Characteristics of Strong Motion Durations in the SMART1 Array Area

KUO-LIANG WEN[1] AND YEONG TEIN YEH[1]

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ABSTRACT

The effects of soil layers on strong motion duration were analyzed by using the strong motion records from 17 earthquakes recorded by the SMART1 array. The strong motion duration of acceleration (ADT), velocity (VDT) and displacement (DDT) at the alluvial sites were 1.8, 1.6 and 1.4 times respectively, longer than for rock sites. These ratios have some correlation with magnitude, distance and the subsurface structure of the Lanyang plain. While strong motion duration has a positive correlation with magnitude and distance, the correlation between duration and distance may in fact be only part of the magnitude effect. Using regression analysis on the records of 30 earthquakes recorded by the SMART1 array, we determined the relationship between strong motion duration of acceleration, velocity and displacement and local magnitude. According to Trifunac and Brady (1975), the variability of the duration is caused by inhomogeneous media through which seismic waves propagate, but the results of our study show that duration variability is primarily caused by the complicated rupture process of the earthquake source.

1. INTRODUCTION

The concept of strong motion duration at a site is crucial for understanding the source dimension and estimating the overall energy which should be incorporated in the input ground motions at any structure. It may significantly affect the extent of the damage caused by an earthquake and figures importantly in many earthquake engineering problems. The response of lightly damped linear systems and of yielding or strength degrading nonlinear systems is known to primarily depend on the duration of the strong movement. Duration is also a key parameter affecting the occurence likelihood of the low cycle fatigue phenomena on structures or liquefaction of soil during earthquakes.

No single quantitative measure of strong motion duration is in common usage in earthquake engineering. Several important contributions were studies

[1] *Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, R. O. C.*

of the dependence of duration on magnitude (Housner, 1965) and on distance and magnitude (Esteva and Rosenbluth, 1964). However these are not based on formal, quantitative definitions of duration. Following these, Bolt (1973) and Page *et al.* (1975) define duration as the time interval between the first and last peaks equal to or greater than a given level, usually 0.05 g, on the accelerogram. A second definition is based on the concept of cumulative energy obtained by integrating square accelerations: duration is the time interval required to accumulate a prescribed fraction of the total energy, for example 95 percent (Husid *et al.*, 1969) or 90 percent (Trifunac and Brady, 1975). Bolt (1973) has suggested that both these definitions could also be applied to sinusoidal components of earthquake motion occurring within different narrow frequency bands. Vanmarcke and Lai (1977) have also defined duration as an equation with total energy, peak acceleration, root-mean-square acceleration, and the dominant vibration period. In this study we use the simple definition from Trifunac and Brady (1975) to calculate duration time. Then we can study the difference between the duration recorded at an alluvial site and a rock site, and the relationships between duration and magnitude or distance. The same comparison could also be made in different frequency bands in order to realize characteristics of strong motion duration in different frequency bands.

2. STRONG MOTION DATA

The SMART1 array is located in the northeast corner of Taiwan surrounding the city of Lotung (Figure 1; Bolt *et al.*, 1982). It consists of 39 stations. The whole array is placed on a plain of Recent alluvium, except for station E02 which is on a slate outcrop at the basin margin. More than fifty events have been recorded by the SMART1 array. In this study we selected 30 events which were recorded by at least 25 of the stations in the SMART1 array. Table 1 lists these events and associated source parameters. The location of the epicenters are shown in Figure 2. There are 963 three-component acceleration records chosen from these 30 events. Among these, 17 earthquakes were recorded by the E02 rock site, therefore, we can compare the difference of duration between rock and soil sites.

3. CORRELATION OF DURATION WITH SITE CONDITIONS

Seventeen earthquakes listed in Table 1 (recorded at the E02 rock site) were used when comparing the acceleration, velocity and displacement duration at soil and rock sites. Only recordings of the three rings and the C00 site are used to calculate the mean value of the alluvium site. Table 2 lists an example of the results for the unfiltered acceleration duration of these 17 events. For the ratio of mean value, strong motion duration of acceleration (ADT), velocity

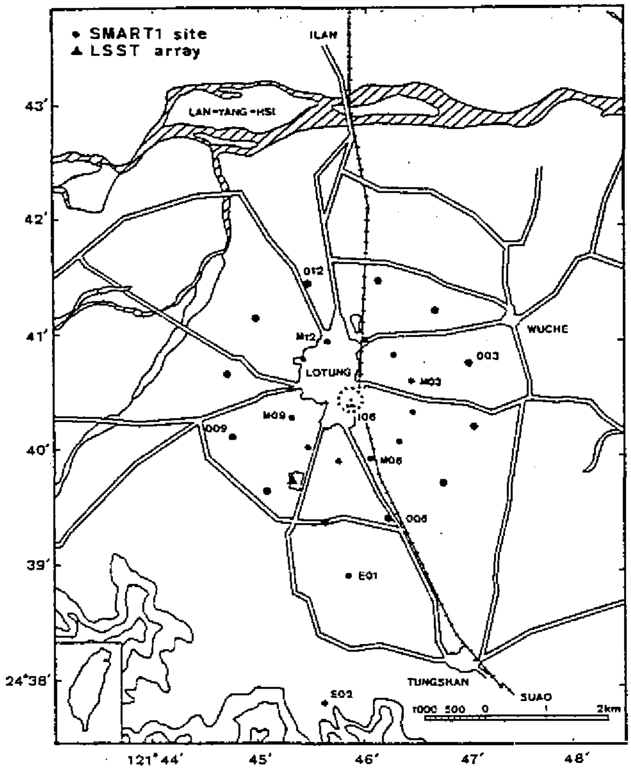

Fig. 1. Layout of the SMART1 array sites.

