AN ENGINEERING SEISMOLOGICAL STUDY ON THE 1976 ÇALDIRAN EARTHQUAKE IN TURKEY

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SYNOPSIS

The Çaldıran earthquake gave a unique opportunity to attack an elucidation of the total feature from seismic source process to spatial damage distribution. A joint research group between Turkey and Japan was organized and a detailed investigation has been continued.

By use of the seismological and field experimental data, a model for seismic intensity analysis, taking consideration into finiteness of earthquake fault, slip distribution, and site geology was applied to this earthquake. Superiority of this new model was clearly demonstrated by comparison between the observed and calculated intensities. The most probable source parameters, which are determined by a sensitivity analysis of the new model, show quite an agreement with those estimated by the WWSSN data.

A disaster analysis, combined loss of human lives with structural damage, was also performed in the similar manner. Calculated composite damage ratio are highly correlated with the observed values. Engineering seismological significance of the new model was also discussed.

INTRODUCTION

Although there have been many reports on seismic disasters, no systematic study which considers all the influential factors such as seismic source process, wave path and site geological effects is appeared.

The recent Çaldıran earthquake, a typical inland and shallow large earthquake, provides us the best situation to persue this subject, since the whole feature of a newly made fault and structural and other damages in the shocked area can be clarified through field surveys. Besides, the seismic records essentially important for the source mechanical solution are also available by the world-wide standardized network.

Between Turkish and Japanese researchers who realized the engineering seismological importance of making a study of the Çaldiran earthquake, a joint research group was organized and an energetic investigation has been continued including several times of field surveys.

In this paper, after a brief description about the general characters of this earthquake, studies on seismic intensity analysis and structural damage evaluation coupled with loss of human lives are mainly reported with an introduction of a new model.

EARTHQUAKE

The Çaldiran earthquake occurred at 14 h 22 m local time on Nov.24, 1976 shaked a wide area in eastern Turkey and carried off about 4000 lives and injured 500 persons. The damaged houses beyond repair were close upon 10000 in number. The magnitudes reported are Ms=7.1, ML=7.6, and Mb=6.9. And the epicenter is about 100 km east of the junction between north and east Anatolian fault lines. The maximum intensity observed was IX(MSK) at

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Çaldıran. For the focal depth, the instrumental observation indicates 40-60 km, but the field evidences suggest a shallower depth (Table 1). A series of fault breakages appeared in the N70°W direction (Fig.1).

Immediately after the earthquake occurrence a field survey was performed by the Turkish Earthquake Research Institute, and an excellent quick report has been published (1977).

INTENSITY ANALYSIS

The isoseismal map in the MSK scale, referred in Fig.2, characterizes that the isoseismals show no symmetricities in both axes along and across the fault line. The seismological information suggest that the fault surface may tilt westwards, slip vectors are different along the fault line. Furthermore, site geology changes from place to place.

The intensity evaluation should take consideration of all the above features. To take account for the fault length, width and dip, slips on the fault surface, and distance from the fault, may not be impossible, since all of them are numerically expressible. However, simultaneous consideration of such metric variates with non metric variate as site geology is beyond the empirical equations proposed in the past. What we examined was an application of the quantification theory developed by Hayashi (1961).

Model The idea is that the intensity at a site is determined as the total contribution of the slips distributed on the fault surface plus site geological effect. Let us define the coordinate-systems as shown in Fig.3. The fault surface with length L and width W is expressed in terms of (ξ,η) coordinates. Angle between y- and η- axes is θ, equal to the tilt of the fault surface. $D(\xi,\eta)$ represents the averaged slip in a small area $d\xi d\eta$. Let us suppose that the seismic strength (effective acceleration) affected by the segmental area can be written at (x,y) as

$$da = \text{const.}\frac{D(\xi,\eta)d\xi d\eta}{r^p}, \text{ where } r=[(x-\xi)^2+(y-\eta\cos\theta)^2+(\eta\sin\theta)^2]^{1/2}$$

