look at walls in isolation but must consider the elements associated with them. Let us consider only one such example, namely water pipes.

If water pipes are torn apart or crack, e.g. at a transition from a column, beam, floor, or diaphragm to the wall, or by the failure of the wall, repairs will cause plenty of indirect damage. Wall-to-wall carpeting, floors, panelling, wall paper, etc. will be spoiled. It is not difficult to arrange such piping in easily accessible ducts. Flexible support of pipes would even minimize the chances of damage to them. This holds good for electrical wiring as well. If no ducts are used one should at least not install wiring or pipes in areas where failures are most likely, e.g. where walls meet ceilings or beams. If such places cannot be avoided one must allow for some differential displacement.

Regularity and Symmetry of Buildings

Regularity and symmetry are very important parameters which contribute much to the performance of buildings during earthquakes. Most buildings are to some extent irregular or asymmetrical. This can be due to non-uniform foundation material or foundations, irregular floor plans or elevations, non-uniform column height, spans, stiffness, masses, and damping of structural elements. Irregularity is often aggravated by the kind, size, shape, and distribution of non-structural elements.

Fig. 5 shows the considerable difference in MDR's of buildings exposed to the M 5.4 San Salvador earthquake of 1986, depending on whether they were regular or irregular. It must be stressed that the irregular buildings in San Salvador were still far from the exotic monstrosities one can see at many other places and which produce much higher MDR's. The results of the San Salvador analysis are in line with our findings from other earthquakes. The MDR therefore depends largely on the configuration of the building and can be influenced by changing parameters as mentioned earlier. Before designing an asymmetrical building one should remember that the MDR of the object could be lowered by a factor of at least 4 either by avoiding irregular floor plans or by separating individual wings of the building adequately, if necessary covering the resulting spaces with facing which can be easily replaced. Reference (1) contains a detailed discussion with tables and factors quantifying irregularity.

Any building which is very irregular, either because it is extremely irregular in one aspect or because it combines various irregularities, requires much attention and a great design strength to bring the damage potential down and to avoid loss of human life. One can modify the example on the influence of orientational sensitivity (cf. relevant section) to assess the additional structural strength such very asymmetrical buildings should have. According to Fig. 7 the general MDR of 3-4% g buildings is about 20% at MM VIII. Very irregular buildings of this resistance will, however, produce an MDR of about 80%. To bring their MDR down to about 20% and assuming that the 1: 4 damage ratio holds good at higher strength also we have to follow the MM VIII MDR-graph upwards until it intersects with the 5% MDR level. This point corresponds to a base shear of about 13%. Knowing this, one can decide whether to abandon the extravagant asymmetrical design or to spend more money on the structure.

Design Philosophy

The general philosophy underlying so-called "earthquake-resistant codes" has so far been the protection of human life. Modern materials and construction methods, however, permit the construction of buildings which will suffer only moderately during most earthquakes and which incorporate a small collapse probability. This can best be discussed with the help of a damage probability matrix. The use of this matrix in conjunction with Fig. 1is suggested when deciding on design standards.

TABLE 1
DAMAGE PROBABILITY MATRIX FOR BUILDINGS

DAMAGE CLASS	MEAN DAMAGE RATIO (%)									
% of value	1.5	3	5	10	25	37.5	50	60	70	85
0 - 1.5	83	73	60	36	9	2				
1.5 - 3	17	25	26	23	9	3				
3 - 6		2	10	18	11	5	2			
6 - 12.5			3	12	18	12	6	2	1	
12.5- 25			1	8	24	24	15	7	3	
25 - 50				3	19	28	29	23	18	10
50 - 100				1	10	29	48	68	78	90

The above matrix tells us that among a comparatively homogeneous class of buildings which have, for instance, a MDR of 37.5%, about 29% of these buildings will be in the highest damage class, i. e. sustain damage ranging from 50% to 100% of their new replacement value. Those with partial or total collapse will belong to this class but they will constitute only a fraction of the 29%.

One should therefore consult Table 2 which shows the approximate percentage of homogeneous buildings in the 80-100% damage class depending on the MDR of the sample. It is stressed that these are approximate average values and that actual observations can produce quite different results, in particular if samples are small. We have, for instance, collected samples with 7% of the cases in the 80 - 100% damage class although the MDR of this sample was only 8%, and another with the same percentage in this damage class although the MDR was 34%.

TABLE 2
PERCENTAGE OF BUILDINGS WITH 80 - 100% DAMAGE DEPENDING ON MDR

MDR	10	20	30	40	50	60	70	80	90
PERCENTAGE	.25	3.5	10	20	30	45	56	70	85

This table can be used to consider the effect of a better code not only on MDR's but on the probability of partial and total collapse. For MM VIII and 2-3%g-buildings on medium-hard alluvium and of moderate irregularity the MDR is about 28% (cf. Fig. 1). According to Table 2 somewhat less than ten percent of such buildings will be in the 80 - 100% damage class. For such buildings but of 6% g base shear the MDR is about 11% and therefore only about one third of one percent of these buildings will be found in this high damage class. This shows that a moderate increase in actual strength reduces the probability of catastrophic failures very much.

