Quantifying the probability and uncertainty of multiple-structure rupture and recurrence intervals in Taiwan

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Abstract. This study identifies structure pairs with the potential for simultaneous rupture in a coseismic period via Coulomb stress change and quantifies their rupture recurrence intervals and uncertainties according to the Gutenberg-Richter law and the empirical formula of rupture parameters. To assess the potential for a multiple-structure rupture, we calculated the probability of Coulomb stress triggering between seismogenic structures included in the Taiwan Earthquake Model. We assumed that a multiple-structure rupture would occur if two structures could trigger each other by enhancing the plane with thresholds of a Coulomb stress increase and the distance between the structures. According to different thresholds, we identified various sets of seismogenic structure pairs. To estimate the recurrence intervals for multiple-structure ruptures, we implemented a scaling law and the Gutenberg-Richter law in which the slip rate could be partitioned based on the magnitudes of the individual structure and multiple-structure ruptures. In addition, considering that a single structure may be involved in multiple cases of multiple-structure ruptures, we developed new formulas for slip partitioning in a complex fault system. By implementing the range of slip area and slip rate of each structure, the magnitudes and recurrence intervals of multiple-structure ruptures could be estimated. Due to a larger characteristic magnitude and a larger displacement of the multiple-structure rupture, the rupture's recurrence interval could be longer. Therefore, application of the multiple-structure rupture could lead to an increase in seismic hazard in a long return period, which would be crucial for the safety evaluation of infrastructures, such as nuclear power plants and dams.

1 Introduction

A rupture taking place along several fault segments and/or structures can cause an earthquake with a large magnitude (e.g., Yen and Ma, 2011) and often leads to disaster. The 1935 M_L7.1 Hsinchu-Taichung, Taiwan, earthquake is an example. This event is attributed to a rupture on the Shihtan and Tunzijiao faults and resulted in more than 3,000 fatalities and the destruction of more than 60,000 buildings. According to the fault parameters determined by Shyu et al. (2020), either the Shihtan or Tunzijiao fault could cause an earthquake with a maximum magnitude of only 6.6 (Wang et al., 2016[a]). This case raises the importance of multiple-structure ruptures on seismic hazard assessment.

Thus, the Taiwan Earthquake Model (TEM) has considered the possibility of several multiple-structure ruptures by a probabilistic seismic hazard assessment for Taiwan (Chan et al., 2020). Chan et al.'s (2020) model implemented a seismogenic structure database summarized by Shyu et al. (2020) that identified possible multiple-structure ruptures based on geomorphological and geological evidence. To quantify their recurrence intervals, Chan et al. (2020) proposed a procedure for partitioning the slip rate of each individual structure to multiple structures. In their procedure, the case that one structure could be associated with multiple pairs was not specified.

Thus, this study aims to identify structures that could rupture simultaneously based on a physics-based model and propose a set of formulas to evaluate their recurrence intervals. The possibility of a multiple-structure rupture is determined based on the Coulomb stress change imparted by each structure and the distance from one to the other. Quantifying the recurrence interval relies on a scaling law (Yen and Ma, 2011) and the Gutenberg-Richter law (Gutenberg and Richter, 1944). Our approach is transparent and can be applied to reexamining the composite ruptures of the seismogenic structure system in Taiwan and other regions, which is beneficial to subsequent probabilistic seismic hazard assessments.

2 Distinguishing possible seismogenic structure pairs according to Coulomb stress change

Previous studies (e.g., Catalli and Chan, 2012) have concluded that changes in the Coulomb stress resulting from previous earthquakes could trigger the occurrence of subsequent events in adjacent areas. Such an approach would be especially applicable to determining the interaction between two fault systems if their rupture mechanisms are well-understood. In the following, we introduce the Coulomb failure criterion to discuss interaction between structure systems, then distinguish seismogenic structure pairs that could rupture simultaneously in a coseismic period, considering different criteria.

2.1 Introduction of Coulomb stress

The Coulomb failure criterion describes mainly the characteristics of material failure (King et al., 1994; Toda et al., 1998). The criterion illustrates a plane encountering stress change, which could be decomposed into two vectors, shear stress change, $\Delta\tau$, and normal stress, $\Delta\sigma_n$:

$$\Delta CFS = \Delta\tau - \mu'\Delta\sigma_n \text{ ,} \quad (1)$$

where ΔCFS is the Coulomb stress change, and μ' is the effective friction coefficient. The μ' for Taiwan is in a range between 0.2 and 0.5, being referenced from the study of earthquake focal mechanisms (Hsu et al., 2010). We first assume a fixed μ' of 0.4 then discuss its impact on the analysis. This study used the COULOMB 3.4 software (Toda et al., 2011) for calculation of Coulomb stress change. Based on the Coulomb stress change, we could quantify the possibility of a coseismic rupture for two fault systems. To explore the interactions between seismogenic structures in Taiwan, detailed structural parameters should be considered.

2.2 Possible coseismic multiple-structure rupture defined by the Coulomb stress transfer

To understand stress interaction between seismogenic structures in Taiwan, we accessed the TEM database, which incorporates 45 seismogenic structures (Shyu et al., 2016; 2020, structure alignment shown in Fig. 1) and corresponding parameters (shown in Table 1). According to the surface trace and dipping angles, the three-dimensional geometry of each structure is illustrated by pieces of sub-faults.

Since these structures could initiate earthquakes and trigger neighboring structures, we investigated their potential interaction through Coulomb stress change. We followed the assumption of the TEM model and considered a characteristic earthquake with corresponding slip (shown in Table 1) on each structure and evaluated the Coulomb stress change solved on each sub-fault of the other structures. Previous studies concluded that stress increases greater than a threshold could trigger subsequent earthquakes. For example, Ma et al. (2005) and Stein (2004) suggested that stress increases greater than 0.1 and 0.01 bar, respectively, could trigger seismicity activity. Assuming that a structure could be triggered if half its plane was enhanced with a stress increase greater than a threshold, we identified potential structural pairs that could trigger each other, considering different stress thresholds, and discuss their credibility. Close distance between two structures is another key factor of rupture triggering. For example, the UCERF3 (Uniform California Earthquake Rupture Forecast, Version 3; Field et al., 2015) defines two faults that could rupture simultaneously if the distance between the two is less than 5 km. We first follow this criterion to identify paired structures and then discuss their impact when different distance thresholds were assumed.

Following the assumptions mentioned above, we could identify seismogenic structure pairs that could rupture in a coseismic period. We first considered the stress threshold of ΔCFS $\geq$ 0.1 and distance threshold of 5 km to identify potential rupture pairs. For example, in the relation between the Meishan fault (ID 20) and the Chiayi frontal structure (ID 21), if the rupture initiates on the Chiayi frontal structure, the stress on the Meishan fault plane would be disturbed significantly. In that instance, 72% of the fault plane could be enhanced by more than 0.1 bar of the Coulomb stress. On the other hand, a rupture on the Meishan fault (ID 20) could result in 64% of the Chiayi frontal structure (ID 21) plane experiencing a stress increase of more than 0.1 bar. Our results show that either of the two seismogenic structures could trigger more than 50% of the other structure plane. In addition, based on the three-dimensional geometries of the two seismogenic structures, their closest distance is 1.87 km, which meets our proximity criteria (< 5 km). Therefore, we conclude that the Meishan fault and the Chiayi frontal structure can mutually induce a coseismic rupture.

According to the ratio by which each structure plane is triggered by other structures (Table S1) and the distance between each pair of structures (Table S2), we defined 17 pairs of seismogenic structures that could potentially rupture in a coseismic period (Table 2).

We further identified potential multiple-structure pairs through different thresholds of stress changes and distances. Considering ΔCFS of 0.01 bar as a lower bound of stress triggering (Stein, 2004), we proposed four sets of stress increase thresholds (0.01, 0.05, 0.1, and 0.2 bars), as well as two threshold sets for the distance between structures (2.5 and 5.0 km).

