calamities are often responsible for loss of data or incomplete recording. Moreover, complete recording would require dense settlements in all regions of a country and this is practically never the case. Therefore historical data will only provide examples of seismicity and at its lowest level and one must carefully search for gaps in such catalogues and ascertain their reasons (3).

There are not only regional seismic gaps, i.e. zones where for an alarmingly long period earthquake energy has accumulated, but there are also global seismic trends, that is periods of world-wide above-average activity alternating with others during which far fewer earthquakes occur. Since about 1911 global earthquake activity has dropped very much. It is stressed that the notion that this "global seismic gap" was closed, e. g. by the 1960 Chile earthquake, is ill-founded.

Historical catalogues and reasoning show that this trend will one day be reversed. During the more active periods earthquake frequency can be several times higher than it has been in recent decades. These facts must be considered in catastrophe probability assessment. Japan, for instance, experienced far more great earthquakes, i.e. of a magnitude of M 8 and above, in the years from 1891 to 1906 than in the course of the 83 years since then.

It is interesting to compare the high earthquake intensities observed during the historical period in Armenia with periods during which global seismicity was substantially above average.

The earthquake reported near Vedi in 139 AD falls into a high seismicity phase (HSP) extending about from 110 - 141 AD.

The earthquake reported near Azizbekov in 735 AD is within the HSP from about 732 - 749.

According to the voluminous global historical catalogue compiled by the author there was an extended phase of high seismicity from about 840 until 892 AD. Within this period the years from 854 - 863 showed very high seismicity (VHSP). It is interesting to note that earthquakes of considerable intensity are reported about south of Yerevan for the years 851, 858, 863, and 869. Two of them coincide with the VHSP mentioned, the 869 event coincides with a sub-peak within the HSP.

The event of 972 AD north-west of Yerevan and south-east of Talin antedates a phase of elevated seismicity (ESP) by a small margin. This ESP lasted from 973 - 978.

North-west of Anipemza a high intensity is reported for 1045 falling into a HSP from 1031 - 1070. The event of 1132 in this area concides with a HSP lasting from 1110 - 1139.

There was a HSP from 1600 - 1619 and a further one from 1646 - 1692. Into the first falls the earthquake of 1605 south-east of Anipemza into the second the earthquake of 1679 south-east of Yerevan.

The high intensity recorded in 1827 west of Sevan falls into the HSP from 1819 - 1835.

The event of 1863 north of Sevan and the one of 1910 south-east of Yerevan are part of the HSP lasting from 1852 until 1911.

According to a preliminary evaluation of HSP's since 358 AD the author found that very active phases appear to have a return period of approximately 139 years, one standard deviation amounting to 48 years. The last HSP started in 1852. It comprised two peaks lasting from 1852 - 1872 and from 1894 - 1911. Even if such preliminary evaluations must be interpreted with care, the extreme exposure of human beings and the colossal accumulations of values suggest that we should consider not only local seismic gaps but also global seismic gaps, i.e. trends, as they may increase the hazard enormously. According to a study which we completed recently there appear to be about 19 great earthquakes (M 8 and above) missing in the respective gaps of the global seismic zones.

A correlative evaluation of volcanic eruptions by the author showed that phases of high volcanic activity (HVP) are correlated with HSP's. The peak of volcanic activity follows the one of the HSP as to be expected according to geophysical reasoning. The average time-shift amounts to 7.5 years and one standard deviation is 3.7 years. This correlation of independent events, i.e. seismicity and volcanism, supports the deduction of seismic trends (3).

Another substantial problem in the hazard assessment is the uncertainty of the attenuation of earthquake intensity as a function of epicentral distance. The extent and shape of isoseismals depend on many parameters, for instance, the extent, type and configuration of rupturing and faulting, the type and characteristics of the geological layers and in particular on the surface geology, etc. Damage caused by shaking of a certain intensity depend inter alia on the depth, composition and softness of the uppermost layer(s) and on their water content including the level of groundwater. The latter parameters differ much between the dry and the rainy season. Attenuation also depends on hypocentral depth.

This means that the area affected by future earthquakes can vary very much and is subject to considerable uncertainties. The graphs in Fig. 4 represent global averages of the gross area affected by different intensities as a function of earthquake magnitude and can be used as a guideline.

Ordinary earthquake maps do generally not offer much guidance on event probability because they mostly give only earthquakes or intensities observed in the past without stating frequencies or probabilities. If probabilities are given such maps generally offer no more than a crude indication. At the same time one notes that there is a growing need for exposure evaluation by those who lack special data banks and/or expertise, and that even experts are sometimes misguided by the limited regional sample of earthquake observations at their disposal, in particular in the less seismic regions of the globe.

Recognizing such problems and requirements, we many years ago developed a Seismic Index Map (SIM). This map, which was originally developed for our own requirements and was refined repeatedly, was presented at the 8th World Conference on Earthquake Engineering in San Francisco in July, 1984 (4). Several updated versions of these map will be ready for distribution along with a handbook in a few months (3). A correlated evaluation of the versions assists in locating seismic gaps as they exist today, in addition to permitting intensity or magnitude probability assessments for the place selected by the investigator. A section of one of these Seismic Index Maps covering the Caucasian region is shown in Fig. 5.

Reference (3) also contains a descriptive catalogue of about 2,500 damaging historic earthquakes which assist assessments when addressing zones of low seismicity. As mentioned earlier it must, however, be noted that historical catalogues are bound to be incomplete for many reasons and therefore generally only indicate the minimum seismicity one should be prepared for.

The Seismic Indices (SI) are used to calculate for instance the return period **R** of selected intensities (MM) or MDR's (mean damage ratios) with the aid of the following formula (cf. (5)). It is stressed that this formula does not give the return period of earthquakes for a comparative large area but for a town, i. e. what one may call the "point probability". As regards intensity one may convert MM to MSK using known conversion rules.

$$R_{MM;\,MDR} = \frac{A_{count}\ n_g\ OP}{f_G\ f_T\ f\ SI\ A_{eff}}$$

Herein A_{count} is the area of the counting ellipse used when developing the attached SIM. In the map presented in Fig. 5 it is 125,000 km², n_G is the global annual number of reference magnitude earthquakes (M 7 - 7.9), i.e. 17.74, **OP** is the observational period used (90 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. **SI** is the seismic index of the place studied according to the SIM. A_{eff} is the effective area of intensities selected from Fig. 6.

To simplify the use of the formula the values of A_{eff} are tabulated below in Table 2. A general description of the model used is presented in (4), a detailed discussion with numerous examples in (3).

TABLE 2
Effective Area (A_{eff}) in km^2 depending on Base Shear (BS) and MM Intensity

BS	X-XII	IX	VIII	VII	VI	V
1 % g	18,845	71,945	320,800	1,369,000	5,428,400	19,737,900
2 % g	13,100	69,380	307,500	1,293,400	4,953,400	16,857,900
4 % g	12,800	66,765	292,500	1,203,400	4,421,400	14,117,900
6 % g	12,700	64,955	281,500	1,137,900	4,036,400	12,387,900
10 % g	12,300	61,985	263,000	1,126,900	3,428,400	9,957,900
15 % g	11,900	58,459	241,400	894,900	2,805,400	7,747,900
20 % g	11,500	57,165	233,300	845,900	2,600,400	7,057,900
25 % g	11,000	55,715	224,600	94,900	2,397,400	6,397,900

NOTE: Adobe, Torquezal and Rubble Masonry Buildings have a Base Shear between about 0.6 % and 1% of gravity. The Base Shear of normal unreinforced Brick buildings with Solid Walls is about 1.5 % g. Cavity walls of brick have a base shear below 1.5 % g.

