studies show that pulse-like ground motion could be observed in many orientations. In order to avoid missing potential pulse-like ground motions, ground motions are rotated and synthesis according to Equation (2):

Figure 1. Locations of 46 strong-motion stations used in this study.

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where $a(t; \theta)$ is acceleration history in the $\theta$ direction, $a_1$ and $a_2$ are the two horizontal ground motions from the station, $\theta$ is the angle with the $a_1$ axis. Figure 2 shows the pulses ground motions occurred in a range of orientations. Figure 2a is a simple case (Chi-Chi earthquake) where pulses are observed around the strike-normal orientation. In contrast, the pulses occurred in the strike-parallel orientation from Hualien earthquake (Figure 2b). In order to further explore the relationship between the direction of rupture propagation and dominant orientation of pulse, a total of 46 pulse-like ground motions (Table 1) are selected from Chi-Chi earthquake and Hualien earthquake.

![Figure 2](image.png)

**Figure 2.** Pulse indicator values as a function of orientation for the ground motion: (a) Chi-Chi earthquake, TCU029 record; (b) Hualien earthquake, HWA007 record.

Note: The solid red line indicates the strike-parallel orientation. The dash red line indicates the strike-normal orientation. Grey shaded areas indicate that pulse indicator is low 0.34. Red shaded areas representants strike-parallel orientation, while white areas are strike-normal orientation.

**Table 1.** Information of pulse-like records in Chi-Chi earthquake and Hualien earthquake.

| Station | $R_{rup}$ | PGV (cm/s) | Station | $R_{rup}$ | PGV (cm/s) |
|---------|----------|------------|---------|----------|------------|
| CHY006  | 14.53    | 59.86      | TCU010  | 2.11     | 74.28      |
| CHY024  | 9.26     | 58.91      | TCU012  | 1.90     | 100.82     |
| CHY101  | 13.31    | 90.45      | TCU013  | 2.42     | 68.66      |
| TCU029  | 24.49    | 66.51      | TCU014  | 12.50    | 39.42      |
| TCU031  | 24.88    | 62.95      | TCU116  | 12.46    | 49.60      |
| TCU036  | 12.71    | 63.80      | TCU128  | 9.08     | 70.24      |
| TCU038  | 18.24    | 45.77      | TCU136  | 7.54     | 52.00      |
| TCU039  | 17.52    | 61.00      | HWA007  | 5.02     | 95.00      |
| TCU040  | 15.02    | 48.99      | HWA008  | 6.62     | 95.00      |
| TCU049  | 3.27     | 57.93      | HWA009  | 5.48     | 106.00     |
| TCU050  | 8.89     | 39.79      | HWA010  | 6.18     | 124.00     |
| TCU052  | 1.84     | 82.75      | HWA011  | 7.58     | 89.00      |
| TCU053  | 5.45     | 42.21      | HWA012  | 4.96     | 86.00      |
| TCU054  | 4.64     | 52.83      | HWA013  | 6.32     | 112.00     |
| TCU056  | 9.76     | 41.44      | HWA014  | 5.62     | 145.00     |
| TCU057  | 11.17    | 45.95      | HWA019-1| 5.29     | 95.07      |
| TCU059  | 16.48    | 61.50      | HWA019-2| 5.29     | 90.80      |
| TCU063  | 10.31    | 84.14      | HWA019-3| 5.29     | 105.34     |
| TCU064  | 12.24    | 54.06      | HWA028  | 7.56     | 54.00      |
| TCU065  | 2.49     | 145.17     | HWA048  | 9.26     | 46.00      |
| TCU068  | 3.01     | 234.92     | HWA050  | 7.46     | 85.00      |
| TCU082  | 4.47     | 63.78      | HWA063  | 7.60     | 95.00      |
3. Analysis of slope stability

The methods currently used to calculate the permanent displacement of seismic slopes can be divided into three categories: rigid-block analysis, decoupled and coupled analysis. The rigid-block method proposed by Newmark (1965) is extensively used in engineering practice to estimate earthquake-induced displacement. It assumed that the sliding block is rigid, which the dynamic response of the block is not considered. Therefore, it is only applicable for estimating shallow slope failure. In order to consider the dynamic response of the block, decoupling analysis (Makdisi and Seed, 1978) and the coupling analysis (Rathje and Bray, 1999, 2000) have been proposed for a deep slope failure. The dynamic response and permanent displacement of the block is decoupled in decoupled analysis, which cannot better reflect the whole process. Therefore, the coupled analysis is selected to explore the relationship between the direction of rupture propagation and dominant orientation of pulse and preferred orientation of landslides.

The sliding block is initiated once the driving force exceeds the frictional strength between the sliding and base. Sliding ends when the sliding velocity becomes zero. Rathje and Bray (1999) proposed the governing equation that takes into account the dynamic response of the sliding block:

$$\ddot{Y}'_i + 2\lambda\omega_1\dot{Y}'_i + \omega_1^2Y'_i = -\frac{L_i}{M_1}(\ddot{s} + \ddot{u}_g)$$

(3)

where $Y_i$ is the modal coordinate, $\lambda$ is the viscous material damping ratio, $s$ is the relative displacement between the sliding block and base, $u_g$ is the ground motion, $L_i$ is a term that distributes the ground motion along the height of sliding-base system with respect to the mode shape, $M_1$ is the generalized mass that accounts for the mass being distributed along the height of the system, and $\omega_1$ is the circular frequency.

