Determining the Earthquake Shaking Force

For Structural and Bridge Engineers

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A new method has been developed for measuring the force of ground shaking during earthquakes at particular locations. The proposed Earthquake Shaking Force (*EqSF*) rating is based on the maximum vector sum of the recorded ground accelerations in the three main directions scaled with the strong ground motion duration. An equation for calculating the Earthquake Force values is proposed. This new method has been used to analyze and compare more than 220 ground station recordings from 48 earthquakes in the United States and around the world. The results show that the new method can provide objective ranking of the ground shaking forces, and can help engineers in designing seismically-resistant structures.

Today geologists and engineers use Magnitude scales and the Modified Mercalli Intensity scale to measure and rank earthquakes. For a century the Modified Mercalli Scale has been used for evaluating the intensity of local ground shaking. Different versions of this scale are still used, with its twelve-point range from I to XII, around the world. The Modified Mercalli Scale is based on the feelings and reactions of individuals and on observed damage to structures and underground facilities. This makes the scale subjective and inaccurate, because of the different individual interpretations (due to different sensitivity and reactions), the specific construction conditions of the country, the year of construction, or the level of building development.

Some improvement was achieved in California by modifying the Mercalli Intensity scale again, using Instrumental Intensity, in an attempt to correlate the intensity scale values with the peak ground accelerations and velocities. Instrumental Intensity is used by the TriNet system to produce ground shaking maps showing the peak ground accelerations and velocities by ground stations for a specific earthquake.

Today, California and many other states and countries have developed large nets of ground motion recording stations. During an earthquake, all necessary ground motion data are recorded and the Mercalli Intensity Scale is no longer providing reliable information. The new Earthquake Shaking Force method is a step forward in providing objective measurement of the ground shaking based on recorded ground motions during an earthquake.

Measuring the Force of Ground Shaking

This new *EqSF* approach is created for measuring and comparing the force of ground motions at local sites at a particular distance from an earthquake epicenter.

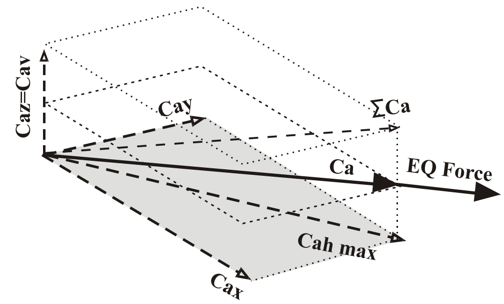

Figure 1. Earthquake Shaking Force, 3D vector sum of ground accelerations.

The Earthquake Shaking Force is based on the well known Newton's Second Law of Motion $F = m*a$, where the inertial force F, equals the mass m, multiplied by the acceleration a. Engineers are using the same basic principle to determine the lateral seismic forces for designing buildings and structures. The shaking force values are calculated using the instrumental readings for ground accelerations and the duration of strong ground motions. Similar to the Richter Scale, the proposed method does not have a fixed top limit and the calculated values are rounded to the first decimal digit. Based on the highest recorded peak accelerations, we should expect a ground motion rarely to exceed *EqSF* level 13–16. As a reference for a recorded ground shaking with total acceleration (the space vector sum) equal to 1.0g and *strong motion* duration of 20 seconds the calculated *EqSF* value is 9.8.

The physical meaning of the proposed scale value is a force equal to the maximum vector sum of the ground accelerations in x, y and z directions (within an interval equal or less than 1.5 sec) in *m/sec/sec* multiplied by one unit mass (*m=1*) (*Figure 1*). This theoretic value is corrected for vertical acceleration and duration. The whole calculated value is scaled in order to receive a range closer to the values used in different intensity scales.

The formula for calculating the Earthquake force of the local ground motion is:

$$EqSF = 9.81\{[Cahx^2 + Cahy^2 + (Cav/2)^2](t/20)^2\}^{0.2} \qquad \text{Equation 1}$$

where,

Cahx, Cahy and *Cav* are the corresponding horizontal and vertical accelerations (*g*) in x, y and z directions that provide the maximum vector sum,

Cav/2 is the correction accounting for a relatively reduced impact of the vertical acceleration,

t is the duration of strong ground motions in seconds,

t/20 is a correction for the strong motion duration,

^0.2 is the scaling correction for the 3D vector value (in lieu of ^0.5),

9.81 is the acceleration of gravity in *m/sec/sec*

m is the mass, taken as 1, which therefore does not appear in the equation.

All accelerations are taken from the three seismograms (two horizontals and one vertical) recorded at a ground station for a particular event. The time interval considering simultaneous action of the corresponding accelerations in three perpendicular directions is taken as 1.5 seconds. The duration of strong motion is the modified "bracketed duration" for the time interval between the first and last acceleration peaks greater than 0.1g. For the strong motion duration an upper limit of 75 seconds is used. An exception is made for seismograms with acceleration peaks smaller than 0.1 g that should result in *t* = 0 and *EqSF* = 0. The *EqSF* value for such earthquake readings is calculated with duration (*t*) equal to 0.5 seconds in order to allow comparing their ground shaking force with the forces at other locations. The original "bracketed duration", proposed by Page et al. and Bolt accounts for the intervals between 0.05 g peaks.

When accelerations are given in *cm/sec/sec*, the *EqSF* values may be calculated directly from:

EqSF = 0.6237{[Cahx^2+ Cahy^2 + (Cav/2)^2](t/20)^2}^0.2 *Equation 2*

The correction for vertical acceleration is introduced to account for its relatively smaller influence on structural damage. Reduction factors from 1 to 3 produce small differential results less than 7 percent; therefore the final selected reduction factor is 2.

The *t*/20 is introduced to account for the influence of ground motion duration on structural damage. Twenty (20) seconds were selected as basic duration based on the analysis of more than 100 earthquake records. The scaling correction (^0.2 in lieu of ^0.5) is to reduce the sharp increase in calculated degrees between smaller and greater acceleration values, and to scale the values closer to the traditionally used values in earthquake scales.

