Structural Eng./Earthquake Eng. Vol. 11, No. 4, 155s—163s, January 1995
Japan Society of Civil Engineers (J. Struct. Mech. Earthquake Eng. No. 507/I—30)

INTERPRETATION OF PUBLISHED DATA OF THE 1976 TANGSHAN, CHINA EARTHQUAKE FOR THE DETERMINATION OF A FATALITY RATE FUNCTION

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Analyzing the seismological and damage data of the Tangshan earthquake, we derived a function correlating the percent loss of masonry buildings to that of human lives. We determined the relationship so that the spatial distribution of the death estimated on the basis of the relationship was the most consistent with that of the data. We employed the method of system identification in this determination. The relationship obtained was a downward-convex, monotonously increasing function having a fatality rate of 30% at a collapse rate of 100%.

Key Words : *earthquake, mass casualty, fatality, Tangshan earthquake, China*

1. INTRODUCTION

With a death toll of 242,000, the Tangshan, China earthquake of July 28, 1976, was one of the most devastating earthquakes in the world. In addition to the massive damage, the earthquake was remarkable for the extensive technical survey that took place after the event. Consequently, a great number of publications on this disaster have appeared.

Despite the vast accumulation of data, however, information on the human losses in the disaster was surprisingly limited compared that of the whole. We found plenty of sound data regarding ground shaking and material losses, including isoseismal maps and collapse rate functions. Concerning human losses, in contrast, we could find very little quantitative data that were applicable to an in-depth interpretation of the disaster. We only found a very little amount of statistics that was fragmentary to say the least, often ambiguous, and, consequently, uncertain regarding their accuracy and reliability.

This situation always resulted in a serious bottleneck preventing us from discussing the human loss aspect of the disaster. We need to learn more concerning what happened to the people in Tangshan toward the development of knowledge applicable to the reduction in human casualties in future earthquakes.

To settle this problem, we decided to develop a tool for deriving reliable estimates that make up for the lack of casualty data. In this development, we particularly focused our attention on the construction of a fatality rate function, namely, the relationship between the percent loss of building stock and that of human lives. We developed the relationship so that we could apply it, together with an isoseismal map and a collapse rate function, to our estimation model[1)~3)] for the spatial distribution of earthquake fatalities.

Since the most part of affected buildings in the Tangshan earthquake was of masonry construction, our product from this study is applicable only to the assessment of disasters in built environment composed of masonry structures. In spite of this limitation, however, the result of this study can be expected useful, if we realize that masonry construction is broadly employed, even in earthquake-prone areas, and, accordingly, there is a large population worldwide living with serious threat of earthquake-related collapse of such kinds of structures.

In addition to the determination of a fatality rate function, which was the primary objective of this paper, we tried to depict in detail the entire structure of our estimation model. The model will be of use being applicable not only to the interpretation of data from a past disaster, which we did in this study, but also to the assessment of human losses in a future event. The model includes building quality in terms of the structural vulner-