As regards damage and failure probability, it is stressed that all the parameters discussed in this paper contribute thereto, and not only base shear. It is therefore important to recognize and consider these parameters in order to arrive at a effective and economically viable design philosophy.

In connection with the experience gathered after the Spitak earthquake of 1988 and the building inspections carried out by the author in Dushanbe during the USSR/UNDP/UNDRO Training Seminar of October 1988 some special features must be considered. The author had warned the audience during his main lecture in Dushanbe that catastrophic failures are very probable because of some special design features observed by him. As the experience from the Armenian earthquake of December 1988 fully supports these warnings it is strongly suggested that in particular the design features described hereunder are reviewed and suitably modified.

Liftslab Buildings

Liftslab buildings of the type constructed so far are an extreme example of vulnerability of prefabricated buildings due to the inadequate interconnection of individual elements and inadequate detailing.

Experience from other earthquakes has shown that columns of buildings are very likely to punch through floor slabs, i. e. to "puncture" them, unless columns and floor slabs are interconnected by well designed and executed reinforcements. Such a mode of failure must be avoided at any expense because the pancaking of the floor slabs is likely to kill most persons in the building at the time of the earthquake. Moreover, this type of catastrophic failure makes rescuing of any survivors extremely difficult.

If it should not be decided to abandon this design altogether the author suggests to replace some of the prefabricated walls in such liftslab buildings by cast in situ shear walls of reinforced concrete. Such walls are to be arranged symmetrically and they should be anchored properly to floor slabs and columns. Such a modification would lend much additional strength and stiffness to the liftslab buildings under construction or in use, reducing failure probability very much.

This type of modification will only cause nominal additional construction expenses. Moreover it is cheaper and much safer than, for instance, jacketing the columns. The method can also be applied to existing buildings and the author is certain that the additional cost involved will be much below estimates given to him in Yerevan.

We moreover point out that the columns which are presently used in high-rise liftslab buildings are very slender and likely to fail during a severe earthquake. This means that this design does not only involve an extremely high probability of failure at the column-floorslab interconnection but that one is confronted with very soft buildings which are very likely to be degraded (softened) during the early phase of an earthquake. Such soft buildings are very vulnerable as discussed earlier. Strong and properly interconnected shear walls will reduce also this problem considerably.

Panel Buildings

The general principles discussed in this section hold good for all varieties of panel buildings, whether the panels are large or small. The essential parameter is not the size of the panels but the quality of interconnections. The opinion encountered in Armenia that large-panel buildings are safer, because several did not collapse, is wrong. Damage depends, as is shown in this report, on many parameters and the better behaviour of several buildings can be due to the positive influence of some of them. Moreover, Tables 1 and 2 prove conclusively that even in a homogeneous sample damage rates of buildings are distributed over a broad spectrum. At an MDR of the entire homogeneous sample of 80%, for instance, thirty of one hundred buildings will be in damage classes which do not include partial and total collapse. This shows how dangerous it is to jump to conclusions.

Buildings which use pre-fabricated wall elements are very vulnerable unless these panels are very well interconnected with columns, floor slabs or beams. This is so far often not the case. Therefore such interconnections are likely to fail early during the earthquake, leading to a softening of the building and increasing the probability of partial or total collapse.

We have inspected an extensive building site at Leninakan. At this site one category of residential buildings was constructed like what one may call monolithic rc-boxes. Others were, however, assembled from prefabricated panels. Although these panels appear to be better interconnected than in earlier designs, the author does not consider this present interconnection adequate, even if stronger bars at the top, medium height and bottom of the walls are introduced. Moreover, not all walls are interconnected this way.

In view of this it is strongly recommended to modify designs suitably in order to guarantee an excellent interconnection of elements.

Prefabricated Industrial Buildings

The interconnection of elements in industrial buildings, like columns and beams, columns and roof elements, etc. as observed in Armenia cannot be considered safe. Therefore also in this case a review of design philosophy is strongly recommended. We point out at this place, a more detailed discussion will be found under the respective heading, that failure of industrial buildings can not only result in many casualties but it may paralyse the respective branch of economy and generate unemployment. Therefore one should not shun efforts and expenses required to improve designs.

It is mentioned at this place that monolithic structural frames are in general to be preferred because well designed interconnecting reinforcements can be introduced at many places, and by less qualified engineers and workmen. The interconnection of prefabricated elements requires a much greater effort as regards proper design and high quality workmanship on the site.

We stress again that the strength of buildings made of prefabricated elements is determined by the quality of the interconnection. If the interconnections are not of excellent quality such buildings will fall apart during a strong earthquake like houses of cards.

Quality of Design

Under this heading some essential details will be briefly discussed. The proper observation of such parameters is a precondition for minimizing earthquake damage and losses. Among the many earthquakes analyzed by us there are a few there are a few where much of the damage was due to bad workmanship and lack of qualified supervision and not to a general deficiency in design. This shows that these parameters also require separate treatment.

