A MODEL FOR THE ASSESSMENT OF SEISMIC RISK

Herbert Tiedemann (I)

SUMMARY

A complete model and essential data for the assessment of seismic risk is presented and illustrated with examples related to buildings. The application ranges from general risk assessment and decisions on code standards, site selection, design, risk optimization, impact of earthquakes up to catastrophe level, to calculation of insurance and reinsurance premiums. The two main components of the model are a detailed global seismic index map leading to the site exposure and the mean damage ratio and damage probability distribution per category of object considered. The approach is based on a very extensive data bank.

INTRODUCTION

The basic requirements for quantified earthquake risk assessment are adequate information on event probability (e.g. earthquake magnitude or intensity) and mean damage ratios (MDR), damage probability distributions, or damage probability matrices per category of building, structure, factory, plant, etc., or risks in insurance parlance. Preferrably such data should be available on a global basis, not only to reduce errors in event probability and damage assessments intrinsically associated with a limited sample but because there is a considerable number of professionals and enterprises working in more than one area.

The acute shortage of such information based on adequate observational data covering all interesting seismic regions and the broad spectrum of exposed objects induced us to prepare a seismic index map (SIM) on the basis of global instrumental earthquake observations. Further, earthquake damage to a large number of risks including, e.g. substantially more than 100,000 buildings exposed to about 25 earthquakes were analysed statistically to develop mean damage ratios, damage probability distributions, and damage probability matrices and the correlation to earthquake intensities (MM-31), as well as to quantify the influence of factors contributing to damage.

SEISMIC INDEX MAP

On maps (scale 1 in 1,000,000) all instrumentally recorded earthquakes above about M 5 or mb 4.6 were entered and the seismicity of a region estimated using a counting ellipse with a ratio of 2.5:1 for the long to the short axis, resembling the proportions of average isoseismals. The seismic indices (SI) entered at the respective center of the ellipse which was moved in small steps represents the average number of M 7 - 7.9 events during a period of 79 years. Corrections considered the actual periods of

(I) Advisory member of the management of Swiss Reinsurence Co., Zürich, Switzerland; Engineering Consultant for Swiss Re Group.

of observational capability per region per magnitude group, in particular as in areas of low seismicity extrapolations were necessary. The corrections were based on the 1953 - 1975 magnitude-frequency correlation which was found to hold for all regions within the accuracy obtainable from the respective samples. This smoothed distribution is shown in Table 1.

TABLE 1
SMOOTHED AVERAGE ANNUAL NUMBER OF EARTHQUAKES FOR 1953 - 1975 (WORLDWIDE)

M	$\bar{n}_{ww}$ p.a.	M	$\bar{n}_{ww}$ p.a.	M	$\bar{n}_{ww}$ p.a.	M	$\bar{n}_{ww}$ p.a.	M	$\bar{n}_{ww}$ p.a.
4.3	1,930	5.3	200	6.3	22	7.3	2.0	8.3	0.105
4.4	1,540	5.4	160	6.4	18	7.4	1.6	8.4	0.07
4.5	1,230	5.5	125	6.5	14	7.5	1.2	8.5	0.046
4.6	970	5.6	100	6.6	11	7.6	0.92	8.6	0.033
4.7	770	5.7	80	6.7	9	7.7	0.7	8.7	0.022
4.8	620	5.8	65	6.8	7.5	7.8	0.52	8.8	0.0145
4.9	580	5.9	52.5	6.9	5.7	7.9	0.4	8.9	0.009
5.0	380	6.0	42	7.0	4.4	8.0	0.28	9.0	0.005
5.1	300	6.1	33	7.1	3.4	8.1	0.21	9.1	0.0027
5.2	250	6.2	28	7.2	2.6	8.2	0.15	9.2	0.0009

The long axis of this ellipse covering 125,000 km^2 was placed parallel to the general direction of minimum attenuation of isoseismals or, if unavailable, to fault systems or valleys. It is recognized that the large area of the ellipse as well as its shifting in small steps results in some loss of detail and smoothing of regional characteristics as the incremental movement produces an effect similar to the one of moving means. However, this is only of importance if local tectonic features warrant a differentiation above the level of accuracy obtained by the process used. In such cases corrections are made. In passing it is noted that regional differences in seismicity are often misjudged on the basis of earthquake observations which, however, do not constitute a satisfactory sample and which are sometimes not representative of average long-term seismicity because of seismic gaps or recording during periods of low or, less likely, abnormally high activity.