(VDT) and displacement (DDT) at the alluvium site are 1.8, 1.6, and 1.4 times, respectively, longer than for that at the rock site. Trifunac and Brady (1975) analyzed data, mostly from California's earthquakes, and found that for the same intensity the average duration of strong motion acceleration at a soft site is about twice the duration than at a hard site. Vanmarcke and Lai (1977) also got the same result based on 140 horizontal components from 70 western United States strong motion records.

Figures 3~5 show the relationships of duration ratio of acceleration, velocity and displacement, respective to magnitude, hypocentral distance and epicentral azimuth. The number on the figures is the event number in Table 1. For the same magnitude, the ratio is small for an event with a larger hypocentral distance. For the same hypocentral distance, the duration ratio is larger for the event with greater magnitude. This may be caused by the fact that the seismic wave has a longer duration before it is propagated into the alluvial basin for an event with larger magnitude or shorter hypocentral distance. It shows clearly in Figure 3a that the ADT ratio increased as the magnitude increased and this trend split into two increasing bands. Compared with Figure 2 and Figure 3a, we can see that those events on the higher band are located in the southern direction of the SMART1 array at the southern edge on the Lanyang plain. This

Table 1. Parameters of the 30 selected earthquakes.

EQ. CODE	ORIGIN TIME (*GMT*)	EPICENTER LONGITUDE	LATITUDE	DEPTH *km*	M_L	DELTA *km*	PGA *gal*	NOTE
5	1981.01.29 04:51:36.1	121-53.78E	24-25.75N	11.1	6.3	30.2	244	
14	1981.08.30 18:54:53.6	121-45.17E	24-27.92N	0.2	5.0	23.1	44	
15	1981.10.05 13:24:30.5	121-44.50E	24-39.30N	3.6	3.6	3.1	72	
19	1982.04.01 04:50:02.8	121-51.12E	24-29.23N	8.0	4.9	22.5	39	
20	1982.12.17 02:43:01.4	122-52.25E	24-23.12N	27.3	6.5	116.6	86	
22	1983.05.10 00:15:03.8	121-30.44E	24-27.49N	1.2	6.4	35.4	71	
24	1983.06.24 09:06:43.0	122-36.80E	23-58.89N	25.0	6.9	115.3	65	*
25	1983.09.21 19:20:40.7	122-18.99E	23-56.29N	18.0	6.8	98.9	39	*
28	1984.04.18 01:34:18.3	122-14.02E	24-47.74N	5.9	5.9	49.3	59	
29	1984.04.23 22:35:04.0	122-05.34E	24-47.31N	8.7	6.0	35.4	83	*
30	1984.12.29 01:07:02.7	122-01.27E	24-47.75N	60.7	6.3	29.3	79	
31	1985.03.09 19:51:00.5	122-13.95E	24-45.59N	4.1	5.9	48.3	101	
32	1985.06.12 13:23:13.3	122-13.93E	24-35.41N	5.3	6.0	48.2	46	*
33	1985.06.12 17:22:50.8	122-11.68E	24-34.38N	3.3	6.5	44.9	149	*
34	1985.08.05 13:00:38.6	121-52.97E	24-22.95N	1.3	5.8	34.4	39	*
35	1985.08.12 00:21:33.3	121-47.10E	24-42.71N	8.0	5.7	4.7	134	*
36	1985.09.20 15:01:24.0	122-11.87E	24-31.97N	6.2	6.3	46.6	113	*
37	1985.10.26 03:30:39.1	121-49.70E	24-24.67N	1.7	5.3	29.8	73	*
39	1986.01.16 13:04:32.0	121-57.67E	24-45.77N	10.2	6.5	22.2	375	*
40	1986.05.20 05:25:49.6	121-35.49E	24-04.90N	15.8	6.5	67.9	251	*
41	1986.05.20 05:37:31.7	121-37.04E	24-02.90N	21.8	6.2	70.9	100	*
42	1986.07.17 00:03:33.5	121-48.89E	24-39.59N	2.0	5.0	5.3	151	*
43	1986.07.30 11:31:47.5	121-47.65E	24-37.73N	1.6	6.2	5.8	283	*
44	1986.07.30 11:38:31.7	121-47.73E	24-38.38N	2.3	4.9	4.9	100	*
45	1986.11.14 21:20:04.5	121-49.99E	23-59.51N	13.9	6.8	79.3	238	*
50	1987.01.06 05:07:49.0	121-48.46E	23-56.71N	27.8	6.2	80.8	47	
51	1987.02.04 12:15:24.3	121-51.03E	24-30.67N	70.1	5.8	20.0	51	
52	1987.06.24 22:38:38.9	122-04.12E	24-17.12N	30.6	5.7	52.9	40	
53	1987.06.27 07:38:55.7	121-37.86E	24-19.41N	0.5	5.3	41.1	63	
54	1987.11.10 04:33:09.2	121-43.42E	24-25.11N	34.5	5.2	28.6	113	*