Based on the criteria, multiple-structure pairs were identified (Table 3). More structure pairs were expected if a lower ΔCFS threshold and/or a longer maximum distance were assumed and vice versa. The number of identified pairs is between 6 (ΔCFS $\geq$ 0.2 bar, distance $\leq$ 2.5 km) and 34 (ΔCFS $\geq$ 0.01 bar, distance $\leq$ 5.0 km).

We have identified potential structures that might rupture in a coseismic period. To understand the activities of these multiple-structure rupture cases, we will next propose a procedure to evaluate their recurrence intervals.

3 Recurrence interval of the multiple-structure rupture

The recurrence interval is a critical parameter in probabilistic seismic hazard analysis. Here, we are going to calculate the recurrence interval of multiple-structure ruptures and discuss their impact on seismic hazards.

3.1 Recurrence interval of multiple-structure ruptures

According to the TEM seismogenic structure database (Shyu et al., 2020) and the TEM PSHA2020 (Chan et al., 2020), the rupture recurrence interval (denoted as R_{L1}) of a single seismogenic structure ($L1$), R_{L1}, can be evaluated as the ratio of slip of a characteristic earthquake to slip rate (denoted as $D_{L1}$and $\dot{D}_{L1}$, respectively):

$$R_{L1} = \frac{D_{L1}}{\dot{D}_{L1}}. \tag{2}$$

To evaluate the seismic rate of a multiple-structure rupture on two seismogenic structures ($L1$ and $L2$), we implemented the Gutenberg-Richter law to describe the relationship between earthquake frequency N and magnitude M:

$$log(\boldsymbol{N}) = a - bM. \tag{3}$$

Considering the different moment magnitudes between single-structure and multiple-structure ruptures, the ratio of earthquake frequency to slip-rate partitioning could be evaluated. The moment magnitude (M_w) of the multiple-structure rupture could be evaluated according to the rupture area (denoted as A) and fault types of the two seismogenic structures. In the TEM structure database, determination of rupture magnitude (Table 1) is based on the scaling law proposed by Wells and Coppersmith (1994), represented as:

$$M_w = 4.33 + 0.90 \times log\,(A) \text{ ... for reverse faulting;} \tag{4}$$

$$M_w = 3.98 + 1.02 \times log\,(A) \text{ ... for strike-slip faulting;} \tag{5}$$

$$M_w = 3.93 + 1.02 \times log\,(A) \text{ ... for normal faulting.} \tag{6}$$

We first follow the procedure of the TEM model to implement these scaling relations and then evaluate uncertainty of this procedure considering different scaling relations.

Based on the M_w-M_0 scale (Kanamori, 1977) and the definition of seismic moment, average displacement of a seismogenic structure (D, in meters) could be evaluated according to M_w and A (in km^2):

$$D = \frac{10^{\frac{2}{3}Mw} \times 10^{-15.85}}{3A}. \tag{7}$$

Here we first implement the same scaling relations as those for the TEM model and then evaluate uncertainty of this procedure considering different scaling relations.

The potential of multiple-structure ruptures could be attributed to the moment accumulation from the first and second structures, $L1$ and $L2$. We assumed their original slip rates, $\dot{D}_{L1}$ and $\dot{D}_{L2}$, could be partitioned into two cases, the rupture on the original structure and the rupture on multiple structures. The slip rate partitioned to individual structure ruptures ($L1$ and $L2$, respectively) can be represented as:

$$\dot{D}_{L1}{}' = \frac{\dot{D}_{L1}}{(\frac{A_{L1+L2}}{A_{L1}} \times C_1 + 1)} \quad \text{and} \tag{8}$$

$$\dot{D}_{L2}{}' = \frac{\dot{D}_{L2}}{(\frac{A_{L1+L2}}{A_{L2}} \times C_2 + 1)}, \text{ respectively,} \tag{9}$$

where A_{L1} and A_{L2} represent the rupture areas of $L1$ and $L2$, respectively; A_{L1+L2} represents the area of the multiple-structure rupture; and C_1 and C_2 represent the obtained partitioned rates from $L1$ and $L2$, respectively, represented as:

$$C_1 = \frac{10^{b(M_{L1} - M_{L1+L2})} \times D_{L1+L2}}{D_{L1}} \tag{10}$$

and

$$C_2 = \frac{10^{b(M_{L2} - M_{L1+L2})} \times D_{L1+L2}}{D_{L2}}, \tag{11}$$

where M_{L1} and M_{L2} represent the magnitudes of $L1$ and $L2$, respectively; D_{L1} and D_{L2} represent the displacements of $L1$ and $L2$, respectively; M_{L1+L2} represents the magnitude of the multiple-structure rupture; and D_{L1+L2} represents the displacement of the multiple-structure rupture. By integrating the obtained partitioned rates (equations 8 and 9) and the slip rate partitioned to individual structure ruptures (equations 10 and 11), the slip rate partitioned to the multiple-structure rupture from the original L1 and L2 can be obtained:

$$\dot{D}^{L1}_{L1+L2} = C_1 \times \dot{D}_{L1}{}' \text{ and} \tag{12}$$

$$\dot{D}^{L2}_{L1+L2} = C_2 \times \dot{D}_{L2}{}', \text{ respectively.} \tag{13}$$

Then the sum of the slip rates for the multiple-structure rupture is calculated using the partitioned rates of the two structures, represented as:

$$\dot{D}_{L1+L2} = \dot{D}_{L1+L2}^{L1} + \dot{D}_{L1+L2}^{L2}. \tag{14}$$

Considering the displacement and slip rate, recurrence intervals for individual structures (R_{L1} and R_{L2}) and the multiple-structure rupture (R_{L1+L2}) can be represented as:

$$R_{L1} = \frac{D_{L1}}{\dot{D}_{L1}{}'}, \tag{15}$$

$$R_{L2} = \frac{D_{L2}}{\dot{D}_{L2}{}'}, \text{ and} \tag{16}$$

$$R_{L1+L2} = \frac{D_{L1+L2}}{\dot{D}_{L1+L2}}, \text{ respectively.} \tag{17}$$

3.2 Single structure contributes to several multiple-structure ruptures

A single seismogenic structure could be involved in multiple cases of multiple-structure rupture. For such cases, however, evaluation of the corresponding recurrence intervals has seldom been discussed. Here, we propose a procedure for quantifying the return period of this case, shown below.

When a single structure (L_1) is involved in multiple cases of multiple-structure rupture (*L1*+*L2*, …, *L1*+*Ln*), the slip rate partitioned to the original structure can be obtained based on the revision of equation (8), represented as:

$$\dot{D}_{L1}{}' = \frac{A_{L1}\times\dot{D}_{L1}\times D_{L1}}{(A_{L1}\times D_{L1})+\sum_{i=2}^{n}(A_{L1+Li}\times D_{L1+Li}\times 10^{b(M_{L1}-M_{L1+Li})})+\sum_{i=2}^{n-1}\sum_{j=3}^{n}(A_{L1+Li+Lj}\times D_{L1+Li+Lj}\times 10^{b(M_{L1}-M_{L1+Li+Lj})})+\sum_{i=2}^{n-2}\sum_{j=3}^{n-1}\sum_{k=4}^{n}\cdots}, \ 1 < \mathrm{i} < \mathrm{j} < \mathrm{k}. \tag{18}$$

where D_{L1+L2}, …,D_{L1+Ln} represent the displacements of the multiple-structure rupture cases $L1$+$L2$, …, $L1$+Ln, respectively.