The above modifications were selected based on calculated *EqSF* values for some sites with available ground motion data from the Northridge, Loma Prieta, San Fernando, and Kobe earthquakes. The data used are from the Strong Motion Data Center on the Internet – homepage of the Department of Conservation, Division of Mines & Geology. Some data for the sites not listed on the web are based on presentations and publications following the Northridge Earthquake by Kircher (1994) and Somerville (1997). The data used was updated later based on the registered seismograms made available on the COSMOS website.

Study on Available Data from Earthquakes Recordings

More than 40 earthquakes have been included in this study. The criterion for selecting these earthquakes was based on available information (seismograms), and on magnitudes near or more than 6.0. The main source of information was the website of the Consortium of Organizations for Strong-Motion Observation Systems (COSMOS), listing recorded earthquake data from more than 500 earthquakes and 6,600 stations (by January 2015). From the selected strongest events, more than 150 recorded seismograms were analyzed. The summary of this analysis is presented in *Table 1* online including data from El Centro, California in 1940 to South Napa, California in 2014. This table lists the magnitude, the focal depth, number of fatalities, number of stations with recorded data and the maximum calculated *EqSF* scale at a ground station for the event. One more piece of data is included – the average from the top five calculated *EqSF* (Average 5 *EqSF*). When only one station recording is available, the Average 5 *EqSF* is calculated as 80% of the single station result. The combination of Max *EqSF* and the Average 5 *EqSF* provides valuable comparative information for the shaking force of earthquakes. The use of Average 5 *EqSF* should be combined with engineering judgment. This information is more credible for earthquakes in California, Japan, or Taiwan, where the instrumentation net is well developed and recordings from multiple stations are usually available.

In *Table 2* are listed the recorded accelerations, strong motion durations and calculated *EqSF* values for representative stations for the earthquakes included in this study. These data are structured additionally in a summary *Table 3* listing the stations by the calculated *EqSF* values and provided maximum horizontal, vertical and vector accelerations.

The maximum registered acceleration in one direction is at Tsukidate Station, Japan, on March 2011 – 2,700 cm/sec/sec (2.75g); during the same earthquake at this station are calculated also the maximum horizontal (vector sum) acceleration – 2,983 cm/sec/sec (3.04g), and the maximum total (3-D) acceleration – 3,526 cm/sec/sec (3.59g).

The maximum vertical registered acceleration is at Tsukidate Station, Japan, on March 2011 – 1,880 cm/sec/sec (1.92g).

In *Table 3* there are 21 stations listed with horizontal accelerations exceeding 1.0g, and 27 stations with total (3D) acceleration exceeding 1.0g.

The longest strong ground motion duration, 68 sec., is recorded at Talca Station, Chile, in 2010, whereas the duration recorded at Hiroo Station, Japan, in 2003 is 65 sec., and the duration at Hokoto Station, Japan, in 2011, is 58 sec. The longest duration in California is at Maricopa Station, during the San Fernando earthquake in 1971 (31.5 sec.).

The highest *EqSF* value is calculated for the Tsukidate Station, Japan, in 2011 (23.4). The Tarzana Station has the highest *EqSF* value calculated in the US (13.5).

The first three places for the Average 5 *EqSF* are for Valparaiso, Chile (12.8), Chi-Chi, Taiwan (12.3), and Western Tottori, Japan (9.8). The highest Average 5 *EqSF* in California is for Northridge (9.4).

Frequency Influence on *EqSF* Determination

Part of this study was an attempt to include in the *EqSF* scale the influence of the earthquake frequency (Hz or cycles in seconds) in addition to the acceleration and strong motion duration. Two optional criteria were studied – average frequency measured for "10-second bracket" and measured for the entire "strong motion duration".

It was concluded that it is difficult to avoid some subjectivity in measuring the frequency. The criteria were based on full cycles (cycles with vibrations registered on both sides of the neutral axis), but objective criteria could not be established. The studied two bracket durations give different results: the variation increases with the strong motion duration. The tolerance in reliability of measurement of the frequency is estimated as 15 to 20%. There is almost no difference in frequency between recorded seismograms in two perpendicular directions. For several records (with peak ground acceleration varying between 226 and 1,019 cm/sec/sec or 450%), the impact on *EqSF* values was found to be less than [(2.3/1.7)^2]^0.2 = 1.12 (or less than 12%).

Considering the element of subjectivity and the small influence of the frequency variation on *EqSF*, determination (less than 12% compared to a larger percentage of non-accuracy from 15% to 20%), the frequency was abandoned as having a minimal effect on the calculated *EqSF* values.

Conclusions

The *EqSF* approach is based on objective measurements and provides useful data for professional engineers. This method provides reliable comparable data for the forces of local ground shaking that will complement the

Table 1. Earthquake Information for Selected Major Earthquakes.