The seismic index (SI) obtained in this way (cf. Fig. 1) is corrected individually where required for the effect of seismic gaps or trends in global seismicity. Further, corrections are possible for the effect of strong aftershocks, abnormal seismic sequences, and with the help of historic data. A global seismic index map will be published shortly.

PROBABILITY OF EXPOSURE AT A PLACE

One way of correlating damage to be expected with seismicity is via intensity. This holds so far in particular for buildings. The approach described hereunder may be illustrated with the help of a cratering analogy. One may assume that there is a correlation between the diameter and depth of craters caused by shelling or bombing of an area. If we deem that intensities are represented by lines of contours connecting points of equal crater depth we would obtain a two-dimensional picture which is rather similar to isoseismal maps, except for the fact that isoseismals are rarely roundish. We may, further, argue that if size and topography of craters per size of bomb or shell as well as the frequency distribution of the projectiles are known, one may estimate the probability that a certain place is in a particular depth-region of a crater, i.e. we may calculate the probability of a certain intensity being observed at a place. (We shall not consider here complicating factors like multiple cratering, grouping of craters, or systematic aberrations of cratering from random performance.)

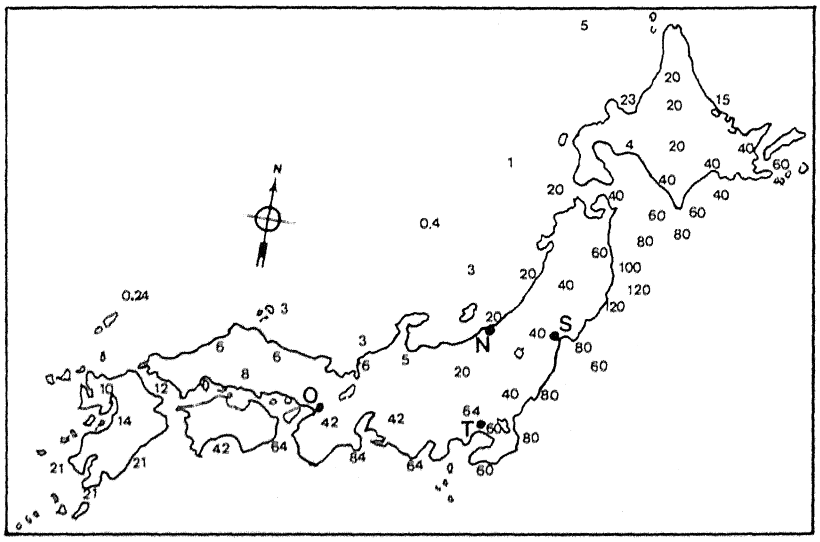

Fig. 1. Section of a somewhat simplified version of a Seismicity Index Map (SIM) showing Japan. As discussed in the text instrumentally recorded earthquakes were considered allowing for a correction factor considering the actual period of observation per magnitude class.

From a global sample of some thousand observations we have calculated the average correlation of gross isoseismal areas per intensity and for one tenth magnitude steps. Herefrom the net area per intensity may be derived. It is stressed that there are not enough reliable observations for MM X and above and that local corrections are necessary to allow for deviations from the global average.