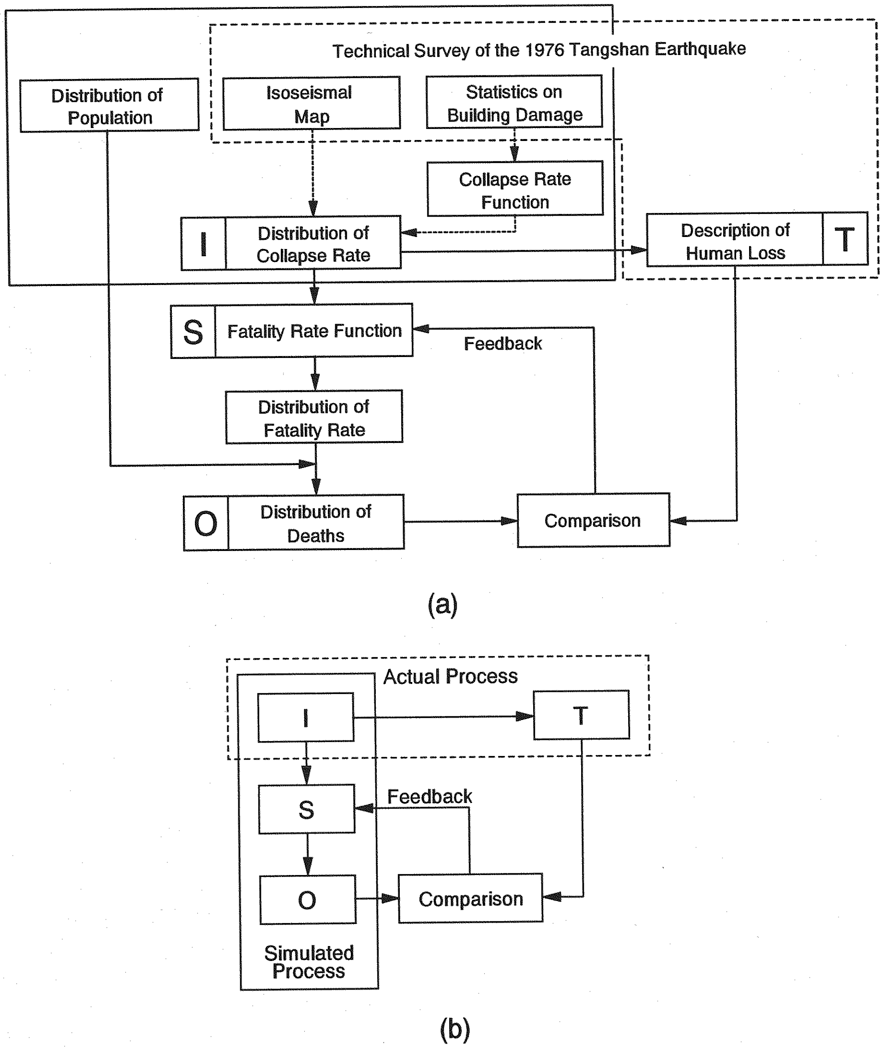

Fig.1 Flow of the analysis toward the determination of a fatality rate function (a) and a generic model of the procedure of system identification (b).

ability to earthquakes and the collapse-related lethality to the occupants. We, therefore, can use the model in the discussion of earthquake casualties in relation to the building quality of an affected area.

One of the problems that often arise when published data are analyzed is those of accuracy and reliability, and we are not free from the problem in this study, too. Also, we are not competent, at this point, to sufficiently discuss those aspects of the analyzed data.

However, we realized, first, that the investigations of seismic intensity and building damage in the Tangshan earthquake were conducted following traditional procedures, and, therefore, those results were not, at least, far from truth. Second, in spite of the lack of quantitative information on the dispersive nature of disaster phenomena, we were able to derive practical information that is applicable to the implementation of disaster safety measures, even if it gives only an average. Third, apart from the quality of data analyzed in this study, the development and introduction of methods to systematically describe the scattering nature of disaster event, as well as its accuracy and reliability, is indispensable as a part of earthquake disaster studies in future.

2. GENERAL

(1) Procedure

Fig.1 (a) shows the general idea that we

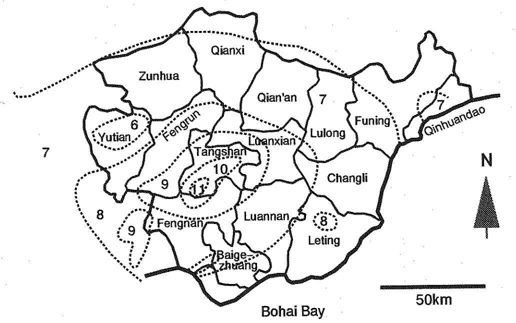

Fig.2 Map of the study area. Dotted lines show isoseismals determined by Yang[4]. Seismic intensities are given on the Chinese scale.

employed in this study. We can compare the flow diagram to a generic model of the procedure of system identification shown in **Fig.1** (b). We have a system to determine (S), an input to the system (I), a tentative output (O), and a target (T) to compare with the tentative output.