For SI = 1 and taking all correction factors equal to 1 we can calculate that the average return period for MM VIII and buildings of a quality similar to UBC 3 (Uniform Building Code, Zone 3, USA) is about 622 years. For more vulnerable buildings, e.g. UBC 2 we would obtain about 584 years. It is mentioned in passing that the quality of many buildings in Yerevan is not better than UBC 2 (cf. III. SPECIFIC THREATS AND ISSUES, I. Earthquakes). For a SI = 0.5 and UBC 2 buildings the return period would be about 1,200 years.

With different formulae (cf. (3)) it is possible to calculate the probability of earthquakes of selected magnitudes or of certain acceleration levels likely to be generated by such earthquakes.

RECOMMENDATIONS

1. It is strongly recommended to subject the region of Armenia to a detailed assessment of the seismicity. Main issues which should be considered are:

    - The historical record of earthquakes should be completed and critically evaluated.
    - The region of Armenia should be searched for seismic gaps.
    - The influence of global seismic trends should be studied.
    - Isoseismals and attenuations of past earthquakes should be carefully reevaluated, considering the damage potential from low-intensity, low-frequency shaking on tall, soft buildings founded on deep alluvial layers. Scatter in attenuation must be considered.
    - It is essential to estimate safety factors related to seismicity estimates and to state them clearly.

- Although this subject has not been discussed in this section it is very important that microzonation maps are completed soonest for the densely populated regions of Armenia. These maps must consider the respective parameters controlling exposure as discussed under III. A. 1. Earthquakes.

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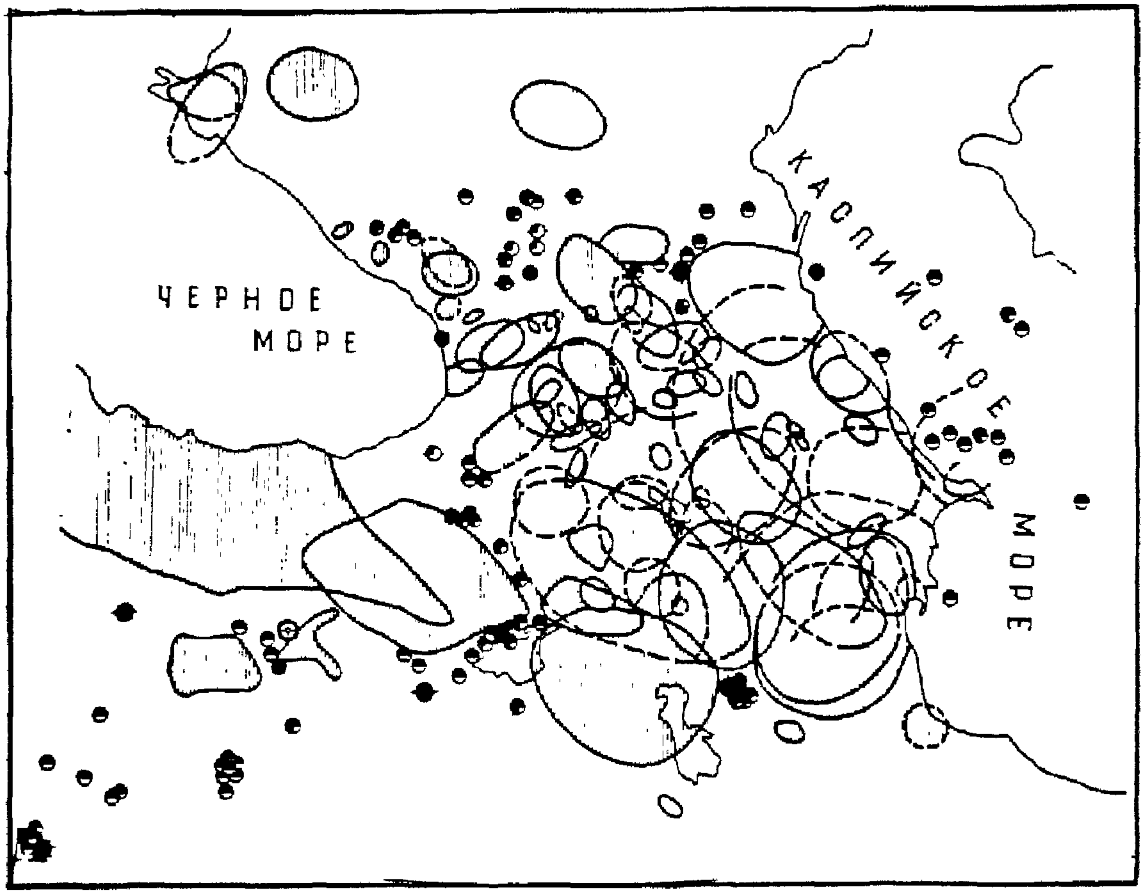
3. Tiedemann, H., Earthquakes and Volcanic Eruptions: A Handbook on Risk Assessment, Swiss Reinsurance Co., Zurich (available by end of 1989 or early in 1990).
4. Tiedemann, H., A Model for the Assessment of Seismic Risk, 8th WCEE, Vol. 1, 199, San Francisco, 1984.
5. Tiedemann, H., The Assessment of the Economic Consequences of Earthquakes: A Scientific Approach, USSR/UNDP/UNDRO Training Seminar, Dushanbe, 1988

Fig.1. Maps of historical isoseismals and epicentres for Armenia put at our disposal during our visit to the Seismological Institute in Leninakan. These maps resulting from the research of an Armenian scientists demonstrate beyond any doubt that the entire region is seismic, i.e. that there are no large regions free of earthquakes. The epicentral map and a similar one for instrumentally recorded earthquakes indicates a seismic gap which is discussed in the main text and which extends from west of Yerewan to south of it and to Lake Sevan and to the north-east of the latter.

