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Cost-benefit considerations related to seismic risk mitigation and socio-economic consequences of earthquakes

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ABSTRACT: Cost-benefit considerations related to socio-economic consequences of earthquakes and seismic risk mitigation are difficult to find in the earthquake literature in spite of the importance of these subjects. Based on the experience derived from the investigation of more than thirty earthquakes and the evaluation of several hundred thousand elements at risk which considered the important parameters which contribute to direct and indirect earthquake damage and losses a quantifying approach is presented regarding the assessment of the economic impact of earthquakes on society and of seismic risk analysis. It is based on detailed stocktaking, vulnerability analysis and cost-benefit considerations. All important categories of elements at risk are considered as well as direct and indirect damage and casualties.

1 INTRODUCTION

As this paper focuses on three different issues of earthquake consequences an introductory note appears desireable which explains the sequence of our discussion. Moreover, as the subject covers problems which are handled by different faculties some general remarks are added to bridge gaps which may exist.

A pragmatic approach has been selected and we shall therefore not get lost in formulae and mathematical models. It is the authors opinion that too much time has been lost in the past with theory and practical research based on the analysis of the consequences of as many earthquakes as possible has been badly neglected in particular during recent years. If investigations have been carried out the results were in general only published in a descriptive manner which is of little use in connection with deliberations centred on cost-benefit issues, risk mitigation and the effects on society. The following lines are, however, based on the analysis of many hundred thousand elements at risk inspected affected by some thirty earthquakes in many parts of the world. In view of the wide range of matters discussed details cannot be given within the space available and reference is therefore frequently made to publications which contain the required information.

The discussion will begin with the consequences of earthquakes as this will bring out the degree of importance of the various categories of direct and indirect damage and losses. It also forms the basis for efficient and economical risk mitigation which will be dealt with in the next chapter. Cost-benefit considerations will be considered last because they are only possible after the consequences of earthquakes and steps to mitigate the risk have be quantified. To render the text more readable some consequences have been discussed in the section dealing with risk mitigation.

2. SOCIO-ECONOMIC CONSEQUENCES OF EARTHQUAKES

A cursory analysis, for instance, of the proceedings of the World Conferences of Earthquake Engineering of the last 20 years or of other conferences shows a disproportionate share of papers on building damage and mostly dealing with structural aspects only but an extreme dearth of papers discussing the consequences of earthquakes in a wider context. It is therefore necessary to list the different elements at risk and the damage and loss categories which contribute to the overall effects of earthquakes. The most important elements of risk will be treated more in detail to facilitate later discussions.

We offer a simple example to illustrate a method which can be used to calculate the socio-economic consequences of earthquakes. The example illustrates a general assessment procedure but does not suggest particular figures. It can be adapted to special conditions in the simple form shown or in a more refined form, using data given in the various references (cf. e.g. Tiedemann 1990, 1992).

For this example we have selected a town of about 100,000 inhabitants, founded on medium-hard alluvium and having modern buildings which are moderately asymmetrical of a quality corresponding to 2 - 3% g. The example covers only the MM VIII zone; it is based on MDR's (mean damage ratios based on the new replacement values in the case of damage to property) and not on maximum loss levels. All values are in US dollars.

2.1 Direct losses ($/Inhabitant)

Residential:	
Investments $ 40,000/inhabitant,	
MDR 30%	12000
Commercial:	
Buildgs. & equipm. 40% of working population	
of 30,000, 200 m^3/pers., $ 150/m^3,	
MDR 30%	9000
Factories:	
50% of working population, 300 m^3/pers.	
$ 100/m^3, MDR 30%	9000
Machinery: 1/3 of factory bldgs.	3000
1 HPI Plant: $ 500,000,000.-, MDR for	
shock, fire & explosion 40%	2000
Contents:	
Private $ 10,000/inhab.,	
MDR 10%	1000
Merchandize in stock $ 200.-/inhab. ,	
MDR 10%	20
Vehicles: prob. of damage = 0.2,	
$ 7,500/vehicle,1 car/lorry/2 inh.,	
MDR 12%	180
Loss of Life: 1,300 pers.,	
$ 50,000 each	650
Injury: 6,500 pers.,	
$ 2,000 each	130

2.2 Indirect losses

General Loss of Production: 27,000 pers.	
affected for 3 months,	
$ 25,000 each	1700
Wages, Salaries, Social Security, Interest, Depreciation, Continuing Expenses, Loss of Markets, Tourism, etc.	
(Depending on actual case)	

2.3 Other losses/damage

Transport, Power, Water, Sewage, Telephones, Roads, Bridges, Medical & Health Services, Schooling, Art Collections & Museums, Cultural Heritage, Agriculture, Aquaculture, etc.