We calculated the spatial variation of collapse rate on the basis of an isoseismal map and collapse rate functions for the buildings. We found those data in engineering materials that we collected from Chinese publications. We used the distribution of collapse rate as the input (I) to the fatality rate function, or the system to identify (S).

We, then, calculated the spatial distribution of the death, which is the tentative output (O) in the process of system identification. We compared the calculated distribution of fatalities with the data, which were the target (T) in the procedure. We carried out this procedure searching for an optimum set of parameters that would give the most plausible feature to the fatality rate function.

This procedure is different from conventional methods, where the limited number of point-to-point data of collapse and fatality rates are simply correlated. Since the spatial distribution of material and human loss is analyzed over a large area in this procedure, we would be able to obtain stable results, avoiding instability that is inevitably included point-to-point evaluation of disaster severity.

(2) Study Area

We selected a region, as a study area, that was composed of the city of Tangshan and the Tangshan municipal district at the time of the disaster (**Fig.2**). The municipal district consisted of the city of Qinhuandao, 12 counties, and an agricultural district and had a population of 7 million over a geographical area of 16,500 km^2. The deaths in the study area numbered 205,000, which was approximately 85% of the total in the earthquake.

Table 1 Surface Area by Seismic Intensity[4]

Seismic Intensity	Area (km^2)
11–12	47
10–12	370
9–12	1 800
8–12	7 270
7–12	33 300
5–12	216 000

Note : Seismic intensity 12 is the maximum on the Chinese scale.

In this study, we termed the population by administrative unit, or city, county and agricultural district, as the average of the population density. Detailed data that include the spatial distribution within each unit, particularly the high tendencies in urban centers, were desired, but were not available at the time of this analysis. The population, surface area, and population density were 1.06 million, 800 km^2, and 1,325/km^2 for the city and 5.95 million, 13,500 km^2, and 441/km^2 for the municipal district, excluding the city.

3. ANALYSIS

(1) Seismic Intensity

Yang[4] reported the distribution of seismic intensity as seen in **Fig.2** and **Table 1**. Seismic intensity was measured on the Chinese scale. The Chinese scale, as the Modified Mercalli, MM, and Medvedev-Sponheuer-Karnik, MSK, scales, has 12 as the maximum intensity, while the Japanese scale, which is given by the Meteorological Agency of Japan, has 7 as the maximum.

We idealized the distribution of the seismic intensity using a simple geometrical expression, so that we could simplify the assignment of the seismic intensity at any given location. We used a set of ellipses to do this, since that of circles, which is the most simple and often provides a reasonable approximation, did not seem appropriate in the case of the Tangshan earthquake.

We determined a set of ellipses through the following two steps, a) and b) :

a) Circular approximation

Using circular approximation of isoseismals, we derived an attenuation function based on the data shown in **Table 1**.

We gave a general expression of the attenuation function[5], which gives seismic intensity at an epicentral distance of r, as follows :

$$I(r)=(I_0+a)+br+c\{\log_{10}(r+d)\} \qquad (1)$$

where

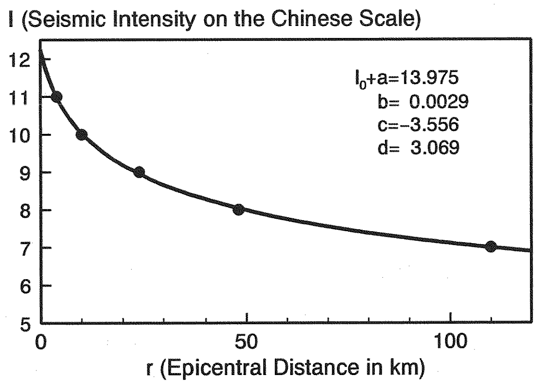

Fig.3 Attenuation function in approximation of isoseismals with circles.