Fig. 1



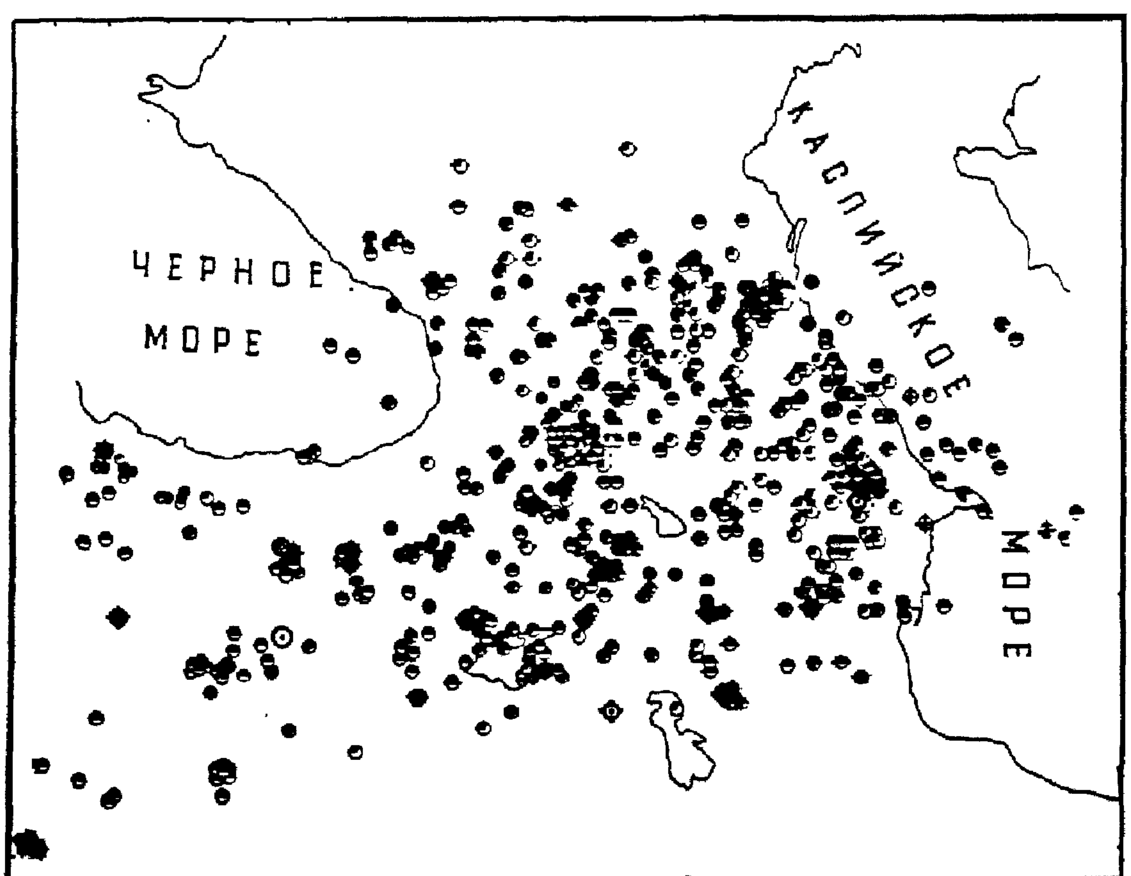
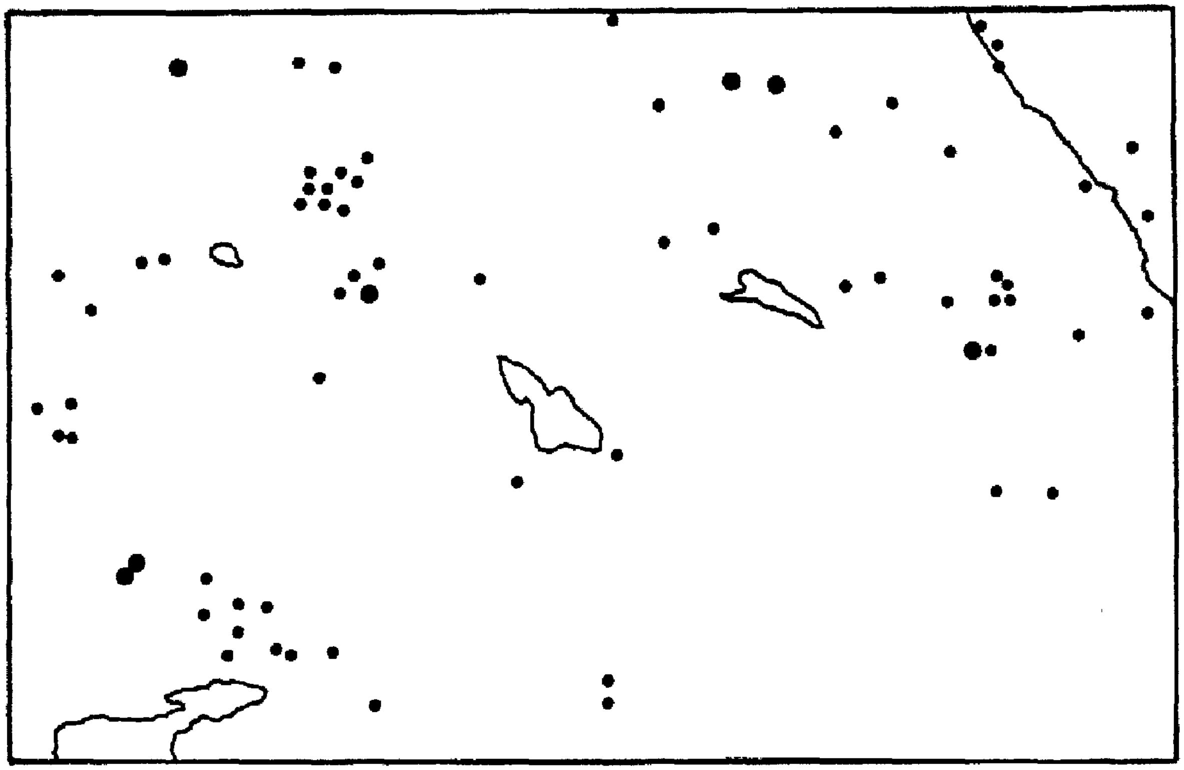


Fig. 2. Simple map of the Caucasian region with Lake Sevan at the centre. Instrumantally recorded earthquakes (cf. Table 1) have been entered, starting with about M 5½. Part of the large zone extending from Turkey, south-west of Yerevan to Lake Sevan and beyond may be a seismic gap. In view of the very large number of people living in this region in comparatively vulnerable buildings, many of which are founded on soft subsoil, a detailed analysis is recommended to determine the exposure to the highest degree of precision which may presently be achieved.

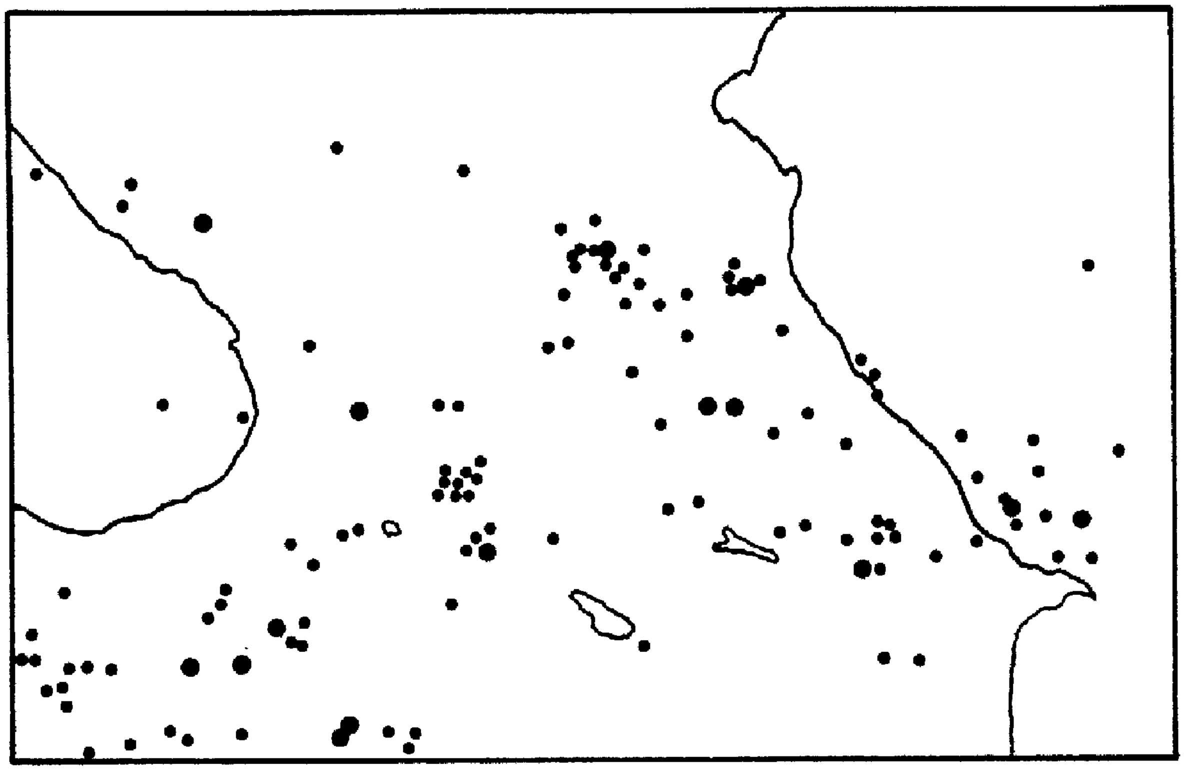
Fig. 2



• M 5 – 5.9 ● 6 – 6.9

Fig. 3. Schematic map with earthquakes above about M 5.5 in the region of the Caucasian Mountains. It is seen that there is a fairly large region without earthquakes in the western part of the Bolshoy Kavka . This could indicate a seismic gap in this region. Moreover, if counting the M 6 - 6.9 earthquakes it is seen that their number reached the ratio of this magnitude group to the M 7 - 7.9 magnitude class. This may be taken as a warning that an earthquake of the latter magnitude class is probable. Details are discussed in the main text.