One may now multiply the relative number of events per magnitude step with the respective net isoseismal areas and sum the resulting values to obtain the global average annual cratering, to revert to the analogy used earlier. However, the cumulative areas obtained this way should not be used to calculate return periods. The first reason is that a lower cut-off magnitude should be established according to the resistance of the structures assessed and, further, that epicentral counting of earthquakes does not consider depth-distribution of hypocenters which reduces the effect of events as foci are assumed at progressive depth. The depth correction appied in the material presented here is based on events recorded between 1953 and 1977. Again local corrections are needed because certain regions show a cumulative depth-frequency of foci which is quite different from the global average. The surmised somewhat different depth-distribution of great earthquakes is not considered at this place as their contribution to overall damage is comparatively insignificant. The lower cut-off magnitudes were selected between about the equivalent of M 4.9 for buildings of 2%g base shear and M 6 for those of 15%g. As regards influence of depth of foci it was assumed that attenuation in this direction is similar to the one along the long axis of elliptical isoseismals. The result of this evaluation is shown in Fig. 2, i.e. the effective area per intensity and depending on the magnitude.

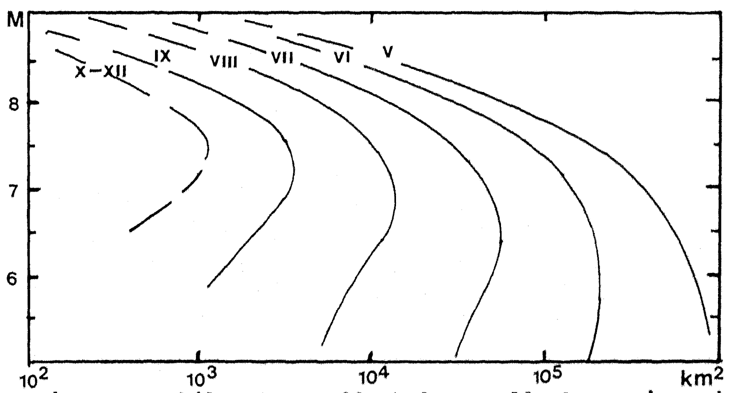

Fig. 2. Area in square kilometers affected annually by various intensities according to the magnitude of the earthquakes. As explained in the text the calculation is based on smoothed average annual numbers of events per one tenth magnitude step and on corresponding average net isoseismal areas. The effect of the average global depth-distribution of foci has been considered.

The next step is calculating the effective area of intensities, viz.

$$A_{eff_{MM_i}} = \Sigma_{M_l}^{M_u} (n_d \, A_{d_{MM_i net}}) \quad , \qquad (1)$$

that is, the sum from the lower magnitude limit to the upper one assumed (M 9.2) of the product of the number of events per depth range and the area at the surface of the corresponding intensity related to events of that hypocentral depth and magnitude step. To permit easy intensity and building quality interpolations the result is shown in Fig. 3.

We may now calculate the return pariods of intensities or of corresponding damage levels (cf. Fig. 4) as follows

$$R_{MM_i;MDR} = \frac{A_{count} \, n_G \, OP}{f_G \, f_T \, f \, SI \, A_{eff}} \quad . \qquad (2)$$

Herein A_{count} is the surface of the counting ellipse (125,000 km^2), n_G is the global annual number of reference-magnitude events (M 7 - 7.9), i.e. 17.74, OP is the observational period used (79 years), f_G is a correction factor for seismic gaps and f_T one for seismic trends whereas f takes care of the statistical uncertainty related to the observational sample and the confidence range desired. SI represents the seismic index of the place and A_{eff} is the effective area selected from Fig. 3. Taking Tokyo and 20%g buildings as an example and calculating here without corrections ($f_G, f_T, f = 1$) we obtain for MM IX

$$R_{MM\ IX} = \frac{125{,}000 \cdot 17.74 \cdot 79}{1 \cdot 60 \cdot 57{,}165} \approx 51 \text{ years} \quad .$$