Then the total contribution of the whole fault surface is easily as

$$a(x,y) = \text{const.}\int_0^L d\xi \int_0^W \frac{D(\xi,\eta)d\eta}{r^p}$$

In case of $D(\xi,\eta)=D(\xi)$, the above equation changes to

$$a(x,y) = \text{const.}\int_0^L D(\xi)d\xi \int_0^W \frac{d\eta}{r^p} \qquad (1)$$

The slip data by the field survey is usually $D(\xi)$ instead of $D(\xi,\eta)$. Therefore Eq.(1) is most appropriate for our investigation. Here, let us rewrite Eq.(1) as $a(x,y) = c\ A(x,y;p)$ and assume $A(x,y;p)$ is evaluated by knowing the fault configuration and the slip distribution, leaving a parameter p undetermined. Now, the most common transform of acceleration to seismic intensity is a form of $I = \alpha \log a + \beta$, therefore,

$$I = c_1 \log A(x,y;p) + c_2.$$

Next, let us introduce site geological effect by assuming soil types classified into m groups such as soft, intermediate, and hard rocks, then

$$I(x,y) = c \log A(x,y;p) + \sum_{j=1}^{m} Z_j \delta(j) \qquad (2)$$

hence Zj ($j=1,2,3, \ldots ,m$) is coefficients relating to the site effect and $\delta(j)=1.0$ only when the site coincides with the assigned rock type and otherwise $\delta(j)=0$. Then the unknowns c, Zj($j=1,2,\ldots,m$) in Eq.(2) are determined by use of the observed intensity data, leaving p as a parameter.

The square residual between the observed and calculated intensities is

$$R(p) = \sum_{i=1}^{n} \{[I(x,y)]_{obs.} - [I(x,y)]_{calc.}\}^2 ,$$

where n means number of the data. So, by employing the condition that R(p) should be minimized, the parameter p may be estimated.

Calculation The data encountered in the calculation were collected from the previous studies, and the field surveys. The Çaldıran earthquake fault is, from the field investigation, recognized approximately as a right lateral strike slip fault of which length is around 50 km. The dip was determined as 78°S and the width as W=24 km by the source process analysis after Toksöz et al (1978). Toksöz et al, referred to the field data, assumes a slip distribution of 2.5 m (10 km from the north western end of fault), 2.1 m (central 40 km), and 0.5 m (the remainder 4 km). These slips were also adopted in our calculations. The intensities as observed values were substituted by those from each segment on the isoseismal lines. The site were classified into three major groups as shown in Fig.4, in terms of measured S wave velocities in the shocked area and the geological rock data. These are Quarternary sediments, Tertiary and Mesozoic rocks, and volcanic and metamorphic rocks. The evaluation of an integral in Eq.(1) was performed numerically. And the attenuation parameter was tentatively fixed as p=2. Actual calculations were performed for the three different source types of shallow-buried point source at Çaldıran, finite line source of 54 km in length and finite area source of 54 km×24 km accompanied with slip distribution due to Toksöz et al. In Fig.5, comparisons between the observed and calculated isoseismal lines by three different source models are, together with obtained equations, depicted. One can easily understand that the third model is exceedingly superior to the other models. This suggests that the finiteness of the source model is very important in the intensity evaluation.

Sensitivity analysis and discussion We arrived at the conclusion that the intensities calculated by introducing a new model agree well with the observed intensities. It is, however, more important to know how the physical factors in the model affect upon the intensity. It is to examine how precisely the fault configuration can be estimated by knowing the observed isoseismal map. Relating parameters to this analysis are L, W, θ, p, and $D(\xi)$. Actually it was performed in the manner outlined in Fig.6, changing the parameters in ranges of $0<L\leq100$ km, $0\leq W\leq60$ km, $0°<\theta\leq90°$, and $1.0\leq p\leq3.0$. And the most probable values, at which the sum of square residuals between the observed and calculated intensities are minimum, were determined. Results are listed in Table 2 in comparison with Toksöz et al. Parameters L, θ, and p are very sensitive to the intensity. Fault width W is sensitive in a range $W\leq25$ km, but insensitive at larger widths. Slip distribution $D(\xi)$ would be effective, if there exists a large scatter on the fault surface. However, in our case this is not so peculiar because the adopted slips have no much divergence to the averaged value of 2.0 m. By the way, in the previous calculation a straight line or a flat plane fault was simply adopted, but Fig.1 suggests that the surface fault breakages are composed of three straight lines. The best equation was obtained by taking this field evidence into the calculation. This is,