Fig. 3



• M 5 – 5.9 ● M6 – 6.9

Fig. 4. Correlation between gross area in square kilometers affected by different intensities, for instance, MM VIII and above and magnitude of the earthquake. The correlation is based on global averages. We have found a consistent correlation although the scatter of the size of the area per intensity step is considerable for each magnitude step. This is to be expected even if erroneous intensity assignments are eliminated from the sample because there are still numerous other parameters determining the areas affected by different intensities. From the gross areas the net areas can be calculated by subtracting the areas of higher intensities.

Fig. 4

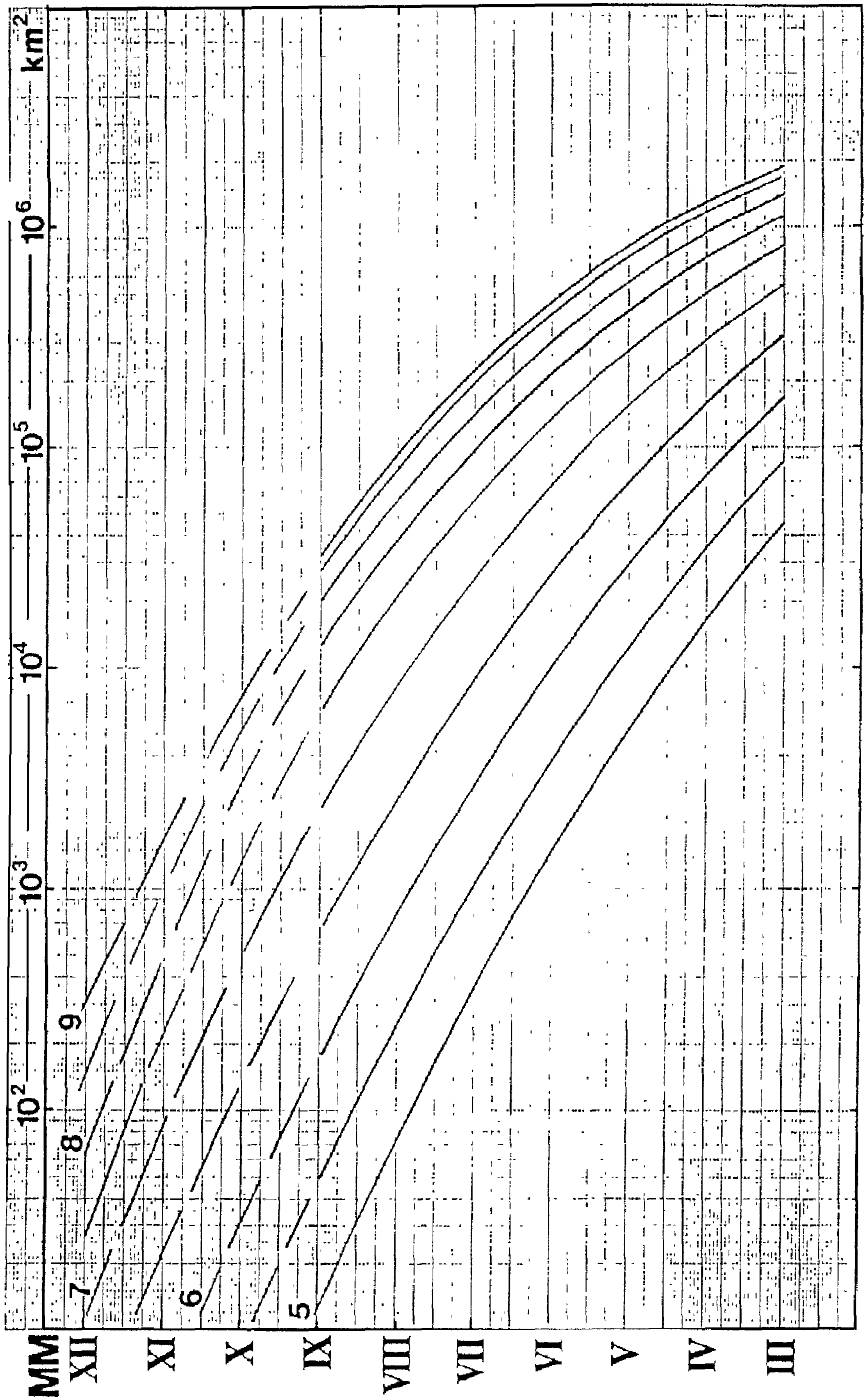


Fig. 5. Simplified version of our Seismic Index Map (SIM) based on a counting area of 125,000 km^2. The Seismic Index (SI) of an area can be used to estimate the average return period of intensities as explained in the main text. The different uncertainties discussed in the paper must, however, be considered. The areas surrounded by broken lines are potential seismic gaps. Areas where no SI has been entered should under no circumstances be considered aseismic. Such a SIM can form the basis for general hazard assessment. A detailed assessment must consider historic earthquake catalogues, not overlooking that such lists are generally incomplete and afflicted with errors, tectonic data and interpretation of active faults.

