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The movement potential of the major faults in Hong Kong area

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The major faults in Hong Kong and its adjacent region can be classified into three sets, striking east-northeast, northeast and northwest, respectively. In this paper, we propose a theoretical model to evaluate the fault movement potential (FMP) based on the relationship between fault geometrical characteristics and regional tectonic stress field. The results show that the east-northeast striking Dangan Islands fault zone and the northwest striking Lau Fau Shan-East Lamma Channel fault zone are of the highest movement potentials in the area. Their intersecting area located to the east of the Dangan Island is inferred to have the possibility of generating destructive earthquakes. To the north, the movement potentials of the northeast striking Lau Fau Shan fault,

Lo Wu fault and San Tin fault of the Lo Wu-Tuen Mun fault zone, especially their converging part near Lo Wu, are also relatively high.

Introduction

Hong Kong is located in the Southeast Coastal Seismic Belt of China. The landforms in Hong Kong and its adjacent region are mainly controlled by three sets of faults, striking east-northeast, northeast, northwest, respectively (Figure 1). The questions to be addressed in this paper are: (1) What are the activity levels of these faults? and (2) Will these faults cause destructive earthquakes? Previous work regarding to these topics was mainly based on geological analyses (Liu, 1981; Lee, 1987; Ding et al., 1992; Ren et al., 1996; Zhong et al., 1996; Lai et al., 1996). However, it is difficult to eval-

Figure 1 The major faults and epicenters of modern small earthquakes (1972-1995) in Hong Kong. Note: 1. Tsing Shan Wan-Tai Po Hoi Fz., 2. Dangan Islands Fz., 3. Lo Wu-Tuen Mun Fz., 3a. San Tin Fs, 3b. Lo Wu Fs, 3c. Tuen Mun Fs, 3d. Tsing Shan Fs, 3e. Lau Fau Shan Fs, 4. Sha Tau kok-Pui O Wan Fz., 5. Lai Chi Kok-Tolo Channel Fz., 6. Po Toi Fz., 7. Kat O Chau-Chek Chau Fz., 8. Lau Fau Shan-East Lamma Channel Fz., 8a. Lau Fau Shan-Tsing Lung Tau Fs, 8b. Sha Kong Village-Tai Lam Kok Fs.

uate the fault activity just based on geological analysis because the surface expressions of recent fault activity in South China including Hong Kong are commonly covered or obscured. In this paper, we propose an alternative method to evaluate fault activity by considering the mechanical relationships between fault geometry and regional tectonic stress field. This method has been used to evaluate the fault movement potentials of all the major faults in Hong Kong and its adjacent region, and the results are consistent with the historical seismic records and present-day micro-earthquake activity.

The major faults in Hong Kong and its adjacent region

Faults are well developed in Hong Kong and its adjacent region. They were classified into three sets: east-northeast-striking, north-east-striking and northwest-striking.

The east-northeast-striking fault set

The east-northeast striking fault set is the major Caledonian-to-recent fault set in Hong Kong region. The faults in this set are multi-staged active faults inferred to have significant effects on the development of the Outer Pearl River Estuary Basin in the northern part of South China Sea during the Quaternary. Striking 60° - 70° with high dip angles, this fault set can be subdivided into the Tsing Shan Wan-Tai Po Hoi fault zone (1) and the Dangan Islands fault zone (2). Of these, the former offset the northeast-striking Tsing Shan fault (3-d) and the Tuen Mun fault (3-c). Thermoluminescence dating from the sample collected at Yim O Tuk in a small fault located to the north of Lantau Island yielded an age of $82,000 \pm 6,800$ years B. P. This suggests that the east-northeast striking faults were still active in the early stage of the Late Pleistocene.

The northeast striking-fault set

This fault set comprises four fault zones striking 30° - 50° with high dip angles. Among them, the Lo Wu-Tuen Mun fault zone (3) in the northwest "New territories" and the Po Toi fault zone (6) to the south of Hong Kong Island are the major fault zones. The Sha Tau Kok-Pui O Wan fault zone (4) and the Lai Chi Kok-Tolo Channel fault zone (5) are the two minor fault zones between the two major fault zones. The fault set forms the western extension of the Lian Hua Shan Fault System. Basic and ultrabasic rocks along the fault set suggest that this fault set cut deeply up to upper mantle. Samples collected at Wu Tip Wan along Lo Wu-Tuen Mun fault zone yielded an age of $265,500 \pm 21,000$ years B. P. by thermoluminescence dating.