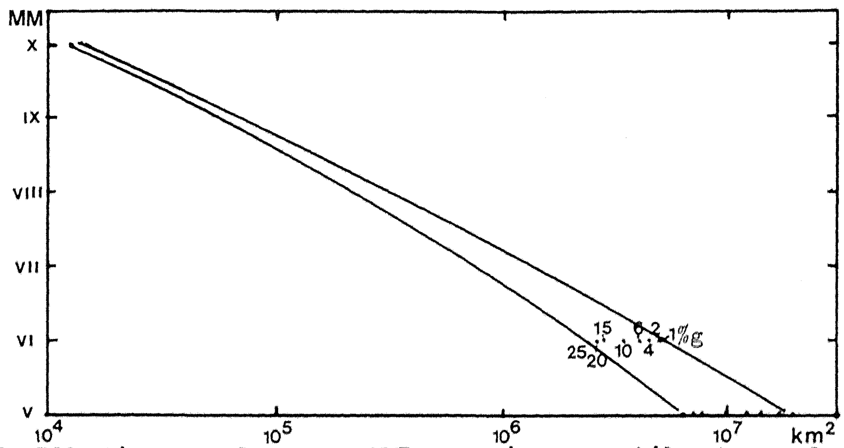

Fig. 3. Effective annual average MMI-areas in square kilometers calculated as shown in the text and considering lower and upper magnitude limit. For use in return period calculations local corrections are needed.

One may not wish to assess the exposure according to intensities but based on magnitude or acceleration, the latter a questionable yardstick for damage but firmly entrenched in the minds of many dealing with earthquake engineering. As magnitudes are not area-related contrary to isoseismals we may ask for the chance of a certain magnitude within a selected distance which may be chosen according to attenuation and subsoil in general, acceleration attenuation, etc. Using in principle the approach described earlier we may write

$$R_{M_i}(\Delta, a) = \frac{A_{count}\ OP}{f_G\ f_T\ f\ SI\ \frac{n_{M_i}}{1.2}\ F_{M_i}\ \frac{2}{3}\ f_d} \quad . \qquad (3)$$

The symbols which do not appear earlier mean: n_{M_i} is the number of events of the selected magnitude (Table 1), F_{M_i} is the area of the ellipse according to the long axis selected, and f_d is the correction factor for the depth distribution in the particular region. Reverting again to the example of Tokyo and asking for the return period of a M 8.3 event within, e.g. 200 km on the long and 80 km on the short axis of an elliptic surface and using the depth distribution of foci in region 19 we would obtain, again without corrections

$$R_{M\ 8.3;\ 200/80\ km} = \frac{125{,}000 \cdot 79}{1 \cdot 60 \cdot \frac{0.105}{1.2} \cdot 50{,}265 \cdot \frac{2}{3} \cdot 0.95} \approx 59 \text{ y}$$

Let us look very briefly at corrections for seismic gaps and trends considering f_G first. In the absence of better information one may use the SIM. If there are no sound and convincing reasons supporting a SI of a place which is quite different from others in the area one may suspect a deficit in energy release as we christened the issue more than a dozen years ago or, in present terminology, a seismic gap. It is, e.g. seen in Fig. 1 that further up or down the coast of Honshu, SI's are higher than in the region of Tokyo. Similarly a lower SI is noted off Sendai (S, Fig.1). Taking this as a symptom of a seismic gap one could estimate that the SI of Tokyo should be corrected accordingly, i.e. 80/60 = 1.3 for f_G.

As regards global seismic trends we have concluded from a catalogue of damaging historic earthquakes which we hope to publish in due course as it would considerably upgrade and amplify information and data available, that the non-randomness in energy release seen in seismic gaps also holds on a global scale. For the time being one may estimate from the seismic index map and Ref. 1 that part of the last global very active period lasting from about 1852 to 1911 caused the rather high SI of 120 east of the northern coast of Honshu. As a first hand approach, a detailed discussion is beyond the scope of this paper, we may estimate $f_T \approx 120/80$, i.e. about 1.5.