Fig. 5

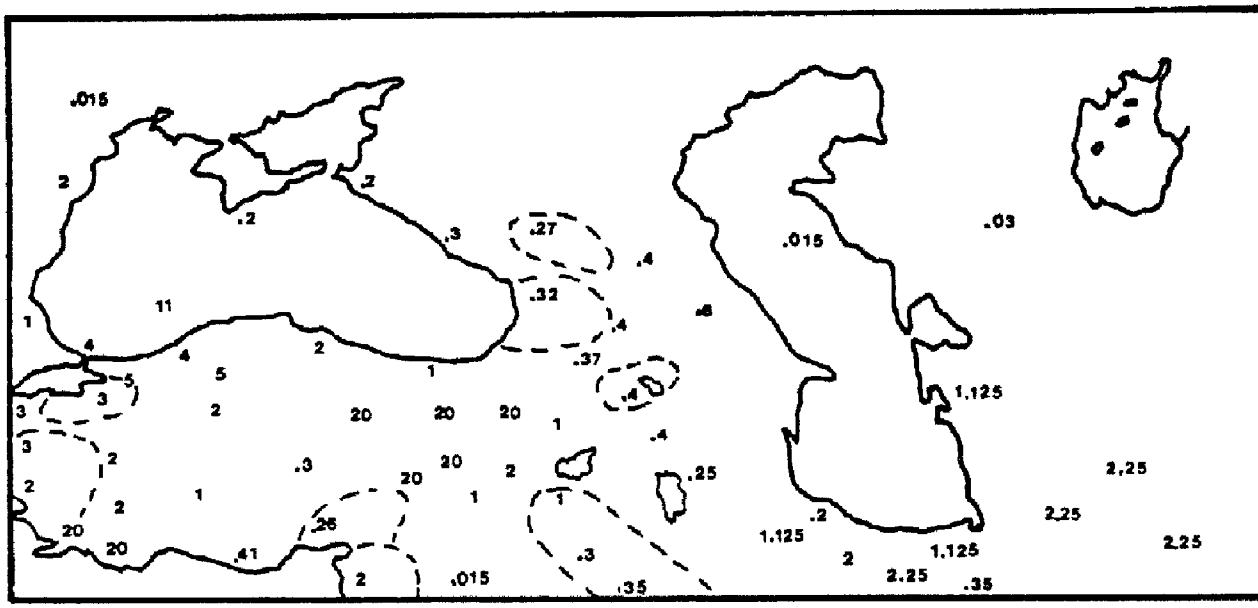


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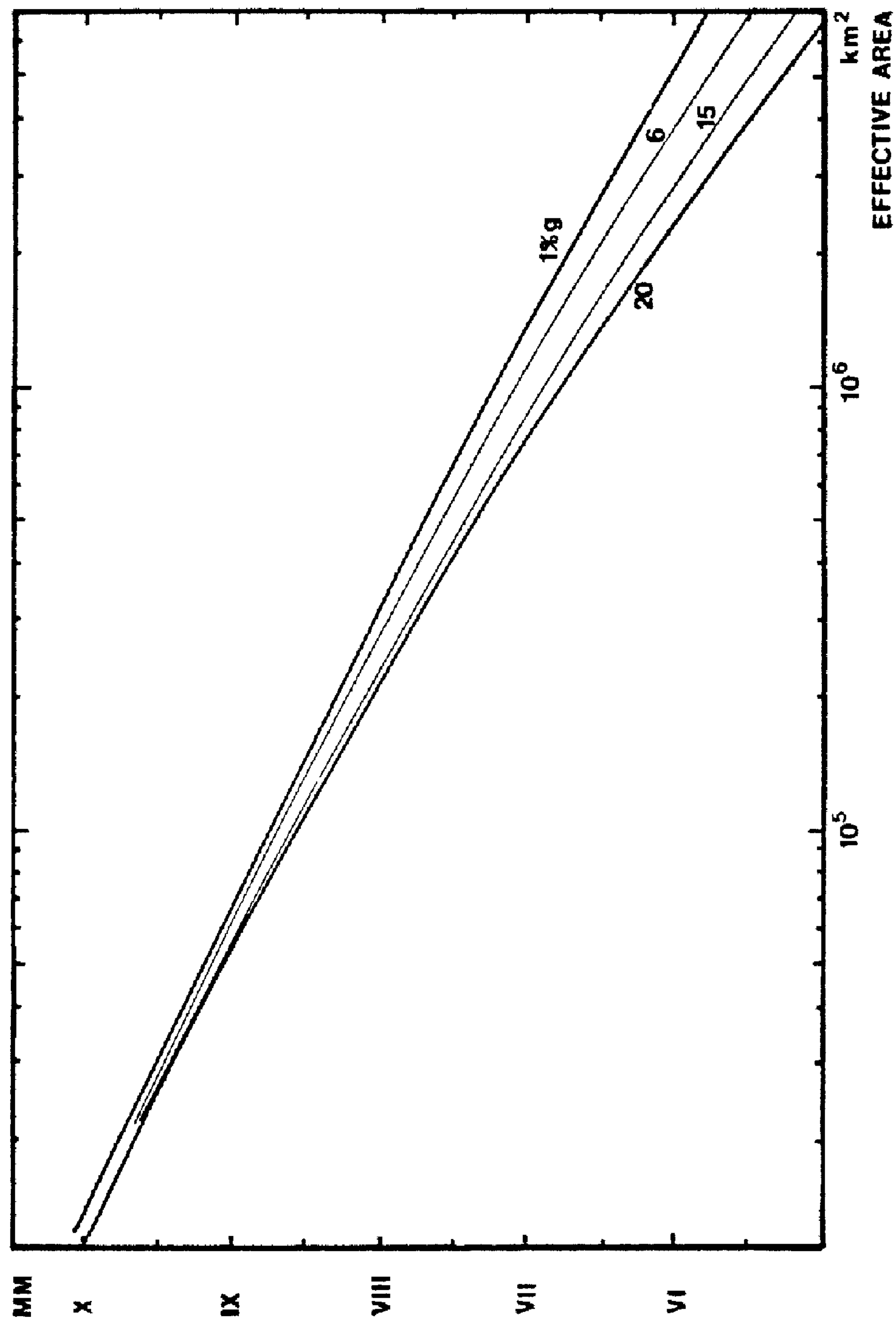
Fig. 6. Graphs of the effective MMI-areas which result if the effect of depth distribution of hypocentres as regards numbers of events per depth-range and the corresponding reduction in isoseismal area is considered. The graphs have been calculated for the global average depth distribution, global average isoseismal area per step of one tenth of a magnitude magnitude, and lower cut-off magnitudes ranging approximately between m_b 4 to 4.5 and M 5.8 depending on building standards. The latter have been indicated as base shear strength in percent of gravity, i.e. ranging from 1% g to 20% g in this case. A number of corrections are thus needed if assessments are made in regions which deviate noticeably from the averages used.

Fig. 6



III. A. 2. EARTHQUAKES

To derive the maximum benefit from our mission to Armenia concerning Disaster Preparedness and Mitigation we shall discuss all essential paramenters controlling vulnerability and not only those which caused, for instance, failures of buildings during the Spitak earthquake of 7th December 1988. As the best mitigation is not to rescue people and property after an earthquake has happened but to optimize the risk before an earthquake occurs the author has endeavoured to compile the information in such a manner that all essential parameters influencing the probability and extent of loss or damage are discussed. This will allow to use the information for disaster preparedness and mitigation planning in other regions as well.

1. Buildings

The importance of buildings in earthquake disasters is illustrated by the fact that earthquake building codes are (unfortunately) so far developed for this group of elements at risk only. If we group buildings according to their use, we find that about 30% of all earthquake damage, i.e. direct and indirect property and financial damage, loss of life and injury, is due to residential buildings, whether we look at low income or high income societies. Earthquake damage to residential buildings is about twice as important as the next important item in non-technological societies. In industrial societies, commercial and factory buildings combined produce damage which is in general about one third above that of residential buildings in the former region. If one adds earthquake damage to all types of buildings, i.e. residential, commercial, administrative and factories in non-technological societies, it is found that this group accounts for somewhat more than 50% of the total of earthquake loss and damage if the long-term loss of productive capacity due to casualties is not considered. This shows how important buildings are and as most other elements at risk are subject to the same damage parameters, we shall treat buildings first. Moreover, loss of life and injury and socio-economic effects of earthquakes are decisively influenced by the performance of buildings.

Vulnerability and the probability distribution of damage depends on the combined action of many parameters. According to the central theorem of statistics we may therefore expect approximately a log-normal distribution if one correlates the quality of a building, i. e. the reciprocal of the vulnerability, with the mean damage ratio (MDR). This holds good, however, only as long as most, i.e. many parameters contribute to determine damage. As damage increases, the effect of individual parameters is progressively eliminated due to what the author calls saturation of damage. Stated as a brief generalization, this means that at a certain stage the most vulnerable fill-in walls will have been completely damaged and all further contribution ceases. Next, the less vulnerable elements of this type are destroyed and their contribution also ceases. Then the vulnerable columns are destroyed, and thereafter the less endangered ones. The same happens to beams, to floor slabs, etc., and each time a component that has so far contributed to damage is eliminated. Eventually only the strongest, i.e. least vulnerable item remains, which is in most cases the foundation, at least as long as the building is founded on proper material.