Even in the absence of aggravating factors, the mean total loss from damage to buildings, commerce and factories can reach or even exceed $ 30,000 per inhabitant in the strongly shaken area (MM VIII). This figure is supported by observations. For a population of about 1 million in the epicentral region the total mean loss could add up to some 30 billion (30,000 million). Quite obviously the MPL (Maximum Probable Loss) and in particular the PML (Possible Maximum Loss) can be substantially higher, and the probability of such a catastrophe is not necessarily small (cf. e. g. Tiedemann 1988b, 1992).

We shall now return to loss of human life, since the above list of losses includes the cost of injuries and loss of life only on the basis of a single figure, like a claim under a life assurance or a single course of medical treatment. In fact the loss to society and the national economy is very much greater, not to speak of the human misery caused by the casualties.

The 1,300 people we assumed as killed by the earthquake are in fact a permanent loss to the economy. Applying actuarial methods and considering the average age in the region, the average production per person, the age at retirement and the life expectancy one can calculate the total additional loss to the national economy. A very simple example must suffice here.

Returning to the general example, we will now briefly discuss indirect losses due to interest on idling capital, loss of rent, wages and salaries and other overhead expenses which continue during the period of interruption of trade and industry. These indirect monetary losses add more than $ 1,000 per inhabitant to the bill, i.e. more than $ 100 million for this town of 100,000 inhabitants.

Assuming a GDP of $ 18,000 per inhabitant, a median age of 30 at the time of the earthquake and a retiring age of 65, the 1,300 inhabitants killed represent about $ 820 million permanent productivity loss, not taking into account normal mortality, interest and other indirect losses related to permanent loss of productivity and buying power. This would amount to $ 8,200 per inhabitant, i.e. substantially more than the direct and indirect losses combined. Considering normal mortality the above figures for permanent productivity losses would have to be multiplied by about 0.73. To this the cost of permanent disablement must be added which is estimated at $300 million, i.e. $ 3,000 per inhabitant.

The above figures do not take into account losses to the infrastructure, to utilities, or to tourism, nor losses due to emigration because of unemployment created by the earthquake (no funds to rebuild), etc. Moreover, the cost to Life assurers and for medical care of the injured and temporarily disabled has not been included.

If in a large town or in a region 100,000 people were killed by collapsing buildings, falling non-structural elements, fires, explosions, and perhaps a tsunami, if the average sum assured were $ 25,000 and if insurance density were about 40%, the disbursements of Life assurers would amount to about $ 1,000 million. A loss of life of 100,000 is is far below the maximum loss scenario for many places on the globe.

This, however, also means that the total loss to the national economy caused by the death or serious injury of the victims assumes gigantic proportions if the number of casualties is much larger than assumed in these examples. The Spitak, Armenia, earthquake killed about 25,000 people and many more were crippled. The Guatemala earthquake of 1976 killed a similar number of people.These earthquakes cannot be taken as a worst-case scenarios. The Tangshan earthquake killed about 255,000 people and about 800,000 were injured. The number of those disabled is not known. An even higher percentage of the population was killed by the M 5.9 earthquake which hit Agadir in 1960.

Should there be any high-value production in the town the indirect losses would rise dramatically. It may take much longer than a year to get a petrochemical, HPI, or complex manufacturing plant back into operation after it has been gutted by an explosion and/or conflagration following an earthquake.

If the town is a coastal tourist resort the indirect loss could be much higher than mentioned earlier. Hotels in general are notoriously vulnerable because they are often founded on soft material next to the sea and are of highly asymmetrical and irregular (showy) design. Their MDR is thus substantially higher than that of ordinary buildings and this means more extensive and time-consuming repairs.

If, for instance, about 2,000 tourists cannot be accommodated for an average period of 6 months a loss of income of about $ 36 million will result. To this we have to add the interest on the investments lying idle. We must be prepared for the complete interruption of the business for most hotels because there will be not only some severe structural damage but also cracks in the walls of most rooms. Guests will not feel at home with bricklayers, plumbers and electricians swarming all over the place. The loss of interest alone may be of something like $ 7 million or more. To this expenses for wages and salaries, bills for utilities and other overheads must be added. Moreover, such earthquake damage may frighten tourists away for a long period, in particular if any hotel collapsed killing many foreign guests.

