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EMPIRICAL RELATION OF EFFECTIVE STRESS ON SUBFAULT IN ASPERITY TO FAULT TYPE AND DEPTH INFERRED FROM EXISTING VARIABLE-SLIP RUPTURE MODEL FOR CRUSTAL EARTHQUAKE

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SUMMARY

For more precise prediction of strong ground motions from future earthquakes, we examined empirical relations of the effective stress on the subfaults in the asperities to the fault type and the depth. The existing variable-slip rupture models for crustal earthquakes showed that the effective stress on the subfaults in the asperities varied several hundred percent as a function of the fault type (strike-slip fault with a surface rupture, oblique-slip fault with a buried rupture, and reverse fault with a buried rupture) and 10 to 30 percent as a function of the depth of the subfaults.

INTRODUCTION

The strong motion pulses of about 1-second period caused huge damage to the structures in the 1995 Hyogo-Ken Nambu, Japan, earthquake of M_{JMA} 7.3 (*e.g.* Tanaka *et al.*[1]; Editorial Committee for the Report on the Hanshin-Awaji Earthquake Disaster[2]).

A lot of efforts have been made to capture the feature of the complexity of the fault rupture and to characterize the source model for predicting the strong ground motions precisely in a wide period range including 0.5 to 2 seconds. Several characterized source models have been proposed for strong motion prediction: a fractal model (*e.g.* Kikuchi and Fukao[3]), a slip wavenumber spectrum model (*e.g.* Somerville *et al.*[4]), and an asperity model (*e.g.* Somerville *et al.*[4]). The asperity model is composed of the asperity, on which larger slip is distributed, and the background, on which smaller slip is distributed, and this model is often used in Japan as a source model for future earthquakes, because it is easy to apply the information of the trench investigation of the active faults or of the locked zone on the plate boundary to the asperity model.

Among the needed parameters given to the asperity and the background for strong motion prediction, the area and the final slip are estimated based on the statistics of the crustal earthquakes by Somerville *et al.*[5] and of the subduction earthquakes by Somerville *et al.*[6].

On the other hand, the effective stress is estimated based on different ideas. Irikura and Miyake[7] applied the equation of the stress drop of a circular fault (Eshelby[8]) to the effective stress on the asperity, noticing that the equation should be checked by a dynamic source model. Dan *et al.* [9] estimated

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the effective stress on the asperity based on the level of the acceleration source spectrum in a short-period range, called short-period level (Dan and Sato [10]).

Recently, Irikura *et al.* [11] and Dan *et al.* [12] applied the equation of the stress drop of the asperity model (Das and Kostrov[13]) to the effective stress on the asperity. Dan and Sato [14] showed that these three different ideas led the same value of about 100 bars on the asperity based on the statistics of the crustal earthquakes by Somerville *et al.* [5].

McGarr[15] showed that the peak velocities and the peak accelerations changed systematically as a function of the fault type and the depth. Here, the fault type was the reverse fault, the normal fault, and the strike-slip fault, and all of them were the crustal earthquakes. Kawase *et al.* [16] carried out a parametric study on the asperity model based on the source model for the 1995 Hyogo-Ken Nambu earthquake derived by Matsushima and Kawase [17], compared their results with the attenuation of the peak ground velocity proposed by Midorikawa [18], and finally suggested that the effective stress on the asperity should be dependent on the depth.

Hence, we first inferred the effective stress on the asperities from the variable-slip rupture models for the crustal earthquakes analyzed by Somerville *et al.* [5], and then examined the empirical relation of the effective stress on the asperities to the fault type and the depth to obtain the basic information of the effective stress on the asperities for the characterized asperity model for the strong motion prediction.

DATABASE USED IN THIS STUDY

Our database was the effective stress on the asperities inferred from the variable-slip rupture models for the crustal earthquakes by the following equation (Dan *et al.*[9]):

$$\sigma_{mpq} = \rho_{mpq}\beta_{mpq}V_{mpq}/2. \tag{1}$$

Here, m is a subscript for each fault, pq is a subscript for each subfault, ρ is the density of the medium at the subfault, β is the S-wave velocity of the medium at the subfault, V is the velocity averaged over the time from 10 % cumulative slip to 70 % cumulative slip. The variable-slip rupture models were taken from those Somerville *et al*.[5] analyzed, but the model for the 1995 Hyogo-Ken Nambu earthquake was replaced by the recent model obtained by Sekiguchi *et al*.[19].

We chose the asperities, which had 1.5 times or larger slip than the averaged slip over the entire fault, based on the procedure of the asperity definition by Somerville *et al.*[5]. Here, we excluded the subfaults with no slip in averaging the slip over the entire fault.