The northwest-striking fault set

The faults of this set are well exposed and can be traced intermittently for a long distance in the direction of 310° - 330° . They are the most recently active faults because they displaced the faults striking in other directions. In this set, there are two major fault zones, the Kat O Chau-Chek Chau fault zone (7) in the east of Kowloon peninsula and the Lau Fau Shan-East Lamma Channel fault zone (8) in the west of the peninsula. The latter can be subdivided into two parallel branches, the Lau Fau Shan-Tsing Lung Tau fault (8-a) and the Sha Kong Village-Tai Lam Kok fault (8-b). A sample from Yim O Tuk to the north of Lantau Island was dated to be $33,300 \pm 2,700$ years B. P. by thermoluminescence dating, indicating that the fault zone may have been active since Late Pleistocene period.

In summary, east-northeast-striking faults were formed earlier than the others and active in different tectonic stages until Late Pleistocene period. Northwest-striking faults were formed last and displaced the other striking faults. Northeast-striking faults were also active in middle Pleistocene. These faults are characterized by

negative landforms and are inferred to control the development of channels, gullies and drainage patterns in the region.

In the following sections, we will evaluate the earthquake risk along these faults, and discuss which fault is most favored to move under the influence of present-day tectonic stress field. We make this evaluation based on the relationships between tectonic stress orientation and fault geometric properties. To test our model, we will compare the results with present-day micro-earthquake activity in Hong Kong and its adjacent region.

Theoretical model for analysis of fault movement potential

The fault movement potential (FMP) is closely related to tectonic stress (σ), fault plane geometry (G) and the physical property of the medium within and on both sides of the fault (P). FMP is the function of these factors:

$$\text{FMP} = f(\sigma, G, P) \quad (1)$$

Although a geological medium is generally heterogeneous and very complicated, it can be taken as homogeneous and isotropic in statistical view. Based on this consideration, and for the purpose of simplification in the theoretical derivation, we take the geological medium containing the faults as a homogeneous, isotropic and elastic material. Thus, fault movement potential can be simplified as:

$$\text{FMP} = f(\sigma, G) \quad (2)$$

To consider the influence of tectonic stress orientation and fault geometry on fault seismicity, Lokajicek et al. (1988) conducted laboratory experiments using block models. Their results showed that changes in fault inclination led to remarkable changes both in the recurrence time intervals between individual seismic events and in the amount of seismic energy; for some dip angles, the fault seismic activity vanishes. To prove the results of the laboratory experiments, He (1989) carried out a theoretical analysis and showed that faults can slip when the angles between the orientations of the maximum compressive principal stress and fault strike are between 20° and 70° . However, there are many exceptions in applying this model to natural fault systems. We consider that the exceptions are caused by the limitation of their two-dimensional consideration. In reality, fault planes are not always vertical and the orientations of the maximum compressive principal stress are also not always horizontal. In this paper, we consider this problem in three-dimensions using the Mohr stress circle.

Theoretical model

Mechanically, the most important factors that affect the onset of slip movement on a pre-existing fault are (suppose compressional stress is positive):

1) the difference between the maximum principal stress (σ_1) and the minimum principal stress (σ_3): ($\sigma_1 - \sigma_3$). This determines the diameter of the Mohr circle.

2) the sum of the maximum principal stress (σ_1) and the minimum principal stress (σ_3): ($\sigma_1 + \sigma_3$). This determines the location of Mohr circle.