The slip rate partitioned to the multiple-structure rupture cases $L1$+$L2$, …, $L1$+Ln can be represented as:

$$\dot{D}_{Lx}^{L1} = \frac{A_{L1}\times\dot{D}_{L1}\times D_{L1+Lx}\times 10^{b(M_{L1}-M_{Lx})}}{(A_{L1}\times D_{L1})+\sum_{i=2}^{n}(A_{L1+Li}\times D_{L1+Li}\times 10^{b(M_{L1}-M_{L1+Li})})+\sum_{i=2}^{n-1}\sum_{j=3}^{n}(A_{L1+Li+Lj}\times D_{L1+Li+Lj}\times 10^{b(M_{L1}-M_{L1+Li+Lj})})+\sum_{i=2}^{n-2}\sum_{j=3}^{n-1}\sum_{k=4}^{n}\cdots}, \quad Lx = L1 + Li + Lj + Lk + \cdots \tag{19}$$

respectively. In this case, evaluation of the recurrence interval for each multiple-structure rupture requires the slip rates contributed from two structures as well, similar to what is shown in equation (14). The total slip rate of each case of multiple-structure rupture can be represented as:

$$\dot{D}_{Lx} = \dot{D}_{Lx}^{L1} + \sum_{i=2}^{n}\dot{D}_{Lx}^{Li}. \tag{20}$$

The recurrence intervals for the original structure and each multiple-structure rupture case can be represented as:

$$R_{L1} = \frac{D_{L1}}{\dot{D}_{L1}{}'} \tag{21}$$

and

$$R_{Lx} = \frac{D_{Lx}}{\dot{D}_{Lx}}, \text{ respectively.} \tag{22}$$

A single earthquake could be attributed to multiple (more than three) structures, for example, the 2010 El Mayor-Cucapah, US, earthquake (Wei et al., 2011); the 2016 M_w7.8 Kaikōura, New Zealand, earthquake (Hamling et al., 2017). In such special cases, the recurrence interval can be also evaluated through the procedure mentioned above. For example, the Chiayi frontal structure (ID 21, here denoted as $L1$) could trigger the Meishan fault (ID 20, here denoted as $L2$) and the Tainan frontal structure (ID 41, here denoted as $L3$), respectively, in some criteria (Table 3), inferring the possibility of multiple ruptures in an event. We assumed this event is reverse faulting and evaluated its fault area and moment magnitude accordingly, described in the following:

$$A_{L1+L2+L3} = 371.7 + 1580.88 + 1722.64 = 3675.22\ km^2;$$

$$M_{w\,L1+L2+L3} = 4.33 + 0.90 \times log\,(3675.22) = 7.54;$$

$$D_{L1+L2+L3} = \frac{10^{(7.54+10.73)\times\frac{2}{3}} \times 10^{-12}}{3\times10^{11}\times3675.22} = 2.305\ m;$$

$$\dot{D}_{L1}{}' = \frac{1580.88\times3.36\times1.71}{(1580.88\times1.71)+(1952.58\times1.829\times10^{1.1\times(7.21-7.29)})+(3303.52\times2.233\times10^{1.1\times(7.21-7.5)})+(3675.22\times2.305\times10^{1.1\times(7.21-7.54)})} = 0.708\ mm/year;$$

$$\dot{D}^{L1}_{L1+L2+L3} = \frac{1580.88\times3.36\times2.305\times10^{1.1\times(7.21-7.54)}}{(1580.88\times1.71)+(1952.58\times1.829\times10^{1.1\times(7.21-7.29)})+(3303.52\times2.233\times10^{1.1\times(7.21-7.5)})+(3675.22\times2.305\times10^{1.1\times(7.21-7.54)})} = 0.414\ mm/year;$$

$$\dot{D}^{L2}_{L1+L2+L3} = \frac{371.7\times2.51\times2.305\times10^{1.1\times(6.6-7.54)}}{(371.7\times0.89)+(1952.58\times1.829\times10^{1.1\times(6.6-7.29)})+(3675.22\times2.305\times10^{1.1\times(6.6-7.54)})} = 0.114\text{mm/year; and}$$

$$\dot{D}^{L3}_{L1+L2+L3} = \frac{1722.64\times0.92\times2.305\times10^{1.1\times(7.24-7.54)}}{(1722.64\times1.74)+(3303.52\times2.233\times10^{1.1\times(7.24-7.5)})+(3675.22\times2.305\times10^{1.1\times(7.24-7.54)})} = 0.159\text{mm/year.}$$

Note that L2 and L3 will not rupture together:

$$\dot{D}_{L1+L2+L3} = 0.414 + 0.114 + 0.159 = 0.687\ mm/year;$$

$$R_{L1} = \frac{1.71}{0.708} \times 1000 = 2415\ years;\ \text{then}$$

$$R_{L1+L2+L3} = \frac{2.305}{0.687} \times 1000 = 3355\ years.$$

Thus, rupture probability of multiple structures could be quantified, which could constrain subsequent probabilistic seismic hazard assessment.

3.3 Multiple-structure rupture recurrence intervals and uncertainties

According to the structure parameters (Table 1), the recurrence intervals of each pair of potential multiple-structure ruptures can be evaluated (Table 2). Here, we consider the 17 pairs with ΔCFS ≥ 0.1 bar and distance ≤ 5.0 km and evaluated their potential magnitudes and recurrence intervals by implementing the range of slip area and slip rate of each structure (Table 1). Considering epistemic uncertainties, the largest magnitude is expected if the maximum slip areas of the two structures are assumed (based on equations 4-6). Also, the shortest recurrence interval is expected if the minimum slip area and maximum slip rate are assumed (based on equations 4-17).

In comparison with the recurrence intervals of the original structures without considering a multiple-structure rupture (Table 1), longer recurrence intervals are expected for multiple-structure ruptures and individual structures due to slip partitioning. For example, the recurrence interval of the Chiayi frontal structure (ID 21) has been extended from 510 to 1,724 years. Based on these results, the seismic hazard level for a short return period (e.g., 475 years, corresponding to a 10% probability in 50 years) would be lower.

Additionally, our results show that a single seismogenic structure sometimes pairs with several cases of multiple-structure ruptures. For example, the Hukou fault (ID 4) potentially ruptures with the Shuanglianpo structure (ID 2), the Fengshan river strike-slip structure (ID 5), and the Hsinchu fault (ID 6), while the Hsinchu fault (ID 6) could also result in multiple-segment ruptures with the Hsinchu frontal structure (ID 8) and the Touhuanping structure (ID 9). Besides these two cases associated with three rupture pairs, several structures could be associated with two multiple-structure pairs (Table 2), raising the importance of implementing slip partitioning from a single structure to several multiple-structure ruptures. Based on our analysis, it might be difficult for the structures that pair with several cases of multiple-structure ruptures might to rupture solely. That is, based on equations 18 to 22, the slip rate of these structures could be partitioned to several cases of multiple-structure ruptures, resulting in longer recurrence intervals. For example, the Hukou fault (ID 4) and the Hsinchu fault (ID 6) involved four and three pairs of multiple-structure ruptures, respectively (Table 2), and their recurrence intervals became 4.4 and 5.3 times, respectively, longer than the cases without considering multiple-structure ruptures (Table 4).

Our calculations of recurrence interval for the multiple-structure ruptures are based on the scaling relations proposed by Wells and Coppersmith (1994). These relationships were obtained based on the global data summarized decades ago. To validate the sensitivity of our procedure to scaling, here we implement alternative relationships proposed by Yen and Ma (2011), who investigated the rupture parameters of the earthquakes mainly from the Taiwan orogenic belt. This relation illustrates average displacement of a seismogenic structure (D, in meters) as a constant:

$$Log(D) = -0.32. \qquad (23)$$

Based on this relation, recurrence intervals for each multiple-structure rupture pairs were evaluated (Table 5). Comparing these to those obtained by Wells and Coppersmith's relations, shorter recurrence intervals were obtained, especially for those with larger magnitude. These results can be attributed to a smaller average displacement obtained for a large event that led to a shorter recurrence interval for the multiple-structure rupture (based on equation 17).

4 Discussion and conclusion

4.1 Interaction between structures and possible coseismic ruptures

In this study, we explored possible coseismic multiple-structure ruptures and quantified their recurrence intervals by implementing the Coulomb stress change and the Gutenberg-Richter law, respectively. The analyzing procedure we proposed is based on physics- and statistics-based models, and the outcomes are reproducible.