When the block sliding relative to the base, the equilibrium at the shear interface is modified as follows:

$$-M(\ddot{s} + \ddot{u}_g) - L_i\ddot{Y}'_i = \mu Mg$$

(4)

where $\mu$ is the coefficient of friction, $M$ is the total of block, and $g$ is the acceleration of gravity. By transforming equation (4), the relative acceleration of the block can be obtained as follows:

$$\ddot{s} = -\frac{\mu g - L_i}{M}\dddot{Y}'_i - \ddot{u}_g$$

(5)

The equations described were proposed and solved by Rathje and Bray (1999) and named as the coupled procedure. The model and results of estimate displacement of flexible sliding mass as Figure 3.

**Figure 3.** The model and results of estimate displacement of flexible sliding mass.
4. Relationship between fracture properties and pulse and initial slope orientation of landslide

4.1. Predominant direction of pulse

In this study, the Chang (2016) algorithm is first used to calculate the pulse indicator ($E_p$) in all range of orientations for horizontal ground motions of each station. Li et.al (2020) recommended to classify multi-component ground motions by rotating them to the maximum PGV orientation. If a given ground motion component in the maximum PGV orientation satisfies the classification criteria, then it can be classified as pulse-like. The two horizontal ground motions of HWA028 from Hualien earthquake were rotated over 60 evenly distributed directions and the pulse indicator was calculated. The orientation-based pulse-like features are displayed in Figure 4(a). The blue axis in the polar coordinate represents the pulse energy, however, black axis represents the PGV. It showed that the orientation with larger PGV is not certainly pulse-like ground motion. A necessary condition for pulse-like ground motion is that PGV is greater than 30cm/s. Figure 4(b) shows the probability distribution of 0.8-1.0 PGV. According to Li (2020), it can be seen that pulse ground motion are more likely to appear in the direction perpendicular to the fault when the velocity satisfies the classification criteria from Hualien earthquake (strike-slip event). The ground motions are rotated to any possible orientations as the Equation (2). According to the algorithm, ground motions with relative pulse-energy values above (or equal to) 0.34 are selected and normalized. The orientations with 0.8–1.0 $E_{p_{max}}$ (the maximum $E_p$) are defined as the dominant orientations of ground motions. The fault strike $\pm 45^\circ$ is regarded as parallel to the fault strike, otherwise is perpendicular to the fault strike.

![Figure 4](image)

**Figure 4.** The probability distribution of (0.8–1.0PGV) in the strike-normal or strike-parallel orientation of fault for each ground motion from Hualien earthquake

The probability of the orientations with 0.8–1.0 $E_{p_{max}}$ (the ratio of the number of $E_p=0.8–1.0$ $E_{p_{max}}$ to the total number) in strike-normal /strike-parallel is calculated. To be specific, the orientations with probability equal to 0.5 is considered as the threshold. If the orientations with probability above 0.5 is observed around the strike-normal orientation, it can be concluded that the dominant direction of the ground motions is perpendicular to the fault rupture. Otherwise, the result is the opposite. Figure 4 shows the probability distribution for ground motions of each station from Chi-Chi earthquake and Hualien earthquake. It can be seen that 60% of the pulse-like ground motions have a dominant pulse direction around the strike-normal orientation, while dominant pulse direction of 40% of the pulse-like ground motions are around the strike-parallel orientation from the Chi-Chi earthquake (Figure 4a). In contrast, there are 62.5% of the pulse-like ground motions have the dominant pulse direction around the strike-parallel orientation, however, the dominant pulse direction of 37.5% of the pulse-like ground motions is perpendicular to the fault strike from the Hualien earthquake (Figure 4b). These cases show that pulse-like ground motions more likely occur around strike-normal orientation in thrust fault; while occur around strike-parallel orientation in strike-slip fault events.
4.2. Preferred orientation of landslides

In order to explore the relationship of between the direction of rupture propagation and preferred orientation of landslides, 46 pulse-like ground motions are selected from the Chi-Chi earthquake and Hualien earthquake. With the initial critical acceleration is 0.05g, the permanent displacements of the slope in different orientation are calculated based on coupled analysis proposed by Rathje and Bray (1999). The maximum displacement is recorded as $D_{\text{max}}$. Displacements smaller than or equal to 0.1cm were defined as “zero” for practical purposes. The “nonzero” sliding displacements are normalized. With $0.8\ldots1.0D_{\text{max}}$ as an indicator of larger displacement, the orientation corresponding to the larger permanent is defined as preferred orientation of landslides. The definition of orientation perpendicular or parallel to the strike of fault is consistent with the orientation described in chapter 4.1.