The indirect losses can even be graver if there is a chemical plant near the town using large quantities of inflammable, explosive, or toxic materials, or if the area is hit by a devastating tsunami.

No great earthquake is required to produce loss levels and indirect losses as discussed in the examples (cf.,e.g. Tiedemann 1987)). A large earthquake happening near a high-value region can cause much higher losses. The loss levels used in the example do not allow, for instance, for the adverse effect of damaging shaking of abnormally long duration. Moreover, we assumed a rather homogeneous mix of risks founded on tolerably good foundation material.

3. SEISMIC RISK MITIGATION

The direct and indirect damage caused by earthquakes, loss of life, permanent disablement, injuries, and business interruption and general overheads are decisively affected by the vulnerability of the buildings. It is therefore evident that any improvement in this field will reduce the impact of an earthquake enormously and that it should therefore receive proper attention. We shall therefore discuss buildings in more detail than other elements at risk.

3.1 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. 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 grand total of earthquake loss and damage as long as we disconsider the consequences of loss of lives.

A detailed account of the parameters contributing to earthquake damage of buildings has been provided elsewhere (Swissre 1977, 1982, Tiedemann 1980, 1980a, 1981, 1981a, 1982, 1982a, 1985, 1987, 1987a, 1988, 1990, 1992) In short the most important factors are:

- Resonance between predominant frequencies of the foundation material and of the building or structure.
- Quality, i.e. predominantly hardness of the foundation material.
- Shear strength of the building resulting from the combined strength of structural and non-structural parts.
- Compatible behaviour of building materials and components under dynamic loads.
- Regularity and symmetry as regards floor plans, elevations, shear strength, distribution of masses and damping.
- Design, quality, arrangement, and fastening of non-structural elements.
- Orientational sensitivity.

If earthquake building codes are studied, it is found unfortunately that only some of the above parameters are addressed and, depending on the location of the building, not necessarily the most important ones. It is therefore evident that risk mitigation of buildings to be constructed may be achieved much more economically than indicated in some publications(Weber 1985, Whitman et al. 1974) if all parameters are addressed and not only structural elements. If all avenues are exploited buildings can be rendered far less vulnerable by spending an extra 1% to 3% of the construction cost (for details cf. Tiedemann 1990, 1992).

Risk mitigation of existing buildings is a far more complex issue which is beyond the scope of this paper.

3.2 Utilities

The proper application of the rules outlined above is particularly important if we analyse utilities, i.e. plants and systems providing electric power, water, gas, oil, and telephone. These services generally fail even if the magnitude of the earthquake was small (Tiedemann 1987, 1990, 1992). As such failures affect many different elements at risk and as the ensuing loss or damage may be enormous, the upgrading appears to be an important task. Proper steps which are in general to be implemented very economically will shift the return period-magnitude distribution to such an extent that the exposure is reduced by a factor of five to ten and even more if vulnerable elements are at hand. As the most essential parameters have already been discussed in connection with building damage they need not be repeated. For a detailed discussion cf. (Tiedemann 1992).

It would be wrong to rely too much on safety devices which protect items against overload, shut off fuel supply or power at the time of an earthquake, but one should aim first of all at the intrinsic safety, i.e. on what one may call passive safety of all items.

Active safety devices, that is those acting when triggered by an earthquake, can be installed in existing utilities. This holds as well for modifications which render the mechanical, electrical and chemical equipment of utilities safer. It is generally much easier to upgrade such items than to modify buildings and civil engineering structures.

3.3 Industrial plants

What has been said in connection with buildings and utilities about earthquake damage parameters, protective devices, and additional steps to be taken is as important in industrial plants, in particular if fire, explosion, or environmental contamination are important risks. Whenever possible one should build as much passive safety as possible into existing plants or upgrade them. Experience shows that passive safety is of primordial importance. What one may call "active safety" like shut off devices or a fire brigade can fail or be inoperative for many reasons.

In highly industrialized regions, the factories and plants represent a substantial percentage of total investments and their failure can greatly affect the economy of the region, the rate of unemployment, and social issues. In low income regions, the economy and the people depend even more on their functioning, in particular as recovery takes long and as there are less alternatives.

3.4 Roads and bridges

Bridges are frequently damaged by earthquakes and often because basic rules have been overlooked in the design. In general substantial improvements can be introduced based on past experience with earthquakes (Tiedemann 1992). This does unfortunately not hold for roads in particular if they are endangered by settlement or slides. Substantial damage to roads and bridges can cause severe indirect losses.