We compared our results with Shyu et al.'s (2020) conclusion that some seismogenic structure pairs—such as the Hsinchu fault (ID 6) and the Hsinchu frontal structure (ID 8), the Touhuanping fault (ID 9) and the Miaoli frontal structure (ID 10), the Meishan fault (ID 20) and the Chiayi frontal structure (ID 21), and the Chiayi frontal structure (ID 21) and the Tainan frontal structure (ID 41)—could rupture simultaneously. Their findings were consistent with our results based on the Coulomb stress triggering.

Additionally, Shyu et al. (2020) suggested some other structure pairs for multiple-structure ruptures, such as the Shihtan fault (ID 13) and Tuntzuchiao fault (ID 15), the Houchiali fault (ID 25) and the Tainan frontal structure (ID 41), and the Chaochou fault (ID 29) and the Hengchun fault (ID 30). These pairs, however, do not fit our hypothesis. Take the Shihtan and Tuntzuchiao faults, for example. The rupture of the Tuntzuchiao fault could result in a Coulomb stress increase of more than 0.1 bar in 79% of the sub-faults of the Shihtan fault, whereas only 2% of the sub-fault in the Tuntzuchiao fault would be triggered when the Shihtan fault dislocates (Table S1). Note that the 1935 Hsinchu-Taichung earthquake is attributed to a coseismic rupture on the two faults. Previous studies (Yan, 2016; Su, 2019) indicated that this earthquake did not initiate on either the Shihtan or the Tuntzuchiao fault, but on a blind fault linking the two. The database we accessed (Shyu et al., 2020) did not include this blind structure. Our analysis could be further improved through better understanding seismogenic structures. In addition, we discussed the interaction between structures through a kinematic model; it is desired to further incorporate dynamic models (e.g., Brodsky and van der Elst 2014; Jiao et al., 2022; Lin, 2021; Ulrich et al 2018) to constrain the behaviors of multiple-structure ruptures.

In 1906, an earthquake with magnitude 7.1 occurred due to the rupture of the Meishan fault (ID 20). Considering its fault geometry, the characteristic magnitude of this fault is only 6.6; therefore, this event with a larger magnitude could be associated with a multiple-structure rupture. In addition, the focal mechanism of this earthquake suggests that this event cannot be attributed solely to the rupture on the Meishan fault. The first motions of P- and S-waves recorded by the seismograph suggest oblique thrust faulting oriented in the northeast-southwest direction, with a small right-lateral component (Liao et al., 2018). Besides, large ground shaking with liquefaction took place to the west of the Meishan fault during the coseismic period (Omori, 1906). Thus, the Chiayi frontal structure might rupture simultaneously. Considering parameters of the Meishan fault and the

Chiayi frontal thrust (structure geometry, characteristic slip), when the Meishan fault is dislocated, the Coulomb stress on 64% of the Chiayi frontal structure plane may rise by more than 0.1 bar, and when the Chiayi frontal structure is dislocated, 72% of the Meishan fault could be closer to failure (Table S1). In addition, the distance between the two faults is 1.87 km (Table S2). Therefore, we concluded that these two structures could have mutually ruptured in a coseismic period and resulted in an event with magnitude 7.1 in 1906.

4.2 Uncertainty of the Coulomb stress model and recurrence interval

In this study, we identified potential rupture pairs by considering Coulomb stress change along the shear and normal components and the effective friction coefficient (equation 1). We simplified this model without implementing a poroelastic assumption (Beeler et al., 2000), since previous studies (e.g., Chan and Stain, 2009) concluded that the differences in their results were trivial for assuming reasonable values of Skempton's coefficients (between 0.5 and 0.9) and dry friction (0.75). The effective friction coefficient (μ') could alter the impact of normal stress change on the Coulomb stress change (ΔCFS). To quantify the deviation on determining multiple-rupture pairs, we further considered $\mu'=0.2$ and 0.5, the boundaries of its reasonable range determined from focal mechanisms in Taiwan (Hsu et al., 2010). Considering the stress threshold of $\Delta\mathrm{CFS}\geq 0.1$ bar and distance threshold of 5 km, the potential paired structures were identified (Table 6). The results suggest slight differences in the reasonable effective friction coefficient in between 0.2 and 0.5.

In this study, we identified potential rupture pairs by considering thresholds of stress change and structure distance. We implemented four threshold sets of Coulomb stress change (+0.01, +0.05, +0.1, and +0.2 bars) and two for distance between structures (2.5 and 5.0 km) to identify plausible pairs for multiple-structure rupture (Table 3). Also, the uncertainty of the structure rake angle could result in deviation. Our standard procedure assumed a fixed rake angle of each structure according to its rupture type (Table 1), while in reality its rupture orientation could alter slightly in small patches of the structure plane.

We expected a long distance between two structures could make it difficult for the two structures to rupture simultaneously. Thus, we followed the criterion by the UCERF3 (Field et al., 2015) and assumed a distance threshold of 5 km. We are aware that an earthquake with a large coseismic slip dislocation could result in significant stress change in far field and then search the pairs with longer distances and significant stress increase. Two additional distance thresholds of 10 and 20 km were considered (Table 7), and 6 and 9 additional pairs that might rupture in a coseismic period were identified, respectively. Generally, potential magnitudes of these structures are relatively large, which could result in larger stress perturbation. For example, the Chiayi frontal structure could cause an event with magnitude 7.21, resulting in a Coulomb stress increase of more than 0.1 bar in 91% of the sub-faults of the Chungchou structures, when 80% of the sub-fault in the Chiayi frontal structure would be triggered when the Chungchou structures dislocates with an M6.89 event (Table S1).

To evaluate the impact of rake angle orientation, we evaluated the Coulomb stress change on the receiving structure with different rotated rake angles (i.e., $\pm 10^\circ$ and $\pm 20^\circ$). The results showed that the larger the rotated rake angles implemented for the receiver structures, the fewer structure pairs were identified (Table 8). Note that 11 pairs were identified even when the rakes rotated for ±20°, suggesting their robustness for coseismic multiple-structure rupture.

Besides the uncertainty of structure pair identification, uncertainties in the rupture parameters of the multiple structures could be evaluated. Considering the range of the structures' slip areas (Table 1), magnitude intervals of multiple-structure ruptures could be estimated (Table 2). That is that the largest magnitude for multiple-structure rupture can be obtained when we consider the maximum slip areas of the two structures (based on equations 4-6). By further implementing structure slip rates, recurrence intervals can be quantified: the minimum slip area and maximum slip rate obtains the shortest recurrence interval (based on equations 4-17).

Rupture recurrence intervals could also be influenced by the implemented scaling relations. We proposed two relations, that is, in addition to the well-known relations by Wells and Coppersmith (1994), we also used the relations proposed by Yen and Ma (2011) that were obtained from the observations mainly from Taiwan. Since the local relationships (Yen and Ma, 2011) infer a smaller displacement, shorter recurrence intervals were obtained (Table 5). Besides, although the scaling relations proposed by Wells and Coppersmith (1994) have been questioned by many modern models, especially for large megathrusts (e.g., Stirling et al., 2013), Wang et al. (2016[b]) concluded a similar maximal magnitude of each seismogenic structure estimated from the relations of Wells and Coppersmith (1994) and Yen and Ma (2011).

For recurrence interval, the magnitude-frequency distribution on a single-structure plays an important role. Evaluating the rupture recurrence interval on a single structure could be based on various models, for example, the Gutenberg-Richter law (Gutenberg and Richter, 1944), the characteristic earthquake model (Youngs and Coppersmith 1984; Hecker et al 2013; Stirling and Zungia 2017) in addition to others (e.g., Geist and Parsons 2019; Page et al 2021). In this study, we evaluated the rupture recurrence interval as the ratio of slip of a characteristic earthquake (with maximum magnitude of the structure) and slip rate, shown as equation (2), based on the assumption proposed by the TEM seismogenic structure database (Shyu et al., 2020) and the TEM PSHA2020 (Chan et al., 2020). This factor could be replaced by other magnitude-frequency distributions since the recurrence interval of the multiple-structure rupture in our procedure is based on slip rate partitioned from individual structure ruptures (shown as equations 8-9, 14, 18, and 20).