DELTA : Epicentral distance from COO.
* : E02 rock site has record.

shows that the effect of subsurface structure and site geology are indicated by strong motion duration. This phenomenon was not shown by the peak ground acceleration (Wen, 1988). From Figure 3 to Figure 5 we can also see that the duration ratio seems to have a positive relationship with the epicentral azimuth (clockwise count from the north). Based on the subsurface geology (Wen and Yeh, 1984) of the Lanyang basin, we know that the path of the wave propagated inside the alluvial layer is longer for an event with a smaller azimuth. So, in this case the amplification of the peak amplitude will be large and the duration will be short for the earthquake with a smaller azimuth.

The PGA for events 39 and 43 were larger than for those of events 40 and 45 (see Table 1). However, only events 40 and 45 caused some damage in Taiwan (Yeh *et al.*, 1986). One reason was that the duration for events 40 (ADT = 13 *sec*) and 45 (ADT = 23 *sec*) were longer than for events 39

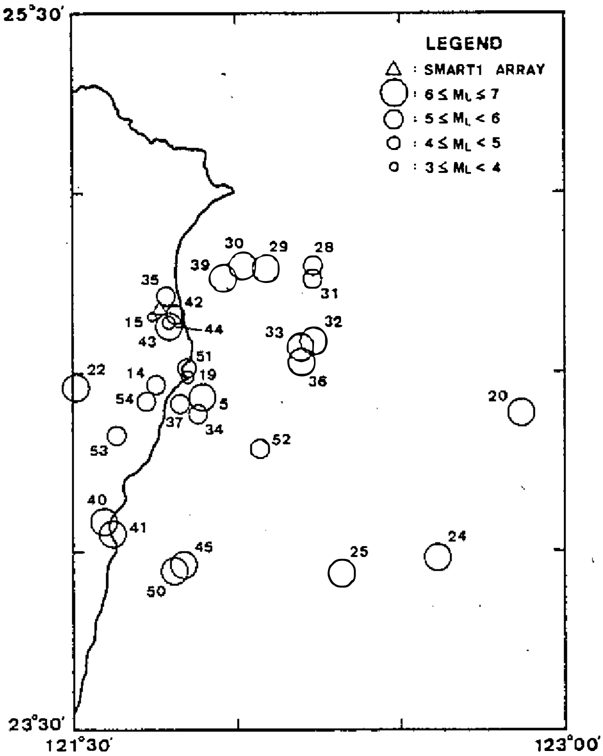

Fig. 2. Location of the SMART1 array and epicenters of the 30 selected earthquakes.

Table 2. Acceleration duration of the earthquakes recorded at the E02 rock site.

EQ. CODE	DURATION TIME (*sec*) ALLUVIUM SITE MEAN	σ	ROCK SITE	RATIO
24	18.122	2.702	12.545	1.44±0.22
25	12.777	2.271	7.765	1.65±0.29
29	7.402	1.528	4.485	1.65±0.34
32	7.342	1.351	6.430	1.14±0.21
33	10.528	1.791	8.165	1.29±0.22
34	8.952	2.494	7.125	1.26±0.35
35	5.016	1.077	3.510	1.43±0.31
36	9.430	2.054	6.210	1.52±0.33
37	5.308	1.028	4.530	1.17±0.23
39	5.376	1.750	2.740	1.96±0.64
40	12.908	3.601	4.550	2.84±0.79
41	8.049	1.601	3.245	2.48±0.49
42	3.676	1.167	1.750	2.10±0.67
43	7.890	2.446	2.685	2.94±0.91
44	3.588	1.185	4.275	0.84±0.28
45	22.562	3.416	12.045	1.87±0.28
54	7.044	2.710	3.045	2.31±0.89