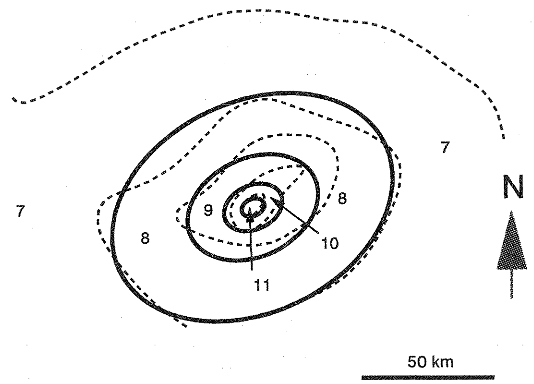

Fig.4 Isoseismals approximated with a set of ellipses.

I : Seismic intensity (Chinese scale)
I_0 : Seismic intensity at the epicenter, or maximum intensity
r : Epicentral distance (km)
a, b, c and d : Arbitrary quantities to characterize an attenuation function.

Since we did not assign the maximum intensity, I_0, we were able to handle (I_0+a) as an arbitrary quantity.

We determined the arbitrary quantities, (I_0+a), b, c and d, applying the method of simplex optimization for curve fitting, in which we used the following definition of the residual :

$$Q_1=\sum_I \{I-I(r_I)\}^2 \qquad (2)$$

where
Q_1 : Residual
I : Seismic intensity (I=7, 8, 9, 10, 11)
r_I : Epicentral distance giving seismic intensity I.

We can evaluate $I(r_I)$ in Eq. (2) using Eq. (1) with $r=r_I$.

We gave epicentral distances at which seismic intensity was I as follows :

$$r_I=(A_I/\pi)^{0.5} \qquad (3)$$

where
A_I : Surface area enclosed by an isoseismal of intensity I.

Through this regression analysis, the arbitrary quantities, which give the attenuation curve shown in **Fig.3**, were determined as follows :

$I_0+a=13.975$
$b=0.0029$
$c=-3.556$
$d=3.069$.

The correlation coefficient between the data and estimates, of which definition is shown in Eq. (4), was obtained at 1.000.

$$w=\sum_j \{(x_j-x_0)(y_j-y_0)\}/\{(n-1)s_x s_y\} \qquad (4)$$

where
w : Correlation coefficient
x : Data
y : Estimate
x_0, y_0 : Averages of data and estimates, respectively
s_x, s_y : Standard deviations of data and estimates, respectively
n : Number of data.

b) Elliptical approximation

We, then, transformed the circles into ellipses, applying the simplex method for curve fitting, as shown below.

A general expression of an isoseismal was given as follows:

$$\{x(\cos\theta)+y(\sin\theta)\}^2/(pr)^2 + \{-x(\sin\theta)+y(\cos\theta)\}^2/(qr)^2=1 \qquad (5)$$

where
(x, y) : Coordinates showing the position of an isoseismal
pr : Major axis of ellipse ($p>1$)
qr : Minor axis of ellipse ($q<1$)
r : Radius of isoseismal when it was represented by a circle
θ : Rotation of ellipse (clockwise).

We used an additional condition to give an ellipse the same surface area as that of the corresponding circle :

$$pq=1 \qquad (6)$$

In the determination of p, q and h through the simplex procedure for curve fitting, we used the following expression to evaluate the residual :

$$Q_2=\sum_j \sum_I \{I(R_{Ij}-r_{Ij})^2/R_{Ij}^2\} \qquad (7)$$

where
Q_2 : Residual
I : Suffix assigning seismic intensity (I= 7, 8, 9, 10, 11)
R_I : Epicentral distance at which

Table 2 Predominant Construction Types of Dwellings in the Tangshan Earthquake

Load-Bearing System	Configuration	Wall Material
Unreinforced Masonry Wall	2- to 4-Story Apartment Building	Brick
Unreinforced Masonry Wall	Single-Story House	Brick, Stone or Adobe
Wood Frame	Single-Story House	Brick, Stone or Adobe