Based on our analyses mentioned above, deviations of multiple-structure rupture pairs were indicated, and epistemic uncertainties of corresponding parameters were quantified, providing a better understanding of multiple-structure rupture behaviors, beneficial to subsequent research, such as the probabilistic seismic hazard assessment (PSHA), mentioned below.

4.3 Application of multiple-structure rupture to probabilistic seismic hazard analysis

Conducting a PSHA requires understanding the recurrence interval and potential magnitude of each seismogenic source, and implementing a hazard model with multiple-structure rupture could improve the assessment. Take the PSHA proposed by the TEM in 2020 (TEM PSHA2020, Chan et al., 2020) as an example—considering the cases of multiple-structure ruptures, the hazard levels in the regions close to the Chaochou fault (ID 29) and the Tainan frontal structure (ID 41) increased significantly for a long return period (recurrence interval of 2,475 years, see Fig. 3 of Chan et al., 2020). Chan et al.'s study (2020) indicated that the seismic hazard level would be misestimated if the probability of multiple-structure rupture is not implemented.

Seismic hazard analysis plays an essential role in constructing infrastructures, such as nuclear power plants, that require assuming a long return period. Thus, a seismogenic source with a long recurrence interval could be crucial for the analysis, raising the importance of multiple-fault rupture with a larger magnitude (larger than the characteristic earthquake of each structure).

The possibility of multiple-structure rupture used to be determined based on geological and geomorphological evidence with subjective judgments. Our study implemented a Coulomb stress change combined with statistical approaches to indicate multiple-structure rupture pairs, which is transparent and reproducible.

In addition, our approach indicated various rupture pairs and quantified uncertainties. These outcomes could be incorporated into a PSHA through a logic tree. For example, larger weightings (possibilities) could be assumed for the pairs that fulfill more thresholds in the distance, Coulomb stress change (Table 3) and rotated rake angles (Table 8). That includes, for instance, the Shuanglianpo fault (ID 2) and the Hukou fault (ID 4); the Hukou fault (ID 4) and the Fengshan River strike-slip structure (ID 5); the Hsinchu fault (ID 6) and the Hsinchu frontal structure (ID 8); the Miaoli frontal structure (ID 10) and Tuntzuchiao fault (ID 15); the Muchiliao-Liuchia fault (ID 22) and the Chungchou structure (ID 23); and the Chishan fault (ID 26) and the Fengshan structure (ID 45).

4.4 Multiple structure rupture (with more than three structures)

The 2016 M_w7.8 Kaikōura, New Zealand, earthquake is an event resulting from ruptures on multiple structures. Hamling et al. (2017) indicated that this earthquake included ruptures along four major faults and up to 12 minor faults. From this case, we are aware that multiple-structure rupture is not limited to the combination of two seismogenic structures.

Based on the multiple-structure rupture database proposed in this study (Table 2), several structures are associated with several possible rupture pairs. For instance, the Shuanglianpo fault (ID 2) may cause coseismic rupture with the Yangmei structure (ID 3) and the Hukou fault (ID 4), and the Hukou fault (ID 4) may link with the Fengshan River strike-slip structure (ID 5) and the Hsinchu fault (ID 6). Since our approach is based on a static Coulomb stress change, it is difficult to evaluate the temporal evolution of rupture probability. The possibility of a multiple-structure rupture in a coseismic period might be overestimated. One potential solution is to implement a dynamic model (e.g., a discrete element model; Cundall and Strack, 1979) that simulates temporal distribution of displacement and stress fields and could be helpful in identifying plausible structures that perhaps rupture within a coseismic period.

5 Acknowledgements

This study was supported by the Ministry of Science and Technology in Taiwan under the grants MOST 109-2116-M-008 -029 -MY3, MOST 110-2124-M-002 -008, and MOST 110-2634-F-008-008. This work is financially supported by the Earthquake-Disaster & Risk Evaluation and Management Center (E-DREaM) from the Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education in Taiwan. The authors would like to thank Jack Williams, João Fonseca, Alexandra Carvalho and an anonymous reviewer for their constructive comments.

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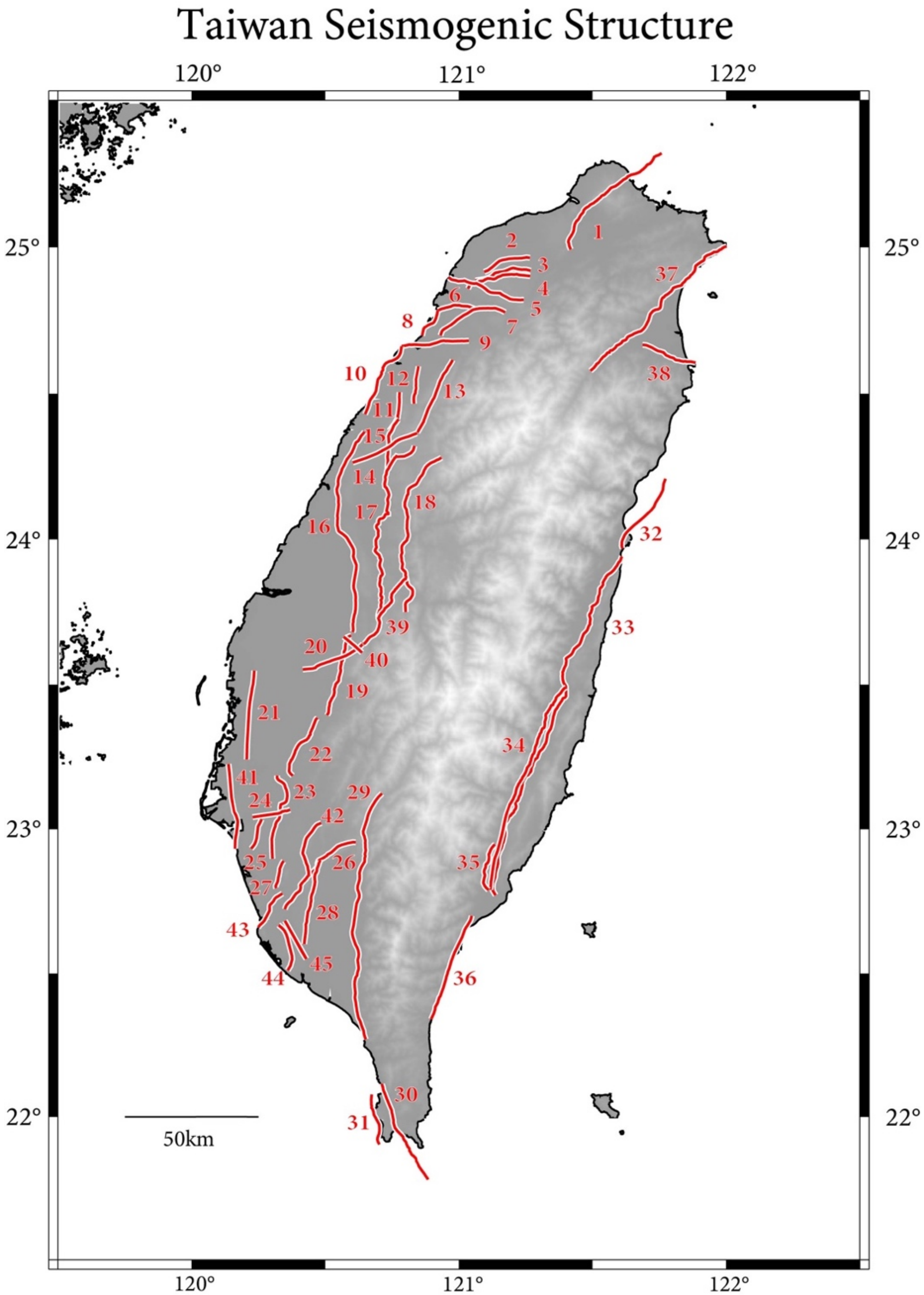

Figure 1: Distribution of the 45 seismogenic structures in Taiwan. Corresponding structure parameters are listed in Table 1.