Interconnection of Elements

It must be realized that most of the modern buildings which failed catastrophically during the Spitak earthquake collapsed before the individual elements were exposed to the full earthquake load. This is due to inadequate interconnections. Before discussing issues related to interconnections we will explain why we arrived at this conclusion.

If a properly designed building with good interconnection of elements is severely damaged during an earthquake the elements proper are damaged. In general columns are more affected than beams, and the latter show more damage than floor slabs (cf. e.g. (16)). Moreover, hinges, i. e. in particular the place where columns and beams are joined, are damaged, but practically never to the extent of total disintegration.

An inspection of the damage caused by the Spitak earthquake, however, showed that the members virtually fell apart, some being left dangling, and this happened before the individual elements experienced the full force of the earthquake. The interconnections disintegrated so early that the elements were not loaded to the point of failing under compressional, bending, or shear forces. This is not surprising in view of the low-quality interconnections.

The main deficiencies noted were:

- The overlap of reinforcements is far too short, in particular for the large-diameter reinforcing bars.
- Interconnection of ribbed (high-strength) steel bars by welding must be stopped. Welding affects the strength of such bars very much and therefore the strength of the building. Moreover, welding often leaves a notch inthe bar and thus weakens it.

- Large-diameter bars should be replaced wherever possible by more bars of a smaller diameter. A short length of embedding or of overlap of large-diameter reinforcements and in concrete of low quality and with little cover is one of the worst solutions one may imagine.

- Columns were "assembled" from prefabricated sections. Such a design requires extreme care. Moreover, the workmanship as well as the quality of the material must be excellent. Joining of large diameter bars will introduce excentricity. Excentricity together with short overlap of reinforcements and low-quality concrete makes the columns particularly vulnerable at the interconnections.

Transitions in Dimensions

This problem is mostly found in industrial buildings. Transitions in dimensions (cross sections) of columns are often observed at the level of crane tracks and supports of beams and roof elements. Such transitions must receive great attention as regards detailing of reinforcements, otherwise the element affected will fail there like a glass plate scratched with a diamond (notch effect).

Detailing of Reinforcements

Detailing of reinforcement does not generally receive the necessary attention. This is true as well foı the buildings inspected after the Spitak earthquake. As there is adequate literature on the subject (cf. e.g. (35-37)) we will mention only some salient issues:

- The load bearing capacity of the hoops (stirrups) must be adequate. The general requirements are:

  - The diameter of the hoops must be adequate and in proper relation to the diameter of the longitudinal reinforcement.
  - The spacing of the hoops should be narrow, as a general rule not more than ten diameters of the longitudinal bars.
  - The spacing of the hoops should be further decreased towards the hinges.
  - Crossties should be introduced in columns, preferably with 180° hooks. The spacing of these crossties should be close enough to prevent basketing.

- As already mentioned earlier, one should avoid having few large-diameter reinforcing bars and use more bars of a smaller diameter.

- The design at interconnections requires special care and attention is invited to reference (35).

Floor slabs which are assembled from individual elements are much more vulnerable than monolithic diaphragms.

Moreover, we noted that reinforcements of floor slabs and walls are often assembled on site from individual bars by welding. Welding will not only reduce the strength of such reinforcements but this method of construction is time consuming and therefore costly and demands skilled labour. It is therefore proposed to consider employing prefabricated reinforcements mats as used in many western countries.

Quality of Workmanship

Bad workmanship should be considered a crime in seismic regions. Those practising it must realize that they are responsible not only for material damage and heavy economic losses but for injury and loss of life. Let us consider some basic rules.

Bricks, blocks or stones must be clean and moist during laying, and water should be used for proper curing not only of concrete but of cement mortar as well. Handling wet bricks may be an unpleasant and heavy task, the latter only if bricks of a large format are used. However, if a low standard of workmanship is applied, walls will develop many cracks even under small earthquake loads or collapse under heavier ones. This is not only unpleasant but dangerous to those occupying such buildings. Moreover such defective walls lend much less additional strength and stiffness to the building and therefore increase its general vulnerability and probability of collapse.

It is essential for bricks or blocks to be fully interconnected by mortar. We mention that we have seen many walls where the spaces between bricks had either not or only inadequately been filled with mortar.

In Armenia it is customary to use stone blocks for the construction of houses. Although some of the tuff is not very resistant to earthquake forces it is still possible to construct comparatively earthquake resistant houses of a few storeys. The prerequisites for obtaining acceptable structures, however, are:

- Low-quality stones should be discarded.
- The stones must be clean and wet when placed, to ensure proper bonding
- The mortar used must be of excellent quality, i.e. good cement mortar or equivalent.
- At the corners, at places where walls meet walls and/or floors and at openings, reinforcing bars should be placed in the mortar to interconnect and strengthen these exposed places and joints.