Mean ratio : 1.76 ± 0.49

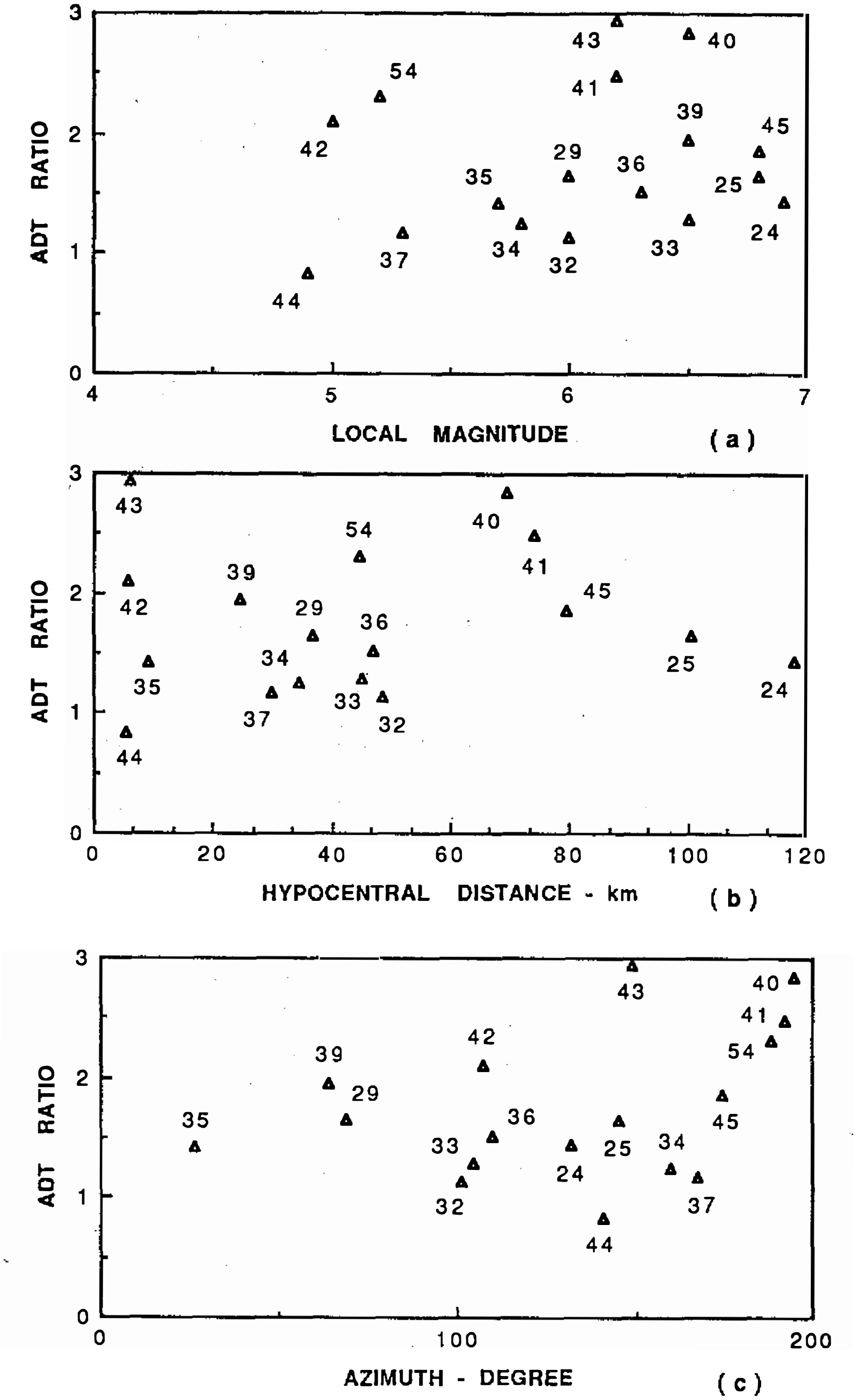

Fig. 3. Correlations of acceleration duration ratio to local magnitude, hypocentral distance, and epicenter azimuth.