The angle between the normal to the fault plane and the maximum principal stress (σ_1) is denoted as θ . The lower and the upper limits of θ between which the fault can slip, are denoted as θ_1 and θ_2 respectively. The symbol θ_0 represents the special value of θ at which fault slip is most likely to occur, φ is the angle of internal friction of the fault, τ_0 is the internal cohesion of the fault, and T_0 is the point where tensile fracture occurs. First, we calculate the angle (θ_0) at which the fault is most likely to slip. According to the sine theorem and Figure 2, we have

Figure 2 Mohr circle representation of stress states during fault slip needed by fault slip.

$$\frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3 + 2\tau_0 \tan \varphi} = \frac{\sin \varphi}{\sin(2\theta - \varphi)} \quad (3)$$

take the derivative of stress (σ) with respect to the angle θ , and let the derivative equal to zero, we get

$$\cos(2\theta - \varphi) = 0, \quad \theta_0 = 45^\circ + \varphi/2 \quad (4)$$

Then, we calculate the lower and the upper limits of the angle θ between which fault slip can occur. From equation (3) we have

$$\sin(2\theta - \varphi) = \frac{\sigma_1 + \sigma_3 + 2\tau_0 \tan \varphi}{\sigma_1 - \sigma_3} \cdot \sin \varphi \quad (5)$$

When $\sigma_3 \rightarrow T_0$, $\sigma_1 + \sigma_3 + 2\tau_0 \tan \varphi \rightarrow \sigma_1 - \sigma_3$ from Figure 2, the range of θ is maximum. Therefore, we can get:

$$\sin(2\theta - \varphi) = \sin \varphi \quad (6)$$

$$\text{and} \quad \theta_1 \rightarrow \varphi, \quad \theta_2 \rightarrow \pi/2 \quad (7)$$

The friction factor on a brittle fracture surface is usually 0.5-0.8 (Wang et al., 1979), which corresponds to

$$\varphi = 27^\circ - 39^\circ$$

For convenience in calculation, take $\varphi = 30^\circ$, which gives

$$\theta = \begin{cases} \theta_0 = 60^\circ \\ \theta_1 \rightarrow \varphi, \\ \theta_2 \rightarrow \pi/2 \end{cases} \quad (8)$$

This means that when $30^\circ < \theta < 90^\circ$, a fault might slip; when $\theta = 60^\circ$, the fault slips most easily. If $\theta \leq 30^\circ$ or $\theta \geq 90^\circ$, the fault can not slip.

To quantify the relationship between fault movement potential (FMP) and the angle θ , we define FMP as a normalized factor by the following

$$\text{FMP} = \begin{cases} 0, & \theta \in [0^\circ, 30^\circ] \\ \frac{\theta - 30^\circ}{30^\circ}, & \theta \in (30^\circ, 60^\circ] \\ 1 - \frac{\theta - 60^\circ}{30^\circ}, & \theta \in (60^\circ, 90^\circ] \end{cases} \quad (9)$$

Calculation of angle θ

If we know the direction of normal (γ_1) to a fault plane and its dip angle (β_1), and the orientation (γ_2) of the maximum principal stress and its dip angle (β_2), then θ can be calculated from their geometrical relationships (Figure 3).

Suppose γ to be the azimuth of a straight line and β to be its dip angle, then the straight line can be expressed as

$$\begin{aligned} l &= OA = \cos \beta \cos \gamma \\ m &= CB = \sin \beta \\ n &= AB = \cos \beta \sin \gamma \end{aligned} \quad (10)$$

and the vector $N = [l, m, n]$ is the direction of the straight line. Therefore, the angle between two straight lines can be calculated as

$$\cos \theta = \cos \beta_1 \cos \beta_2 \cos(\gamma_1 - \gamma_2) + \sin \beta_1 \sin \beta_2 \quad (11)$$

The value of β_2 should be negative when taking the angle of σ_1 axis as elevation.

Figure 3 The expression of a straight line in three dimensions.

Fault movement potentials in Hong Kong and its adjacent region

Regional tectonic stress orientations

Tectonic stress means an additional stress to lithostatic stress state, in other words, the part of stress deviated from lithostatic stress. Earthquake focal mechanism solution is one of the commonly used methods in the study of contemporary tectonic stress field. Although the orientation of the maximum principal compressive stress obtained from the focal mechanism solution of a strong earthquake represents the characteristics of large regional tectonic stress field (Lanzhou Institute of Seismology, State Seismological Bureau of China, 1992), some of the focal mechanism solutions of macroseisms reflect more complicated deep structure condition and stress feature, which means an exceptional stress field in instantaneous focal process in addition to regional tectonic stress field in earthquake genetic process, and the focal mechanism solution of a single small earthquake has random features. Fortunately, synthetic focal mechanism solutions of many small earthquakes may reflect a regional tectonic stress state. Therefore, we analyzed both of the focal mechanism solutions of large earthquakes and the average solutions of small earthquakes in order to get the general configuration of the regional stress state in Hong Kong and its adjacent area (Table 1). The statistical result shows that the average azimuth of P axes is 110° at elevation angle 8° .