What was mentioned above in connection with mortar is true for plaster as well. Walls which are covered by high-strength plaster gain in strength. After the Campania-Basilicata, Italy, earthquake of 1980, for instance, we saw many buildings which had sustained less damage than others just because of good plaster. To ensure a good bond proper workmanship is needed here too.

In view of the very extensive use of concrete in construction work in Armenia and in other parts of the USSR and the sensitivity of concrete to poor workmanship, the need for good workmanship cannot be overestimated. Most of the severe damage to modern buildings during the Spitak earthquake was due to the inadequate quality of the concrete. Such concrete will not only fail under compressive or shearing loads but will also not transmit forces to the reinforcing steel as required. It does not make sense to place high-strength reinforcing bars, particularly if of large diameter, in a concrete of poor quality.

Concrete technology is fairly simple and the few important rules can easily be stated. They are:

- The aggregate must be of acceptable quality. Soft and friable stones and low quality sand must be avoided.
- The aggregate has to be clean.
- The aggregate grading must follow accepted standards.
- The cement content must be according to design. In seismic zones one should not use less than about 250 kg of cement per cubic meter of concrete.
- The water-cement ratio must be watched carefully. It is stressed that too much water nullifies the effect of even the best earthquake code.
- Unmixing must be avoided when placing the concrete. It should not , for example, be dropped over more than about one meter into the formwork.
- Concrete in columns, beams, slabs and other load-supporting elements should be properly vibrated.

All this requires no more than proper control by an experienced foreman. The absence of such control can cost thousands of people their lives, result in even larger numbers of injuries, and cause untold misery and ruinous economic losses.

Similarly it is important that the reinforcing steel be properly handled, be clean, bend according to design and be properly placed, interconnected, and secured inside the formwork. High-tensile strength steel should not be welded. Overlap must be long enough to transmit the full carrying capacity of the steel to the concrete and viçe versa. The rule that overlap should be e.g. 30 diameters does not hold good for all diameters. The cross-section, that is the carrying capacity, grows with the square of the diameter, but the bonding surface only linearly. Adequate concrete cover must be provided.

Non-structural Elements

Non-structural elements constitute a particular problem which has so far been badly neglected. They contribute at least 80% to building damage (10). In spite of the immense direct and indirect loss and damage resulting from their failure and although they also cause loss of life and injury, practically no earthquake building code provides adequate guidance. We have mentioned this item repeatedly under various headings. Now we shall briefly discuss some aspects of the design, arrangement, and fastening of such elements.

The single most important item, fill-in walls, has been mentioned earlier. In addition to selecting proper material and seeing to it that workmanship is impeccable, one could consider separating walls from columns, e.g. by inserting some elastic material. This, however, imports a disadvantage as such walls do not contribute much to the stiffness of buildings, which is particularly important for those founded on soft subsoil, i.e. the majority built today. If one must decide between strong walls or walls separated from the structure by an elastic layer it is better to opt for strong walls which reinforce the entire structure. The performance of walls also controls damage to items placed inside walls or fastened to them, like electrical wiring, piping, sanitary items, doors and windows.

A very important non-structural element in panel buildings is the wall panels. Because of the mostlyinadequate interconnection of them to columns and floor slabs they did lend very little additional strength and stiffness to a building. Damage to the joints between the panels is difficult and costly to repair and there is a good chance that the repaired building will have less strength than the original one. If such walls, of good quality - here too quality control of concrete is extremely important - are very well attached to the structural members of the building a stiff and resistant building results. Very probably a better than average workmanship in some of the buildings contributed to their resistance. This does, however, not warrant general conclusions. Panel buildings with inadequately interconnected elements are houses of cards.

The most important non-structural elements after walls are suspended ceilings,elements like tiles or stone slabs used to facade walls and windows. Whereas high MDR's must be predicted for suspended ceilings fastened according to present methods a very substantial gain can be achieved by applying proper care.

Damage to elements which facade buildings is determined by the performance of walls, discussed above, and by the fastening of the elements. Much has to be done in the latter respect and it should not be overlooked that the fastening of such elements and of suspended ceilings with all fixtures attached to them also influences loss of life and injuries, in particular in strong buildings, i.e. where the probability of partial or total collapse is small and where loss of life and injury are overwhelmingly determined by the performance of non-structural items.

We shall not discuss windows in detail because, contrary to general belief, damage to windows is generally not significant. The glass panes can often move in their frames to some extent. Moreover, glass is at least as elastic as brick walls, and panes are easily replaced - indeed occasional replacement is a recognized feature.

Our list of non-structural items is not complete. There are doors, lifts, floor covering, bathrooms and toilets, paintwork, etc. It is evident that damage to walls and some structural members will result in costly repair work to these non-structural elements as well. It must be remembered that in ordinary buildings structural elements cost only about 30% of the total value of buildings, and in better-equipped buildings even less. The remaining 70 to 80% are non-structural elements. Damage to such items generally constitutes more than 80% of all damage and losses involving buildings. It is therefore very important to pay more attention to protecting non-structural components. So far the most economical approach is to design buildings with an improved base shear which are stiff and not very asymmetrical. As the structure of a building cocts only a fraction of the total cost of a building a stronger structure does not increase total cost much, as a rule not more than a few percent.