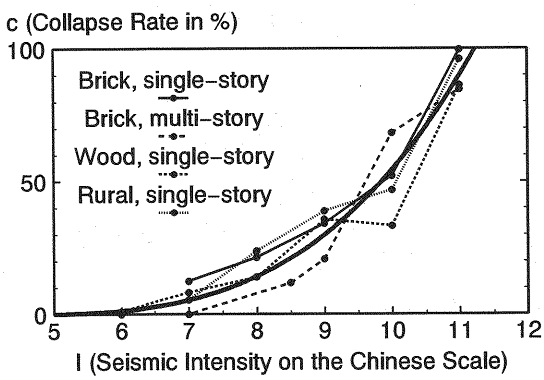

Fig.5 Collapse rate functions. The thick line shows the representative relationship derived with no distinction of construction type. "Rural" buildings include load-bearing wall and wood frame construction having masonry walls of brick, stone or adobe.

observed seismic intensity was $\bar{I}$

r_I : Epicentral distance at which calculated seismic intensity was I

j : Suffix assigning a direction ϕ_j, with $\phi_j=(j-1)\pi/2 \quad (j=1, 2, 3, 4)$.

Coefficients p, q and θ, which derived ellipses shown in **Fig.4**, were determined, as follows :

$p=1.182$

$q=0.8463$

$\theta=-0.141(=-25.4$ degrees).

The regression coefficient between the data and estimates, which is defined as shown in Eq. (4), was obtained at 0.989.

Substituting the coefficients obtained above in Eq. (5), we calculated the seismic intensity for each square area having dimensions of 5 km×5 km to use in the evaluation of the spatial distribution of the death.

(2) Collapse Rate of Buildings

In the 1976 earthquake, the predominant construction types of dwelling structures in Tangshan[6)~9)] were as shown in **Table 2**.

We, unfortunately, did not find any clear data on the relative number of buildings by construction type. However, several publications[6),8)] suggested the limited number of adobe construction, and, for this reason, we excluded adobe houses, of both

Table 3 Distribution of Deaths in the 1976 Tangshan Earthquake[10)]

Area	Deaths
City of Tangshan	135 919
Tangshan Municipal District	69 065

load-bearing wall and wood frame systems, from our analysis.

We defined "collapse" as a damage status where a building is affected "beyond repair."

In **Fig.5**, we enumerate the collapse rate functions, or the relationship between seismic intensity, I, and collapse rate of buildings, c, for various building. The thick line in **Fig.5** shows the regression curve, or the representative collapse rate function, determined on the basis of the 20 data points, which were collected from references 7) and 8) and are shown in the figure, through the procedure described in the following part.

We gave a general expression of the collapse rate function, $c(I)$, which gives the percentage of collapsed buildings as compared with the total number of dwelling structures, as follows :

$$c(I)=\frac{100}{(I_{100}-I_0)^n}(I-I_0)^n \tag{8}$$

where

c : Collapse rate (%)

I : Seismic intensity (Chinese scale)

I_0 : Seismic intensity defined as $c=0$ at $I \leqq I_0$

I_{100} : Seismic intensity defined as $c=100$ at $I \geqq I_{100}$

n : Coefficient that accounts for the non-proportional characteristics between seismic intensity and collapse rate.

To determine the arbitrary quantities, I_0, I_{100} and n, through the of simplex procedue for curve fitting, we defined a residual as follows :

$$Q_3=\sum_I (C_I-c_I)^2 \tag{9}$$

where

Q_3 : Residual

C : Observed collapse rate

c : Calculated collapse rate

I : Suffix to assign seismic intensity.

Fig.5 illustrates that the collapse rate functions were not very much different among the construction types. We, therefore, provided a single function that represents the vulnerability of the buildings in the study area with no distinction of construction type.

The results, which give the thick line in **Fig.5**, were as follows :

$$I_0=4.29$$
$$I_{100}=11.23$$
$$n=3.11.$$

Correlation coefficient, which was evaluated with Eq. (4), was 0.969.

(3) Fatality Rate

We found a description concerning the distribution of deaths[10], as shown in **Table 3**. This seemed to be the most reliable, being released after detailed documentation that took place for the 10 years following the disaster, among the collected data, although it was too rough, or sketchy, to offer sufficient information for an in-depth interpretation.