Earthquake	Date	Magnitude	Focal Depth	Fatalities	Number Stations	Max EqSF/ (Average 5 EqSF)	
El Centro, CA	May 18,1940	6.9	9.0 km	9	1	7.6	(6.1)
San Fernando, CA	Feb 9, 1971	6.6	8.4 km	65	114	9.9	(6.9)
Gazli, Uzbekistan	May 17, 1976	7.0	15.0 km		1	8.1	(6.5)
Imperial Valley, CA	Oct 15, 1979	6.5	12.1 km		35	8.3	(7.3)
Valparaiso, Chile	Mar 3, 1985	7.8	33.0 km	180	26	14.2	(12.8)
Loma Prieta, CA	Oct 17, 1989	7.1	15.0 km	63	87	7.7	(6.5)
Cape Mendocino/Petrolia, CA	Apr 25, 1992	7.0	15.0 km	0	14	12.3	(8.4)
Landers, CA	Jun 28, 1992	7.3	4.5 km	1	99	11.0	(8.9)
Northridge, CA	Jan 17, 1994	6.7	18.4 km	57	265	13.6	(9.4)
Kobe, Japan	Jan 17, 1995	6.9	14.0 km	> 5,000	5	10.0	(8.7)
Izmit, Turkey	Aug 17, 1999	7.4	15.9 km	> 17,000	11	9.1	(7.7)
Athens, Greece	Sep 7, 1999	5.9	N/a	124	14	5.5	(4.8)
Chi-Chi, Taiwan	Sep 21, 1999	7.6	10.3 km	> 2,000	215	13.2	(12.3)
Hector Mine, CA	Oct 16, 1999	7.1	5.0 km	0	94	4.1	(3.8)
Yountville, CA	Sep 3, 2000	5.2	9.4 km	2	28	5.9	(3.5)
W. Tottori, Japan	Oct 6, 2000	7.1	10.0 km	>130	64	15.6	(9.8)
El Salvador	Jan 13, 2001	7.6	39.0 km	> 700	18	11.7	(8.9)
Gujarat, India	Jan 26, 2001	7.7	22.0 km	> 18,000		1.0 *	NA
Nisqually, WA	Feb 28, 2001	6.8	52.4 km	1	95	6.5	(5.0)
Kure, Japan	Mar 24, 2001	6.4	33.0 km	2	55	10.2	(8.4)
Arequipa, Peru	Jun 23, 2001	8.1	9.0 km	> 100	1	6.7	(5.4)
Honshu, Japan	May 26, 2003	7.0	60 km		73	13.1	(11.8)
Hokkaido, Japan	Sep 25, 2003	8.0	33 km	1	100	16.8	(12.4)
Hokkaido, Japan	Sep 25, 2003	7.0	33 km		48	9.2	(6.6)
San Simeon	Dec 22, 2003	6.5	7.9 km	2	55	5.2	
Bam, Iran	Dec 26, 2003	6.6	10 km	>40,000	24	9.1	(4.3)
Parkfield	Sep 28, 2004	6.0	7.9 km		43	7.4	(6.4)
Ojiya, Japan	Oct 23, 2004	6.6	16 km	31	87	13.1	(8.7)
Hawaii, USA	Oct 15, 2006	6.7	29.0 km	0	14	13.9	(8.9)
Honshu, Japan	Mar 25, 2007	6.7	5.0 km	1	>160	9.1	(7.6)
Chile	Feb 27, 2010	8.8	35.0 km	525	35	16.4	(13.5)
Calexico, Mexico	Apr 4, 2010	7.2	32.3 km	4	>160	7.6	(6.9)
Canterbury, New Zealand	Sep 3, 2010	7.0	5.0 km	1	120	8.9	(7.1)
Christchurch, New Zealand	Feb 21, 2011	6.3	5.0 km	185	106	9.0	(7.2)
Tohoku, Japan	Mar 11, 2011	9.0	29.0 km	>15,000	>160	23.4	(18.5)
Iquique, Chile	Apr 1, 2014	8.2	25.0 km	6	2	4.4	(3.5)
South Napa, CA	Aug 24, 2014	6.0	11.3 km	1	>160	6.3	(5.1)

*1.0 * EQF calculated from readings of a single station located at 238 km from the epicenter*

TABLE 2. Earthquake Shaking Force (EqSF)

CahX	CahY	CaV	t	EQF	Station	Distance	Note	Depth
cm/sec/sec	*cm/sec/sec*	*cm/sec/sec*	*sec*			*km*		*km*
El Centro, CA, May 18, 1940 M 6.9					Average 5 EQF = 7.6*0.8 = 6.1 (single station)			6.0
341.70	185.00	144.00	24.70	7.4	El Centro ARRAY Station 9	8.2		
San Fernando, CA, February 9, 1971 M 6.6					Average 5 EQF = 6.9			8.4
1148.00	1055.00	434.00	11.50	9.5	Pacoima Dam	8.5		
366.20	282.10	161.10	8.00	5.1	Elizabeth Lake - Lake Hughes	23.10		
327.60	280.90	173.70	14.80	6.3	Costaic-Old Ridge Route	27.60		
268.10	221.20	139.10	9.00	4.7	Glendale Municipal Serv Bldg	32.10		
341.40	258.00	165.00	31.50	8.5	Maricopa Array Sta 4	119.50		
Te Aroha, New Zealand, January 5, 1973 M 6.6								
153.00	143.00	68.00	10.50	4.1	Atene - C Valley	75.00		
Gazli, Uzbekistan, May 17, 1976 M7.0								
703.10	518.00	1331.70	11.00	8.1	Karakyr, Uzbekistan	unknown		
Imperial Valley, CA, October 15, 1979 M 6.5					Average 5 EQF = 7.3			12.0
351.40	229.90	889.40	14.80	7.2	Agrarias	1.8		
763.20	582.50	434.90	13.00	8.3	Bonds Corner, Hwys 115 & 98	9.0		
476.80	346.40	596.00	7.20	5.6	El Centro, Differential Array	28.7		
607.10	469.30	403.90	6.50	5.7	El Centro, Array Sta 8	29.6		
478.60	361.20	240.70	6.50	5.2	El Centro, Array Sta 4	29.7		
444.30	147.00	1703.60	12.00	8.0	El Centro, Sta 6, 551 Hudston Rd	29.8		
521.30	373.40	511.10	10.50	6.6	El Centro, Array Sta 5	30.4		
Valparaiso, Chile, March 3, 1985 M 7.8					Average 5 EQF = 12.8			33.0
656.00	437.00	849.00	53.80	14.0	Llolleo	n/a		
698.00	437.00	463.00	53.80	13.8	Llolleo	n/a		
425.00	303.00	189.00	46.80	10.8	San Felipe	n/a		
465.30	345.50	222.80	47.00	11.3	Llayllay	n/a		
673.00	518.00	250.00	45.00	12.9	Melipilla	n/a		
333.00	285.00	119.00	27.00	8.0	San Fernando	n/a		
707.00	696.00	393.00	54.30	14.8	San Isidro	n/a		