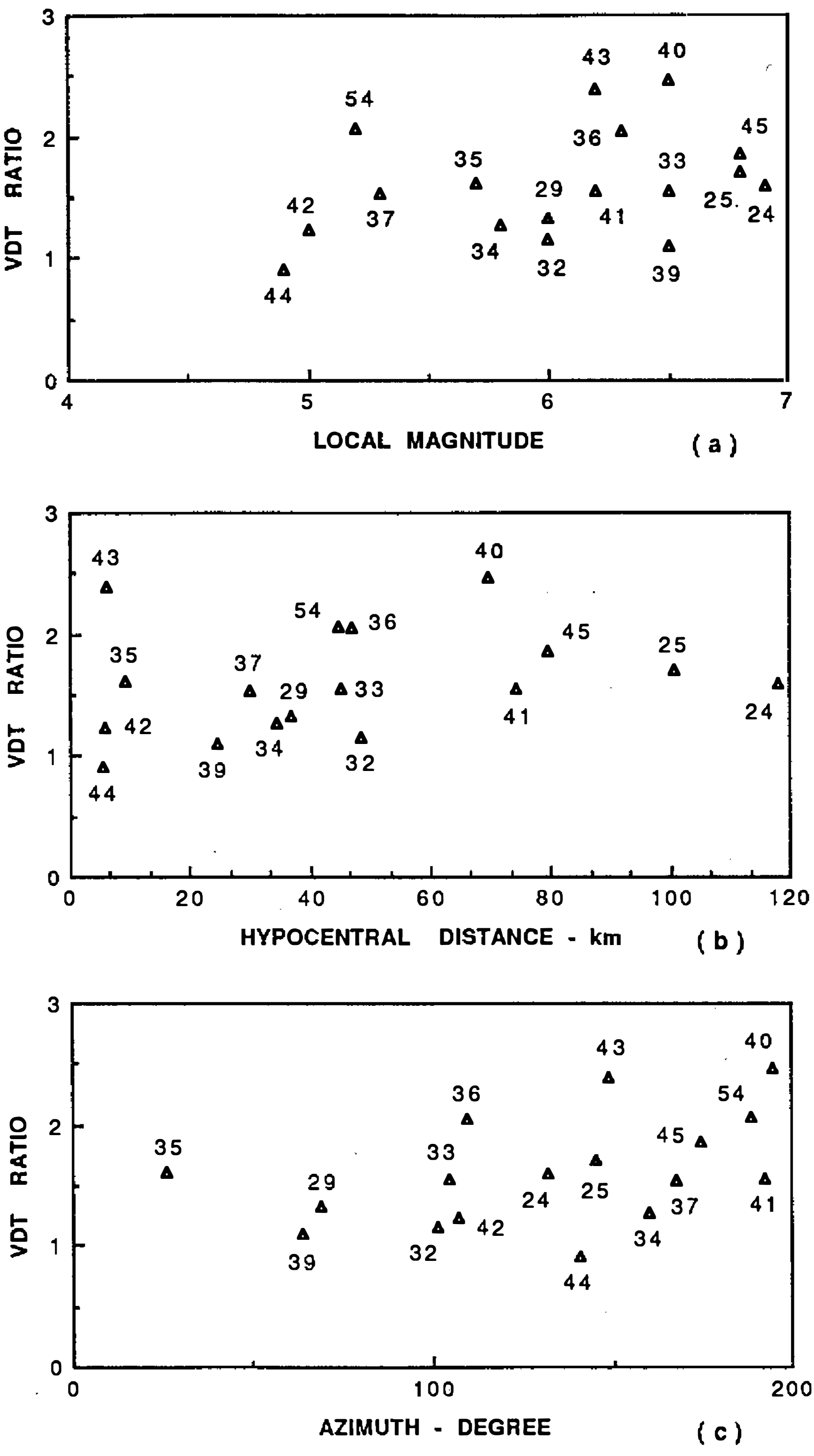

Fig. 4. Correlations of velocity duration ratio to local magnitude, hypocentral distance, and epicenter azimuth.

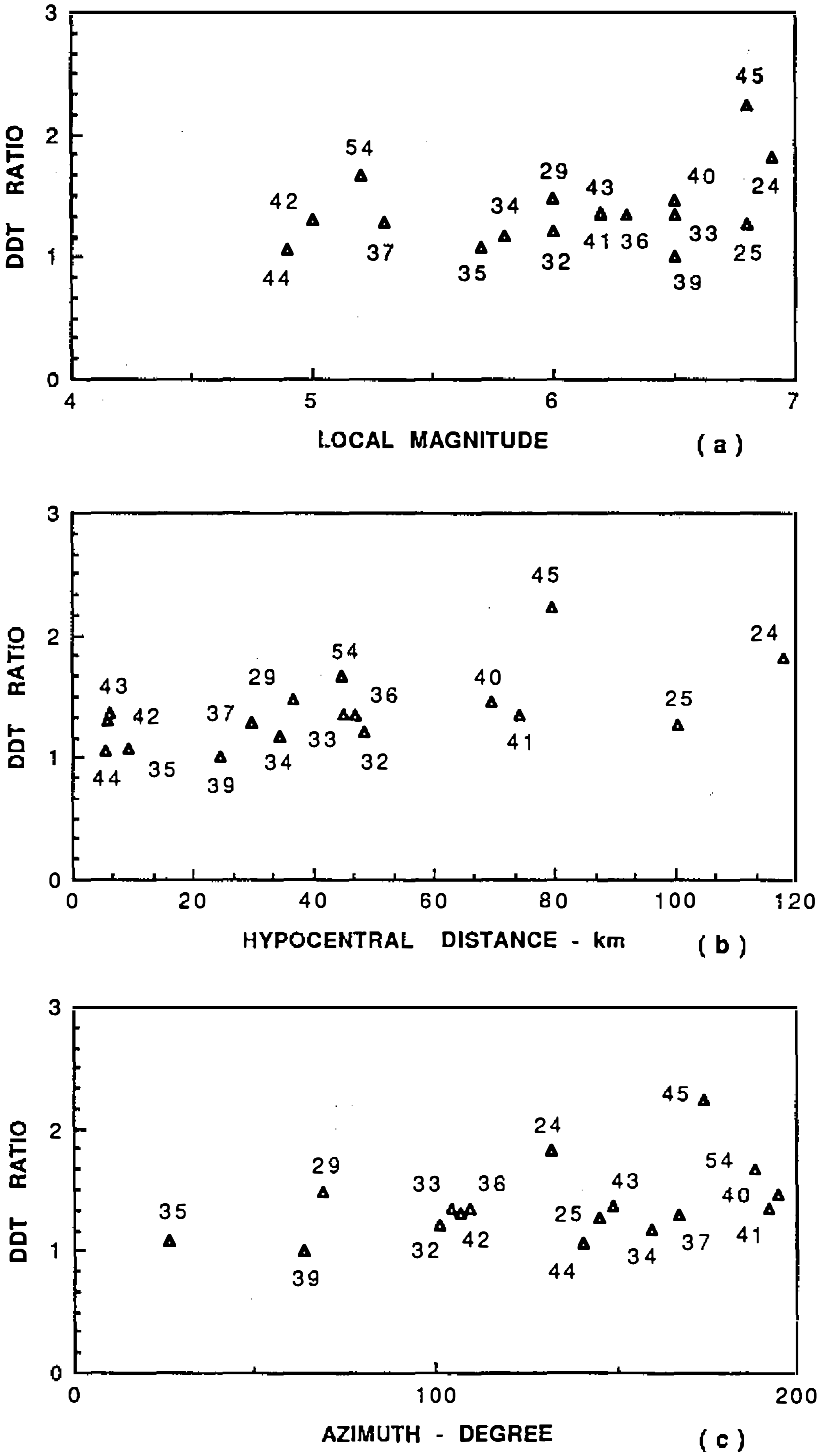

Fig. 5. Correlations of displacement duration ratio to local magnitude, hypocentral distance, and epicenter azimuth.

