Disaster prevention and control in the earth sciences

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Among the critically useful applications of our basic knowledge of the sciences, especially physics, and our ability to exploit mathematics to the advantage of man wherever he lives on the planet, is that of disaster prediction. Here are described what we are currently capable of doing to mitigate seismic and volcanic cataclysms and how we should be able to improve our capacity to predict these natural catastrophes.

Introduction

A disaster can be defined as a situation involving the loss of life, injury to life, or destruction of property on a scale with which normal emergency services cannot cope. It therefore implies the occurrence of an unusual event which was not adequately predicted in time or place to allow measures to be taken for the protection of the threatened people or property. The two main types of event which belong to the earth sciences and which are capable of causing major disasters are earthquakes and volcanic eruptions. The purpose of the discussion which follows is to describe and critically review the present level of exposure of mankind to these hazards, and the means of protecting it from them.

The two different types of hazard pose considerably different problems with regard to both the geographical extent and the nature of the damage, as well as the premonitory signs and the duration of the phenomenon. It is simpler, therefore, to consider each type of hazard separately.

The scale of earthquake disasters

Since earthquakes are capable of causing destruction over much larger areas of the world's surface, and are more difficult to predict both in time and in place than volcanic eruptions, they result in larger losses. Details given by Montandon [1][1] show that the mean annual death rate from earthquakes between 1926–50 was about 14,000. According to Latter [2], this rate diminished for the period 1951–68 to about 3,750. When data through July 1976 are added, however, the annual average since 1951 increases to at least 10,000, whilst for the last 7.6 years, and assuming the loss of 100,000 lives in the Tangshan earthquake of 27 July 1976 (for which estimates of between 100,000 and 1 million have been quoted), the mean annual loss of life has been about 29,000.

The only general conclusion which can be drawn from these numbers is that the mean annual loss of lives through earthquakes remained reasonably static during the present century. But with the progressive concentration of world population in urban areas, and with the spectacular recent increase (in many cities) in the proportion of masonry and other earthquake-susceptible structures—especially high-rise

1. Numbers in brackets correspond to the references at the end of the article.

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buildings—there is a corresponding increase in the potential for losses of unprecedented size in a single earthquake.

Means of earthquake disaster prevention

The means of earthquake disaster prevention fall into two broad categories: first, those which we consider technically practicable and ensure a fair measure of success in most cases; second, those which at present are likely to be only rarely successful, or which mitigate only limited aspects of the disaster.

The first category involves the identification of regions subject to earthquake risk, the reinforcement of structures to resist an appropriate level of ground shaking, and the avoidance of certain local areas identified as the most exposed to earthquake damage. Seismology has already identified high-risk areas in broad terms, for example in the form of earthquake epicentre maps from about the year 1900 onwards–published by the International Seismological Centre in Edinburgh (United Kingdom); by the National Earthquake Information Center in Boulder (United States), and by many other national or regional authorities.

In addition to these maps which show the distribution of instrumentally recorded earthquakes, there exist for most regions catalogues of earthquake damage, extending over the period of historical documentation (over 2,000 years for Europe and China, about 300 years for Latin America, and 150 years for California). From these data, earthquake risk can be assessed in the climatological sense, in terms of recurrence intervals for events of different magnitude (energy at source) and distance, or for events causing different damage intensities at the point of reference. The recurrence figure will indicate the mean interval between similar, consecutive events, but will specifically not define actual intervals between such events. Magnitude values at a given distance, or intensity scale values, can be converted into approximate maximal ground accelerations for structural design purposes.

A relatively new type of instrument, the strong-motion accelerograph, is now being installed widely in order to measure the strong shaking close to the source of the largest earthquakes. Systematic, large differences in the frequency and amplitude of shaking are seen between local areas of bedrock and of thick alluvium, and observations to date provide a basis for predicting the characteristics of a given site once the local geology and the distribution of near earthquakes are known. The seismic response of the different parts of a large building can also be measured by accelerographs.

Application of existing technology

With regard to earthquake-resistant building construction, the technology is being actively developed (e.g. Page *et al.* [3]) and practised at least for tall buildings and important engineering structures in most countries with high seismic risk. The identification of high risk localities such as those subject to particularly strong shaking because of site geology, or subject to secondary effects such as liquefaction or tsunami, provides cogent arguments for the restriction of future land-use in some urban areas which, regrettably, government authorities are often reluctant to accept.