Loma Prieta, CA, October 17, 1989 M 7.1					Average 5 EQF = 6.5				18.0
617.70	469.40	431.10	11.60	7.3	Corralitos	6.9			
617.70	469.40	431.10	11.60	7.3	Corralitos	7.9	pick interval=1.3 sec		
617.70	327.00	431.10	11.60	7.0	Corralitos	7.9			
449.00	390.80	500.10	16.40	7.7	Capitola	11.7			
433.10	340.70	324.60	11.70	6.4	Santa Cruz Lick Observatory	18.6			
433.60	401.60	131.00	5.00	4.6	Lexington Dam	19.0			
494.50	316.20	353.40	7.00	5.3	Saratoga	27.4			
434.00	427.00	206.00	6.00	5.0	Gilroy Station 1	28.4			
531.70	362.00	360.10	6.00	5.2	Gilroy Station 3	31.1			
378.20	341.50	193.00	5.50	4.5	Palo Alto, VA Hospital	46.3			
325.80	230.80	63.30	7.00	4.5	SF Airport	79.4			
238.30	187.30	141.30	4.00	3.3	Oakland	91.9	no seismograms available		
281.40	265.50	65.10	4.00	3.6	Oakland, 14th str. Wharf	94.5	no seismograms available		
120.20	104.20	47.40	2.50	2.1	SF, Transamerica Basement	96.3			
155.80	97.90	15.90	3.00	2.4	Treasure Island	97.6			
194.90	97.90	56.20	2.50	2.3	SF Presidio	98.0			
238.70	124.20	57.50	4.00	3.1	Golden Gate Bridge	100.1			
Cape Mendocino/Petrolia, April 25, 1992 M 7.0					Average 5 EQF = 8.4				15.0
1468.30	1019.40	738.90	19.00	12.3	Cape Mendocino/Petrolia	3.8			
649.40	578.00	159.70	18.90	9.2	Petrolia, General Store	5.4			
471.00	317.60	122.80	16.00	7.2	Centerville Beach	22.0			
538.50	378.30	191.50	16.00	7.7	Rio Dell	23.7			
373.60	263.00	73.70	11.10	5.7	Eel River, Ferndale Fire Sta	24.0			
Landers, CA, June 28, 1992 M 7.3					Average 5 EQF = 8.9				1.1
256.00	268.00	156.00	30.90	8.0	Joshua Tree	13.7			
216.10	161.40	169.60	20.00	6.0	Morongo Valley	21.0			
213.00	204.00	103.00	24.50	6.6	Fun Valley, Reservoir 361	31.0			
798.00	716.80	383.00	24.00	11.0	Lucerne Valley	42.0			
301.70	126.00	81.90	31.30	7.6	Indio, Jackson Road	54.0			
240.00	148.60	133.20	15.00	5.4	Yermo, Fire Station	85.8			
Northridge, CA, January 17, 1994 M 6.7					Average 5 EQF = 9.4				19.0
467.90	357.00	785.00	14.30	7.5	White Oak Covenant Church	2.2			

1744.50	912.00	1027.50	21.50	13.5	Tarzana, Cedar Hill Nursery	5.5		
922.70	535.30	325.00	11.60	8.2	Sepulveda, VA Hospital	7.3		
266.00	302.00	361.00	10.00	5.4	Arleta	9.9		
825.50	471.00	830.00	12.00	8.2	LA Reservoir	9.9		
739.50	593.00	584.00	15.20	8.8	Sylmar, Converter, Valve Group 7	12.3		
814.80	377.00	396.00	9.00	6.9	Sylmar, Converter Station East	12.7		
782.40	375.50	324.30	9.00	6.8	Sylmar, County Hospital	15.8		
578.20	571.60	537.30	8.00	6.4	New Hall	20.2		
866.00	362.60	227.70	10.50	7.5	Santa Monica, City Hall	22.5		
Arthurs Pass, New Zealand, June 18, 1994, M 6.8					Average 5 EQF = 5.0			
428.40	329.30	367.30	19.00	7.7	Arthurs Pass	11.0		
140.00	116.00	53.00	5.60	3.0	Flock Hill	28.0		
Kobe, Japan, January 17, 1995, M 6.9					Average 5 EQF = 8.7			16.0
843.70	510.10	506.22	15.00	8.9	JMA Kobe	3.4	Assumed Vertical	
323.70	255.00	194.22	15.00	6.2	Ceorka University, Kobe	3.8	acceleration and duration	
657.30	529.70	394.38	15.00	8.3	Ceorka, Kobe	6.2	Same as above	
421.80	137.30	253.08	15.00	6.5	Port Island, Kobe	6.6	Same as above	
680.81	679.83	424.77	15.00	8.8	Takarazuka	1.2	Same as above	
818.00	617.00	332.00	13.50	8.6	Marine Observation, Kobe	17.0	From seismogram	
	Vertical acceleration assumed = 0.6*CahX							
Izmit/Kocaeli, Turkey, August 17, 1999, M 7.4					Average 5 EQF = 7.7			17.0
287.00	226.00	236.20	32.70	8.2	Yarimca	11.0		
224.90	123.00	146.40	33.00	7.1	Izmit	13.0		
264.80	141.50	198.50	5.50	3.7	Gebze	36.0		
207.00	131.50	81.50	3.80	2.9	Arcelik	41.0		
399.50		243.00	11.00	5.5	Sakarya	43.0	CahY is N/A	
207.00	131.00	82.00	5.00	3.3	Darica	44.5		
173.70	129.40	56.50	3.50	2.7	Cekmece	99.7		
373.70	314.80	479.90	9.50	5.8	Duzce	109.0		
Athens, Greece, September 7, 1999 M 5.9					Average 5 EQF = 4.8			10.0
243.30	221.70	91.20	4.00	3.3	Sepolia	15.0	t=4 sec assumed	
215.82	182.50	154.00	4.00	3.2	Keratsini	15.0	t=4 sec assumed	