3.5 Fire, explosions and toxic materials

In this connection a very large number of parameters must be considered. The important aspects are treated extensively in (Tiedemann 1992), and we shall here not discuss individual categories of elements at risk individually but rather concentrate on some important parameters.

An analysis of the exposure and of efficient risk mitigation should start with the investigation of the physical and chemical properties of all dangerous materials, and whether such material is installed or available in the form of raw material, feedstock, semifinished or final product. The physical properties include the phase, i.e. gaseous, liquid, or solid materials, the quantity and in the case of solids the surface to volume ratio. Chemical/biological properties are, for example, calorific value, ignition point, toxic or irritating properties, corrosiveness, stability, oxidizing, reducing, basic, acidic, and reaction velocities.

In industrial facilities in particular, the pressure of stored or processed liquids and gasses must be considered.

The release of dangerous materials is determined by many parameters, in particular by the failure probability of tanks, pipes and other equipment in which they are contained, but also by the characteristics of structural elements, building components and devices which are supposed to contain the liquids if the tanks fail. Vehicles transporting dangerous material should also not be overlooked.

When considering ignition sources not only those normally present in buildings and plants but also additional sources generated by the earthquake should be considered.

"Exogenic" parameters which can trigger or contribute to a catastrophe should not be overlooked. These factors include tsunami, liquefaction, slides, failure of power or water supply and meteorological conditions.

Last but not least we must allow for human error if the course of an event is determined by the reaction of operators. The reliability of human beings is much reduced under severe stress unless they have been very well trained.

The Tokyo earthquake of 1923 is one dramatic exampleof the fact that enormous casualties can be caused because of the presence of much combustible material and of many ignition sources. This earthquake occurred at a time when many meals were cooked on open fires. The severe shaking spread the burning fuel, and alegedly 277 fires broke out, 133 of which spread. The most important single factor, however, was the strong wind, initially blowing at a speed of 45 km/h. It changed direction repeatedly and reached velocities in excess of 75 km/h. The conflagration killed more than 100,000 people, 38,000 lives were lost in an open area of Tokyo to which the people had fled for refuge.

Modern construction materials have replaced much of the wood used decades ago, including other fuels which may cause devastating fires and a large number of casualties. This is true of both industrial plants and of buildings. Still in the department store in San

Salvador which collapsed; quite a number of the victims were not killed by the crumbling building but by a fire which later engulfed the site.

In many industrial facilities today there are numerous tanks and even large tank farms storing liquid fuel, and many facilities where liquified gas is stored. A few years ago a comparatively small facility of this kind caused the death of about 500 people in Mexico City. If a devastating earthquake shakes an area where many such installations are to be found many failures in the equipment are bound to occur, and fires and even conflagrations are likely to result. Cylindrical gas tanks are known to cause disastrous BLEVE's with fire-balls reminiscent of nuclear blasts. When exploding, such large tanks have been known to travel like rockets over distances of up to a mile. If they impact on a critical facility further fires and explosions may result.

Moreover, one must be prepared for burning liquids and gasses heavier than air to spread rapidly along roads, sewers, ditches and topographic features. It must be stressed that the average retaining facilities available today will not stop such massive releases of combustible and explosive material. As multiple failures of containments are probable during an earthquake unless special precautions are taken, the ensuing loss of life can be very severe.

In conclusion, it must not be forgotten that events like the tragedy at Bhopal, India, where about 2,500 people were killed by the release of toxic material and where many more were seriously injured, or at Guadalajara, Mexico become far more likely if such plants are shaken by earthquakes. If the worst comes to the worst casualties and damage can be caused by the combined action of several hazards.

3.6 Tsunami

We shall not go into details of the probability of tsunami at a given point along a coast as this depends not only on the frequency of more or less distant earthquakes which may generate trains of waves which can reach a particular place on a coast, but on many other parameters, like the shape of the sea floor in front of the coast, shape and topography of the coast, obstacles in the path of the waves, etc. (for details cf. Tiedemann 1990, 1992).

Apart from the general probability of tsunamis the next most important parameter controlling the exposure is the elevation of the surface of the land where elements at risk are found. The probability of a given tsunami and therefore implicitly of the run-up height decreases greatly as the postulated wave height increases. We purposely mention the elevation of the land surface because the waves of tsunamis may generate forces of 3 - 9 tonnes per square metre, enough to make buildings collapse unless the are very resistant or protected by other features. If buildings are not very resistant residents in their upper storeys are not necessarily safe.

