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Development of probability bases of strong ground motion duration in the seismic microzonation

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ABSTRACT: This paper is designed to provide the probability bases for a simple procedure in seismic hazard analysis and microzonation of duration. So called attenuation law of duration of earthquake ground acceleration on rock and soil sites are presented by means of multiple regression analysis. Duration definition is cited from E.H.Vanmarcke's study. The Poisson model is adopted to describe earthquake occurence, the different probabilities that are exceeded during the lifetime of a structure are summarized. The proposed technique has intended to be applied to construct a probabilistic duration microzoning map, which led to combination with a series of probabilistic microzoning maps for PGA, response spectra, ground failures to be used for improvement of engineering understanding of strong ground motion and for comprehensive estimation of seismic hazard of site.

1 INTRODUCTION

The effects of ground motion duration on damage have been recognized by numerous researchers such as Zhang in the early stage. The ground motion duration exceeding certain intensity could be the principal reason of extradamaging effect to nonelastic structures and intensifying the liquefaction at a given site. For example, the 1906 great San Francisco earthquake (duration 40~60 sec), 1957 Mexico earthquake(duration 60 sec), 1964 Alaska earthquake(duration about 3 minutes), 1985 Nichoacan, Mexico earthquake, 1988 Spitak earthquake, 1990 Luzon, Philippines earthquake(duration 45 sec) were all of events of greatly excessive damage resulting from longer duration. In spite of the low peak acceleration (about 0.02g) in the Anchorage with 80 miles of epicentral distance from the source, the saturated sand site was still severely liquefied as a result of a consequence of significant long ground motion duration of 3 minutes. The comparative studies of building damage have noted that in the same intensity of earthquakes, the longer duration an earthquake has, the higher damage degree structures will sustain. For example, 1968 Tokachi-oki earthquake (M=7.9) and 1970 Hiroo-oki earthquake, the former caused severe damage in Hachinohe (JMS intensity V, PGA=0.23g, duration 11.0 sec), but in Hiroo(JMS V, PGA=0.44g, duration 3.5 sec) a negligible damage was found owing to a short duration of latter earthquake, even though this earthquake had stronger PGA than the first. The theoretical study emphasized that for extrashort duration earthquake such as 1957 Port Hueneme and 1966 Parkfield earthquakes if the structures were collapsed within 1 sec at the ending stage of strong part of ground motion unless the PGA of this earthquake is greater than 5 times of normal earthquake with duration of 25 sec. The effect of long duration on response spectra is demonstrated by increasing spectra values in low and middle frequency ranges, it is obvious that the time history of strong ground motion with long duration contains longer period waves. The aforementioned examples aid in understanding such a fact that the strong ground motion duration is an independent parameter for evaluating seismic effects, and it is not sufficient for analysis based on only PGA and spectra to evaluate seismic effects.

2 DEFINITION OF STRONG GROUND MOTION DURATION

There has not been unified definition of strong ground motion duration for long time, the results given by various researchers are quite different with large deviation, sometimes it is unable to be compared with each other. From point of view of earthquake engineering, the definition regarding strong ground motion duration has a lot, but the popular definitions are as follows.
(1) Duration is definded as the time interval between the first and last peaks when absolute value of amplitude of ground motion acceleration equal to or greater than α times absolute value of PGA, i.e. $|A(t)| \geqslant \alpha |A_{max}|$, where α is a constant ranging from 0 to 1, usually $\alpha=0.5$ because the acceleration amplitude to be thrown away is just equal to half of peak ground acceleration, it is also a unit of intensity as suggested by Aptikaev.
(2) The second definition of duration recommended by Trifunac and Brady, is based on the concept of cumulative energy obtained by integrating of acceleration square, duration is the time interval required to accumulate a prescribed fraction of

the total energy, e.g. 90 percent.
(3) The third definition of duration suggested by Vanmarcke and Lai, is defined as $T_d=7.5I_0/A^2_{max}$, where A_{max} is the maximum ground acceleration, and $I_0=\int_0^T A^2(t)dt$. In this paper, the third definition of ground motion duration is adopted for multiple regression analysis, based on which the "attenuation law" of ground motion duration is developed, and probabilistic seismic hazard analysis of duration which might be expected to occur in a studied region is carried out.