297.20	259.00	154.00	4.00	3.6	Piraeus Str.	16.0	t=4 sec assumed	
523.85	218.75	218.75	4.00	4.2	Monastiraki	17.0	t=4 sec assumed	
Jiji, Taiwan, September 20, 1999 M 7.6					Average EQF = 12.3			8.0
440.00	302.70	171.00	28.63	8.9	Taichung TCU 078	7.1		
580.30	278.00	384.20	35.40	10.6	Taichung TCU 079	9.9		
990.10	423.30	265.00	31.00	12.2	Taichung TCU 084	10.5		
865.00	611.30	335.30	35.00	12.7	Taichung TCU 129	11.9		
983.90	389.00	150.00	35.00	12.7	Taichung TCU 129	11.9		
639.60	518.40	416.00	29.70	10.8	Taichung TCU 071	13.9		
775.10	438.00	125.00	36.00	11.9	Taichung TCU 065	24.6		
842.50	793.20	716.70	32.00	12.9	Chiayi CHY 080	31.7		
750.00	624.00	336.00	15.80	9.0	Chiayi CHY 028	32.1		
508.00	362.00	519.00	15.50	7.6	Taichung TCU 068	46.3		
128.00	106.00	43.00	6.00	3.0	Taipei	151.0		
Hector Mine, October 16, 1999 M 7.1					Average 5 EQF = 3.8			6.0
178.40	146.80	130.00	9.30	4.1	Amboy	48.4		
186.00	143.00	118.00	9.00	4.1	Joshua Tree	51.5		
169.70	153.10	43.80	5.00	3.2	Big Bear Lake	67.5		
128.00	89.20	66.30	3.00	2.2	Baker, Fire Station	77.6		
123.60	104.00	54.50	3.50	2.4	Fort Irwin	83.8		
133.30	123.60	33.40	9.00	3.6	Palm Spring, Hospital,	87.9		
Yountville (Napa), September 3, 2000 M 5.2					Average 5 EQF = 3.5			9.4
498.10	401.30	502.80	4.00	4.5	Napa, Fire Station	10.0		
180.70	120.80	55.60	4.00	2.8	Sonoma, Fire Station	10.0		
330.20	178.50	94.10	2.50	2.9	Napa College	16.9		
15.70	10.30	6.40	2.50	0.9	Petaluma Fire Station 2	25.0		
28.50	15.80	7.70	2.50	1.1	Vallejo, Fire Station	33.0		
16.30	14.80	6.80	2.50	0.9	Novato, Fire Station 4	36.0		
Western Tottori, Japan, October 6, 2000 M 7.1					Average 5 EQF = 9.8			12.0
927.20	753.00	775.80	50.00	15.6	Hino, Station TTRH02	8.0		
927.20	753.00	775.80	50.00	15.6	Hino, Station TTRH02	8.0		
720.40	607.10	459.00	32.70	11.9	Hakuta, Station SMNH01	12.5		
283.80	181.80	251.60	20.00	6.6	Yubara, Station OKYH09	29.0	First event	

564.00	314.90	367.20	12.00	6.9	Nita, Station SMNHO2	29.7		
443.00	260.30	167.00	6.30	4.8	Hokubou, Station OKYH14	45.5		
341.10	224.80	238.40	26.50	7.9	Mitsugi, Station HRSHO3	90.2		
El Salvador, January 13, 2001 M 7.6					Average 5 EQF = 8.9			6.0
288.00	253.00	270.00	20.50	7.0	Hosp. St. Teresa, La Paz	51.2		
551.60	486.80	451.10	24.00	9.6	Unidad de Salud, La Paz	61.8		
551.60	486.80	451.10	24.00	9.6	Unidad de Salud, La Paz	61.8		
1155.00	574.00	342.00	23.00	11.6	Unidad de Salud, La Libertad	75.0		
486.50	476.90	238.60	17.30	8.0	Hosp. San Rafael, Santa Tecla	86.0		
608.00	444.00	215.00	16.00	8.1	Unidad de Salud, Sansonate	108.0		
Gujarat, India, January 26, 2001 M 8.0					**(Bhuj/Kachchh, India)**			
103.8	78.2	68.6	0.5	1.0	Ahmedabad, India	238.0	Dt < 1 sec	
Nisqually, WA, February 28, 2001 M 6.8					Average 5 EQF = 5.0			5.2
250.1	217.7	86.0	6.7	4.1	Olympia	18.3		
209.0	199.8	151.7	12.5	5.1	Frederickson	33.0		
188.1	124.2	103.8	6.0	3.4	Seattle Airport	45.3		
222.0	177.0	86.0	4.5	3.3	West Seattle	52.3		
268.0	167.0	76.0	5.5	3.7	King County, Boeing Field	53.0		
212.3	183.1	86.4	15.5	5.4	Harbor Island, Seattle	54.5		
218.5	209.7	130.8	12.5	5.1	Seattle, SDS	55.3		
674.1	167.0	564.1	9.0	6.4	Seattle, SDW	55.3		
Geiyo, Japan, March 24, 2001, M 6.4					Average 5 EQF = 8.4		Previously Hiroshima	50.0
336.1	285.0	265.4	20.4	7.3	Kure	21.2		
506.4	504.4	370.9	14.5	7.7	Tobe	44.6		
328.5	313.9	168.5	9.8	5.5	Tanbara	40.4		
493.0	422.0	604.0	24.0	9.3	Mihara	42.4		
396.8	285.4	499.9	17.2	7.3	Saijou	52.2		
554.5	368.0	488.3	30.5	10.2	Mitsugi	61.3		