($ADT = 5\ sec$) and 43 ($ADT = 8\ sec$) (see Table 2). Therefore strong motion duration is an important factor in producing damage and failure at some kinds of structures.

In order to determine the characteristics of the strong motion duration in different frequency bands we decomposed the records over the SMART1 array into four frequency bands, i.e. $BAND\ 1 = 0.5 - 2\ Hz$, $BAND\ 2 = 2 - 3.5\ Hz$, $BAND\ 3 = 3.5 - 5\ Hz$ and $BAND\ 4 = 5 - 10\ Hz$. The average duration ratio of each frequency band with the result of the unfiltered band ($BAND\ 0$) is listed in Table 3. Generally, strong motion duration between an alluvial site and a rock site does not differ greatly over the various frequency bands. Only the displacement duration ratio at $BAND\ 1$ is smaller. The average duration ratio of $BAND\ 1$ is very similar to that of the unfiltered band. So this parameter is either related to the seismic wave characteristics of this frequency band or the strong motion records at the SMART1 array were primarily affected by the ground motion of the $0.5 - 2\ Hz$ frequency band.

Table 3. Duration ratios of different frequency bands.

	ADT RATIO	VDT RATIO	DDT RATIO
BAND 0	1.76±0.49	1.61±0.41	1.38±0.33
BAND 1	1.75±0.49	1.65±0.45	1.33±0.33
BAND 2	1.72±0.58	1.77±0.54	1.89±0.95
BAND 3	1.60±0.66	1.70±0.62	1.78±0.91
BAND 4	1.68±0.70	...	...

4. CORRELATIONS OF DURATION WITH MAGNITUDE AND DISTANCE

Thirty earthquakes recorded by the SMART1 array were selected to calculate strong motion duration. This was in turn used to show correlation with magnitude and distance. Figures 6~8 plotted the unfiltered ($BAND\ 0$) acceleration, velocity and displacement duration, respectively, with respect to magnitude and distance. From these figures we can see that the duration increases as magnitude increases because the larger the magnitude, the greater the length of the ruptured fault. This trend was also noted by Bolt (1973). Figure 6b shows the relationship between hypocentral distance and acceleration duration of $BAND\ 0$. The duration also has a slight tendency to increase with increasing distance up to about 80 km. This may indicate some source effect because the greater the distance of the earthquake recorded by the array the greater the magnitude.

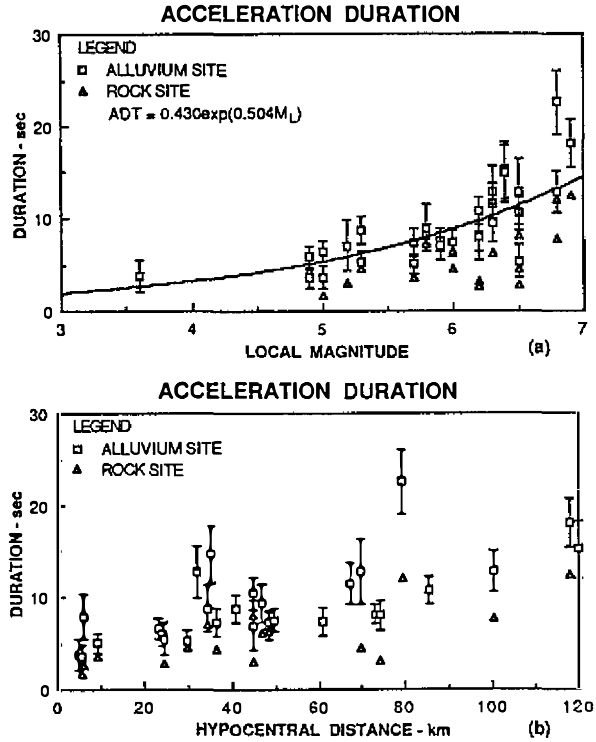

Fig. 6. Correlations of acceleration duration to local magnitude and hypocentral distance.

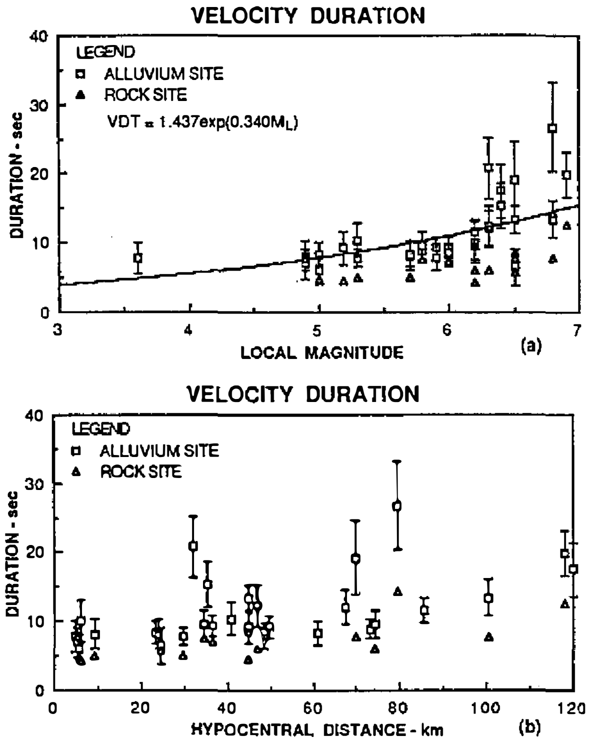

Fig. 7. Correlations of velocity duration to local magnitude and hypocentral distance.