The speed of propagation of tsunami depends on the depth of the water, in that it corresponds approximately to the square root of the product of the gravitation of the earth times the depth of the water. For a depth of 5,000 m it is about 220 m/sec or 800 km/h. This means that a tsunami warning will not achieve much if the epicentre of the earthquake is only 100 or 200 km from the coast.

As regards exposure, let us consider some examples which will also show that tsunamis are not confined to the Circum-Pacific belt.

The region of Beirut, Lebanon, was ravaged by tsunamis in 551 AD and again in 746. Many ships were sunk.

At Cumaná, Venezuela, 8 m waves killed many people in 1530, and in Lima, Peru, the sea rose by 23 m in 1586. The next devastating tsunamis occurred there in 1687 and in 1746, when five to six thousand inhabitants of Callao, the port of Lima, were killed, and only 200 survived. In 1868 a great earthquake off the South American coast, at about the Chile-Peru border, generated a 15 m tsunami which killed many people along the coast. On Hawai 5 m waves were measured, which caused an estimated run-up of nearly 20 m. More than 80 people were killed there. The tsunami from the1960 earthquake in southern Chile killed about 185 people and injured 855 in Japan.

About 20 minutes after the famous Lisbon earthquake of 1755 a large tsunami hit the Portuguese coast. Of the 60,000 to 100,000 people that were allegedly killed many died due to the tsunami. A tsunami from this earthquake also affected the Caribbean islands ten hours after the earthquake. On Martinique the waves were as high as the upper storeys of the houses. The number of victims is not known.

Even for Japan, which gave the tsunami its name, figures for people killed are rarely available for early earthquakes. In 869 about 1,000 people were drowned by the Sanriku earthquake. In 1493 200 persons were drowned at Kamakura. 3,800 tsunami victims were estimated after the earthquake of 1605 which affected the Boso peninsula. More than 2,000 persons were killed in the Sanriku region in 1611. In 1771 a tidal wave allegedly killed 11,941 persons near Ishigaki Island. In 1854 3,000 people were killed by a big tsunami on Boso Peninsula. In 1896 a 25 m tsunami at Yoshi Hama killed 27,122 persons and in 1933 the M 8.9 earthquake off Sendai generated a 24 m tsunami killing 2,986 people and injuring 12,053, but also in this case it is not certain whether all the casualties were due to tsunami. In 1944 a 6 m tsunami killed nearly 1,000 persons and injured 2,135. The loss of life among young mothers refusing to leave their children were particularly grave in the latter case.

A worst case scenario would be a large damaging earthquake during night in the vicinity of a large coastal town located on a shore-line which enhances the tsunami. Earthquake damage in the town would create chaos because of severe damage to buildings and disruption of traffic, water and power supply as well as telephone services. People rescuing their families members and others would for these reasons, and because of the difficulty of retreating to higher ground in darkness and over roads blocked by debris, fall victim to the trains of waves.

The above shows that it is extremely difficult to estimate the number of people killed and injured and the physical and indirect damage caused by tsunami, as many different scenarios must be evaluated, each of which is afflicted by many uncertainties. Past experience is of little help in view of the small and unreliable sample and because of substantial changes in towns over the course of time and particularly during recent decades.

3.7 Landslides and mudflows

Landslides and mudflows [which should more properly be called (seismic) lahars because the flow consists only in part of mud but mostly of boulders, stones, tree trunks and debris picked up by the flow on its way] are, like tsunami, indirect earthquake effects. The earthquake triggers a slide and this slide causes the damage and the casualties.

Probability assessments are very difficult because of the compounded uncertainties of the parameters playing a role. Briefly, the probability assessment of seismicity proper in the respective region is not free of uncertainties. Next, the stability of the slopes in the vicinity of human populations must be assessed. If it is not easy to establish the general stability of slopes it is even more difficult to state with certainty what characteristics an earthquake must have in order to cause slides of different magnitude on a particular slope. Moreover, slides are also controlled by hydrological parameters and by other factors (Tiedemann 1988a). Whereas an earthquake occurring after a long dry summer may not cause a slope failure, the same earthquake will cause a slide if it occurs after an extended wet spell.

There have been many earthquake-induced slides in the past. Some of them have killed people and a few have resulted in catastrophic loss of lives. We will discuss a few examples involving casualties. It must, however, be stressed that even a complete list of earthquake-triggered slides will not produce a precise description of the exposure of human life. This is evident if one considers the very many parameters influencing slides, the limited number of large earthquakes in regions exposed to dangerous slides, and demographic developments.