Figure 5. The probability distribution of $(0.8\ldots1.0E_{\text{pmax}})$ in the strike-normal or strike-parallel orientation of fault for each ground motion. (a) Chi-Chi earthquake; (b) Hualien earthquake

Figure 6. The probability distribution of the larger permanent displacements $(0.8\ldots1.0D_{\text{max}})$ in the strike-normal or strike-parallel orientation of fault for each ground motion. (a) Chi-Chi earthquake; (b) Hualien earthquake
strike-parallel orientation in Figure 5a. In contrast, in Hualien earthquake, there are 56.25% of landslides in the strike-parallel orientation with larger displacement, 43.75% of landslides in the strike-normal orientation with larger displacement (Figure 5b). It is consistent with the results given by Chen et al. (2014) and Chigira et al. (2010). These cases illustrated in Figure 5 are simple cases where landslides are observed around strike-normal orientation for thrust fault and strike-parallel orientation for strike-slip fault.

In this study, the relationship of the pulse and initial slope orientation of landslide and fracture properties is examined. Our researches indicate that the fracture properties of fault have a great influence of the distribution of landslides, which is consistent with the previous studies (eg. Chen, 2014).

5. Conclusion
This paper investigated the relationship between the direction of rupture propagation and dominant orientation of pulse and preferred orientation of landslides used the energy-based approach and coupled analysis from the Chi-Chi earthquake and Hualien earthquake. Many studies have showed that the distribution of landslides is perpendicular to strike from Wenchuan earthquake (mainly thrust fault), the results of this study are consistent with previous studies. However, the distribution of landslide has not been studied yet for strike-slip thrust, and the conclusion is consistent with conclusion from Chen (2014) about the relationship between rupture propagation and landslides. Therefore, the field investigation and statistical research are still further studied. Results of the this study conducted led to the following conclusions:

(1) The pulse-like ground motion could be observed in many orientations. In this study, $0.8-1.0E_{pmax}$ as an indicator of pulse ground motion containing high-energy pulse, the dominant orientation of pulse ground motion has been studied. The results show that it is easier to form high-energy pulse in the strike-normal orientation of thrust fault, while is easier in the strike-parallel orientation of strike-slip fault.

(2) Slopes can dip in all directions in a given geographic region. Numerous permanent displacements were calculated with the constant critical acceleration ($a_c=0.05g$). The preferred orientation of landslides was researched with $0.8-1.0D_{max}$ as an indicator of larger displacement. It can be concluded that higher probability of instability of slope in the strike-normal orientation of thrust fault, while is higher in the strike-parallel orientation of strike-slip fault.

(3) The direction of rupture propagation has a key effect on the spatial distribution of pulse-like ground motions and landslides, which can provide research foundation for the risk zoning of regional earthquake landslides.

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References
[1] Chigira M, Wu X, Inokuchi T, et al. Landslides induced by the 2008 Wenchuan earthquake, Sichuan, China. Geomorphology, 2010, 118(3-4):225-238.
[2] Chong X U. Detailed catalog of landslides triggered by the 2008 wenchuan earthquake and statistical analyses of their spatial distribution. Journal of Engineering Geology, 2013.
[3] Xiaoli Chen, Hongjun Hui, Yonghong Zhao. The relationship between fracture properties and landslide distribution-the large-scale landslide in the Wenchuan earthquake. SEISMOLOGY AND EGOLOGY, 2014, 36(002):358-367.
[4] Baker J W. Quantitative Classification of Near-Fault Ground Motions Using Wavelet Analysis. Bulletin of the Seismological Society of America, 2007, 97(5):1486-1501.
[5] Shahi S K, Baker J W. An Empirically Calibrated Framework for Including the Effects of Near-Fault Directivity in Probabilistic Seismic Hazard Analysis[J]. Bulletin of the Seismological Society of America, 2011, 101(2).
[6] J Xie. Strong-Motion Directionality and Evidence of Rupture Directivity Effects during the Chi-Chi Mw 7.6 Earthquake. Bulletin of the Seismological Society of America, 2019, 109(6).
[7] Chang Z, Sun X, Zhai C, et al. An improved energy-based approach for selecting pulse-like ground motions. Earthquake Engineering & Structural Dynamics, 2016, 45(14):2405-2411.
[8] Rathje E M, Bray J D. An examination of simplified earthquake-induced displacement procedures for earth structures. Canadian Geotechnical Journal, 1999, 36:72-87.
[9] Lee S, Lin T, Liu T, et al. Fault to Fault Jumping Rupture of the 2018 Mw 6.4 Hualien Earthquake in Eastern Taiwan. Seismological Research Letters, 2018, 90(1).
[10] Newmark NM (1965) Effects of earthquakes on dams and embankments. Geotechnique. 15:139–159
[11] Makdisi FI, Seed HB (1978) Simplified procedure for estimating dam and embankment earthquake-induced deformations. J Geotech Div ASCE 104:849–861
[12] Rathje EM, Bray JD (2000) Nonlinear coupled seismic sliding analysis of earth structures. J Geotech Geoenvironmental Eng 126:1002–1014
[13] Li C, Zuo Z, Kunnath S, et al. Orientation of the strongest velocity pulses and the maximum structural response to pulse-like ground motions. Soil Dynamics and Earthquake Engineering, 2020, 136:106240.