Hammering between Buildings

Hammering is generally allowed for in codes by stipulating a separation between buildings. The distances specified are, however, in general inadequate if buildings are founded on deep alluvial material and if large earthquakes may cause shaking of long duration. Tall and soft buildings, in particular, will experience large-amplitude oscillations. As neighbouring buildings never shake in harmony, if only because earthquake waves arrive earlier at one than at the other site, hammering will occur. For these reasons the cases of hammering were abnormally high during the Mexican earthquake of 1985. It should be noted that severe hammering between buildings may have serious consequences, leading, for instance, to partial collapse.

Some readers may be surprised that the author does not propose increasing the gaps between buildings as the most important remedial step but rather recommends reducing amplitudes. The first and foremost tenet should be not to erect tall soft buildings on deep alluvium, i.e. on soft layers. This was already propounded by Charles F. Richter (32) but this lesson still appears to be largely unlearned. Reducing amplitudes means reducing structural damage, non-structural damage, injury, loss of life and indirect losses!

Orientational Sensitivity

Analysis of damage to oblong buildings which are otherwise symmetrical persistently shows that MDR's depend on the orientation of the long axis of the buildings (1, 3, 9, 12, & 15). Those with their short (weaker) axis in the general direction of predominant earthquake shaking suffer much more damage than identical buildings standing about perpendicular to them and therefore shaken mostly in the direction of their long (stronger) axis.

Orientational sensitivity gives rise in the main to two problems. First of all it will not always be easy to predict the general direction in which shaking will be strongest during future earthquakes, although this is not to be considered an unsurmountable problem particularly in regions where earthquakes are generated by a subduction process. Secondly, owners, architects, and structural engineers will have to live with the plots of land available and with building laws demanding a certain orientation of the long axis of the building. The latter factor could, however, be influenced if authorities and architects who developed such rules or plans were properly informed about important parameters controlling earthquake damage.

The MDR's of oblong buildings could be reduced very much if structural engineers were to compensate for the smaller stiffening effect of fill-in walls which run parallel to the short axis of the building by making the structure stronger in this direction. Data in the various papers dealing with factors contributing to earthquake damage and with orientational sensitivity can be used to design much better buildings. We give some figures below to show how important this matter is.

Oblong buildings with their short axis in the predominant direction of the strongest shaking will in the medium MDR-range and at MM VIII experience damage which is 3-4 times higher than those predominantly shaken along their strong (long) axis. Here to it is important to allow for details. As shown in Fig. 9 the general MDR-level of 8 & 9 storey buildings in a very large housing colony in Mexico City was substantially below that of 14 & 15 storey buildings. For the taller buildings which experienced a high MDR, the ratio of damage depending on the orientation of the long axis was 3.6 :1, but for the 8 & 9 storey buildings 100 : 1. Structural engineers should understand what such obvious flaws in design mean. At an MDR of 0.12% the utility of the buildings will hardly be affected but at a MDR of 12.81% many walls are cracked, part of such buildings will have to be evacuated to make repairs possible, substantial inconvenience is caused, and indirect losses arise. At an average 30:70 ratio of the cost of structural to non-structural elements an MDR of about 13% means a loss of about one fifth of the value of all non-structural items.

It must be stressed that collapsed buildings were only found in those sub-samples of identical buildings in housing colonies which had their weak axis about parallel to the direction of strongest shaking. At an MDR of about 10% only 1% of all buildings will sustain damage ratios between 50 to 100%, and only about one quarterof one percent will sustain damage between 80 and 100% (Table 2), the damage class which includes collapse. At an MDR of 25% about 10% of the buildings will be in the 50-100% damage class, at 37.5% MDR nearly one third of the sample is in this high damage class, and at 50% MDR nearly half of all buildings. If designers combine the negative effect of several parameters, e.g. orientational sensitivity and a soft ground floor, severe loss of life, and not only very heavy physical damage, can be the consequence .

These cases point to very serious flaws still existing in structural design. In the present case the mistake is to neglect the strengthening effect of fill-in walls. As it is obviously impossible to arrange so many fill-in walls parallel to the short axis that they stiffen the building as much as those in the direction of the long axis the structure must be made stronger in other ways. Figs. 5 & 7 provide some guidance. We shall use a simplified example to illustrate what can be done. A more detailed explanation is to be found in the caption of Fig. 7 (cf. also 1).

We assume that a normal, i.e. not extremely oblong but otherwise regular building designed with a base shear of 4% g is to be strengthened in the short axis sufficiently to reduce the damage to the general MDR of 4% g buildings if exposed to MM VIII. We assume that the damage ratio (DR) depending on orientational sensitivity is 1:4. Intersecting 4%g with MM VIII in Fig. 7 and applying this DR we estimate a general MDR of about 18% of the new replacement value of such buildings. Buildings with their long axis in the direction of strongest shaking will suffer an MDR of about 9%, those perpendicular to them one of 36%. If we wish for the MDR of the latter buildings to be about 18% we have to see at what base shear the general MDR is 9%. This is so for about 8%g buildings. Therefore the structure should be designed for 8%g base shear in the direction of the short axis.