Because of such damage saturation encompassing more and more elements the distribution gradually levels off in the high and very high damage states, i.e. it departs from a log-normal distribution and progressively becomes what one may call an "extreme distribution of extremes" (1). We have seen this when analysing hundred of thousands of cases of losses or damage and learned to appreciate its great importance in any field associated with risk analysis, and therefore also in connection with earthquake damage reduction.

A pragmatic approach to earthquake disaster preparedness and mitigation should therefore be based on as many actual data obtained from field inspections of earthquake loss and damage as possible and, if necessary, on models which must, however, be in agreement with such data. In line with this the following sections will discuss elements at risk and parameters controlling the vulnerability of buildings.

Before entering into this discussion a general statement combined with a warning is appropriate. Earthquake damage to a homogeneous sample of structures and buildings does not follow an "all-or-nothing"-law. Incipient damage is observed even if earthquake forces are well below the design strength of buildings. As the earthquake loads approach and surpass the design base shear the damage probability distribution shifts from positive skewness to a flat and roughly bell-shaped distribution with its peak near to the MDR, and then to a negatively skewed distribution (cf. e.g. (1 & 5)). The reader is referred to Table 1 in this connection. The reason for this is that damage is the result of the interaction of a large number of parameters.

The foregoing signifies that it is wrong to arrive at general conclusions about the vulnerability of certain types of buildings unless the sample is large, normally many hundreds of buildings and unless such a homogeneous sample has been carefully analysed as to the contribution of the important damage parameters discussed in the following pages.

DAMAGE PARAMETERS

A detailed account of the parameters contributing to earthquake damage of buildings has been provided elsewhere (1. & 3. - 16.) In short the most important factors are:

- Quality, i.e. predominantly hardness of the foundation material.
- Liquefaction
- Resonance between predominant frequencies of the foundation material and of the building or structure.
- Shear strength of the building resulting from the combined strength of structural and non-structural parts.
- Stiffness of the building
- Compatibility of behaviour of building materials and components under dynamic loads.
- Ease of repair.
- Regularity and symmetry as regards floor plans, elevations, shear strength, distribution of masses and damping.
- Design philosophy (codes, etc.).
- Quality of the design.
- Quality of workmanship.
- Vulnerability of non-structural elements, their arrangement and fastening.
- Hammering between buildings.
- Orientational sensitivity.

If we study earthquake building codes we unfortunately find that only some of the above parameters are addressed and, depending on the location of the building, not necessarily the most important, and as will be shown not adequately.

The general correlation, albeit for an already "decontaminated" sample, between MMI, building quality and mean damage ratio (MDR) is shown in Fig. 1. (MM-intensity can be converted easily to MSK.) It represents the situation for a moderately irregular and asymmetrical sample of buildings founded on alluvium of average hardness. The graphs show that if one decides to change code-requirements or design criteria from, for instance, 2.5% g base shear (Q/40) to 6% g MDR's will be reduced by a factor of 3, 2.5 and 2 for intensities corresponding to MM VII, VIII and IX. The effect of an upgraded design philosophy on collapse probability will be discussed in a later chapter.

Although not much extra money has to be invested to make a the building stronger by simply increasing the shear strength, namely about 3% of the value of the complete building in the case cited above, an even more economic approach can be employed, because damage depends on other factors as well. Out of the 14 factors listed above twelve can be influenced, in general with little extra trouble and cost. We shall now investigate how each parameter influences the earthquake performance of buildings.

Quality of the Foundation Material

The quality of the foundation material is basically represented by its hardness and its water content. In general the softer the material and the higher the groundwater level the greater the damage potential and the probability of damage (Fig. 3). There is some very simple reasoning which should convince anyone who believe that stories of soft foundation material increasing earthquake damage are fiction. Any careful contractor or engineer shuns bad or unreliable foundation material. If such subsoil gives reason enough to worry under normal conditions, will it not produce additional problems if shaken by an earthquake?

Early observers, e.g. after earthquakes in Calabria, Italy, in February 1783, noted that damage to buildings on soft ground was more severe than to others on firm ground. The San Francisco earthquake of 1906 confirmed this (24, 25).

After the 1960 earthquake in Chile the dependence of damage on ground hardness was seen in Castro, Ancud, Conceptión (26), Puerto Mont (27), and Valdivia. Soft subsoil contributed to damage in Miyagi-Ken-Oki, Japan, (1978) (23, 29-30). Other examples are given in (12). A general correlation is shown in Fig. 3.

The problems created by soft foundation material can be generalized as follows. There is a chance of differential settlement of the building, not only because safety margins applied in the design of the foundations may have been inadequate or because such material is compacted by earthquake loads, but also because deposits of alluvium are often not homogeneous and their quality may differ very much. One must be particularly careful in regions where rivers may once have meandered, even if this happened aeons ago. Such deposits are known to contain lenses of inferior material, and many cases of severe differential settlement are known to the author which occurred even in the absence of an earthquake.

Soft subsoil will amplify the ground shaking. This is easily understood because material of low intrinsic strength is deflected more by a force than isstrong material. The amplification depends, however, on many parameters (1). In general one should be prepared for 3 - 5 times higher accelerations, velocities, and displacements of soft alluvium as compared to rock. Part of this is due to resonance between low frequency earthquake shaking and a low natural frequency of soft layers. The larger amplitudes of shaking on soft deposits induce larger deflections in buildings and therefore increase damage. The approximate impact of soft subsoil can be quantified in terms of MDR with the help of Figs. 1 & 3.

These characteristics, however, also increase the probability of damaging ground shaking. Because of non-linear transmission characteristics of geological formations ground shaking becomes richer in low-frequency components as the distance to the hypocentre grows. Such low frequencies are picked up and amplified by soft foundation material. As dangerous shaking of soft foundation material can happen at a much greater distance from the earthquake source than on hard rock, the probability of such shaking rises because the likelihood of earthquakes increases in general with the square of the distance (8).

Particularly in valleys, the depth of soft layers may vary greatly over short distances. If buildings are founded on soft subsoil of differing depth this will introduce non-uniform shaking. The design of such buildings requires special attention.

Liquefaction

Liquefaction has caused very serious damage in past earthquakes. Probably the best publicised case is the Niigata, Japan, earthquake of 1964. The preconditions for liquefaction are a granular soil and groundwater. A good and easily accessible description of the phenomenon is to be found in (34) but there too it will be in vain to look for easy and economical rules for optimizing this risk.

Liquefaction damage differs from normal earthquake damage to buildings. It represents a digression from the normal chain of action in which earthquake shaking causes the damage directly. As in the case of slides, the earthquake leads to liquefaction which in turn affects the buildings. Secondly, damage will often follow the "all-or-nothing"-law, which means that up to a certain amount of settlement the building can still be used, which above that amount it must be considered a constructive total loss. Thirdly, particularly strong buildings will in many cases show little ordinary earthquake damage. They have settled either uniformly or non-uniformly, i.e. they list like a ship.

As improving subsoil is in general costly and no guarantee of perfect safety, probably the best advice is to analyse the subsoil as regards its tendency to liquefy and to abandon dangerous sites if economic improvements are not possible. The growing scarcity of good sites tend to increase the general exposure to liquefaction.