3 "ATTENUATION LAW" OF GROUND MOTION DURATION

The results obtained from massive statistic data indicated that within a relative short epicentral distance, the ground motion duration does not decrease with decreasing of epicentral distance, but still increase with increasing of earthquake magnitude, it is different from so called "saturated phenomenon" of peak ground acceleration. At a certain epicentral distance the ground motion duration increases slightly with increasing of epicentral distance, On the contrary, the peak acceleration attenuates with increasing of epicentral distance. Therefore, the study on effects of ground motion duration on engineering damage under approximated condition of PGA and spectra is meaningful. By the way the duration time is related to multireflection effect induced by seismic waves propagating from bedrock to soft soil layers, in other words, the duration time is also dependent upon local site condition. The attenuation law of ground motion duration is expressed usually in terms of magnitude, epicentral distance and local site condition. Herein the duration T_d defined by some reseachers is given in Table 1.

Tab. 1 Attenuation law of duration T_d

Researcher	Definition of duration	Attenuation law
R.McGuire (1978)	90% energy	$\ln T_d=0.19+0.15M+0.35\times\ln R+0.73S+0.23V$ $\sigma_{\ln}=0.47$
E.H. Vanmarcke & Lai Shi-Sheng P. (1980)	$7.5I_0/A^2_{max}$	$T_d=0.0706\times10^{0.218M}\times(\Delta+30)^{0.257}$ where $\Delta\geqslant\Delta_0(M)$ $T_d=0.0717\times10^{0.280M}$ where $\Delta<\Delta_0(M)$
H. Kameda & K. Kohno (1983)	$7.5I_0/A^2_{max}$	$T_d=0.0325\times10^{0.168M}\times(\Delta+30)^{0.572}$ where $\Delta\geqslant\Delta_0(M)$ $T_d=0.0338\times10^{0.306M}$ where $\Delta<\Delta_0(M)$
Aptikaev & Kopnichev (1980)	$(1/2)A_{max}$	$\lg T_d=0.20M+0.50\lg\Delta-1.30$
K.Kawashima (1985)	$\lvert A(t)\rvert>\alpha\lvert A_{max}\rvert$ where $\alpha=0.5$	for soil class I $T_d=4.43\times10^{-4}\times10^{0.292M}\times(\Delta+30)^{1.041}$ for soil class II $T_d=0.00691\times10^{0.301M}\times(\Delta+30)^{0.498}$ for soil class III $T_d=0.0149\times10^{0.207M}\times(\Delta+30)^{0.691}$
Japan Road Association (1983)	$(1/2)A_{max}$	for soil class I $T_d=3.89\times10^{-4}\times10^{0.466M}\times\Delta^{0.589}$ for soil class II $T_d=1.37\times10^{-2}\times10^{0.262M}\times\Delta^{0.485}$ for soil class III $T_d=2.75\times10^{-2}\times10^{0.291M}\times\Delta^{0.265}$ for soil class IV $T_d=2.28\times10^{-1}\times10^{0.199M}\times\Delta^{0.233}$

In the Tab. 1, where M-magnitude, R-hypocentral distance, S-soil variable(for bedrock S=2, median soil S=1, alluvium S=0.), V-velocity, $\Delta_0(M)$-constrained condition, namely

$$\begin{aligned}&\Delta_0(M)=1.08\times10^{0.242M}-30 &&\text{for } M>6.0\\&\Delta_0(M)=0. &&\text{for } M\leqslant6.0\end{aligned}\qquad(1)$$

Because of "saturated phenomenon" of duration in the case of relative short epicentral distance, make use of $(\Delta+30)$ instead of Δ in the attenuation law and constrained conditions when $M>6.0$ as well as $M\leqslant6.0$ is appropriate and reasonable. The overall attenuation laws show that the regression constants in each formula depend on local site conditions. It seems to be very impotrtant for evaluation of duration to consider the soil classification. The definition of duration presented in this paper is widely recognized definition of Vanmarcke & Lai. because the concept of energy duration is much more reasonable than $(1/2A)_{max}$ This paper brings together the available data of US, Japan and Yugoslavia and produces multiple regression analysis by using functional relation of

$$T_d=A\times10^{BM}\,(\Delta+30)^C \qquad (2)$$

In this study site condition has been taken to be related to the bedrock (based on 65 data) and soil layer (based on 244 data) only, but it is impossible to distinguish soil into more detail kinds, due to lack of original records, then these attenuation relations take the form:
for bedrock site

$$T_d=0.03525\times10^{0.1736M}\times(\Delta+30)^{0.6169} \quad \text{for} \quad \Delta>\Delta_0(m) \tag{3}$$

for soil site

$$T_d=\begin{cases}0.01080\times10^{0.1072M}\times(\Delta+30)^{0.6506} & \text{for } \Delta>\Delta_0(m)\\ 0.08851\times10^{0.4415M} & \text{for } \Delta\geqslant\Delta_0(m)\end{cases} \tag{4}$$

In the meanwhile more than 200 data has been processed statistically according to the thickness of soil layer for evaluating the relationship between duration and the thickness, it can be considered by multiplying a modified factor:

$$\eta=\exp[0.0019(H-40)] \tag{5}$$

where H-the thickness of soil layer in m, 40-average thickness among statistical samples, 0.0019-the regression constant.