This approach is admittedly an approximation because damage depends on many different parameters, but it is based on a substantial observational sample and not on theoretical models not backed up by pragmatic research.

2. Utilities

The proper application of the rules outlined above is particularly important in assessing utilities, i.e. plants and systems providing electric power, water, gas, oil, and telephone and other communication facilities. These services generally fail even if the magnitude of the earthquake was small (15). As such failures affect many different elements at risk, and as the ensuing loss or damage may be enormous, the upgrading (retrofitting) is an important task. The proper steps, which can in general 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.

A very important gain could be made by introducing proper earthquake construction codes for electrical, chemical and mechanical plant, equipment, machinery and other systems employed in utilities. These codes should allow for the most important parameters determining damage and failure (1, 8) and not confine themselves to acceleration only which is a very unreliable yardstick of damage.

It would be wrong to rely too much on safety devices which protect items against overload, or shut off fuel supply or power at the time of an earthquake; the first aim should be inherent safety, i.e. what one may call passive safety of all items. We shall revert to this when discussing fires and explosions in plants.

Active safety devices, that is those acting when triggered by an earthquake, can be installed in existing utilities without requiring lenghty shut down. This is true 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.

There are other steps that can be taken by those responsible which do not require additional devices or equipment, etc. A case in point is the lowering of the water level in a reservoir behind a dam representing a high risk.

In addition to foregoing the more general remarks, we shall now summarize some important aspects learned from the failure of mechanical, electrical, and chemical apparatus.

Most important is proper anchoring. This means an anchoring system which, besides being strong enough, also provides some hysteretic, i. e. shock-absorbing properties if sensitive items in the piece of equipment which is anchored would otherwise break.

Pipe systems are very vulnerable to differential displacement, which is why the water supply and sewer systems in a town are up to now certain to fail if earthquake shaking ist strong (MM VIII and above). It should be noted that it is neither ground acceleration nor velocity but differential displacement that causes the damage. The pipes, and also cables for that matter, are pulled apart, compressed or sheared by the displacement of the ground in which they are firmly embedded.

While it is difficult to provide much flexibility in the case of embedded conduits, so as to compensate for differential displacement without breakage, this is easy to achieve in above-ground pipe systems. Mechanical engineers long ago introduced flexibility in pipe systems to permit thermal expansion and contraction. This should also be done whenever differential displacement by earthquakes cannot be ruled out

How this can be achieved economically, at least in the case of some embedded pipe systems, will be briefly discussed. It is customary to put fire-fighting ring-mains in petrochemical plants into trenches which are backfilled. If such pipes were only covered with loose sand they could move without breaking. One may also place pipes in rc-boxes within which they can move. If such boxes were pre-fabricated the additional cost would not be prohibitive.

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.

The last two items to be discussed here are roads and bridges, because they are sometimes discussed under lifelines. The possible gain from vulnerability analysis and risk optimization is as a rule insignificant for roads and the like, e.g. railways and runways, but it can be substantial for bridges. The latter are frequently damaged by earthquakes, often because basic rules have been overlooked in the design. It is most important for supports for bridge decks and girders to be long enough to accommodate substantial differential displacement. Moreover, sturdy piers, pylons, or supporting columns designed for high base shear are required. Bridges are after all the most important elements in roads. Their failure can, moreover, cause very heavy economic losses.

3. Industrial Plants

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. In low-income regions, the economy and the people depend even more on their functioning, in particular as recovery takes a long time and as are less alternatives in industry and economy of such regions.

What has been said of utilities in connection with earthquake construction standards, protective devices, and additional steps to be taken is also important in industrial plants, in particular if fire, explosion, or environmental contamination are important risks. Passive safety is of primordial importance, "active safety" may be unreliable.

The gain from the introduction of proper construction codes can be very substantial. It will result not only in much improved performance of the elements at risk but also in greatly reduced indirect losses.

It must be recognized that the distribution correlating probability or return period of accidents and their magnitude could in many cases be much improved, i. e. the risk reduced if such plants were designed on the basis of adequate actual earthquake damage experience and guidelines or literature showing what to take into account (1, 8).

Briefly, the most essential precautions against damage in industrial plants are proper anchoring and the provision of flexibility where substantial differential movement can occur. High-value industries and components should never be located in buildings which are very vulnerable.

4. Indirect Damage and Losses as well as General Loss Data

Rising values, growing investments and populations in terms of number and density, as well as the increasing number of elements at risk which are actually exposed or which represent critical installations because of particular risks associated with them put, an increasing demand on qualified scientific assessments of the consequences of earthquakes. Up to now practically only the physical damage has been considered, not indirect damage or what we shall call consequential damage and loss. These losses very often weigh heavier than the direct physical damage, moreover their effect on society and national economy can be profound and lasting.