$$I(x,y) = 4.16 \log A(x,y) + [3.39/3.49/3.60]_{\text{rock type}} \quad (3)$$

The site effect due to different geology is rather small around 0.2 in MSK scale. This unexpected result can be explained as the isoseismal lines do not necessarily guarantee site-by-site preciseness because of smoothing process on their drawings. One more thing extraordinary is that the site intensity at hard rocks is larger than the softer rocks. One may understand by considering the fact that the residential houses in this district, composed of some masonry and adobe walls, are very short in period ($T<0.1$ sec) and therefore the seismic load to the structure is severer at the hard rock sites.

DISASTER ANALYSIS

Composite damage ratio No earthquake disaster was explicitely encountered. It is, however, obvious that the intensity is determinable only by knowing structural and other damages. This requires a disaster analysis. By the way, only the data we have on the structural damage are percentages of (collapsed + heavily damaged) houses at every settlement on the shocked area. However, these structural damages can not be a good index to measure earthquake strength at a site, since almost all the houses in this district were severely damaged even at moderate intensities. On the other hand the loss ratio of human lives increases gradually, as is depicted in Fig.7, at higher intensities. This encourages us to examine if the structural damage ratio coupled with loss ratio of human lives can be a better index for describing earthquake disasters.

Now, let us define a composite damage ratio at a site as

$$J(x,y) = \frac{1}{1+k}\,\frac{e(x,y)}{e_{max}} + \frac{k}{1+k}\,\frac{f(x,y)}{f_{max}},$$

where $e(x,y)$, $f(x,y)$, e_{max}, f_{max}, and k are structural damage ratio, loss ratio of human lives, their observed maximum values, and a weighted coefficient, respectively. In the calculation $k=1$ was apriori adopted. And yet in our case e_{max} and f_{max} were 1.00(100%) and 0.36(36%), respectively.

Analysis An empirical equation was similarly assumed as

$$J(x,y) = c_1 \log A(x,y) + \sum_{j=1}^{n} Z_j \delta(j).$$

In the calculation we adopted the most probable source parameters obtained in the previous intensity analysis. Derived equation is

$$J(x,y) = 0.720 \log A + [-0.063/0.033/0.004]_{\text{rock type}}$$

A comparison of the calculated damage ratio by this equation with the observed values is made in Fig.8. The correlation coefficient is above 0.80. Now, by combining this with the intensity equation we arrive at

$$I(x,y) = 5.78\, J(x,y) + [3.75/3.68/3.62]_{\text{rock type}},$$

and

$$J(x,y) = 0.173\, I(x,y) - [0.649/0.637/0.627]_{\text{rock type}}.$$

These equations will be convenient as conversion formulas between seismic intensity and composite damage ratio. For example, the intensity at which structural damage is almost 100 % (J=0.5) is estimated as 6.5-6.6 and is consistent with the fact that the rural dwelling houses are almost perfectly collapsed at I(MSK)≥VII . In spite of this, coincidence is not enough. For improving this coincidence a more detailed and sophisticated field investigation on structural damage should preceed. Bayülke(1980) reports variety of structural damages of apparently uniform rural houses.

CONCLUSION

Results are summarized as follows. (i) An empirical equation for estimating seismic intensities at sites and structural damage coupled with loss of human lives was proposed, considering simultaneously seismic source, wave path, and site geological effects. (ii) The new equation was applied to the Çaldıran earthquake, and a good agreement with the observed data was ascertained. Important seismic source factors were numerically determined by means of the sensitivity analysis, and were compared with those by the wave analysis due to the WWSSN data. (iii) From engineering seismological point the significance of the new model was clarified.

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Table 1 Outline of earthquake.