Quite a number of old gigantic slides have been found by scientists (Tiedemann 1988a). Several of them occurred in seismic regions and it is therefore not improbable that they were triggered by earthquakes.

Perhaps the most massive mountain slide in history in the European Alps buried 17 villages and hamlets near Villach, Austria, in 1348. 5,000 people were killed. An earthquake had rendered huge quantities of limestone unstable on the south wall of the 2,167 m high Dobratsch and sent it thundering down 1,500 m into the valley. A similar prehistoric slide has been discovered. Today a much larger number of people live in the exposed region than in 1348.

In 1911, after an earthquake of about M 7 in Pamir, 2,500 million cubic metres of material blocked the Murgab river in Turkestan and buried the village of Usoy, with its 54 inhabitants.

Probably one of the most devastating slides occurred in Peru after an earthquake. The M 7.5 earthquake in 1970 triggered an ice/rock avalanche about 100 million cubic metres in volume on Huascarán. Travelling at an average speed of 170 km/h, but with a maximum speed of 400 km/h, it raced towards Yungay, 15 km away, jumped over a mountain ridge several hundred metres high in its path and buried the town with its 18,000 inhabitants.

Obviously the only safe manner to mitigate this type of risk is to avoid endangered sites.

3.8 Failure of dams

We would now like to discuss a special issue: the failure of dams and/or reservoirs. Such a failure may be due to several reasons, for instance,

- very severe shaking of the dam by a nearby earthquake,
- large faulting traversing the dam and damaging the dam proper and/or its foundation,
- substantial deformation of the dam in its vertical plane by wave-like deformation of the dam's foundation in the course of earthquake wave propagation,
- slope failure in the vicinity of the dam causing substantial damage to it, and
- sliding of a large volume of material into the reservoir causing the water to spill over the dam.

If the water from a large reservoir is released within a short time because of such phenomena it can cause enormous casualties in the valley below the dam. Under certain circumstances the devastation will extend over dozens and even hundreds of kilometers.

Unless the dam proper is fairly safe, (a rockfill dam, for instance, is for intrinsic reasons much safer than an earth dam, or can be rendered safer by later modifications) it will in general be difficult to protect the people in the valley below the dam. Urban development schemes should take this into account. Because of the high probability of failure of comunication systems during an earthquake, evacuation will often not be possible. Moreover, the time available for warning will generally be much shorter than in the case of excessive rain endangering the dam.

If towns, big factories with a large work-force, big camping sites, etc. are situated only many kilometres downstream of a reservoir, a warning system similar to a tsunami warning system can be installed. It must be fail-safe, and proper information and training of the people is necessary to guarantee correct reactions and to avoid chaos.

It is very difficult to estimate the casualties due to the sudden failure of a dam or reservoir. A prerequisite is a detailed zoning map indicating the possible water level for the exposed regions. Next, the vulnerability of the buildings must be estimated for each sub-zone, as well as their type.

Whereas people on roads are most exposed and a very high percentage of them may be killed (cf. Tiedemann 1988a), the exposure of people staying inside buildings depends on the resistance of the structures and on the number of storeys. Single storey buildings normally offer little protection. Multi-storey buildings will only reduce casualties if they do not collapse. Protection is only afforded by strong buildings with a frame or shear walls of reinforced concrete and with foundations which are not endangered by scouring.

3.9 Indirect damage and losses

The range of indirect damage, i.e. damage to property caused indirectly by the earthquake, is so wide (Tiedemann 1992) that only a few examples can be given. If a roof of a warehouse is damaged by an earthquake, rain can affect merchandise stored in it. If power fails which would be needed for an orderly shutdown, material in process may be affected or a fire or explosion may result. A power failure can also affect machinery, cooling processes, refrigerated material, or hospitals, to cite some examples. Any reduction in the probability of direct damage due to risk mitigation will also bring such losses down. The gain is about proportional to the one described under material damage.

As discussed earlier indirect losses are mostly loss of production or income, interest, depreciation, continuing expenses, loss of markets, etc. Such indirect losses increase with the level of development of a region, but not necessarily in relative importance. As indirect losses depend on many factors (Tiedemann 1992), predominantly the composition of industry and commerce in the region and the respective vulnerabilities and the time needed to go back to operation, no general figures can be given regarding the effect of risk mitigation.