As there is practically no special literature quantifying the consequential damage or losses caused by earthquakes we shall treat some important aspects here. In view of the many parameters which must be considered we must, however, limited ourselves to a general discussion of indirect loss and damage and of the respective parameters (for details cf. (1)).

It is the author's opinion that the assessment of exposure to the consequences of earthquakes must allow for probabilistic aspects at all stages, in order to put risk assessment, risk mitigation and risk management on an economic basis. The assessment of the economic consequences of earthquakes must therefore consider probability distributions of earthquake magnitude or intensity of the area under study as well as those related to direct and indirect damage and loss levels. These aspects are discussed in the respective sections.

We offer two simple examples to illustrate a method which can be used to calculate the economic consequences of earthquakes, including therefore the economic loss from direct damage. The examples illustrate a general assessment procedure but do not suggest particular figures. They 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. 1, 38).

For these examples we have selected a town of about 100,000 inhabitants, founded on medium-hard alluvium and having moderately asymmetric buildings of a quality corresponding to 2 - 3% g. The example covers only the MM VIII zone; it is based on MDR's and not on maximum loss levels. All values are in US dollars.

4.1 LOW TO MEDIUM INCOME LEVEL

1. DIRECT LOSSES	$/Inhabitant
<u>Residential buildings</u>: constr. cost abt. $ 4,000 per inhabitant, MDR 30%	1200
<u>Commercial bldgs & equipm.</u>: 40% of working population of 30,000 50 cubic metres per person, $ 150.- per cubicmetre, MDR 30%	270
<u>Factories</u>: 50% of working pop. 150 m^3 /pers. 100.-/m^3, MDR 30%, 10% of the working population	675

Machinery: abt. 1/3 rd. of factory buildings	225
Contents:	
Private $2,000.-/inhab., MDR 10%	200
Merchandize in stock $100.-/inhab., MDR 10%	10
Vehicles: prob. of damage = 0.2, $5,000/car, 1 car/4 inhab., MDR 12%	30
People killed: abt. 1,300 people, $20,000 each	260
Injuries: abt. 6,500 persons, $1,000 each	65

(Casualties will be re-evaluated below)

2. INDIRECT LOSSES

General Loss of Production: abt. 15,000 people affected for 3 months, $15,000 each — 562
Wages, Salaries, Social Security, Interest, Depreciation, Continuing Expenses, Loss of Markets, Tourism, etc.
(Depending on actual case)
This item will be discussed more in detail after the second example

3. OTHER LOSSES/DAMAGE
Transport, Power, Water, Sewage, Telephones, Roads, Bridges, Medical & Health Services, Schooling, Art Collections & Museums, Cultural Heritage, etc.
(These losses can be very heavy but are difficult to state in a specific way as they depend on the local setting. Therefore a detailed stock-taking is required)

Additional information is furnished after the second example

4.2 HIGH INCOME LEVEL

1. DIRECT LOSSES

	$/Inh
Residential: $40,000/inhab., MDR 30%	12000
Commercial: 40% of 30,000, 200 m^3/pers. $150.-/cubicmetre, MDR 30%	9000
Factories: 50% of 30,000, 300 m^3/pers. $100.-/cubicmetre, MDR 30%	9000
Machinery: 1/3 rd. 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. INDIRECT LOSSES

General Loss of Production: 27,000 pers. affected for 3 months, $25,000 each	1700
Interest, etc.: as in earlier example	.....

3. OTHER LOSSES/DAMAGE

Transport (incl. shipping & aviation), etc.: as described in earlier example	.....

(Cf. discussion below)

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. 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) (cf. Ref. 1 in SEISMICITY) can be substantially higher, and the probability of such a catastrophe is not necessarily small.

We shall now return to loss of human life, SINCE the above list of losses includes the cost of injuries and loss of lives 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 parameters which determine casualties are discussed below in a separate section.

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. It is based on the about 25,000 people killed by the Spitak earthquake, to which we must add about 14,000 permanently disabled citicens.

Assuming a GDP of about Ruble 10,000 per inhabitant, an average age of 30 at the time of the earthquake and a retiring age of 65, the 39,000 persons removed forever prom the productive population represent about Rbl. 1.365×10^{10} permanent productivity loss. This amount of Ruble 13,650,000,000 is similar to the total 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 medical treatment of those who were injured must be added. If we assume medical expenses of only Rbl. 1000 per injured, a figure which is probably on the low side because of the high cost of treatment of those permanently disabled and seriously injured, a sum of Rbl. 100 million would result.

Returning to the general examples we shall also allow for indirect losses due to interest on the idling capital, loss of rent, wages and salaries and other overhead expensed which continue during the period of interruption of commerce and industry. Moreover, the cost of those persons permanently lost (killed & disabled) will be considered.

For the first example (low to medium income level) these indirect losses add more than $ 2,000 per inhabitant to the bill, i.e. more than $ 200 million for this town of 100,000 inhabitants.