As the SI provides information on the number of earthquakes to be expected in an area one may, allowing for actual observation periods which depend on magnitude, and selecting confidence ranges, calculate the statistical correction factor f.

DAMAGE PARAMETERS

A number of publications contain information on MMI/MDR correlations (cf., e.g. Ref. 2 - 10). As most of such data does not cover the wide range of building quality actually encountered and as much of such information does not quantify or consider adequately the influence of factors determining MDR, like subsoil, site effects, orientational sensitivity, asymmetry and irregularity, performance of non-structural components, or compatibility of different building materials as regards performance under dynamic load, we have started publishing the lessons learned when analysing a large number of objects exposed to earthquakes, taking care to cover the entire range from no damage to total failure (cf., e.g. Ref. 11 - 17). For the sake of this paper we use the average correlation between intensities and MDR based on building resistance (Fig. 4). It was derived for buildings of moderate irregularity and founded on medium-hard alluvium. Some indications dealing with corrections for conditions other than those underlying Fig.4 may be found in the references cited; a comprehensive treatment will be published soon also covering risks other than buildings.

RISK RATING

One may now rate the risk, e.g. in permille p.a. as below (X) for insurance purposes, cost-benefit assessments, site evaluations, design decisions, etc., for instance according to the following formula

$$X_{(\text{‰ p.a.})} = \frac{1{,}000\ \Pi f}{V} \sum_1^n \frac{LE_i\ u_i\ P_i}{R_i} \qquad (4)$$

in which Πf is the product of the correction factors, 1,000 a constant to obtain the risk-rate in permille of the value of the building or project (V) the expected loss (LE) can be correlated with the MDR (Fig. 4) if there are no deductions, priorities, or indemnity limits as applied in insurance, P is the period of exposure in years and R is the return period of the different intensities within the range selected.

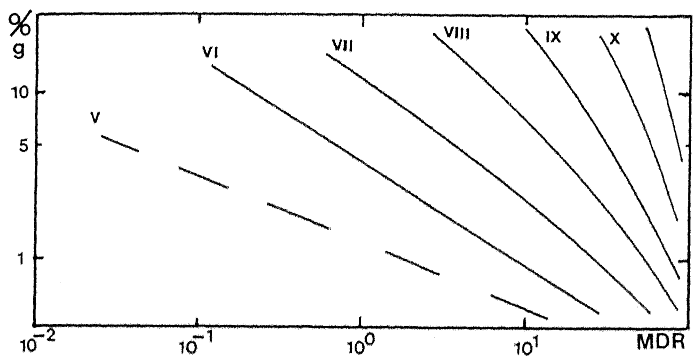

Fig. 4. Mean damage ratio (%) depending on building quality expressed as base shear (%g) and on intensity. Graphs apply to buildings of moderate irregularity and founded on medium hard alluvium.

Sticking to the example of 20%g buildings in Tokyo we would obtain on the basis of $\Pi f = 1$ but allowing for uncertainties (u) at 90% confidence level related to the LE/R-complex, and considering intensities IX to VII and P equal to 1 year

$$X = \frac{1{,}000}{100}\left[\frac{12 \cdot 2.0}{51} + \frac{3 \cdot 1.4}{12.5} + \frac{0.4 \cdot 1.2}{3.5}\right] = 9.44\text{‰ per year}$$

To conclude the discussion on risk rating we may briefly mention the question of damage probability matrices and present Table 2 to indicate the number of cases found on the average in the various damage states depending on the MDR (cf. also Ref.17). It is stressed that only for an absolutely homogeneous sample are deductions on losses possible on the basis of numbers of cases per damage state without considerable error. Using such information one may estimate the chance of being confronted with damage above the MDR on the basis of the R_{MM_i} calculated (2).