Table 1

ID	Seismogenic structure name	Type	Rake	Depth 1 (km)	Dip (°) between depth 0-1	Depth 2 (km)	Dip2 (°) between depth 1-2	Depth 3 (km)	Dip3 (°) between depth 2-3	Slip area (km^2)			M_w*	Characteristic slip (m)	Slip rate (mm/year)		
										Minimum	Mean	Maximum			Minimum	Mean	Maximum
1	Shanchiao fault	N	-90	7.0	60	10.0	45	14	30	714	1054	1732	7.01	1.29	1.1	1.7	2.9
2	Shuanglienpo structure	R	90	3.0	45	5.0	15	-	-	79	132	238	6.24	0.72	0.1	0.1	0.5
3	Yangmei structure	R	90	3.0	60	-	-	-	-	47	76	115	6.03	0.60	0.1	0.2	0.7
4	Hukou fault	R	90	10.0	30	-	-	-	-	319	512	898	6.77	1.16	0.2	0.5	2.3
5	Fengshan river strike-slip structure	LL	0	13.8	85	-	-	-	-	363	425	492	6.66	0.95	1.8	3.2	10.2
6	Hsinchu fault	R	90	10.0	45	-	-	-	-	142	205	303	6.41	0.83	0.3	0.7	2.9
7	Hsincheng fault	R	90	12.9	30	-	-	-	-	482	733	1238	6.91	1.31	0.5	1.1	5.4
8	Hsinchu frontal structure	R	90	10.0	30	-	-	-	-	151	242	425	6.48	0.90	0.6	1.4	6.8
9	Touhuanping structure	RL	180	12.0	85	-	-	-	-	258	311	367	6.52	0.80	0.1	0.1	0.1
10	Miaoli frontal structure	R	90	10.0	30	-	-	-	-	385	618	1084	6.84	1.22	0.8	1.8	8.8
11	Tunglo structure	R	90	3.5	30	-	-	-	-	61	110	207	6.17	0.68	0.2	0.5	2.6
12	East Miaoli structure	R	90	4.0	30	-	-	-	-	67	115	211	6.19	0.69	0.4	0.8	3.9
13	Shihtan fault	R	90	10.8	75	-	-	-	-	274	343	418	6.61	0.99	0.6	1.4	5.3
14	Sanyi fault	R	90	9.0	15	-	-	-	-	610	1036	1888	7.04	1.45	0.3	0.9	4.6
15	Tuntzuchiao fault	RL	180	14.8	85	-	-	-	-	345	401	460	6.64	0.94	0.3	0.5	1.7
16	Changhua fault	R	90	3.0	45	5.0	30	12	10	2036	3991	9799	7.57	2.35	1.0	1.9	7.0
17	Chelungpu fault	R	90	12.0	15	-	-	-	-	2687	4260	7409	7.60	2.45	6.9	6.9	6.9
18	Tamaopu - Shuangtung fault	R	90	6.0	30	-	-	-	-	538	830	1417	6.96	1.38	0.5	1.1	4.9
19	Chiuchiungkeng fault	R	90	12.0	30	-	-	-	-	523	806	1375	6.95	1.37	1.9	4.7	23.4
20	Meishan fault	RL	180	14.7	85	-	-	-	-	320	372	427	6.60	0.89	2.5	2.5	2.5
21	Chiayi frontal structure	R	90	12.0	15	-	-	-	-	997	1581	2749	7.21	1.71	1.4	3.4	16.1
22	Muchiliao - Liuchia fault	R	90	12.0	30	-	-	-	-	411	634	1081	6.85	1.23	4.4	5.8	7.1
23	Chungchou structure	R	90	12.0	30	-	-	-	-	454	701	1195	6.89	1.28	9.0	12.2	18.7
24	Hsinhua fault	RL	180	15.0	85	-	-	-	-	192	223	255	6.38	0.69	0.8	2.7	4.5
25	Houchiali fault	R	90	5.0	45	-	-	-	-	60	86	128	6.07	0.61	6.1	7.1	8.7
26	Chishan fault	LL/R	45	10.8	75	-	-	-	-	358	447	545	6.68	0.97	0.7	1.1	1.5
27	Hsiaokangshan fault	R	90	7.0	30	-	-	-	-	104	155	260	6.30	0.75	0.8	1.8	8.0
28	Kaoping River structure	LL/R	45	12.3	75	-	-	-	-	348	425	507	6.66	0.95	0.2	0.3	1.1
29	Chaochou fault	LL/R	45	11.1	75	-	-	-	-	919	1142	1385	7.10	1.62	0.6	1.0	3.0
30	Hengchun fault	LL/R	45	15.0	75	-	-	-	-	553	651	758	6.85	1.20	5.7	6.2	6.6
31	Hengchun offshore structure	R	90	4.0	30	-	-	-	-	92	158	288	6.31	0.77	1.9	3.2	7.0
32	Milun fault	LL/R	45	10.0	75	-	-	-	-	265	337	416	6.56	0.85	9.9	10.2	10.5
33	Longitudinal Valley fault	R/LL	45	5.0	75	15.0	60	20	45	2805	3509	4676	7.52	2.25	5.6	11.4	17.1
34	Central Range structure	R	90	20.0	45	-	-	-	-	1894	2438	3307	7.38	2.00	4.8	7.3	11.2
35	Luyeh fault	R	90	2.0	45	4.0	30	-	-	90	134	223	6.24	0.71	3.6	5.3	8.0
36	Taimali coastline structure	R/LL	45	10.6	75	-	-	-	-	373	470	574	6.73	1.10	5.7	7.3	9.0
37	Northern Ilan structure	N	-90	9.4	60	-	-	-	-	591	814	1115	6.90	1.14	1.0	3.3	6.3
38	Southern Ilan structure	N	-90	11.3	60	-	-	-	-	216	284	379	6.43	0.64	4.5	5.5	6.9
39	Chushiang structure	R/RL	135	3.0	55	-	-	-	-	44	72	112	6.00	0.57	2.0	5.0	9.0
40	Gukeng structure	LL	0	12.0	85	-	-	-	-	92	111	131	6.07	0.48	0.6	0.9	2.6
41	Tainan frontal structure	R	90	3.0	30	12.0	15	-	-	1076	1723	2964	7.24	1.74	0.5	0.9	3.5
42	Longchuan structure	R	90	12.0	60	-	-	-	-	246	320	422	6.58	0.96	0.9	1.7	6.5
43	Youchang sturcture	R/RL	135	12.0	75	-	-	-	-	172	206	256	6.41	0.83	0.9	1.6	5.5
44	Fengshan hills frontal structure	R	90	15.0	30	-	-	-	-	386	573	949	6.81	1.19	0.4	0.9	4.2
45	Fengshan structure	LL/R	30	15.0	85	-	-	-	-	218	253	290	6.50	1.19	10.0	10.0	10.0

*Obtained through a scaling law by considering mean slip area

Table 1: The structure parameters of the 45 seismogenic structures in Taiwan. The alignments of the structures are presented in Figure 2. LL: left-lateral strike-slip mechanism; N: normal mechanism; R: reverse mechanism; RL: right-lateral strike-slip mechanism.