Arequipa, Peru, June 26, 2001 Mw 8.4								33.0
294.30	166.77	137.34	32.60	7.9	Moquegua	100.0		
304.11	264.87	176.58	30.00	8.2	Arica Casa	148.0		
255.06	245.25	147.15	30.00	7.7	Poconcile	168.0		
323.73	264.87	78.48	30.00	8.2	Arica Costanera	148.0		
Gilroy, CA, May 14, 2002 M 5.2								7.6
75.30	35.20	31.70	0.50	0.8	Morgan Hill, El Toro Fire St	20.1	str. duration=0 sec.	
93.88		35.00	0.50	0.9	San Isydro		str. duration=0 sec.	
Nenana Mountain, AK, October 23, 2002 M 6.7								
29.70	29.00	20.20	0.50	0.6	Fairbanks, AK	149.0	str. duration=0 sec.	
Japan, November 3, 2002 M6.2								
214.10	145.20	101.30	1.00	1.7	Touwa Japan, stn MYGH11	78.3		
Denali, AK, November 3, 2002 M7.9								5.0
84.50	69.30	47.20	0.50	0.9	Fairbanks, AK	152.0	str. duration=0 sec.	
East Coast of Honshu, Japan, May 26, 2003 M7.0					Average 5EQF=11.8			60.0
809.10	650.80	459.80	28.60	11.7	Karakuwa, MYGH03	19.0		
888.10	556.10	636.50	32.90	12.5	Rikuzentakata, IWTH27	34.1		
570.60	501.70	338.00	30.00	10.5	Fujisawa, IWTH05	39.2		
664.70	502.60	376.00	21.50	9.6	Touwa, MYGH04	40.9		
729.60	679.20	1279.90	22.90	11.2	Sumita, IWTH04	54.7		
521.30	454.70	511.30	22.90	9.2	Ichinoseki-E, IWTH26	71.3		
586.20	549.90	711.10	22.90	9.9	Yamada, IWTH21	75.5		
615.00	579.00	168.00	20.00	9.3	Onoda, MYGH05	91.6		
795.60	409.00	379.00	44.00	13.1	Tamayama, IWTH02	119.0		
CahX	**CahY**	**CaV**	**t**	**EQF Scale**	**Station**	**Distance**	**Note**	Depth
cm/sec/sec	*cm/sec/sec*	*cm/sec/sec*	*sec*			*km*		*km*
Hokkaido, Japan, September 25, 2003 M8.0					Average 5EQF=12.37			27.0

972.60	618.00	316.00	65.00	16.8	Hiroo, HKD120	97.7		
366.10	290.00	201.60	32.50	8.9	Taiki, HKD098	116.0		
559.50	345.30	168.50	51.50	12.2	Seika, HKD097	120.0		
470.00	416.10	395.40	38.00	10.8	Taiki, TKCH08	123.0		
403.90	366.70	116.70	41.00	10.4	Toyokoro, TKCH07	135.0		
404.60	373.10	118.80	34.00	9.6	Akan-S, KSRH02	157.0		
500.20	339.60	442.20	31.00	9.9	Tsurui-S, KSRH07	160.0		
406.10	357.20	199.80	27.00	8.8	Honbetsu, TKCH05	165.0		
580.40	534.60	216.30	28.50	10.4	Tsuruui-S, KSRH10	184.0		
299.50	806.20	588.00	32.80	11.6	Shibecha-N, KSRH03	190.0		
437.80	428.30	147.00	17.00	7.6	Bekkai-E, NMRH04	203.0		
514.10	442.00	391.90	24.00	9.2	Shibecha-S, NMRH02	228.0		
Hokkaido, Japan, September 25, 2003 M7.0 (Aftershock)						Average 5EQF=6.2		
425.90	271.40	112.10	32.50	9.2	Hiroo, HKD100	76.2		
591.80	397.00	80.60	13.60	7.4	Urakawa, HKD109	99.5		
169.30	130.80	43.00	19.00	5.2	Taiki, TKCH08	102.0		
175.00	120.40	60.50	6.50	3.4	Monbetsu, HDKH03	155.0		
258.40	164.00	85.90	17.00	5.8	Minamidohri, AOM007	207.0		
211.10	217.20	53.90	14.00	5.3	Toi, HKD159	232.0		
CahX	**CahY**	**CaV**	**t**	**EQF Scale**	**Station**	**Distance**	**Note**	**Depth**
cm/sec/sec	*cm/sec/sec*	*cm/sec/sec*	*sec*			*km*		*km*
San Simeon, CA, December, 22, 2003 M6.5								4.7
459.00	122.10	86.60	8.60	5.2	Templeton, CA	38.4		
175.00	122.10	86.60	9.00	3.9	Cambria, Hwy 1, Bridge	14.8		
201.50	159.60	48.30	8.50	4.1	Parkfield, Hwy 46, Cholame Creek Br.	73.8		
Bam, Iran, December 26, 2003 M6.6				Average 5EQF=5.76				10.0
623.44	567.00	979.95	16.50	9.1	Bam, Iran	0.0		
166.69	109.47	83.81	12.00	4.3	Abaraq, Iran	49.0	assumed duration	
115.94	66.79	69.17	12.00	3.7	Mohamad Abad	49.0	assumed duration	
40.17	27.56	30.32	10.00	2.3	Jiroft	76.0	assumed duration	
33.59	31.82	14.07	8.00	2.0	Andoohjerd	139.0	assumed duration	

Parkfield, CA, September 28, 2004 M6.0					Average 5EQF=6.4			7.9
802.96	580.69	118.00	7.00	6.5	Parkfiels, Fault Zone 1	8.8		
1108.53	559.17	706.32	6.50	7.0	Parkfield, Fault Zone 11	9.2	Preliminary	
535.81	486.80	246.49	6.30	5.5	Parkfiels, Fault Zone 8	12.0		
592.86	362.23	182.19	4.00	4.5	Chalome 2W	12.0		
244.68	227.97	78.00	2.10	2.6	Cholame 5W	13.8		
1285.11	578.79	588.60	6.80	7.4	Parkfiels, Fault Zone 14	14.0	Preliminary	
609.00	487.00	301.00	6.10	5.6	Joaquin Canyon	16.8		
Chuetsu, Japan, October 23, 2004 M6.6					Average 5EQF=9.99			15.8
1307.91	852.80	820.17	22.80	12.6	Ojiya, NIG019	0.7		
587.85	454.43	325.16	10.00	6.7	Kawanishi, NIGH11	15.2		
871.04	706.45	435.51	10.00	7.9	Nagaoka-Shisho, NIG028	15.8		
521.43	407.40	312.14	10.00	6.4	Koide, NIG020	16.5		
1715.50	849.55	564.40	9.50	9.6	Tonkamachi, NIG021	19.9		
Niigata-ken Chuetsu, Japan, October 23, 2004 Aftershock M6.3								
526.62	524.43	329.31	24.50	9.6	Koide, NIG020	9.7		
815.50	811.34	320.35	8.00	7.3	Tohkamachi, NIG021	23.5		
Niigata-ken Chuetsu, Japan, October 23, 2004 Aftershock M6.0								
523.10	387.58	530.32	5.80	5.2	Koide, NIG020	8.4		
Hokkaido, Japan, November 28, 2004 M7.0								
550.20	493.44	319.30	8.30	6.2	Nosappu, HKD074	82.8		
Honshu (East Cost), Japan, August 16, 2005 M7.2								
449.51	313.00	121.00	19.50	7.7	Oshika, MYGo11	81.2		
501.28	300.86	161.00	29.00	9.3	Utatsu, MYG002	104.0		
513.99	381.57	111.02	22.00	8.6	Tsukidate, MYG004	138.0		
Island of Hawaii, October 15, 2006 M6.7					Average 5EQF=8.9			29.0
268.00	259.00	233.00	10.70	5.3	Kailua-Kona, Fire Station	46.9		
1030.00	579.00	723.00	22.50	11.3	Waimea, Fire Station	50.9		
508.00	362.00	283.00	11.10	6.5	KeaLakekua, Hospital	55.4		
640.00	639.00	350.00	10.90	7.5	Honokaa, Police Station	66.7		