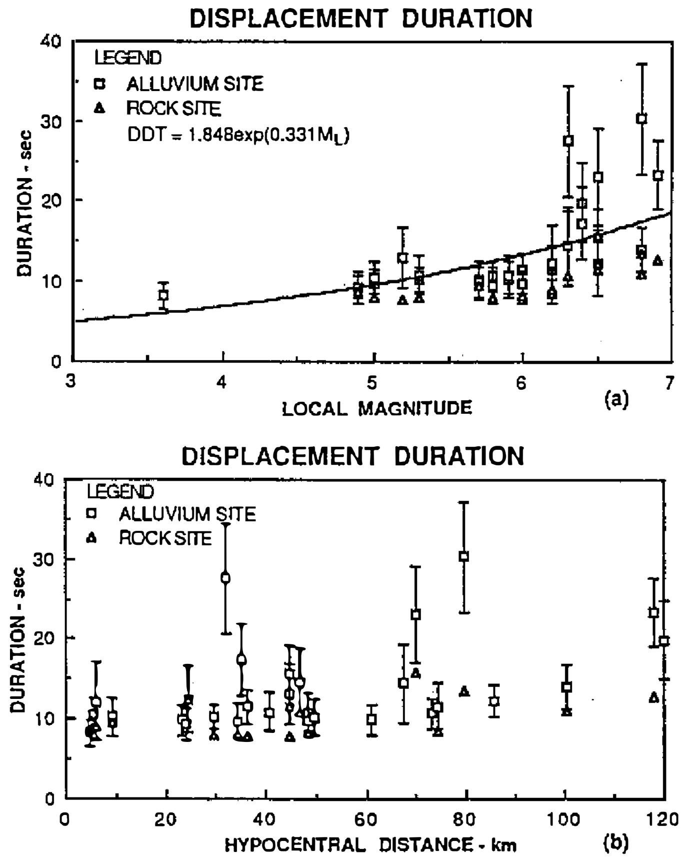

Fig. 8. Correlations of displacement duration to local magnitude and hypocentral distance.

By using regression analysis, we obtained the relationships between strong motion duration and local magnitude as follows:

$$ADT = 0.430 \exp\left(0.504\, M_L\right) \pm 2.749, \quad (1)$$

$$VDT = 1.437 \exp\left(0.340\, M_L\right) \pm 2.393, \quad (2)$$

$$DDT = 1.848 \exp\left(0.331\, M_L\right) \pm 2.845, \quad (3)$$

where all of the units of ADT, VDT and DDT are second. These results are also shown in Figures 6~8.

Based on Trifunac and Brady (1975), the variability of duration increased as the epicentral distance increased. However, our study shows that variability of duration does not correlate with distance (Figure 9). It shows that variability increases as magnitude increases. According to Trifunac and Brady (1975), variability of duration is caused by inhomogeneous media, through which seismic waves propagate, but the results of this study show that variability of duration is primarily caused by the complicated rupture process of the earthquake source.

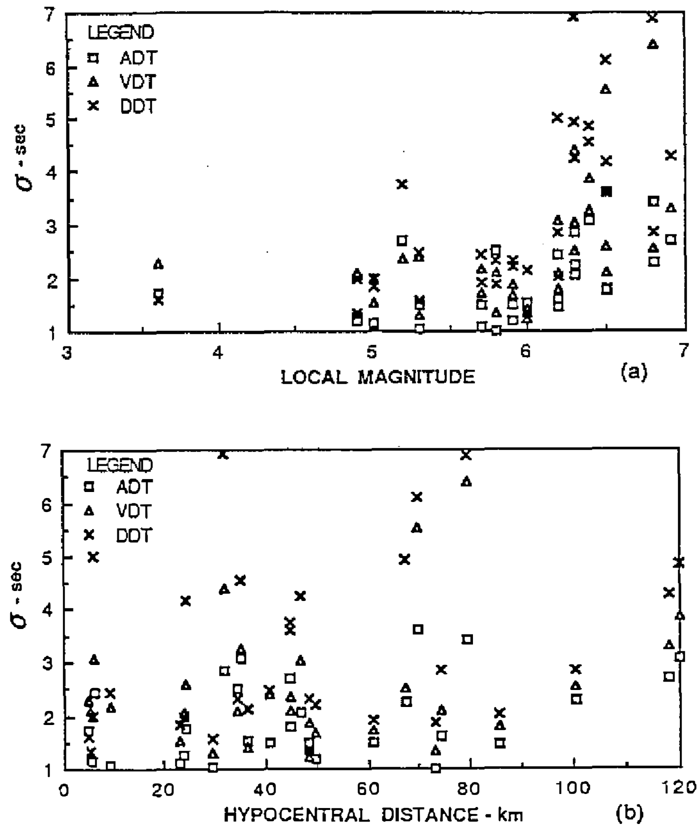

Fig. 9. Correlations of the duration variability to local magnitude and hypocentral distance.