Table 1 lists the parameters of the variable-slip rupture models for the crustal earthquakes used in this study. In the table, SS shows a strike-slip fault, RV a reverse fault, OB an oblique fault, NM a normal fault, SR a surface rupture fault, and BR a buried rupture fault.

EFFECTIVE STRESS INFERRED FROM VARIABLE-SLIP RUPTURE MODEL

The open circles in Fig. 1 (a) shows the effective stress on the subfaults in the asperity and the depth for the 1992 Landers, California, earthquake. This figure indicates that the effective stress increases as the depth increases. Figs. 1 (b) to (l) also show the effective stress on the subfaults in the asperities and the depth for other crustal earthquakes, indicating again that the effective stress increases as the depth increases.

McGarr [15] compiled strong motion records from crustal earthquakes and showed that the peak ground velocities, normalized in the distance and the seismic moment, were described by a linear function of the focal depth and that the peak ground velocities from reverse faults were systematically larger than those from normal faults. Moreover, the shear strength of the crust is described by a linear function of the depth (*e.g.* Scholz[20]). From these two points, we assumed the effective stress σ_{asp} on the asperities as

Table 1 List of variable-slip rupture models for crustal earthquakes used in this study.

	Type#1		M_W	M_0 dyne-cm	A #2 dyne-cm/s ^{2}	Depth km	Dip degree	Area km×km	Subfault km×km	$S_{asp}^{\#3}$ km^2	k #4 bar/km	$k_0^{\#4}$ bar
1992 Landers, California	SS	SR	7.18	7.50E+26	1.15E+26	0.0 ～ 15.0	90	69.0 × 15.0	3.0 × 2.5	248	0.5	47
1978 Tabas, Iran	RV	SR	7.11	5.80E+26	1.45E+26	1.0 ～ 20.0	25	95.0 × 45.0	4.52 × 4.5	834	3.5	23
1989 Loma Prieta, California	OB	BR	6.92	3.00E+26	1.70E+26	1.5 ～ 20.3	70	40.0 × 18.0	2.0 × 2.0	140	3.1	53
1995 Hyogo-Ken Nambu, Japan	SS	SR	6.85	2.40E+26	9.62E+25	0.0 ～ 20.5	78～90	64 × 20.5	2.05 × 2.05	256	0.5	43
1983 Borah Peak, Idaho	NM	SR	6.84	2.30E+26	2.81E+26	1.0 ～ 20.9	49	49 × 26.4	3.25 × 3.3	204	4.4	107
1985 Nahanni, Dec 23, Canada	RV	BR	6.72	1.50E+26	1.81E+26	2.0 ～ 9.0	25	48.0 × 21.2	2.67 × 2.36	120	3.5	117
1994 Northridge, California	RV	BR	6.63	1.10E+26	1.80E+26	5.0 ～ 20.4	40	18.0 × 21.0	1.29 × 1.71	88	3.5	102
1985 Nahanni, Oct. 5, Canada	RV	BR	6.60	1.00E+26	2.81E+26	0.2 ～ 8.2	35	40.0 × 17.4	2.67 × 1.74	107	3.5	174
1979 Imperial Valley, California	SS	SR	6.40	5.00E+25	3.77E+25	0.0 ～ 10.0	90	42.0 × 10.0	3.0 × 2.5	90	0.5	41
1986 North Palm Springs, California	OB	BR	6.10	1.80E+25	7.40E+25	4.0 ～ 13.63	46	20.0 × 13.3	2.0 × 1.9	53	3.1	45
1987 Whittier Narrows, California	RV	BR	5.93	1.00E+25	9.88E+25	12.1 ～ 17.1	30	10.0 × 10.0	1.0 × 1.0	21	3.5	132
1979 Coyote Lake, California	SS	BR	5.63	3.50E+24	2.84E+25	4.3 ～ 8.8	80	5.5 × 4.57	0.52 × 0.38	6	0.5	103

#1 SS=strike slip, RV=reverse, OB=oblique slip, NM=normal slip, SR=surface rupture, BR=buried rupture
#2 short-period level
#3 asperity area determined in this paper
#4 see eq. (2) in the text

$$\sigma_{asp} = kH + k_0. \tag{2}$$

Here, H is the depth, k is a constant for the fault type, and k_0 is a constant for each fault.