4 PROBABILISTIC SEISMIC HAZARD ANALYSIS OF GROUND MOTION DURATION

As a matter of fact, in the probabilistic seismic hazard analysis any ground motion parameter (acceleration, velocity, displacement, response spectra, duration, intensity, etc.) could be expressed as resulting seismic hazard curves which is determined from appropriate earthquake reocurrence model and attenuation law of those parameters with distance. For the destructive earthquake expected at a site the cumulative probability distribution function of magnitude can be illustrated by distribution of a truncated exponential function as follows:

$$F_M(m)=1-\exp[(-\beta(m-m_0)] \quad \text{for } m\geqslant m_0 \tag{6}$$

If m_0 represents the lower limit value of earthquake magnitudes within time interval considered, the earthquake with magnitude $m\geqslant m_0$ can be assumed to be a Poisson process, let ν_0 is the annual average value of earthquake occurence with $m\geqslant m_0$ at a given site, then cumulative distribution function of yearly maximum earthquake can be obtained by product of K independent events

$$F_{M\ max}(m)=\sum\{1-\exp[(-\beta(m-m_0)]\}^K\times\nu_0^K/K!\times\exp(-\nu_0)=\exp\{-\nu_0\exp[-\beta(m-m_0)]\} \quad \text{for } m\geqslant m_0 \tag{7}$$

in the case of $\Delta\geqslant\Delta_0(m)$ and attenuation law of duration $T_d=A\times10^{BM}\times(\Delta+30)^C$ which leads to inverse function

$$m=(1/B)\times\log[T_d/(A\times(\Delta+30)^C)] \tag{8}$$

it is understood that the probability $P[T_{dmax}\geqslant T]$ is equivalent to the probability $P[M_{max}\geqslant m]$, i.e.

$$\begin{aligned}P(T_{dmax}\geqslant T)&=P[M_{max}\geqslant(1/B)\log(T_d/A(\Delta+30)^C)]\\&=1-[F_M(m)]=1-\exp\{\nu_0\exp[-\beta(m-m_0)]\}\\&=1-\exp[\nu_0\exp\{-\beta[(1/B)\log(T_d/A(\Delta+30)^C)-m_0]\}]\end{aligned} \tag{9}$$

If the number of potential seismic source is n, then

$$P(T_{dmax}\geqslant T)=1-\exp[-\sum\nu_{0i}\exp\{-\beta_i[(1/B_i)\times\log(T_d/A_i(\Delta_i+30)^{C_i}-m_{0i}]\}] \tag{10}$$

Assuming maximum earthquake of each year is independent statistically, and annual probability of exceedance of each year is a constant, as a result of that the related probability of exceedance within t years is

$$P(T_{dma}\geqslant T_d)_{t\ year}=1-[P(T_{dmax}\geqslant T_D)_{1\ year}]^t \tag{11}$$

In the case of $\Delta<\Delta_0(m)$ the attenuation law of duration may be written also as $T_d=A_1\times10^{B\ M}$ then the inverse function becomes

$$m=(1/B_1)\times\log(T_d/A_1) \tag{12}$$

therefore

$$P(T_{dmax}>T_d)_{1\ year}=1-\exp[-\sum\nu_{0i}\exp\{-\beta_i\times[(1/B_1)\times\log(T_d/A_1)-m_{0i}]\}] \tag{13}$$

5 CASE STUDY

The calculation example is given at the site which is an Oil field set up in Henan province, central China. The seismicity parameters, source type and related geometric parameters of each potential source of the Oil field are shown in Tab.2 and Tab.3.

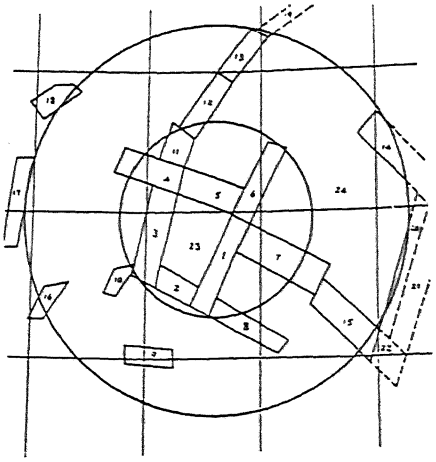

Fig. 1 The potential seismic sources of the Oil field (figures in the potential seismic sources are it's order number)