We determined a fatality rate function, having a criterion in which the function can explain most consistently the data shown in **Table 3**. We also used the spatial variation of collapse rate, which we obtained through the two previous sections, to calculate the distribution of deaths. In other words, we determined the fatality rate function so that the function could consistently correlate the distribution of building collapses and human losses.

We carried out the determination employing the inversion procedure, of which detail is described below.

We gave a general expression of the fatality rate function, $f(c)$, which determines a fatality rate as a function of a collapse rate of buildings, c, as shown in Eq. (10). We gave this expression referring a summary done by Coburn et al.[11]

$$f(c)=F_{100}(c/100)^n \qquad (10)$$

where

- f : Fatality rate (%), or the percentage of deaths as compared with the population before disaster
- c : Collapse rate of buildings (%)
- F_{100} : Fatality rate at $c=100$
- n : Coefficient that accounts for the non-proportional characteristics between the collapse and fatality rates.

We attached a condition shown in Eq. (11). The condition includes a description[10] that the average fatality rate was 25% in the area of seismic intensity 11. We gave the average of collapse rate in the corresponding area at 90% referring to **Fig.5**.

$$F_{100}=25/(0.9^n) \qquad (11)$$

We introduced this condition to avoid coming up with an inadequately high fatality rate in the high

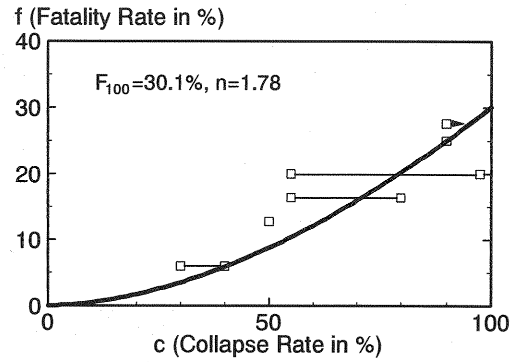

Fig.6 Fatality rate function. Pairs of squares connected with horizontal bars show the range of collapse rate for an area in which a fatality rate was indicated.

end part of the collapse rate. The highest collapse rate, which was close to 100%, was recorded in the urbanized area of the city of Tangshan. While the population density in the urbanized area was significantly higher than the average for the entire city, we used the average in the evaluation of the fatality rate. Therefore, without the above condition, we would have come up with an incorrectly high estimate of the fatality rate to explain the actual death toll. If we give an improperly low population density, we inevitably need a high fatality rate to compensate.

We decided to use the relationship shown in Eq. (11), since that was the most definite and, therefore, seemed to be the most reliable among several data we found in the publications (see **Fig.6**).

The definition of the residual that we used in the optimization was as follows :

$$Q_4=\sum_i (F_i-f_i)^2 \qquad (12)$$

where

- Q_4 : Residual
- F : Observed fatality rate
- f : Calculated fatality rate
- i : Suffix to distinct areas, between the city of Tangshan and the Tangshan municipal district.

Arbitrary quantities for "n" and the corresponding F_{100} were determined as :

$$n=1.78$$
$$F_{100}=30.1.$$

The estimated deaths in the city of Tangshan after the optimization were 124,000 with a fatality rate of 11.7%, while the actual deaths were 136,000 with a fatality rate of 12.8% ; The optimum estimate for the municipal district was 75,000 with a fatality rate of 1.3%, while the data was 69,000

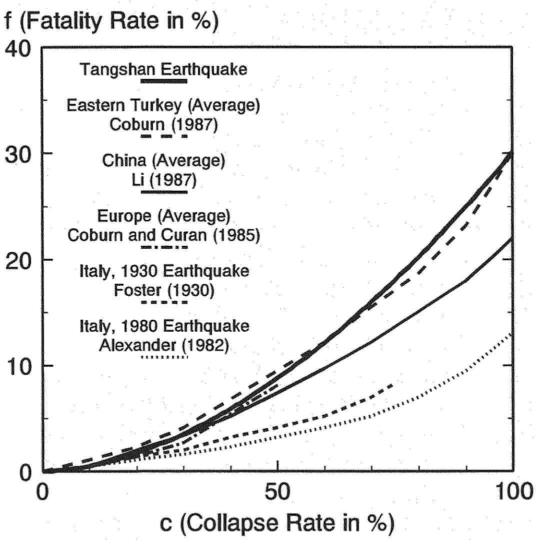

Fig.7 Comparison of fatality rate functions for various types of masonry construction. The relationship for the Tangshan earthquake was determined in this study with $n=1.78$ and $F_{100}=30.1$ in Eq. (9).