A final, and much neglected aspect of earthquake-resistant building design which was illustrated especially in the Guatemala earthquake of 4 February 1976, is the urgent need for the upgrading of the standard of construction of private dwelling houses [4]. At the Unesco Intergovernmental Conference in February 1976, it was noted that a communication gap exists between the élite of structural engineers working almost exclusively on large buildings, and small builders who in some parts of the world are using new materials (new to them, e.g. masonry and reinforced concrete) without proper knowledge of the appropriate techniques; or in other parts of the world where traditional building materials with no resistance to earthquake are being used (e.g. adobe), there is a need to introduce some form of cheap and readily available reinforcement. It was also recommended at the same conference that not only small builders, but also the population in general, should be educated in simple, earthquake-resistant building techniques for private dwelling houses. In Andean, Central American and certain eastern European countries, this is probably the most important single aspect of earthquake risk mitigation.

Accurate earthquake prediction

The second category of methods for earthquake disaster prevention should be regarded as possible but not yet widely practicable. The most important of these is the prediction of specific earthquakes. If accurate to within days or hours, this will allow the evacuation of the population; and if convincingly established as likely to happen weeks or months ahead, this would allow, to a modest degree, the strengthening of some smaller buildings. The main limitations of this method at present are the low prospects for accurate prediction and the fact that although, where prediction is successful, the primary goal of protection of human life may be achieved, the loss of property and hence the economic disaster ensuing, may not be significantly reduced. A very comprehensive review of the state-of-the-art in earthquake prediction has been published by Rikitake [5].

Within the same category may be included methods such as the proposed control of seismic energy release, for example by pumping water to great depths in active fault zones—thereby lubricating the fault and hopefully producing frequent small slips rather than the long-term accumulation of elastic strain energy to higher and more dangerous levels. The feasibility of such control has been shown by the creation of man-made earthquakes through fluid pressurization of deep wells, e.g. at Denver, Colorado [6], but the high cost of such an operation along a major fault zone, and the possibility of triggering an earthquake of larger magnitude than intended, detract from the practicability of this method.

The case for earthquake prediction

Although the first of the two categories described above, i.e. the universal application and continued refinement of improved building techniques, probably remains the best method for earthquake disaster prevention, there are strong arguments for increasing research efforts directed towards earthquake prediction. The arguments are three. First, as a means of protecting populations which live in highly vulnerable structures and which cannot be rehoused more safely in the early future; second, assuming a warning period of several months as a means of identifying the areas which are most immediately in need of reinforcement for existing buildings, or alternative accommodation; and third, assuming a final warning period of a few days, as a means of double security for the occupants of nationally earthquake-resistant, but possibly vulnerable (e.g. high-rise) buildings, in the event of a particularly severe earthquake.

The case in favour of intensifying efforts towards earthquake prediction is also supported by the spectacularly successful example of prediction of the Haicheng earthquake of 4 February 1975 in China [7], in which, after one false alarm, the time and place of occurrence were successfully refined to the extent that the population in the epicentral region were warned to evacuate their houses only five and a half hours before the main shock, whilst factory work was allowed to continue as normal, and did so without adverse consequences, only 50 km from the epicentre. This success represented the reward of what must be the most massive human effort that has yet been made in earthquake prediction, although the fallibility of such effort has, sadly, been illustrated in the Tangshan earthquake of 27 July 1976.

The key to the specific success in China in February 1975, and to the general problem of earthquake prediction, is the wider deployment and gradual refinement of existing techniques and the continued search for new methods and more reliable criteria. Descriptions in the world press of the first success in prediction, and uncertainties about the efficacy of present earthquake-resistant building codes, have given rise to popular hope and demand for the early achievement of accurate earthquake prediction. Usami [8], for example, writes that

> the special background of earthquakes and earthquake damage in Japan and memory of tragic damage [enlarge] the social demand for earthquake prediction. People know the status of Tokyo and are afraid counter measures will not be [taken] in time for the next event....

Bases of earthquake prediction and prospects

With regard to what has been called the 'physical basis' for earthquake prediction [9], it is clear that a variety of physical measurements can be used as predictors, and that the coincidence of these various lines of evidence and their interpretation through the supposedly irreversible mechanism of rock dilatancy, opens the door to a deterministic approach to earthquake prediction. This provides encouragement that, given favourable natural circumstances and adequate monitoring by several different methods, there are excellent prospects that, as in the Chinese earthquake of February 1975, similar predictions involving the successful evacuation of the population will be repeated.