Tab.2 Seismicity parameters of potential source of the Oil field

Number of potential source	Upper limit M_u	Source type	β	ν ($M_0 \geqslant 4.5$)
1	7.0	II	1.3585	0.027344
2	6.5	II	1.3585	0.006838
3	7.0	II	1.3585	0.022217
4	7.5	II	1.3585	0.005128
5	6.5	II	1.3585	0.008547
6	6.5	II	1.3585	0.005128
7	6.5	II	1.3585	0.005128
8	6.5	II	1.3585	0.003419
9	6.5	II	1.3585	0.005128
10	6.5	II	1.3585	0.005128
11	6.5	II	1.3585	0.010254
12	7.5	II	1.3585	0.018799
13	6.5	II	1.3585	0.005128
14	6.5	II	1.3555	0.008547
15	6.5	II	1.3555	0.005128
16	6.5	II	1.3585	0.008547
17	8.0	II	1.2664	0.018799
18	6.5	II	1.2644	0.015381
19	7.0	II	1.3585	0.008547
20	6.5	II	1.3585	0.008547
21	8.5	II	1.3355	0.018799
22	7.5	II	1.3355	0.017094
23	5.5	III*	1.3816	0.027344
24	5.5	III*	1.3816	0.044438

Tab. 3 Geometric parameters of potential source of the Oil field

Number of potential source	r_0 (Km)	L_1 (Km)	L_2 (Km)	L (Km)	W (Km)
1	21.0	17.1	-135.0	152.1	30.3
2	102.0	29.4	-33.0	62.4	33.0
3	67.5	114.6	-24.0	138.6	41.4
4	13.8	171.6	72.0	99.6	42.6
5	13.8	69.6	-24.6	94.2	42.6
6	21.0	141.0	17.4	123.6	30.3
7	0.0	189.3	51.3	138.0	29.4
8	102.0	192.0	60.6	131.4	28.5
9	201.2	121.5	45.0	76.5	28.8
10	57.0	186.0	138.0	48.0	22.8
11	73.2	106.8	58.2	48.6	39.6
12	97.5	190.8	81.6	109.2	30.6
13	110.7	267.9	181.2	86.7	28.5
14	243.0	171.0	60.0	111.0	43.5
15	6.0	300.0	192.0	108.0	52.0
16	129.0	277.5	219.0	58.5	25.2
17	295.8	99.0	-39.0	138.0	29.4
18	282.0	120.9	49.2	71.7	36.9
19	181.0	300.0	226.8	73.2	21.0
20	291.0	114.0	-98.1	212.1	21.0
21	312.0	180.0	-99.0	279.0	38.0
22	291.0	156.0	102.0	54.0	52.5
23*	R_1=0 Km		R_2=150 Km		
24*	R_1=150 Km		R_2=300 Km		

* -- background seismic source

So in case of soil site, the duration can be computed using the method proposed by the authors. 10% probability of exceedance within 50 years T_d=28 sec. 3% probability of exceedance within 50 years T_d=36 sec. Once the probability consistent seismic hazard curve of duration with PGA response spectra is determined , the evaluation of seismic hazard of the given site becomes relatively perfect and reasonable. If the duration values in each mesh are computed, it is easy to compile microzoning map. On the application of duration as an engineering seismic hazard parameter it can be estimated by $\lg T_d$ such as suggested by Japanese professor Omote Shunichiro, this information will be useful in assessing and delineating seismic hazards at a given site. Of course, the Omote recommendation should be considered as preliminary, it may be modified upon further studing and analysis of new data gathered in later. Certainly the resulting duration obtained from this seismic hazard analysis is slightly greater than that obtained from a given magnitude and epicentral distance of separate seismic potential source. It is understandable that the result from probabilistic methodology presented in the paper is total contribution of all seismic source (including near and far-field earthquake), that is similar to other hazard parameters (e.g. PGA, intensity etc.) in the engineering seismic hazard analysis.

6 CONCLUSION REMARKS

(1) Probability bases duration at a given site can be computed by using formulas (10) and (13) developed in this paper, with consideration of thickness of soil layer the modification may be taken in the formula (5)

(2) The sensitivity analysis shows that the duration is not so much susceptible to magnitude and epicentral distance, hence, if the studied area is not large enough, then the duration microzone depends mainly on the variation of the thickness of soil layer.

(3) The comparative study shows that the results of probability of exceedance statistically averaged to provide an estimate of duration defined as $T_d=7.5I_0/A^2_{max}$ have not much difference from duration defined as $T_d=(1/2)A_{max}$, although the duration definition is different.

(4) With the consideration of upper limit of earthquake magnitude in each potential seismic source the duration will be reduced to a certain extent.

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