As indirect losses depend decisively on the span of time required to make temporary and final repairs or reconstruct certain items, delays must also be considered arising from scarcity of funds, e.g. because of lack of insurance, or due to import restrictions or government interference. We have seen many comparatively simple production units which were not yet re-commissioned two years after earthquakes, for the reasons mentioned.

If seismic risk mitigation improves the most salient parameters which control direct loss and damage, the gain can be enormous. As risk improvement will modify accidents in such a manner that a positively skewed distribution results (cf., e.g. Tiedemann 1982a, 1988b, 1992) it can safely be predicted that upgraded elements at risk will have a damage probability matrix with most of the cases in low damage states. It is on the other hand symptomatic for vulnerable objects that their damage distribution is negatively skewed with many cases in the high damage states. Our observations show that very often no or insignificant indirect losses arise if the MDR is low for material damage. Therefore upgrading can result in disproportionately large gains as regards indirect losses.

3.10 Environmental pollution

This risk has become more important in recent years and it can safely be assumed that this trend will continue, in particular if a spectacular environmental contamination should result from an earthquake. The probability of such an event is far from negligible (Tiedemann 1992). The very great number of noxious, deleterious and even toxic compounds makes it impossible to give a list. Many of them exist in a form which makes their dispersal likely after an earthquake has damaged the machinery, apparatus, pipe system and tanks used when producing, transporting or storing them. Two examples may suffice.

Some of the most vulnerable items in chemical plants are pipe systems and tanks. An earthquake will cause many such failures in a large plant unless special precautions are taken. Dangerous gases will escape freely and liquid compounds will probably not be retained completely. Even if safety systems exist, they may be overtaxed by the unexpected volume or because much additional water from ruptured pipes or fire fighting adds to the quantities to be handled.

The second example concerns a simple galvanizing plant. Tanks in such facilities hold acids, chemicals, molten zinc, fuel oil and other substances. If such materials escape or mix due to an earthquake and/or enter groundwater, the consequences can be serious.

3.11 Loss of life, injury

Loss of life and injury depend very much on the vulnerability of buildings. If the MDR of buildings is, for instance, reduced from 30% to 10% the percentage of buildings suffering damage of 80-100% which include the cases of total or partial collapse is reduced by a factor of approximately fourty. This paper cannot present details, which are to be found in the references (Tiedemann 1990, 1992).

The number of casualties depends, however, also on the performance of non-structural elements. In particular if the structure of buildings is strong or even very strong making partial or total collapse unlikely, non-structural items do not only control the number of people killed or injured but also the ratio of injured to killed.

It is evident that improving the factors which contribute most to direct damage, and in an economic manner if based on long and medium-term predictions, will pay rich dividends. Not just because at MM VIII only about 0.07% of the people staying in 6%g buildings will be killed, even much less if these buildings were fairly regular and symmetrical. In unreinforced brick buildings, however, about 10% of the population will be killed. By attending to the parameters which determine earthquake damage one is killing many birds with one stone reducing at the same time all other losses.

3.12 Socio-economic issues

We can only present an overview of what an earthquake may mean in terms of socio-economic consequences and of risk mitigation. The general rule is, the poorer and less developed a region, and the more sluggish the administration of it or of the country, the graver the consequences. Under such conditions people appear paralysed by a catastrophic earthquake. Even if enough vitality is left to initiate repairs and replacements, this will strain financial resources and the absence of funds may render speedy recovery impossible. Loss of wages and income, damage to products ready for sale, etc. will add to the direct material loss. Under such conditions one should not be surprised to observe a substantial drain of manpower from the region and it is worthwhile noting that the best, most enterprising and dynamic people will leave first.

Even if such negative parameters are not at hand one must remember that a large earthquake can trigger a real catastrophe. On medium-hard alluvium a M 7.5 earthquake will generate MM VIII and above over an average area of about 20,000 square kilometres, for M 8 this area is approximately 36,000 and for M 8.5 about 56,000 square kilometres. The number of people living in such large zones can easily be estimated for each hypothetical scenarium and multiplying it by US $ 10,000 to 30,000, the total economic impact can be assessed. This per capita loss applies if the building quality is about 2 - 3% g. It must, however, be stressed that earthquake losses have shown an inflationary tendency.

Risk mitigation is therefore an extremely important issue and it is deplorable that one looks in vain for such activities in most earthquake regions of the world. The vulnerability of the important elements at risk and the respective damage parameters have been discussed earlier and the information given there and particularly in the references can be used for efficient risk mitigation.