Fault movement potential results and their analysis

The fault movement potentials of the major faults in Hong Kong and its adjacent region are calculated using the above equations and the regional stress orientation as well as the fault plane attitudes. The results are shown in Table 2.

1. The east-northeast striking Tsing Shan Wan-Tai Po Hoi fault zone has complicated geometric shapes, and the angle between the normal to the fault plane and the compressive principal stress along this fault zone changes remarkably. The fault movement potential of this fault zone ranges from middle to high, suggesting that this fault zone has the potential for generating earthquakes. Most interestingly, the Dangan Islands fault zone, a segment of the Tsing Shan Wan-Tai Po Hoi fault zone, is calculated to have the highest movement potential of 1.0, and a destructive earthquake ($M_s = 5.75$, June 23, 1874) occurred right on this fault zone in the sea area to the east

Table 1 Focal mechanism solution of Hong Kong and its adjacent area

Date	Location	ϕ N	λ E	M	P	T	N			
1918. 2. 13	Nanyue, Guangdong	23.5	117.0	7.25	83	2	352	18	189	80
1962. 3. 19	Heyuan, Guangdong	23.7	114.7	6.1	287	9	17	6	141	80
1964. 9. 23	Heyuan, Guangdong	23.7	114.7	5.3	78	32	338	17	225	53
1965. 10. 7	Xisha			5.9	355	5	264	76	85	14
1966. 9. 26	Shantou off shore, Guangdong	22.3	117.5	5.3	256	10	351	25	121	63
1969. 7. 26	Yangjiang,Guangdong	21.7	111.8	6.4	299	22	206	7	100	67
1971. 8. 21	Nanpeng, Guangdong	23.1	117.3	3.7	145	37	44	13	298	51
1972. 4. 6	South China Sea			5.5	328	6	227	65		
1972. 5. 29	Fugang, Guangdong	23.8	113.6	3.1	159	19	55	35	273	49
1972. 12. 18	Heyuan, Guangdong	23.7	114.7	4.5	103	8	13	8	238	80
1973. 7. 16	Haifeng, Guangdong	average of small earthquake solutions			101	50	3	8	266	40
1974. 2. 22	Lufeng off shore Guangdong	22.0	115.5	4.0	73	28	328	28	200	50
1974. 4. 24	Yangjiang, Guangdong	average of small earthquake solutions			102	11	193	4	303	78
1975. 2. 11	Yangjiang, Guangdong	21.7	111.8	3.4	88	15	335	58	186	29
1973-1977	Shantou, Guangdong	statistics of small earthquakes			290	36	191	13	38	51
1979. 9. 14	South China Sea			5.2	292	23	68	59		
1992. 2. 18	Nanri Island			5.2	92	51	234	32	332	20

(modified from Liu, 1981; Ren et al., 1996)