Table 2

ID	Seismogenic structure name	Type	with minimum area		Recurrence interval (year)			with mean area		Recurrence interval (year)			with maximum area		Recurrence interval (year)		
			Area (km)	M_w	for min slip rate	for mean slip rate	for max slip rate	Area (km)	M_w	for min slip rate	for mean slip rate	for max slip rate	Area (km)	M_w	for min slip rate	for mean slip rate	for max slip rate
2, 3	Shuanglienpo structure, Yangmei structure	R, R	126.27	6.22	20647	10029	2489	208.14	6.42	27419	13281	3346	353.29	6.62	37000	18500	4604
2, 4	Shuanglienpo structure, Hukou fault	R, R	397.92	6.67	23444	9953	2010	643.67	6.86	29929	12324	2499	1136.23	7.08	39026	16191	3287
4, 5	Hukou fault, Fengshan river strike-slip structure	R, LL	681.33	6.88	2141	1192	360	937.34	7.00	2794	1550	464	1390.65	7.16	4098	2254	668
4, 6	Hukou fault, Hsinchu fault	R, R	460.39	6.73	18377	7574	1586	717.03	6.90	21949	9250	1930	1201.64	7.10	28556	11953	2495
6, 8	Hsinchu fault, Hsinchu frontal structure	R, R	292.32	6.55	4000	1721	368	447.03	6.72	5096	2184	467	727.93	6.91	6809	2929	626
6, 9	Hsinchu fault, Touhuanping structure	R, RL	399.67	6.63	16926	9723	2874	515.92	6.75	20226	11527	3268	670.22	6.86	24140	13120	3636
9, 10	Touhuanping structure, Miaoli frontal structure	RL, R	642.71	6.86	6423	2881	630	928.89	7.00	7204	3209	695	1451.16	7.18	8858	3914	842
10, 15	Miaoli frontal structure, Tuntzuchiao fault	R, RL	730.04	6.91	5510	2513	572	1018.95	7.04	6371	2870	643	1544.63	7.20	7811	3473	769
11, 14	Tunglo structure, Sanyi fault	R, R	671.08	6.87	11664	4000	741	1146.05	7.08	15090	5276	975	2094.44	7.32	21747	7478	1387
13, 14	Shihtan fault, Sanyi fault	R, R	884.47	6.98	6920	2735	598	1379.38	7.16	9667	3757	806	2305.96	7.36	14093	5391	1135
19, 22	Chiuchiungkeng fault, Muchiliao - Liuchia fault	R, R	933.60	7.00	998	539	151	1440.00	7.17	1270	691	196	2455.80	7.38	1755	965	278
20, 21	Meishan fault, Chiayi frontal structure	RL, R	1316.87	7.14	2104	1251	345	1952.58	7.29	2722	1553	409	3176.28	7.48	3871	2097	527
21, 41	Chiayi frontal structure, Tainan frontal structure	R, R	2073.57	7.32	4475	1966	438	3303.52	7.50	5726	2512	558	5713.10	7.71	7776	3402	755
22, 23	Muchiliao - Liuchia fault, Chungchou structure	R, R	865.13	6.97	364	271	184	1334.40	7.14	471	351	239	2275.71	7.35	663	494	337
24, 25	Hsinhua fault, Houchiali fault	RL, R	251.94	6.43	559	326	222	309.14	6.52	609	367	254	383.06	6.61	661	413	288
26, 45	Chishan fault, Fengshan structure	LL/R, LL/R	576.00	6.80	615	573	534	742.38	6.91	706	661	619	834.77	6.96	825	766	713
43, 45	Youchang sturcture, Fengshan structure	R/RL, LL/R	390.21	6.62	405	374	265	501.35	6.73	465	432	314	546.44	6.77	530	487	341

Table 2: Potential pairs of multiple-structure ruptures, their parameters, and recurrence intervals of earthquakes. LL: left-lateral strike-slip mechanism; R: reverse mechanism; RL: right-lateral strike-slip mechanism.

Table 3

ID	Seismogenic structure name	5.0 km				2.5 km				Max. distance between a pair
		0.01 bar	0.05 bar	0.1 bar	0.2 bar	0.01 bar	0.05 bar	0.1 bar	0.2 bar	ΔCFS triggering threshold
2, 3	Shuanglienpo structure, Yangmei structure	✓	✓	✓	✓	✓	✓	✓		
2, 4	Shuanglienpo structure, Hukou fault	✓	✓	✓	✓	✓	✓	✓	✓	
4, 5	Hukou fault, Fengshan river strike-slip structure	✓	✓	✓	✓	✓	✓	✓	✓	
4 ,6	Hukou fault, Hsinchu fault	✓	✓	✓		✓	✓	✓		
4, 8	Hukou fault, Hsinchu frontal structure	✓	✓			✓				
6, 8	Hsinchu fault, Hsinchu frontal structure	✓	✓	✓	✓	✓	✓	✓	✓	
6, 9	Hsinchu fault, Touhuanping structure	✓	✓	✓	✓	✓				
9, 10	Touhuanping structure, Miaoli frontal structure	✓	✓	✓		✓	✓	✓		
10, 15	Miaoli frontal structure, Tuntzuchiao fault	✓	✓	✓	✓	✓	✓	✓	✓	
10, 16	Miaoli frontal structure, Changhua fault	✓	✓			✓	✓			
11, 14	Tunglo structure, Sanyi fault	✓	✓	✓		✓	✓	✓		
11, 16	Tunglo structure, Changhua fault	✓				✓				
13, 14	Shihtan fault, Sanyi fault	✓	✓	✓		✓	✓	✓		
13, 16	Shihtan fault, Changhua fault	✓				✓				
14, 17	Sanyi fault, Chelungpu fault	✓	✓			✓	✓			
15, 16	Tuntzuchiao fault, Changhua fault	✓				✓				
16, 19	Changhua fault, Chiuchiungkeng fault	✓	✓			✓	✓			
16, 20	Changhua fault, Meishan fault	✓				✓				
16, 40	Changhua fault, Gukeng structure	✓								
17, 19	Chelungpu fault, Chiuchiungkeng fault	✓				✓				
17, 20	Chelungpu fault, Meishan fault	✓				✓				
17, 40	Chelungpu fault, Gukeng structure	✓								
19, 22	Chiuchiungkeng fault, Muchiliao - Liuchia fault	✓	✓	✓	✓	✓				
20, 21	Meishan fault, Chiayi frontal structure	✓	✓	✓		✓	✓	✓		
21, 41	Chiayi frontal structure, Tainan frontal structure	✓	✓	✓		✓				
22, 23	Muchiliao - Liuchia fault, Chungchou structure	✓	✓	✓	✓	✓	✓	✓	✓	
23, 27	Chungchou structure, Hsiaokangshan fault	✓	✓			✓	✓			
24, 25	Hsinhua fault, Houchiali fault	✓	✓	✓		✓	✓	✓		
24, 41	Hsinhua fault, Tainan frontal structure	✓				✓				
26, 45	Chishan fault, Fengshan structure	✓	✓	✓	✓	✓	✓	✓	✓	
27, 42	Hsiaokangshan fault, Longchuan structure	✓	✓			✓	✓			
30, 31	Hengchun fault, Hengchun offshore structure	✓								
32, 33	Milun fault, Longitudinal Valley fault	✓				✓				
43, 45	Youchang sturcture, Fengshan structure	✓	✓	✓	✓	✓				
	Total pairs of each criteria	34	23	17	10	31	18	13	6	

Table 3: Multiple-structure rupture pairs considering different thresholds in structure distance and Coulomb stress change.

Table 4

ID	Seismogenic structure name	Type	Original slip rate (mm/year)	Remained slip rate (mm/year)	Original recurrence interval (year)	Updated recurrence interval (year)
2	Shuanglienpo structure	R	0.13	0.033	5540	21818
3	Yangmei structure	R	0.18	0.074	3330	8106
4	Hukou fault	R	0.46	0.104	2520	11154
5	Fengshan river strike-slip structure	SS	3.18	1.337	300	710
6	Hsinchu fault	R	0.66	0.125	1260	6640
8	Hsinchu frontal structure	R	1.44	0.642	1170	1401
9	Touhuanping structure	SS	0.13	0.034	6150	23529
10	Miaoli frontal structure	R	1.84	0.547	660	2230
11	Tunglo structure	R	0.50	0.151	1360	4509
13	Shihtan fault	R	1.38	0.519	720	1908
14	Sanyi fault	R	0.85	0.269	1710	5390
15	Tuntzuchiao fault	SS	0.50	0.204	1880	4601
19	Chiuchiungkeng fault	R	4.66	2.093	290	503
20	Meishan fault	SS	2.51	0.871	350	1059
21	Chiayi frontal structure	R	3.36	0.992	510	1724
22	Muchiliao - Liuchia fault	R	5.75	1.573	210	782
23	Chungchou structure	R	12.2	5.393	100	237
24	Hsinhua fault	SS	2.65	1.238	260	557
25	Houchiali fault	R	7.07	2.806	90	217
26	Chishan fault	SS/R	1.10	0.492	880	1971
41	Tainan frontal structure	R	0.92	0.405	1890	4294
43	Youchang sturcture	R/SS	1.64	0.699	510	1188
45	Fengshan structure	SS/R	10.00	2.604	75	288

Table 4: Original and revised recurrence intervals of the seismogenic structures that involve the cases of multiple-structure rupture. LL: left-lateral strike-slip mechanism; N: normal mechanism; R: reverse mechanism; RL: right-lateral strike-slip mechanism.