Island of Hawaii, October 15, 2006 M6.0									29.0
166.00	128.00	129.00	3.50	2.7	Waimea, Fire Station	40.3			
West Coast Honshu, Japan, March 25, 2007 M6.7					Average 5EQF= 7.6				5.0
849.15	717.47	462.18	14.30	9.1	Togi	16.3			
781.67	473.46	555.75	14.35	8.5	Anamizu	27.7			
396.04	518.99	141.46	11.00	6.6	Wajima	30.1			
359.34	274.27	203.95	7.00	4.8	Yanagida	40.4			
588.81	622.19	146.88	18.00	8.9	Noto	48.6			
Chile, February 27, 2010 M8.8					Average 5EQF= 13.5				35.0
529.74	343.35	618.03	45.00	11.9	Constitution	69.7			
393.38	360.03	280.57	50.00	11.2	Conception	82.4			
639.61	598.41	568.98	53.50	14.2	Conception San Pedro	109.1			
461.07	215.82	412.02	68.00	12.7	Talca	113.1			
461.07	196.20	402.21	56.00	11.7	Hospital Curico	164.0			
686.70	922.14	284.49	61.00	16.4	Angol	209.3			
323.73	657.27	549.36	38.00	11.6	Lyllelton Port Company	274.3			
480.69	549.36	235.44	45.00	12.1	Santiago Maipu	320.7			
462.44	452.34	235.44	53.00	12.3	Municipal San Jose de Maipu	332.0			
Calexico, Mexico, April 4, 2010, M7.2					Average 5EQF= 6.9				32.3
568.98	431.64	235.44	14.00	7.5	El Centro Array 11, McCabe Sch	61.8			
375.72	267.81	361.99	12.00	6.1	El Centro - Imperial & Ross	63.5			
374.74	196.20	356.10	12.00	7.5	El Centro - Array 10, Reg. Hospital	63.7			
500.31	539.55	304.11	14.00	7.6	El Centro Differential Array	77.3			
320.79	253.10	396.32	10.70	5.6	El Centro-Array 12 Meloland Cattle	78.3			
Canterbury, New Zealand, September 3, 2010 M7.0					Average 5EQF= 7.1				5.0
737.70	663.50	932.00	14.00	8.9	Greendale	8.0			
479.80	449.70	307.00	10.00	6.4	Darfield High School	9.0			
452.50	423.80	622.20	11.00	6.7	Hororata School	18.0			
428.90	402.50	752.60	11.00	6.7	Lincoln Crop & Food Research	25.0			

544.80	606.60	275.00	10.00	6.9	Heathcote Valley Primary School	43.0		
Christchurch, New Zealand, February 21, 2011 M6.3					Average 5EQF= 7.2			5.0
1426.70	1163.60	1438.10	8.00	9.0	Healthcote Valley Primary School	2.1		
767.30	862.20	404.70	5.00	6.0	Lyllelton Port Company	1.2		
651.80	577.90	1598.00	8.30	7.4	Page Roads Pumping Station	8.3		
473.90	359.70	678.30	8.50	6.0	Christchurch Cathedral College	8.5		
699.90	358.60	518.40	6.00	5.7	Christchurch Resthaven	10.4		
519.10	422.30	265.30	13.50	7.2	Christchurch Botanic Gardens	10.6		
Tohoku, Japan, March 11, 2011 M9.0					Average 5EQF= 18.5			32.0
921.00	688.20	253.85	52.00	15.4	Oshika - MYG011	75.7		
758.43	1969.18	500.76	31.00	15.9	Shiogama - MYG012	118.1		
2699.89	1268.49	1879.93	55.00	23.4	Tsukidate - MYG004	125.9		
1517.16	982.27	290.15	17.00	11.8	Sendai - MYG013	126.1		
1597.64	1185.91	1165.74	48.00	18.8	Hitachi	245.2		
1354.64	1070.26	811.18	58.00	19.0	Hokota	292.3		
Iquique, Chile, April 1, 2014 M8.2					Average 5EQF (only two stations recording)			25.0
231.60	355.60	161.00	6.00	4.4	Chusmiza	170.2		
13.80	15.60	8.20	6.00	1.3	Limon Verde	383.9		
South Napa, CA, August 24, 2014, M6.0					Average 5EQF= 5.1			11.3
304.11	598.41	235.44	6.00	5.2	Main Street Napa	9.1		
461.07	215.82	88.29	6.00	4.7	Vallejo, Broadway w/ Sereno	11.7		
421.83	402.21	313.92	6.00	5.0	Napa Fire Station	12.3		
174.62	415.94	169.71	6.00	4.5	Carquinez Br. Array 2	19.5		
510.12	961.38	313.92	6.00	6.3	Carquinez Br. Array 1	19.6		
The following row is for calibrating, acceleration equal to 1.0 g, strong duration equal to 20 sec.								
981.00	0.00	0.00	20.00	9.8	*PGA=1g with t=20 sec.*			
Last updated on Jan 18, 2015 - over 500 earthquakes reviewed with over 6600 station recordings								
	48 earthquakes with more than 200 station recording are included on the table above.							