4. COST-BENEFIT CONSIDERATIONS

The discussion shows that a professional cost-benefit analysis must be based on all essential parameters which influence the socio-economic consequences of earthquakes including seismicity as such which was not the subject of this paper.

It is, moreover, evident that expert stocktaking of the exposure in a region is a precondition to well-aimed cost-benefit deliberations indicating which steps are economically and generally warranted in each case. Most countries are still very remote from coming to grips with the socio-economic impact of earthquakes or of other natural perils for that matter, because detailed stocktaking together with vulnerability analysis of all essential elements at risk is for all practical purposes "terra incognita".

Moreover, one must note that whenever some attempts were made they were based on theoretical assuptions and models involving sometimes much computer-time but little hard facts gained from a detailed investigation of earthquake damage and consequences. As the field of cost-benefit considerations is extremely wide and as even the evaluation of a single element at risk would cover several pages it is impossible to present details here and the reader is referred to (Tiedemann 1992).

5. LESSONS AND CONCLUSIONS

The paper shows that the most important gain from the assessment of the socio-economic consequences of earthquakes, which requires detailed stocktaking and use of correct vulnerability functions for all essential elements at risk is cost-benefit-conscious risk optimization. It is evident that relying on the presently available earthquake building codes is not sufficient to judge and minimize the impact of an earthquake on society also because important parameters which determine direct and indirect earthquake damage are not considered. Moreover, there are many other elements at risk and categories of damage and losses which must be considered in addition to direct damage to buildings.

The the examples demonstrate a method which can be used to estimate the extent of loss from earthquakes and how it can be reduced. It shows that each important setting merits a detailed praqgmatical investigation and that we are dealing here with a field which has so far been badly neglected.

REFERENCES

Swissre 1977 & 1982. Earthquake risk assessment, Swiss Reinsurance Co., Zurich, Switzerland.

Tiedemann, H. 1980. A statistical evaluation of the importance of non-structural damage to buildings, 7th WCEE, Vol. 6, 617, Istanbul.

Tiedemann, H. 1980a. Risk optimization considering vibrational behaviour of subsoil, 7th WCEE, Vol. 2, 267, Istanbul.

Tiedemann, H. 1981. Some statistics of the South Italian and Algerian earthquakes, Symposium on Earthquake Engineering, Roorkee, India.

Tiedemann, H. 1981a. The effects of building quality on earthquake damage, Journées Scientifiques Sur le Seisme D'Ech-Chelif (ex-El Asnam), Alger.

Tiedemann, H. 1982. Quantification of factors contributing to earthquake damage in buildings, 7th Symp. on Earthqu. Eng., Vol. 1, 203, Roorkee, India.
Tiedemann, H. 1982a. Structural and non-structural damage related to building quality, 7th Europ. Conf. on Earthqu. Eng., Athens, Vol. 6, 27.
Tiedemann, H. 1985. Orientational sensitivity of buildings revealed by the Mexican earthquake of September 1985, 8th Europ. Conf. on Earthqu. Eng., Lisbon.
Tiedemann, H. 1987. Small Earthquakes - small exposure?, Swiss Reinsurance Co, Zurich.
Tiedemann, H. 1987a. Earthquake damage in Mexico City, Nature, Vol. 329, 677.
Tiedemann, H. 1988. Lessons from the Mexican earthquake of 1985; Quantitative evaluation of damage and damage parameters, Vol. VIII - 957, SJ-7, 9th WCEE, Tokyo & Kyoto.
Tiedemann, H. 1988a. The force of water, Swiss Reinsurance Co., Zurich.
Tiedemann, H. 1988b. The echnical assessment of catastrophe risks, Rendez-Vous de Septembre, Monte-Carlo.
Tiedemann, H. 1990. Newcastle: The writing on the wall, Swiss Reinsurance Co., Zurich.
Tiedemann, H. 1992. Earthquakes and volcanic eruptions: A handbook on risk assessment, Swiss Reinsurance Co., Zurich.
Weber, Stephen F. 1985. Cost impact of the NEHRP recommended provisions on the design and construction of buildings, Earthquake Hazards Reduction Series 14, Federal Emergency Management Agency, Washington, D.C.
Whitman, R.V., J.M. Biggs, J.Brennan III, C.A. Cornell, R.de Neufville & E.H. Vanmarke 1974. Seismic design decision analysis, MIT-CE-R74-15, Structures Publication No. 385 Massachusetts Institute of Technology, Cambridge.