Resonance

Resonance, which in discussions is often disguised under general headings like 'site effects', confounding subsoil quality and resonance, a generalization which we do not support, is known to be responsible for spectacular damage to modern - especially multi-storey - buildings, even those although they were designed according to what are considered by many as "good" earthquake building codes Its importance was again illustrated dramatically by the Mexican earthquake of 1985. Frail adobe buildings of few storeys suffered practically no damage, whereas the MDR of modern engineered buildings in resonance with the nearly harmonic shaking of the ground was very high (13, 14, 16).

This lesson - if it is recognized as such at all - is certainly not new. Already after the Mexican earthquake of 1957 selective damage to high-rise buildings was observed (20). This happened again during the earthquakes of 1964 and 1979 (1, 12).

After the great earthquake of 1960 in Chile a difference in damage was noted between 3 and 6-8 storey buildings (21).

Stiff buildings performed better on deep alluvial layers in Bucharest in 1977 than soft ones (22). Such differences in behaviour were also observed at Miyagi-Ken-Oki in 1978 (23).

The author found a correlation between damage and building height after the Campania-Basilicata, Italy, earthquake in 1980, and a 1:3 increase of MDR's of 145 buildings in the downtown area of El Asnam, Algeria, after the earthquake of 1980 which depended on building height (1).

A sample of modern buildings in Guatemala City (1976) showed a significant increase in damage in harmonic frequency bands (1, 10).

From a sample of 228 buildings in Los Palos Grandes, Caracas, Venezuela, we calculated MDR's increasing from 2.75% to 22.5% for buildings from 3 and 4 storeys to 10 storeys and above, in spite of the fact that the lower ones had received less attention during design and construction.

Investigators analysing the spectacular building failures in Leninakan ascribed damage to high-rise buildings founded on deep alluvium to resonance. Whereas it is certain that this caused an important amplification of building oscillations it must be stressed that the disaster was primarily caused by other factors which will be discussed under the respective headings. Resonance was only of secondary importance as regards damage to tall buildings.

There is little doubt that buildings "in resonance" with prominent frequencies of the subsoil suffer much higher MDR's than others which are clearly outside such "frequency bands".
This is not only shown by our very large sample but so supported by theoretical reasoning. Resonance increases the amplitude of deformations of the building and this amplification is considerable if shaking lasts for a time long enough to achieve maximum displacement even for tall buildings. One

must consider that little intrinsic damping is found in buildings. This means that amplification can be substantial.

As regards design philosophy aimed at avoiding resonance, one must not only try to avoid resonance in the range of natural frequencies and of harmonics but also allow for the fact that strong shaking will "soften" the building lengthening its period.

There is no hard and fast rule for calculating the difference in MDR's between buildings in resonance and buildings not in resonance with the subsoil. This difference depends on many other parameters and, in addition, on the damage level, i.e. on saturation of damage. The MDR of frail adobe buildings of 1-2 storeys in the region of the extinct lake of Texcoco (Mexico DF) was below 1%. Bungalows on soft volcanic subsoil in San Salvador suffered very little damage. Modern engineered buildings, however, suffered MDR's of several tens of percent (13-16).

A further important lesson should be learned from these two earthquakes. The MDR of buildings in Mexico City (1985) was somewhat higher than that suffered by comparable buildings in San Salvador (1986), although the latter ones were exposed to peak accelerations which were roughly three times higher. Many more examples from other earthquakes can be adduced to prove that it is not peak acceleration that damages the buildings, at least in most cases, but the deflection or distortion of the members. If a wooden stick is clamped in a vice and its upper end is given a very brisk push deflecting it slightly, nothing happens although the acceleration was high. If the same stick is, however, gently pulled to one side, that is without hardly any acceleration, it breaks when a certain deflection is reached. The same holds good for any building material. It is not the acceleration which damages the material but its deformation, and the latter is not predominantly determined by acceleration.

As most building activity is today on sites underlain by soft layers which have low natural frequencies, there is a substantial chance of severe damage to modern tall buildings unless one avoids resonance. Avoiding resonance is a basic tenet heeded by mechanical engineers in the design of machinery, but it appears to be terra incognita to structural engineers: not a single earthquake building code includes any or any adequate proviso. If one is guided by the theory of forced, damped vibrations the frequency of the force must be known. The frequency of the force is not the one observed in the epicentral region but is the predominant frequency of the foundation material carrying the building. How is it to be estimated?

There are a number of theoretical models addressing this question, but one should not lose sight of the fact that the average builder or authority is generally not in a position to judge the appropriateness of such models or to select parameters correctly. It is felt that a simpler method should be favoured, at least for the foreseeable future and in most seismic regions. The approach we suggest here is based on the depth of soft layers, and it is supported by theoretical reasoning. Fig. 2 shows two alternatives of soft deposits, A represents a special case, e.g. as prevails to some extent in the central part of Mexico City in the region of the extinct lake of Texcoco, and B the more common case of extensive soft layers.

Deposits of soft material as illustrated by A will oscillate like a soft pudding in a bowl, especially if the ground is saturated with water. The frequency of such an oscillating mass, which is not influenced much by restoring forces other than gravity, is mostly determined by the dimensions of the "bowl". This is illustrated by an experiment everyone can do, the frequency of tea agitated horizontally in its cup is higher than that of soup in a plate, and that of water in a bathtub is even lower. Lower still is the frequency of an earthquake-generated seiche in a lake.

In the normal case (B) the main criterion is the depth of the soft layers. Each column of material (the density of which increases with depth because of compression) is acted upon by several restoring forces if deflected sideways. The "neighbours" react elastically and plastically. If centres of gravity are lifted to a higher level, gravity will have a restoring influence. Moreover, even soft material incorporates some elastic restoring forces (spring constant), as one can see when deflecting a piece of foam rubber or plastic.

Years ago we analysed the observed natural frequencies of soft subsoil layers (11) and found a good correlation between period of prominent shaking and depth to hard strata. A reasonably good approximation between depth (d) to hard strata in metres and period (T) in seconds is given by

$$\mathbf{T = a\ d^{\frac{1}{2}}}$$

in which a = 0.1. One may also consult Fig. 4 in this connection. Before discussing remedial steps it must be mentioned that several codes indicate how to estimate the period of the building. It should, however, also be understood that the theory of forced damped vibration teaches that it is a vain exercise to assess the frequency of the building without also considering the frequency of the force, i.e. of the subsoil. In fact not much theoretical knowledge is needed to understand this. Such deliberations moreover show that it may be very wrong to provide less base shear to tall buildings than to those of only a few storeys. If tall buildings are founded on deep and soft alluvial layers they can be in resonance with the subsoil and therefore very exposed.

If a building is likely to be in resonance with predominant frequencies of the ground, additional stiffness can be introduced not only by strengthening the structure proper. Much ained from using a better mortar in brick walls. If good-grade bricks are used the weak spot is usually the mortar and the bond between mortar and bricks if workmanship is poor. Changing from ordinary lime mortar to good cement mortar will make a wall about twice as strong.

The use of strong bricks renders a building quite stiff, shortens its period and makes it more resistant to damage. We have observed this after many earthquakes. Walls incorporating a thin-latticed variety of bricks were shattered whereas others of strong bricks had a only few cracks or no damage at all.

As brick walls sustain serious damage, not only is the natural period of the building lengthened but also random frequencies of shaking (white noise) are introduced. Admittedly the thermal insulating properties of thin-walled bricks are good, but there are today other and safer means of achieving this. In addition their sound insulating properties are bad. Thin-walled bricks should therefore not be used in seismic regions unless in connection with a strong monolithic structure.