Table 5

ID	Seismogenic structure name	Area (km)	M_w	Recurrence interval (year)		Difference
				W&C*	Y&M#	
2, 3	Shuanglienpo structure, Yangmei structure	208.1	6.42	13281	8863	-33.3%
2, 4	Shuanglienpo structure, Hukou fault	643.7	6.86	12324	6381	-48.2%
4, 5	Hukou fault, Fengshan river strike-slip structure	937.3	7.00	1550	950	-38.7%
4, 6	Hukou fault, Hsinchu fault	717.0	6.90	9250	4739	-48.8%
6, 8	Hsinchu fault, Hsinchu frontal structure	447.0	6.72	2184	1429	-34.6%
6, 9	Hsinchu fault, Touhuanping structure	515.9	6.75	11527	6058	-47.4%
9, 10	Touhuanping structure, Miaoli frontal structure	928.9	7.00	3209	1703	-46.9%
10, 15	Miaoli frontal structure, Tuntzuchiao fault	1019.0	7.04	2870	1564	-45.5%
11, 14	Tunglo structure, Sanyi fault	1146.1	7.08	5276	2766	-47.6%
13, 14	Shihtan fault, Sanyi fault	1379.4	7.16	3757	2019	-46.3%
19, 22	Chiuchiungkeng fault, Muchiliao - Liuchia fault	1440.0	7.17	691	385	-44.3%
20, 21	Meishan fault, Chiayi frontal structure	1952.6	7.29	1553	743	-52.2%
21, 41	Chiayi frontal structure, Tainan frontal structure	3303.5	7.50	2512	1224	-51.3%
22, 23	Muchiliao - Liuchia fault, Chungchou structure	1334.4	7.14	351	202	-42.5%
24, 25	Hsinhua fault, Houchiali fault	309.1	6.52	367	281	-23.4%
26, 45	Chishan fault, Fengshan structure	742.4	6.91	661	383	-42.1%
43, 45	Youchang sturcture, Fengshan structure	501.4	6.73	432	252	-41.7%

*W&C: The scaling law by Wells and Coppersmith (1994)
#Y&M: The scaling law by Yen and Ma (2011)

Table 5: Potential pairs of multiple-structure ruptures, their parameters, recurrence intervals of earthquakes evaluated by the scaling laws of Wells and Coppersmith (1994) and Yen and Ma (2011), respectively, and their differences.

Table 6

μ’	0.2	0.4	0.5
Paired structures at each specific rake condition	2 3	2 3	2 3
	2 4	2 4	2 4
	4 5	4 5	4 5
	4 6	4 6	4 6
	6 8	6 8	6 8
	6 9	6 9	6 9
	9 10	9 10	9 10
	10 15	10 15	10 15
	11 14	11 14	11 14
	13 14	13 14	13 14
	16 18	16 18	16 18
	19 22	19 22	19 22
	20 21	20 21	20 21
	21 41	21 41	21 41
	22 23	22 23	22 23
	24 25	24 25	24 25
	26 28	26 28	26 45
	26 45	26 45	43 45
	27 42	27 42	27 42
	43 45	43 45	43 45
Number of pair	18	17	17

2 3 Paired structures at the condition

2 3 Not paired structures at the condition

Table 6: Multiple-structure rupture pairs considering different effective friction coefficients (μ’).

Table 7

ID	Seismogenic structure name	20.0 km	10.0 km	5.0 km	2.5 km
2, 3	Shuanglienpo structure, Yangmei structure	✓	✓	✓	✓
2, 4	Shuanglienpo structure, Hukou fault	✓	✓	✓	✓
4, 5	Hukou fault, Fengshan river strike-slip structure	✓	✓	✓	✓
4 ,6	Hukou fault, Hsinchu fault		✓	✓	✓
5, 7	Fengshan river strike-slip structure, Hsincheng fault	✓	✓		
6, 8	Hsinchu fault, Hsinchu frontal structure	✓	✓	✓	✓
6, 9	Hsinchu fault, Touhuanping structure	✓	✓	✓	
7,10	Hsincheng fault, Miaoli frontal structure	✓	✓		
8, 12	Hsinchu frontal structure, East Miaoli structure	✓	✓		
9, 10	Touhuanping structure, Miaoli frontal structure	✓	✓	✓	✓
10, 15	Miaoli frontal structure, Tuntzuchiao fault	✓	✓	✓	✓
10, 16	Miaoli frontal structure, Changhua fault				
11, 14	Tunglo structure, Sanyi fault	✓	✓	✓	✓
11, 16	Tunglo structure, Changhua fault				
12, 15	East Miaoli structure, Tuntzuchiao fault	✓			
13, 14	Shihtan fault, Sanyi fault	✓	✓	✓	✓
19, 22	Chiuchiungkeng fault, Muchiliao - Liuchia fault	✓	✓	✓	
20, 21	Meishan fault, Chiayi frontal structure	✓	✓	✓	✓
21, 23	Chiayi frontal structure, Chungchou structure	✓	✓		
21, 41	Chiayi frontal structure, Tainan frontal structure	✓	✓	✓	
22, 23	Muchiliao - Liuchia fault, Chungchou structure	✓	✓	✓	✓
23, 44	Chungchou structure, Fengshan hills frontal structure	✓			
24, 25	Hsinhua fault, Houchiali fault	✓	✓	✓	✓
26, 45	Chishan fault, Fengshan structure	✓	✓	✓	✓
27, 44	Hsiaokangshan fault, Fengshan hills frontal structure	✓	✓		
28, 43	Kaoping River structure, Youchang sturcture	✓	✓		
39, 40	Chushiang structure, Gukeng structure	✓			
43, 45	Youchang sturcture, Fengshan structure	✓	✓	✓	
	Total pairs of each criteria	26	23	17	13

Max. distance between a pair

Table 7: Multiple-structure rupture pairs considering different thresholds in structure distance.

Table 8

Rake angle rotation	+10°	-10°	+20°	-20°
Paired structures at each specific rake condition	2 3	2 3	2 3	2 3
	2 4	2 4	2 4	2 4
	4 5	4 5	4 5	4 5
	4 6	4 6	4 6	4 6
	6 8	6 8	6 8	6 8
	6 9	6 9	6 9	6 9
	9 10	9 10	9 10	9 10
	10 15	10 15	10 15	10 15
	11 14	11 14	11 14	11 14
	13 14	13 14	13 14	13 14
	19 22	19 22	19 22	19 22
	20 21	20 21	20 21	20 21
	21 41	21 41	21 41	21 41
	22 23	22 23	22 23	22 23
	24 25	24 25	24 25	24 25
	26 45	26 45	26 45	26 45
	43 45	43 45	43 45	43 45
Number of pair	16	15	13	11

Number of pairs without rake angle rotation: 17

2 3 Paired structures at the condition

2 3 Not paired structures at the condition

<u>Table 8</u>: Potential paired structures considering various rake angle rotations. In these cases, the stress threshold of ΔCFS ⩾ 0.1 bar and distance threshold of 5 km were considered to identify potential rupture pairs. The total number of paired structures without rake rotation is 17 (Table 2).