In our example the most important item is the loss to the national economy due to the lives lost. It amounts to more than 60 % of the items considered here. The next important item is rent, interest and overheads which amount to about 28%. As loss of life and business interruption and therefore general overheads are decisively affected by the vulnerability of the buildings, it is evident that any improvement in this field will reduce the impact of an earthquake enormously.

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 earthquake killed about 25,000 people and many more were crippled. This earthquakes cannot be taken as a worst-case scenarios. An earthquake of the same magnitude but very near to Leninakan would not only have killed and injured far more people but also resulted in a much greater economic loss. Similarly, had the M 5.8 aftershock followed the main shock after, e.g. 30 seconds and not after 4 minutes many more would have been killed and injured and the economic los would have been much severer. The Tangshan earthquake in China killed about 255,000 people and about 800,000 were injured. The number of those disabled is not known.

Should there be any high-value production in the town (the high-income level example contains such a case) the indirect losses would rise dramatically. This shows that each particular location must be assessed carefully by someone with adequate experience.

We shall now discuss a few additional aspects which can be important at specific sites.

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 in the context of this paper 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 business for most hotels because there will be not only some severe structural damage but also cracks in the walls of most rooms. It is not possible to accomodate guests 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 to the town which contains inflammable, explosive, or toxic materials (or if the area is hit by a devastating tsunami, which hazard does not exist in Armenia).

No great earthquake is required to produce loss levels and indirect losses as discussed in the examples (cf.,e.g. (15)) and a large earthquake happening near a high-value region can cause much higher losses. The loss levels stated in the respective tables and used in the examples do not allow, for instance, for the adverse effect of damaging shaking of abnormally long duration. Moreover, the first example in particular assumed a rather homogeneous mix of risks. The second example shows that one large exposed installation in a low income area, can cause as much loss as all the buildings, commerce and factories taken together. A conflagration and/or some explosions in such a plant can result in an interruption of production of more than one year.

5. Casualties Caused by Earthquakes

5. 1. Introduction

Earthquakes have repeatedly killed large numbers of people and injured many more. Casualties are caused not only by the collapse of buildings and the failure of parts of buildings but by fires following earthquakes or explosions, release of toxic substances, landslides, the failure of dams, or traffic accidents, and by tsunamis. The probability and extent of the contribution of each of these sources to casualties depends on many parameters, and it is impossible in this paper to discuss in detail the entire spectrum of elements at risk and the parameters contributing to casualties. We will therefore concentrate on the most essential of these elements and on the most important of these parameters. This information is essential both in risk assessment and in planning risk mitigation and the management of disasters.

The element at risk which is in general responsible for the largest number of casualties is buildings of all kinds. This is particularly true if their vulnerability is high.

In the past buildings have also played an important role in connection with casualties due to fire following earthquakes. Old paintings depicting earthquake catastrophe often show flames engulfing buildings or entire quarters of towns. During the present century two very destructive earthquakes occurred where most of the overall loss, and in one case the loss of life, were caused by the ensuing conflagration. The first case was the San Francisco earthquake of 1906 and the second the earthquake disaster which hit Tokyo in 1923. Although construction methods incorporating less combustible. material and the disappearance of open fires have in most modern towns reduced the chance of numerous casualties from fires following earthquakes, the risk still exists in a few towns and has not been wholly eliminated in others.

Modern process industries and chemical and petrochemical plants have added a new dimension to the exposure of the populations, and this exposure still has to be assessed. It will be shown that it is extremely important to use caution in analysing this "new" risk category and to allow for adequate safety margins because of fires caused by earthquakes, to the chance of devastating explosions and to the spread of toxic material from some plants. One can learn in this respect not only from a critical analysis of the plants themselves but also from fires, explosions and the release of toxic material during normal operation. Earthquakes add further dimensions to the probability of failure, the role of ignition sources and the probability of such accidents.

While landslides and rockfall do not normally contribute much to the number of people killed and injured by earthquakes, there are examples to the contrary. Their analysis shows that more attention should be focussed on questions related to geology, topography and soil mechanics. The risk of dam failure due to earthquakes must also be taken into account, determined not only by pure engineering features but also by problems of geology and soil mechanics and by issues related to hydrology. There are many dams in earthquake regions.

Before discussing the various parameters which determine casualties caused by the failure of the different elements at risk or by other phenomena it is, however, important to spent some time on basic problems afflicting casualty statistics. This discussion will show that the number of casualties experienced during the Spitak earthquake can not be taken as the average to be expected and still less as the maximum possible.

5. 2. General Uncertainties Related to Casualties

Earthquake literature is extremely short of data on loss of life as related to earthquake intensity, general building quality, and the many other sources and parameters which influence casualties. We have for this reason analysed a large number of earthquakes ourselves in order to improve the data-base. Considerable general uncertainties still remain and we shall discuss the most important of them in this chapter. Particular parameters controlling the failure of buildings or other elements at risk and