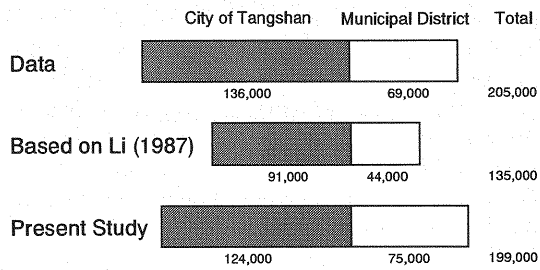

Fig.8 Comparison of death tolls.

with a fatality rate of 1.2%.

These quantities gave the fatality rate function shown in **Fig.6**. Also in the figure are several data, which we interpreted on the basis of descriptions collected from publications on the disaster[10),11)]. We showed these data to compare with the derived function. A horizontal bar connecting a pair of squares shows the range of collapse rate for an area in which a fatality rate was indicated. Namely, the square in the left shows the minimum of collapse rate interpreted from a description, while that in the right shows the maximum. Although most of the data are ambiguous, we can see that the curve is essentially consistent with those fragmental data.

4. DISCUSSION

In **Fig.7**, we compared the fatality rate function determined in this study with those for different types of masonry construction from several parts of the world[12)]. We can point out, first, that the relationship for the buildings in Tangshan is a downward-convex, monotonously increasing function. This general feature is in common with the curves appearing in **Fig.7**, enhancing reliability of the relationship.

Second, we can see that the building collapse in the Tangshan earthquake was more lethal, or life-threatening, than that in the two earthquakes of 1930 and 1980 in Italy. This difference may be explained by the region-to-region variety of construction type and quality, although among other possible reasons are : 1) Occurrence time of an earthquake, on which temporal occupancy depends and 2) Effectiveness of rescue activity. Concerning the three disasters mentioned above, however, we may not have to seriously include the effect of these two factors based on the following reasons:

As for occurrence time, there was virtually no difference, particularly as long as we relate it to temporal occupancy among the three earthquakes. The Tangshan and the 1930 Italian earthquakes occurred at 3:42 a.m. and 0:08 a.m., respectively, and we can appropriately assume an occupancy rate of 100% for each of the two events late at night. Also, we may be able to make an acceptable assumption, for the 1980 Italian earthquake, that most of the population in the affected area stayed indoors at the onset of ground shaking, since it struck mountain villages in the evening (6:35 p.m.) in the late fall (November 23).

As for rescue activity, it does not seem reasonable to expect significant difference among affected areas in the past disasters mentioned above. Local resources, which are composed of man-power of survivors and common tools such as shovels and ladders, are by far more effective as compared with external resources, either national or international. We may be able to appropriately assume that there is essentially no difference in the availability of local resources for rescue activity.

We have realized that the difference in life-threatening nature by the construction type depends on the nature of building collapse and its impact on the occupants. Among the significant factors are : 1) the weight of debris, which affects the initial status of the injury of the trapped occupants ; 2) the amount of void, or interior safe space, remaining in the stack of debris, which affects the entrapment and the survival rate of the victims over time[13)]. However, we need to have an in-depth discussion about this problem beyond the scope of the present study. We must admit that we still do not have enough data to interpret the difference in lethality among construction types in a quantitative manner.