Openings in walls affect not only stiffness but also the regularity of the building, an aspect which is discussed later. Unless corners at openings are properly reinforced (1, 15), cracks will start from there because of a notch-effect. Some additional internal walls at critical places can stiffen the building considerably, in particular if external walls are few, asymmetrically arranged, or absent because large windows have been installed.

The chance of resonance can also be diminished by reducing weights and loads in upper storeys. One must understand that a soft ground floor produces a building which is not only asymmetrical but also in general top-heavy. Such buildings are dangerous. Much weight in upper storeys reduces the natural frequency of the building and this may increase the chance of resonance. In this respect not only architects, builders, contractors and engineers need to be educated, but owners or users of commercial and industrial buildings as well. The catastrophic failure of many multi-storey factory buildings in Mexico City was only to some extent due to the overloading of upper floors by storing textiles, paper, etc.. These considerable masses also lengthened the period of these buildings so much that they were in resonance with the 2-3 sec. period of the ground shaking.

It must not be overlooked that most modern buildings are on soft alluvium because sites with hard and level ground have become scarce. This means a high chance of resonance (11) and of substantial damage and loss of life unless special precautions are taken.

Shear Strength of Buildings

Structural engineers concentrate, in keeping with the name of their profession, on the strength of the structure. We shall show that this approach and the resulting performance of buildings is far from satisfactory. Regrettably, even fairly simple designs are flawed, as the analysis of tens of thousands of building proves. A simple example may serve to illustrate important shortcomings.

In normal, simple residential buildings of several floors damage is generally concentrated in the ground floor area, sometimes extending to the second storey even if the floor plan is quadratic and the building otherwise symmetrical, and even if each storey has been designed to resist earthquake forces. Had design achieved approximately identical resistance of all storeys, damage should have been uniformly distributed. If such simple structures do not perform as one should expect one can easily visualize the problems in asymmetrical buildings. In fact, buildings which are somewhat more than moderately asymmetrical and irregular suffer MDR's several times higher than do those which are regular (1, 12), and this in spite of all engineering.

The simplest stumbling block so far is not the complex shape of buildings, columns, spans, etc., differences in height or size, uneven distribution of masses, or earthquake waves which induce torsional loads or a tendency of the building to respond with torsional movements, but the lack of knowledge about the contribution of "fill-in walls" to the shear strength of a building. This appears to stem from a "philosophical" problem. The differentiation between structural and non-structural, or load-bearing and non-load-bearing members of a building is too parochial. This attitude is responsible for very severe damage and even for loss of life. The rigid distinction between structural and non-structural elements is not logical. In a building constructed entirely of brick the respective walls are considered load-bearing. However, as soon as bricks fill the spaces between columns, they are thought of as non-structural elements and their contribution as regards strength (and damping) is neglected.

How much such "non-structural fill-in walls" do in fact contribute to the strength of buildings will be discussed in more detail in connection with orientational sensitivity. This much can be stated now: the shear strength of a building can be improved dramatically by using strong fill-in walls. Our research shows (cf. e.g. 3, 9 & 12) that the stiffening effect of properly designed and built fill-in walls cannot be overestimated. As discussed in a later example and shown in Fig. 7, in moderately strong buildings walls can contribute about as much strength as the structure proper. The factor of improvement can amount to two orders of magnitude in the low MDR-range, depending on the general quality of the building, on earthquake intensity and other parameters influencing damage level, and on damage saturation.

Stiffness of Buildings

Quite obviously a high base shear designed into the structure, in the extreme case strong shear walls, lends much stiffness to a building. Similarly, strong fill-in walls increase stiffness, although this contribution is more complex, if only because of the differing properties of the materials in the structure and in the wall.

As the issue of general shear strength has been discussed above we shall now concentrate on additional effects including what the author considers to be the problems in prevailing modern design philosophy in this field.

The only generally disadvantageous consequence of stiffness is the frequent failure of short columns. Here again, however, it is not the stiffness of these members which causes their damage or destruction. The amount of deflection that columns will tolerate without being damaged, which means deflection in their elastic range, is related to the cube of their length. Thus the deflection which a column, of say 3 m can accommodate without damage is about 27 times as large as for a 1 m column. If the short column is not strong enough to resist the force exerted on it by the shaking building - or by the subsoil being displaced too swiftly for the building to follow - it will be bent beyond its elastic range and will fail. Also here it can be shown that the parameter responsible for failure is not acceleration but excessive bending.

There is no doubt at all that the overall damage to stiff buildings, and therefore also the probability of their collapse, is much below that of soft buildings (cf. e.g. (16)). A soft design, whether with a frame of reinforced concrete or steel, will be subject to large-amplitude shaking, i. e. to considerable distortion, and therefore, even if the structure does not fail, non-structural damage will be often severe.

This does not mean that we advocate brittleness, especially not in load-supporting elements. It must, however, be realized that soft designs which rely on ductility as a last defence against catastrophic failure add much to the economic disaster and misery inflicted by a catastrophic earthquake. Ductility means plastic deformation and therefore extreme non-structural failure and even partial or total collapse of the structure. A stiff building is a much better risk in all respects, in particular if constructed on alluvial layers. As the additional cost needed to achieve a strong and therefore stiff building is nominal if compared to the total value of the building, such buildings should be the rule in seismic regions.

The philosophy underlying modern building codes should aim at proper base shear and stiffness, penalizing asymmetrical designs and cases of resonance by requiring adequate additional strength, proper reinforcement and detailing of it, etc. and not relying on ductility in soft structures. Designers of codes should also recognize that the time has come to avoid not only human but also economic disasters, i.e. to reduce structural and particularly non-structural damage, and not only think of avoiding collapse. Stiff (strong) designs are of very great assistance in achieving this.

Compatibility of Building Materials

The selection of building materials (cf. 8) should allow not only for their intrinsic strength but also for the compatibility between interacting items. In building engineering this has so far been a badly neglected issue. Strength requires no explanation, but we must discuss compatibility of materials.

If a structure which tolerates comparatively large deflections without damage, and reacts plastically if deformed even more is combined with items which are shattered by much smaller amplitudes of deformation, materials have been brought together which are not compatible. Cases in point are residential, commercial or industrial buildings with a skeleton of steel and walls of brick. A comparatively flexible (soft) rc-design is a further example albeit not as pronounced.

Industrial buildings and structures or warehouses of steel which are covered by asbestos or other brittle sheets belong to this category. In the case of factory sheds the damage to the building which results from such a mismatch is generally not costly. If on the other hand roofs are shattered and rainwater damages costly goods or machinery, the consequences of combining incompatible materials may be serious.

Ease of Repair

The cost of repairs has developed into a very worrying issue as buildings have become more and more sophisticated and wages have persistently risen. Particularly those commercial and administrative buildings which today are equipped with air conditioning and/or heating ducting, concealed wiring in places difficult of access, sophisticated panelling and suspended ceilings, and technical equipment, are far more costly to repair than their comparatively simple counterparts of several decades ago. In this context it must not be overlooked in this context that modern manufacturing and building techniques have rendered the original construction much more efficient, but in general not the repairs required after earthquakes, which for many reasons are very labour-intensive. Architects and engineers should take more interest in designing buildings and components which are easy to repair. This will pay dividends during all repairs, and not only after earthquakes!

We will consider walls first, i.e. the element which contributes most to earthquake damage. It is so far not customary in most countries to use wall elements which can be easily changed if cracked by an earthquake, although this would be possible in particular for the internal walls of commercial buildings. Where such walls are employed today which is only the case in technologically advanced societies, they are often covered with expensive facading (compatibility of characteristics?), panelling, etc.. As walls carry numerous fixtures and as many elements are built into them we cannot afford to