Table 3. Ground accelerations for earthquakes listed per EqSF values.

CahX	CahY	CaV	Scah (2-D)	SCah	SCa (3-D)	SCa (3-D)	Event	Location	EqSF	Rank
cm/sec/sec	*cm/sec/sec*	*cm/sec/sec*	*cm/sec/sec*	*g*	*cm/sec/sec*	*g*				
2699.90	1268.50	1879.90	2983.04	3.04	3525.99	3.59	Japan, March 2011	Tsukidate, MYG004	23.4	1
1597.60	1185.90	1165.70	1989.64	2.03	2305.98	2.35	Japan, March 2011	Hitachi, IBR003	18.8	2
972.60	618.00	316.00	1152.33	1.17	1194.88	1.22	Japan, September 2003	Hiroo HKD 120	16.8	3
686.70	922.14	284.49	1149.74	1.17	1184.41	1.21	Chile, Feb. 2010	Angol	16.4	4
927.20	753.00	775.80	1194.45	1.22	1424.28	1.45	Western Tottori, Jap., 2000	Hino, Station TTRH02	15.6	5
639.61	598.41	568.98	875.90	0.89	1044.48	1.06	Chile, Feb. 2010	Concepcion San Pedro	14.2	6
656.00	437.00	849.00	788.23	0.80	1158.49	1.18	Valparaiso, Chile, 1985	Llolleo	14.0	7
758.40	1969.20	500.80	2110.19	2.15	2168.81	2.21	Japan, March 2011	Shiogama, MYG012	13.6	8
1744.50	912.00	1027.50	1968.51	2.01	2220.54	2.26	Northridge, CA, 1994	Tarzana	13.5	9
842.50	793.20	716.70	1157.14	1.18	1361.11	1.39	Taiwan	Chiayi CHY 080	12.9	10
1307.91	852.80	820.17	1561.38	1.59	1763.68	1.80	Japan, 2004	Ojiya, NIG019	12.6	11
1468.30	1019.40	738.90	1787.48	1.82	1934.18	1.97	Cape Mendocino/Petrolia, CA	Cape Mendocino/Petrolia	12.3	12
720.40	607.10	459.00	942.10	0.96	1047.96	1.07	Western Tottori, Japan	Hakuta, Station SMNH01	11.9	13
1155.00	574.00	342.00	1289.77	1.31	1334.34	1.36	El Salvador	Unidad de Salud, La Libertad	11.6	14
1030.00	579.00	723.00	1181.58	1.20	1385.23	1.41	Hawaii, October 2006	Waimea Fire Sration	11.3	15
798.00	716.80	383.00	1072.66	1.09	1138.99	1.16	Landers, CA	Lucerne Valley	11.0	16
580.30	278.00	384.20	643.45	0.66	749.43	0.76	Taiwan	Taichung TCU 079	10.6	17
554.50	368.00	488.30	665.50	0.68	825.43	0.84	Kure, Japan	Mitsugi	10.2	18
551.60	486.80	451.10	735.69	0.75	862.98	0.88	El Salvador	Unidad de Salud, La Paz	9.6	19
1148.00	1055.00	434.00	1559.14	1.59	1618.42	1.65	San Fernando, CA	Pacoima Dam	9.5	20
1427.00	1163.60	1438.10	1841.28	1.88	2336.33	2.38	Christchurch, New Zealand	Heathcole Valley	9.0	21
737.70	663.50	932.00	992.19	1.01	1361.27	1.39	Darfield, New Zealand	Greendale	8.9	22
739.50	593.00	584.00	947.90	0.97	1113.36	1.13	Northridge, CA	Sylmar, Converter	8.8	23
922.70	535.30	325.00	1066.73	1.09	1115.14	1.14	Northridge, CA	Sepulveda, VA Hospital	8.2	24
444.30	147.00	1703.60	467.99	0.48	1766.71	1.80	Imperial Valley, 1979	El Centro, Station 6	8.0	25
256.00	268.00	156.00	370.62	0.38	402.11	0.41	Landers, CA	Joshua Tree	8.0	26
449.00	390.80	500.10	595.25	0.61	777.45	0.79	Loma Prieta, CA, 1989	Capitola	7.7	27
500.31	539.55	304.11	735.82	0.75	796.18	0.81	Calexico, Mexico, 2010	El Centro Differential	7.6	28
341.70	185.00	144.00	388.57	0.40	414.39	0.42	El Centro, CA, 1940	El Centro, Station 9	7.4	29
674.10	167.00	564.10	694.48	0.71	894.71	0.91	Nisqually, WA	Seattle, SDW	6.4	30
510.12	961.38	313.92	1088.34	1.11	1132.70	1.15	South Napa, CA, 2014	Carquinez Br.,Array 1	6.0	31

NOTE: The largest three values for accelerations in each direction, as for the vector accelerations are highlighted in yellow.

current information available after an earthquake. The *EqSF* takes into account all three components of the ground accelerations plus the strong motion duration. The *EqSF* values can be calculated for all local ground stations with recorded seismograms. The force at a particular location can be compared with the force at any other locations during the same seismic event or previous events. The *EqSF* values could be provided for different locations after an earthquake, much like temperatures and rainfall recordings. Depending on the relative locations and specific soil characteristics, *EqSF* values will differ even between parts of a large city. These results will reflect the different levels of ground shaking and therefore will provide a more realistic representation of the event.

The *EqSF* method is devised to measure and compare the force of ground motion but is not intended to measure earthquake damage.

However, the *EqSF* method could be used to calculate and rank all ground motions recorded at particular locations from previous earthquakes, and used to create maps as visual logs of *EqSF* values based on previously recorded seismograms. The accumulated data may be used in the future by local building departments, insurance and real estate companies for better assessing the potential seismic danger and may help creating micro-seismic zones. Comparing the performance of different structural lateral resisting systems during earthquakes resulting in identical or similar *EqSF* values may help adjust the response modification factors (R) used in the seismic design for buildings and structures. Further analysis and research using the *EqSF* scale may provide improved understanding of earthquakes and the resulting propagation of ground motion and damaging forces.▪

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