We determined k and k_0 in eq. (2) for four strike-slip faults, for five reverse faults, for two oblique faults, and for one normal-slip fault to minimize the following error:

$$\varepsilon = \Sigma_m w_m \Sigma_{pq} \left[\sigma_{aspmpq} - (kH_{mpq} + k_{0m})\right]^2. \tag{3}$$

Here, w_m is a weighting factor for the area of the subfault of each fault.
The results are shown in the two right columns in Table 1.

The lines in Fig. 1 are the empirical relation of the effective stress on the subfaults in the asperities to the depth by eq. (2), twice the relation, and a half of the relation, covering the effective stress shown by the open circles.

Fig. 2 shows the effective stress on the subfaults in the asperities normalized at the depth of 0 km and the seismic moment. The normalized effective stress of the reverse faults is larger than that of other fault types, and the normalized effective stress of the surface rupture faults is smaller than that of the buried rupture faults.

The slip direction (rake) on the fault and the difference between the surface rupture fault and the buried rupture fault depend on the stress and strength status at the source. Hence, it is necessary to study the relation between the stress and strength status and the effective stress.

We averaged the normalized effective stress for the strike-slip faults with a surface rupture, for the oblique-slip faults with a buried rupture, and for the reverse faults with a buried rupture, and obtained the following relations:

σ_{asp}[bar] =0.5× [km]+ 44 for strike-slip fault with a surface rupture, (4)

σ_{asp}[bar] =3.1×H[km]+ 49 for oblique-slip fault with a buried rupture, (5)

σ_{asp}[bar] =3.5×H[km]+131 for reverse fault with a buried rupture. (6)

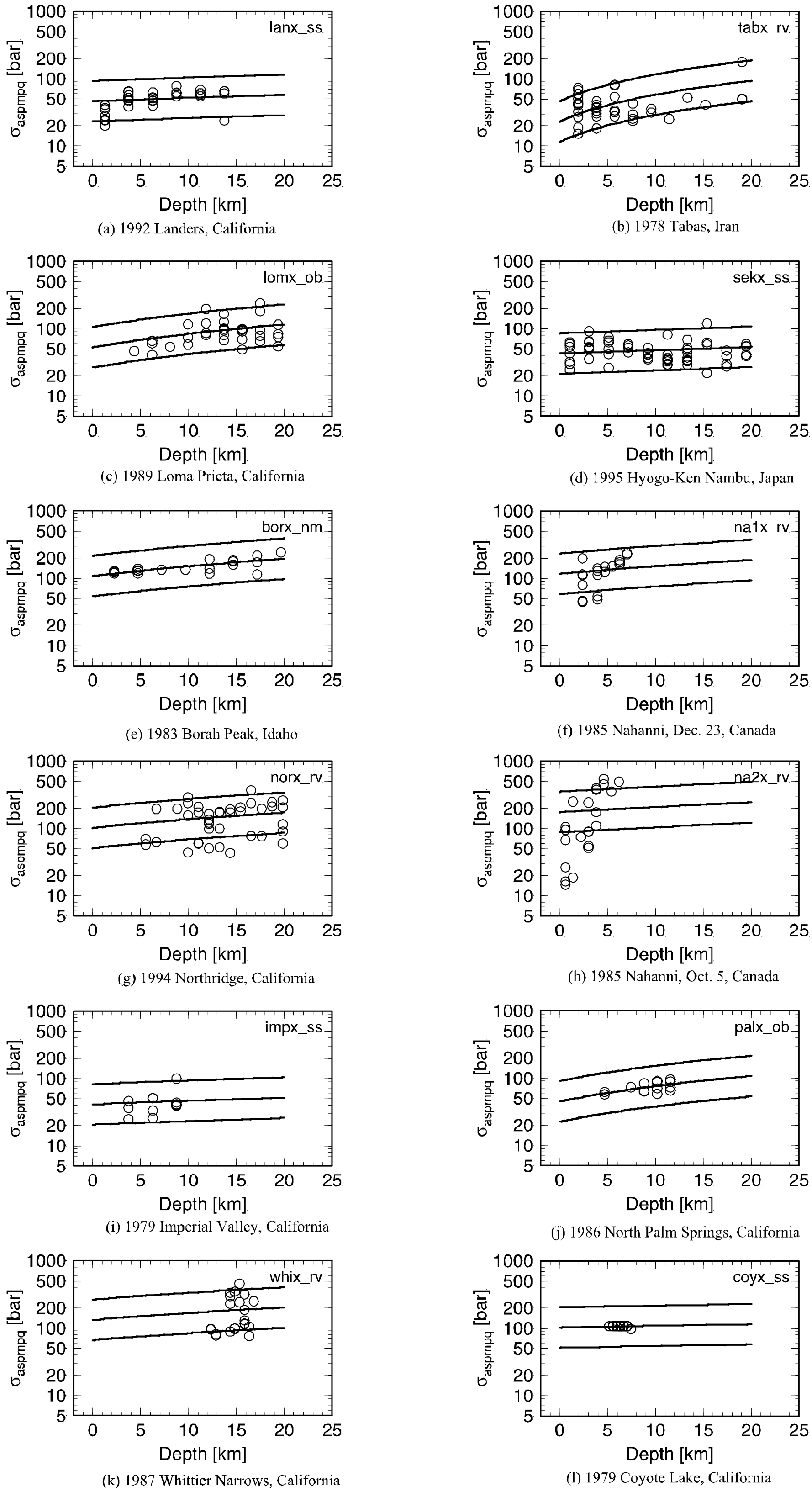
In order to compare these relations of eq. (4) to eq. (6), we normalized the relations by the effective stress for the strike-slip faults with a surface rupture at the depth of 10 km:

1.0±0.10 for strike-slip fault with a surface rupture (depth 10±10 km), (7)

1.6±0.63 for oblique-slip fault with a buried rupture (depth 10±10 km), (8)

3.4±0.71 for reverse fault with a buried rupture (depth 10±10 km). (9)

Eq. (7) to eq. (9) indicate that the effective stress on the subfaults in the asperities varies several hundred percent as a function of the fault type (strike-slip fault with a surface rupture, reverse fault with a buried rupture, and oblique-slip fault with a buried rupture) and 10 to 30 percent as a function of the depth of the subfaults.



(a) 1992 Landers, California
(b) 1978 Tabas, Iran
(c) 1989 Loma Prieta, California
(d) 1995 Hyogo-Ken Nambu, Japan
(e) 1983 Borah Peak, Idaho
(f) 1985 Nahanni, Dec. 23, Canada
(g) 1994 Northridge, California
(h) 1985 Nahanni, Oct. 5, Canada
(i) 1979 Imperial Valley, California
(j) 1986 North Palm Springs, California
(k) 1987 Whittier Narrows, California
(l) 1979 Coyote Lake, California

Fig. 1 Empirical relation of effective stress on the subfaults in the asperities to the fault type and the depth for crustal earthquakes.

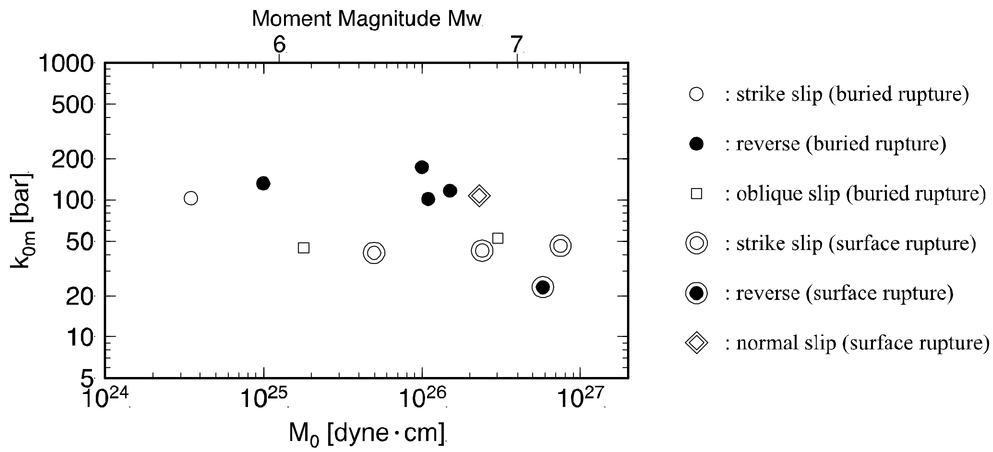


Fig. 2 The effective stress on the subfaults in the asperities normalized at the depth of 0 km and the seismic moment.

CONCLUSIONS

For more precise prediction of strong ground motions from future earthquakes, we examined empirical relations of the effective stress on the subfaults in the asperities to the fault type and the depth. The existing variable-slip rupture models for crustal earthquakes showed that the effective stress on the subfaults in the asperities varied several hundred percent as a function of the fault type (strike-slip fault with a surface rupture, oblique-slip fault with a buried rupture, and reverse fault with a buried rupture) and 10 to 30 percent as a function of the depth of the subfaults.

Because the slip direction (rake) on the fault and the difference between the surface rupture fault and the buried rupture fault depend on the stress and strength status at the source, it is necessary to study the relation between the stress and strength status and the effective stress.

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