In Japan, in an inquiry (using the Delphi method) carried out among geophysicists, Usami showed that the successful prediction of earthquakes which may occur in the following month was estimated as achievable by 1990, but that it was not clear whether precision to within twenty-four hours would ever be consistently achieved. In the United States, no prediction resulting in evacuation has yet been made, although Press [10] claims that ten 'California earthquakes were preceded by tilt changes in the vicinity of the epicenter' and that 'precursory changes in seismic velocity have been reported for about 10 earthquakes in California and New York'.

One of the particular problems of earthquake prediction in Western societies is that the public is more exacting than in other parts of the world in its demand for accurate information, and would be quicker to claim compensation for any inconvenience or economic loss following a false alarm. In China, by contrast, a significant section of the population is involved in making simple observations aimed at earthquake prediction, so that as Adams [7] concludes after a recent visit to China, this has resulted ... in ... an awareness among the people that this is their programme, and that any failures or false alarms are the responsibility of the people themselves, as well as of the scientific experts. Such an attitude is essential if people are going to accept the disruption to their lives that must follow any earthquake prediction.

Cost-benefit assessment in disaster prevention

There is little difficulty in justifying, in absolute terms, any serious attempt at earthquake hazard mitigation. It has to be recognized, however, that major earthquake disaster will strike a given community only rarely, and that human optimism is generally such that, even within a few years of a catastrophe, the possibility of the recurrence of a similar event—and the willingness to take precautions against it—are rapidly forgotten. The commitment of appropriate funds and effort not only to earthquake prediction, but also to earthquake engineering, building codes, land-use regulations and disaster preparedness, must be sustained for several decades if rapid progress towards the goal of earthquake disaster prevention is to be achieved.

In a recent review, Press [10] claimed that

> scientists can question the policy of a government that spends billions in construction but is unable to support research that would safeguard its own investment. They can question the wisdom of budgeting less than a tenth of a percent of the total 'construction investment for research on possible hazards.

At the same time as making the above claims, it should be clarified that the present status of earthquake disaster mitigation is that, with appropriate funding over several decades, there is an excellent prospect of achieving the prediction of many major earthquakes, but not necessarily all, in the region of intensive study.

For the immediate future, it appears that each individual government will weigh the advantages of various levels of investment in earthquake disaster prevention, and will provide funding according, first, to its available means, and, secondly, to the demands of interested scientists. These demands, if presented and discussed before the population, may be echoed by public demand. In any representation to the government involved, it is clear that the scientists will be finally answerable for their performance. It is most important, for their own credibility in the long term, that they do not overstate their present ability.

Perhaps the most hopeful, although imponderable, aspect of earthquake prediction is that within the last ten years numerous completely new physical methods and models have been developed for earthquake prediction (e.g. seismic-wave velocity changes, radon emission and the dilatancy model). It is possible that the next decade may provide technological advances which will result in new and even more effective methods of monitoring and data processing. In this respect, the ability of seismology to achieve new breakthroughs in earthquake prediction will depend on the present goodwill of funding authorities and, if a prerequisite for financial support, the gambling instincts of the more optimistic seismologists.

The scale of volcanic disasters

The scale of volcanic disasters, in terms of area seriously affected and population killed, is considerably less than that of earthquakes. Latter [2], for example, quotes approximate world casualty figures of 0.5 million from volcanoes compared with 5 million from earthquakes for the period since A.D. 1000. From 1900 to 1976, the mean annual population losses amount to about 14,000 from earthquakes, and about 800 from volcanic eruption. Similarly, the largest single loss to date from volcanic eruption does not exceed 100,000 whilst for earthquakes the corresponding figure is 830,000 (Shansi province, China, in 1556).

The total number of potentially active volcanoes or volcanic centres in the world is estimated by Latter to be about 380. If the mean area around these centres that are subject to disaster is assumed to have a radius of 10 km, then the total area of the world's surface threatened seriously by volcanic eruption is about 120,000 km^2. This can be compared with earthquake belts close to land which, assuming a total length of 25,000 km and width of 100 km, amount to a total populated area subject to high earthquake risk of about 2.5 million km^2, or over twenty times the area exposed to high volcanic risk.

The conclusion from these data is that volcanic disasters in the world as a whole represent between one-tenth and one-twentieth of the scale of earthquake disasters, but that damage from volcanoes is equally as intensive within the relatively small areas which they affect. In those countries which are small enough for a significant proportion of the population to live around the flanks of a volcano, the scale of the national disaster may be equally as great as that inflicted in a larger country by a great earthquake.

Furthermore, the coincidence of volcanoes with certain of the zones of high seismicity means that volcanic hazard is usually additional to tectonic earthquake hazard. In particular the subduction zones, which include island arcs and certain continental margins such as Central America and the Andes, are the location not only of many of the world's largest earthquakes but also of the most violent type of volcano.