Origin Time Epicenter Depth Magnitude	Nov. 24 , 1976 39.12 N , 44.19 E 40 ~ 60 Km M_s=7.1 , M_L=7.6 , M_b=6.9
Killed Injured	3840 497
Collapse and heavy damage Slight and Moderate damage	9232 10175

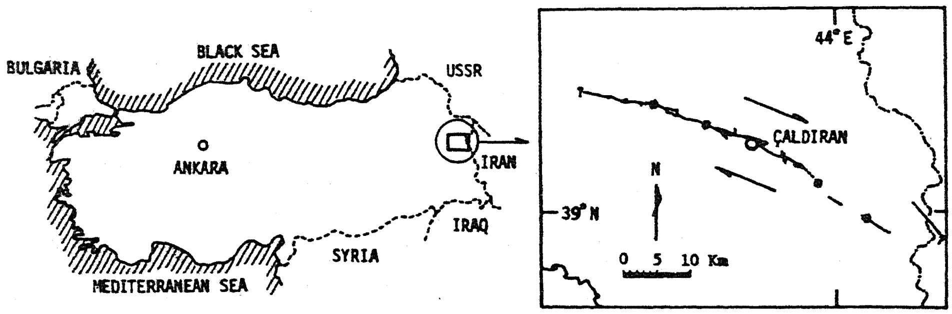


Fig.1 Location of the Çaldıran earthquake (left) and closed-up view of fault traces (right).

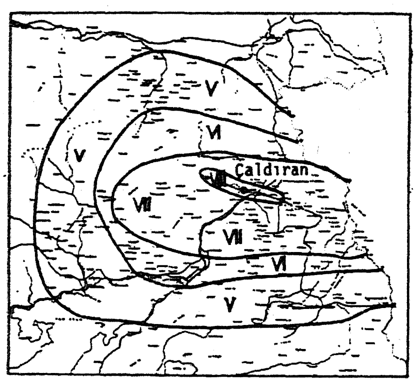


Fig.2 Isoseismal intensity map and location of macro-seismic epicenter.

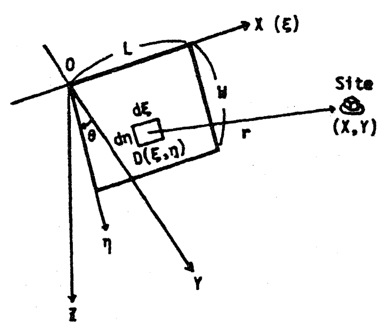


Fig.3 Fault model and its coordinates system.

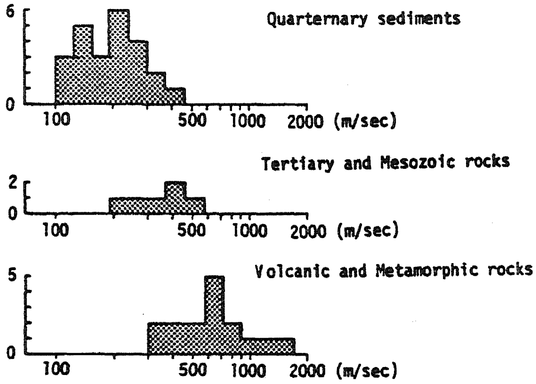
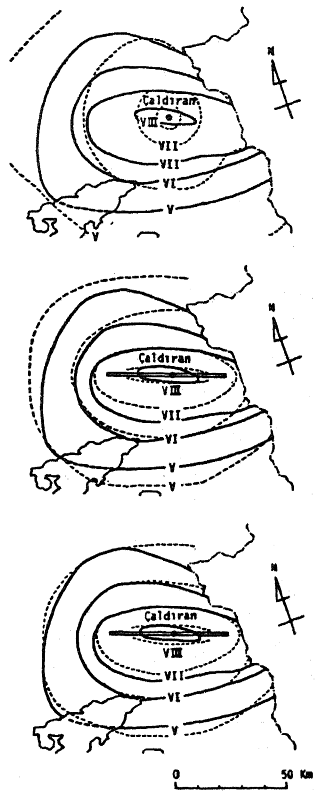


Fig.4 Histograms of measured S wave velocities at the damaged sites, classified in terms of rock types.