TABLE 2

DAMAGE PROBABILITY MATRIX FOR BUILDINGS (GLOBAL AVERAGE)

DAMAGE CLASS	M E A N			D A M A G E			R A T I O			(%)
% of Value	1.5	3	5	10	25	37.5	50	60	70	85
0 - 1.5	83	73	60	36	9	2				
1.5 - 3	17	25	26	23	9	3				
3 - 6		2	10	18	11	5	2			
6 - 12.5			3	12	18	12	6	2	1	
12.5 - 25			1	8	24	24	15	7	3	
25 - 50				3	19	28	29	23	18	10
50 - 100				1	10	29	48	68	78	90

CONCLUSIONS

The model presented may be refined considerably. On the SI-side one may incorporate historic data and it is hoped that high-precision laser ranging will open a further avenue. As regards consequences of earthquakes we are trying a new concept, viz. isonoxiae, lines of equal MDR for buildings and other structures of specified resistance per magnitude step. This would eventually do away with the circuitous and problematic approach via intensities. Further, damage statistics on a variety of risks and, in particular from great earthquakes are presently inadequate as is information on fire following earthquake related to various industries.

REFERENCES

1. Swissre, 1977, Atlas on Seismicity and Volcanism, Swiss Reins. Co. Zürich
2. Culver, et al., 1975, Natural Hazards Evaluation of Existing Buildings, Building Science Series No. 61, U.S. Govt. Print. Off., Washington, D.C.
3. Sauter, F. and Shah H.C. 1978, Estudio de Seguro contra Terremoto, Instituto Nacional de Seguro, San Jose, Costa Rica.
4. Steinbrugge, et al., 1969, Studies in Seismicity and Earthquake Damage Statistics (Appendix A) U.S.G.S., Washington, D.C.
5. Steinbrugge, K.V., 1971, Modified Mercalli Intensity Relationships to Wood Frame Dwelling Earthquake Insurance, Technical Paper.
6. Iordacescu, E. et al. 1979, Statistical Surves of the Performance of one Standard-Design Type, etc. Building in Bucharest, Proc. 2nd Nat Conf. on Earthquake Engineering EERI, Stanford University, 803-812.
7. Marsal, R. J., 1957, Efectos del Macrosismo registrado et 28 de Julio en las construcciones de la ciudad, Symp. Org. Nac. de Est. Ing., Mexico.
8. Veneziano, D., 1975, Probabilistic and Statistical Models for Seismic Risk Analysis, MIT Publication No. R 75-34, Cambridge, Mass.
9. Whitman, R.V., 1973, Damage Probability Matrices for Prototype Buildings, MIT Structural Publication No. 380, R73-57, Cambridge, Mass.
10. Whitman, R.V. et al., 1974, Seismic Design Decision Analysis, Methodology and Pilot application, MIT Publ. No. 385, MIT-CE-R74-15, Cambridge, Mass.
11. Tiedemann, H., 1980, A Statistical Evaluation of the Importance of Non-Structural Damage to Buildings, 7th WCEE, Istanbul, Vol. 6. 617-624.
12. Tiedemann, H., 1981, The Effect of Building Quality on Earthquake Damage, Journées Scientifiques Sur le Seisme D'Ech-Chelif, Alger
13. Tiedemann, H., 1981, Some Statistics of the South Italian and Algerian Earthquakes, Symposium on Earthquake Engineering, Roorkee, India
14. Tiedemann, H., 1982, Structural and Non-Structural Damage related to Building Quality, 7th Europ. Conf. on Earthqu. Eng., Athens, Vol. 6, 27-34
15. Tiedemann, H., 1982, Quantification of Factors Contributing to Earthquake Damage in Buildings, Europ. Seism. Comm. Symp., Univ. of Leeds, U.K.
16. Tiedemann, H., 1982, Quantification of Factors Contributing to Earthquake Damage in Buildings, 7th Symp. on Earthqu. Eng., Vol 1, 203-207, Roorkee, India.
17. Swissre, 1982, Earthquake Risk Assessment, Swiss Reinsurance Co. Zürich.