Table 2 The calculation of fault movement potential in Hong Kong region

No. and name of fault zone	attitude of fault	normal line of fault plane	θ	FMP
1. Tsing Shan Wan				
–Tai Po Hoi Fz	60°-70°/NW $\angle$ 50°-65°	330°-340° $\angle$ 25°-40°	42°-55°	0.4-0.8
2. Dangan Islands Fz	70°/SE $\angle$ 60°	160° $\angle$ 30°	61°	1.0
3. Lo Wu--Tuen Mun Fz				
a. San Tin Fs	40°/NW $\angle$ 35°-50°	310° $\angle$ 40°-55°	37°-50°	0.2-0.7
b. Lo Wu Fs				
NE segment	50°-55°/NW $\angle$ 58°	320°-325° $\angle$ 32°	37-41	0.2-0.4
SW segment	50°-55°/SE $\angle$ 60°	140°-145° $\angle$ 30°	48°-51°	0.6-0.7
c. Tuen Mun Fs				
NE segment	40°/NW $\angle$ 50°-67°	310° $\angle$ 23°-40°	21°-37°	0.0-0.2
SW segment	15°/NW $\angle$ 40°-50°	285° $\angle$ 40°-50°	33°-43°	0.1-0.4
d. Tsing Shan Fs				
NE segment	50°-55°/NW $\angle$ 50°-67°	320°-325° $\angle$ 23°-40°	33°-45°	0.1-0.5
SW segment	10°-20°/NW $\angle$ 40°-50°	280°-290° $\angle$ 40°-50°	34°-42°	0.1-0.4
e. Lau Fau Shan Fs	60°/NW $\angle$ 51°-67°	330° $\angle$ 23°-39°	41°-48°	0.4-0.6
4. Sha Tau kok				
–Pui O Wan Fz	30°-50°/NW $\angle$ 60°-70°	300°-320° $\angle$ 20°-30°	15°-36°	0.0-0.2
5. Lai Chi Kok				
–Tolo Channel Fz				
NE segment	40°-50°/NW $\angle$ 83°-85°	310°-320° $\angle$ 5°-7°	21°-30°	0.0
SW segment	40°-50°/SE $\angle$ 75°-80°	130°-140° $\angle$ 10°-15°	27°-37°	0.0-0.2
6. Po Toi Fz	50°/SE $\angle$ 60°-70°	140° $\angle$ 20°-30°	41°-48°	0.4-0.6
7. Kat O Chau				
–Chek Chau Fz	320°/NE $\angle$ 50°	50° $\angle$ 40°	49°	0.6
8. Lau Fau Shan--East				
Lamma Channel Fz				
a. Lau Fau Shan				
–Tsing Lung Tau Fs	330°/NE $\angle$ 55°	60° $\angle$ 35°	64°	0.9
b. Sha Kong Village				
–Tai Lam Kok Fs	340°/SW $\angle$ 70°	250° $\angle$ 20°	41°	0.4

of Dangan Islands. Therefore, it is highly possible that more destructive earthquakes would occur along this fault zone in the future.

2. The northeast striking fault zones are extensively distributed through Hong Kong and its adjacent region. This fault set is often diverging to southwest and converging to northeast. For example, the Lo Wu-Tuen Mun fault zone diverges to southwest in a fan shape branching into five secondary-faults with high movement potentials. Of them, the Lau Fau Shan fault, Lo Wu fault and San Tin fault are of high movement potentials up to 0.7. Considering that there are many small earthquakes clustering along the northeastern parts of the faults (Figure 1), we believe that the converging area of the fault zones (near Lo Wu) is another place where major earthquakes are likely to occur. The other three northeast striking fault zones, Sha Tau Kok-Pui O Wan, Lai Chi Kok-Tolo Channel and Po Toi fault zones, are low in terms of movement potential.

3. The northwest striking Kat O Chau-Chek Chau fault zone has intermediate movement potential values, but the movement potentials of the northwest striking Lau Fau Shan-East Lamma Channel fault zone is relatively high. This is consistent with the fact that few earthquakes occur along the former and many small earthquakes occur at the intersection of the latter and the northeast striking Sha Tau Kok-Pui O Wan fault zone. Besides, the 1874 destructive earthquake occurred at the intersection of this fault zone with the east-northeast striking Dangan Islands fault zone.

Discussion and conclusions

Seismicity is closely related to active Quaternary faults. This attracts many researchers to investigate the quantitative relationships between them. As a new parameter, FMP is defined to quantify earthquake risk along active faults and is formulated as a function of the fault geometry and the tectonic stress field. The contemporary movement potentials along fault zones of different orientations are different under the action of present-day regional west-northwest compressive stress field in Hong Kong and its adjacent region. The region where the northwest striking Lau Fau Shan-East Lamma Channel fault zone intersects with the east-northeast striking Dangan Islands fault zone is prone to destructive earthquakes since both of these two fault zones have high movement potentials. The movement potential of the northeast striking Lo Wu-Tuen Mun fault zone is also relatively high. But its southwestern segment is unlikely to cause major earthquakes because its divergence towards southwest may cause dispersion of strain energy. In contrast, the converging part of this fault zone at its northeastern segment, near Lo Wu, is expected to accumulate strain energy. This is another area with relatively high seismic potential.

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