Point Source

$$I(x,y) = 1.15 \log A(x,y) + \begin{bmatrix} 9.54 \\ 9.25 \\ 9.62 \end{bmatrix} \text{rock type}$$

$$A(x,y) = \frac{1}{r^2}$$

Finite Line Source

$$I(x,y) = 1.73 \log A(x,y) + \begin{bmatrix} 7.44 \\ 7.46 \\ 7.64 \end{bmatrix} \text{rock type}$$

$$A(x,y) = \int_{-30}^{24} \frac{D(\xi)}{r^2}\, d\xi = 2.5\int_{-30}^{-20} \frac{d\xi}{r^2} + 2.1\int_{-20}^{20} \frac{d\xi}{r^2} + 0.5\int_{20}^{24} \frac{d\xi}{r^2}$$

Finite Area Source

$$I(x,y) = 2.83 \log A(x,y) + \begin{bmatrix} 4.78 \\ 4.85 \\ 4.95 \end{bmatrix} \text{rock type}$$

$$A(x,y) = \int_{-30}^{24} D(\xi)d\xi \int_{0}^{24} \frac{1}{r^2}\, d\eta$$

$$= \{\, 2.5\int_{-30}^{-20} d\xi + 2.1\int_{-20}^{20} d\xi + 0.5\int_{20}^{24} d\xi \,\} \int_{0}^{24} \frac{d\eta}{r^2}$$

Fig.5 Comparisons of the isoseismal lines for the three different source models. Solid and dotted lines are for the observation and the calculation respectively.

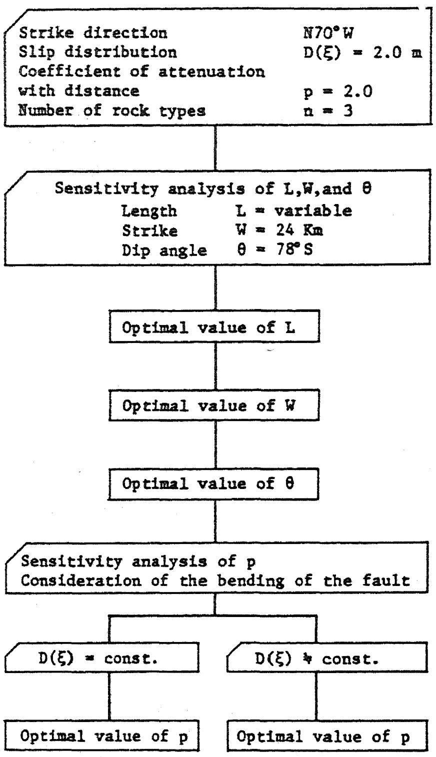


Fig.6 Flow of sensitivity analysis.

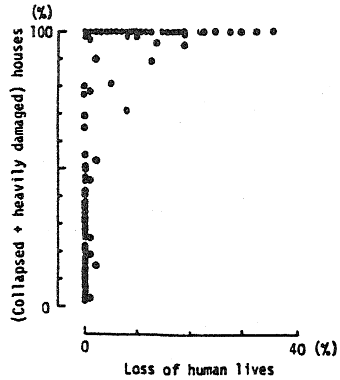


Fig.7 Relation of (collapsed + heavily damaged) houses to loss of human lives.

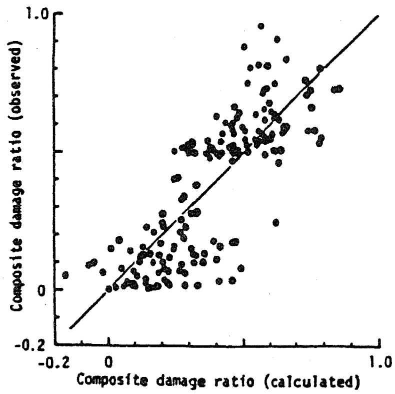


Fig.8 Comparison of the calculated and observed composite damage ratios.The correlation coefficient is larger than 0.8.

Table 2 Estimated source parameters and their comparison with Toksöz et al.

	Intensity Analysis		Wave Analysis
	Permissible range	Most probable value	(Toksöz et al.(1978))
L	55~70 Km	65 Km	55 Km
W	W≳20 Km	25 Km	25 Km
θ	80°≳θ≳65°	70°	78°
p	2.0≳p≳1.8	1.9	