Figure 10 also shows acceleration duration and magnitude/distance relations for the four different frequency bands. From Figure 10a we can see that the ascending trend of the high frequency band is not greatly different from that of the low frequency band. The duration-magnitude relationship of velocity and displacement have the same characteristics as the result of acceleration duration. However, these are omitted in order to reduce the number of figures.

5. DISCUSSIONS AND CONCLUSIONS

The strong motion duration of acceleration (ADT), velocity (VDT) and displacement (DDT) at an alluvial site are 1.8, 1.6 and 1.4 times, respectively, longer than that at a rock site. Comparing the duration ratio, calculated between the alluvium and rock sites, with local magnitude, hypocentral distance and epicentral azimuth, we can see that the duration ratio increases as local magnitude increases for the same hypocentral distance, and the duration ratio increases as the hypocentral distance decreases for earthquakes with the same local magnitude. The positive relationship between the duration ratio and the epicentral azimuth and the negative relationship between the peak amplitude

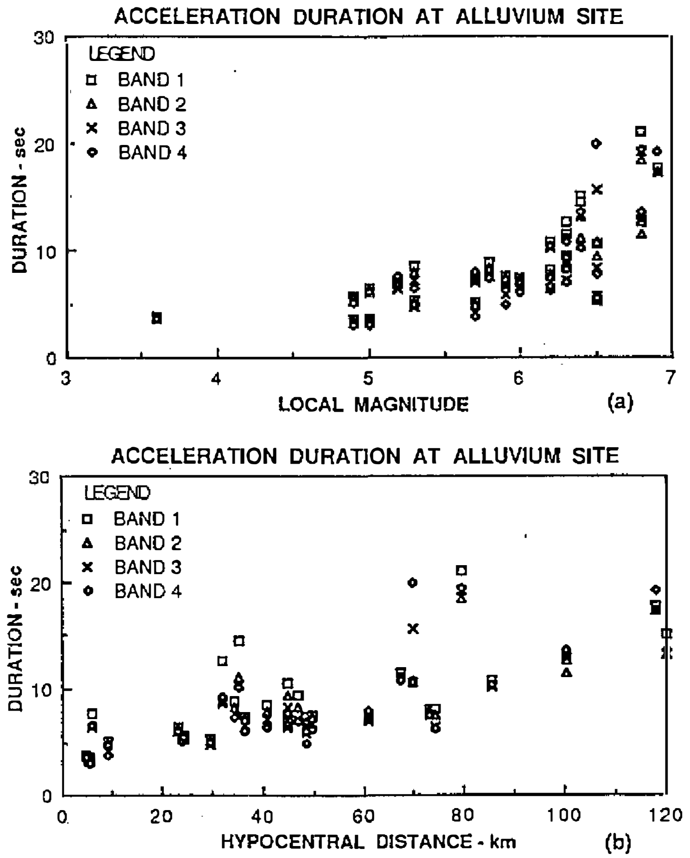

Fig. 10. Correlations of the duration variability of four frequency bands to local magnitude and hypocentral distance.

ratio and the azimuth show that these relationship were caused by the subsurface structure of the Lanyang plain. This phenomenon can be demonstrated with a theoretical study, but the effects of the three dimensional subsurface structure must be considered.

The peak accelerations of event 39 and event 47 are larger than those of event 42 and event 51, but did not cause damage in the Taipei area as events 42 and 51 did. The reason is that the duration time of events 42 and 51 was longer than for events 39 and 47. Strong motion duration is one of the causes of damage and is an important factor to earthquake engineering problems.

While strong motion duration has a slight positive relationship to distance, it might be part of the effect of magnitude. The relationship between strong motion duration and local magnitude is obtained by using regression analysis. According to Trifunac and Brady (1975), the variability of duration is caused by inhomogeneous media through which seismic waves propagate, but the results of this study show that variability of duration is primarily caused by the complicated rupture process of the earthquake source.

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SMART1 陣列區強地動延時之特性

溫國樑　葉永田
中央研究院地球科學研究所

摘要

利用 SMART1 陣列所收錄之 17 個地震分析土層對強地動延時之影響可知，加速度、速度和位移記錄在沖積層測站之強地動延時分別爲岩盤測站之 1.8、1.6 和 1.4 倍，此比值與規模、距離及蘭陽平原之地下構造有關。強地動延時隨規模之增大而增長，與距離亦有正比之關係，但這亦可能爲震源之效應。經由 SMART1 陣列三十個地震之資料回歸分析，我們亦得出加速度、速度和位移強地動延時與規模之關係式。根據 Trifunac 和 Brady (1975) 之研究認爲，延時之變異度主要由震波傳遞過程中所穿透介質之非均質性造成，而由本研究之結果顯示，主要爲震源錯動之複雜過程產生。