In **Fig.**8, we compared the actual deaths with two sets of estimates that we calculated using two fatality rate functions appearing in **Fig. 7**. One we derived in this study for the buildings in Tangshan, and the other Li proposed as the average for Chinese buildings[14]. The estimates calculated on the basis of Li's relationship are obviously lower compared with the data, as well as our estimates. The lower estimates can be explained simply by the low fatality rates given by Li. For example, he gave a fatality rate of 22% at a collapse rate of 100%, while the corresponding value in our relationship, F_{100}, was as high as 30%.

The difference between the two fatality rate functions, Li's and ours, can be attributed to that between the data employed in each study. Li used data collected from several earthquakes in different parts of China, while we analyzed data only from the Tangshan earthquake. Currently, we still do not have adequate material to discuss the specific reasons why the buildings in Tangshan had higher lethality than the average, but among possible reasons are : 1) the region-to-region variation of the building quality and 2) the difference in occurrence time of the earthquakes.

As for building quality, the regional variation was recognized in several publications, although the discussion was not in the scope of lethal characteristics but of structural vulnerability. For example, in a study carried out by the State Seismological Bureau of China[15], they developed three damage matrixes of brick buildings applicable to different regions of the country, respectively.

As for temporary occupancy, we can point out difference as follows. On the one hand, we derived our relationship on the basis of the data of the Tangshan earthquake, which occurred 3 a.m. having a very high occupancy rate of almost 100%. On the other hand, Li determined his relationship as an "average" on the basis of several earthquakes including those that occurred in the daytime and had a lower occupancy rate.

The procedure we used in this analysis proved itself applicable to the determination of the fatality rate function. It works based on data available even from conventional disaster investigation, including an isoseismal map, collapse rate functions of local building stock, and spatial distribution of casualties. For casualty distribution, what is needed in the procedure is not well-organized data but fragmentary information, as long as quantitative. Since those data are usually available in the past disasters, the procedure can be vastly employed in the determination of the fatality function on a case study basis.

5. CONCLUSIONS

Interpreting published data on the 1976 Tangshan, China earthquake, we determined a fatality rate function, or the relationship between the percent loss of buildings and that of human lives. We constructed the relationship to explain the spatial distribution of the deaths in the disaster. The relationship determined was a downward-convex, monotonously increasing function having a fatality rate of 30% at a collapse rate of 100%.

We can apply this empirical equation to the interpretation of the fatality, including its spatial distribution, in the Tangshan earthquake. The equation is also expected to be applicable to areas where buildings are "similar" to those in Tangshan, although further examination on the "similarity" of construction type is needed. The predominant building types in Tangshan were : 1) single- to several-story, unreinforced masonry of brick or stone and 2) single-story, wood-frame construction having masonry infill walls of brick or stone, and both the types had comparable vulnerability in earthquakes. Inclusion of the region-to-region and country-to-country variation of building quality, in the aspects of both structural vulnerability and lethality, is a problem for future investigation needed as the extension of this study.

Among items for future investigation is the elucidation of the accuracy and relaibility of field data from past disasters. Since seismic intensity and collapse rate are valuable as practically exclusive tools for describing the extensiveness of a disaster, in-depth understanding concerning the nature of such field data, particularly when we use those to derive quantitative information.

The procedure we used in this study is applicable to the determination of a fatality rate function on the basis of disaster data available from conventional investigations. The data needed in the determination are : 1) an isoseismal map, 2) collapse rate functions for local buildings, 3) spatial distribution of casualties, even fragmentary, and 4) elementary regional data including population and geographical area.

ACKNOWLEDGMENTS : The author thanks Dr. Hitomi Murakami and Professor Shigeyuki Okada of Hokkaido University for their collaboration in gathering material carried out in China. He is sincerely grateful to Professor Yutaka Ohta of the University of Tokyo for his support and suggestive discussion. His special thanks are due to Professor Zhengxiang Fu of Center for Analysis and Prediction, State Seismological Bureau of China for his valuable comments and criticisms.

This research was supported in part by grants from the Japanese Ministry of Education (Project Numbers 02044043, Y. Ohta, Principal investigator and 03832036, K. Shiono, Principal investigator).

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(Received April 12, 1993)