The means of volcanic disaster prevention

The main difference between volcanic and earthquake disasters is that the former are almost invariably preceded by obviously abnormal activity at or beneath the volcano. This activity may include frequent local earthquakes and increased steam emission for up to many months before the climax, and ash or lava emission in stronger explosions over a period of, usually, between a day to a month before the destructive cataclysm.

The problem of disaster prevention therefore becomes, first, one of identifying abnormal local earthquakes, gas emission, ground deformation, or temperature increase in time for the authorities and population to make detailed plans for evacuation; and second, one of identifying the rate of escalation and hence the probability of a destructive climax. A detailed description and examples of the application of the various monitoring methods are given in the handbook, *The Surveillance and Prediction of Volcanic Activity*, published by Unesco [11].

The duties of the volcanologist are (a) to establish from the sequence and types of deposits, both historic and prehistoric, the probability of different kinds of eruption and the areas likely to be affected. Work of this kind will take one or more years to complete and should be done prior to abnormal activity. After abnormal activity has begun, the volcanologist will (b) advise government authorities of every new development, as well as on the probability of the eruption becoming violent. The authorities need, preferably before the onset of any abnormal activity, to consider what level of risk they are prepared to run for the population in various model situations to be specified by the volcanologist.

From my own experiences, I conclude that it is best for the volcanologist to quote numerical risk estimates (acknowledging that these are crude) to the government authorities. The two critical figures are (a) the possibility of the eruption becoming destructive, and (b) the minimal period of time in which it may become destructive. For both of these figures, the volcanologist will be guided by his knowledge of the history of the particular volcano, by general reference to the descriptions of events leading to serious eruptions at similar volcanoes elsewhere in the world, and by the sequence and rate of change of activity of the volcano in question.

Continuous observation of a volcano during a state of abnormal activity should provide a progressive refinement of the date and nature of any eruptive climax, whilst the use of the largest possible number of monitoring methods will give the most reliable prediction.

Concretizing the action

With regard to specific figures, the authorities should estimate as carefully as possible for each volcano the maximal time in which a complete evacuation could be called of those zones designated by the volcanologists as dangerous in the event of a major eruption. During a crisis, the volcanologists should give regularly updated numerical estimates of the probability of the eruption becoming serious within the critical minimal time for evacuation. Concerning the appropriate date for the return of the population, the administration will be guided, in the same way as for evacuation, by the probability estimates given by the volcanologists.

A tentative flow diagram for planning against volcanic disaster is given in Figure 1, in which the suggested activities of government officials and the volcanologists are shown in the left and right columns respectively, whilst the sequence down the diagram is divided into pre-crisis, alert, evacuation and return phases. From my own experience, it is clear that there are numerous potentially dangerous volcanoes in populated areas which have not received the attention recommended in the pre-crisis phase. In these areas, the government authorities have not made adequate provisions for protecting the population from volcanic hazard.

General conclusions

The most reliable prospect for earthquake disaster prevention, probably for the next several decades, lies in the wider application and refinement of anti-seismic building techniques. These give the dual benefit of reducing both human and economic losses. At the same time, the ability to predict individual large earthquakes, and thereby to reduce further human losses, will progressively increase in proportion to the effort devoted towards this objective. However, until technological breakthroughs provide for more accurate predictions in time and place, the attempt to save additional lives by the evacuation of threatened areas or buildings will lead to numerous and costly false alarms.

The fixing of a threshold level for calling an evacuation will develop gradually, first, from public willingness to respond to such calls and, second, from the ability of a national economy to absorb the cost. This will apply equally to earthquake and to volcanic hazard. For the assessment of each new situation, earth scientists will be required to quantify the risk. They should specifically not be expected by the authorities to call the evacuation, since this involves the balancing of the risk against the social and economic consequences of evacuation—which earth scientists are not competent to assess.

With reference to these consequences, it should be emphasized that, whereas the present feasibility of giving early warning for volcanoes has already resulted in evacuations of close to 100,000 people for several weeks, future predictions of major earthquakes might involve comparable risks, including the secondary effects of fire and tsunami, to a major city of over 10 million inhabitants. The physical possibility as well as the cost of moving millions of people, except very locally (e.g. outdoors), and for a brief time (e.g. twenty-four hours), need to be carefully examined.

In all potential disaster areas, pre-crisis meetings between scientists and the administrative authorities are essential to develop a mutual understanding, first, of the problems of prediction and evacuation and, second, of the personalities of the individuals concerned—hence an insight into their ability to perform calmly under stress. For both

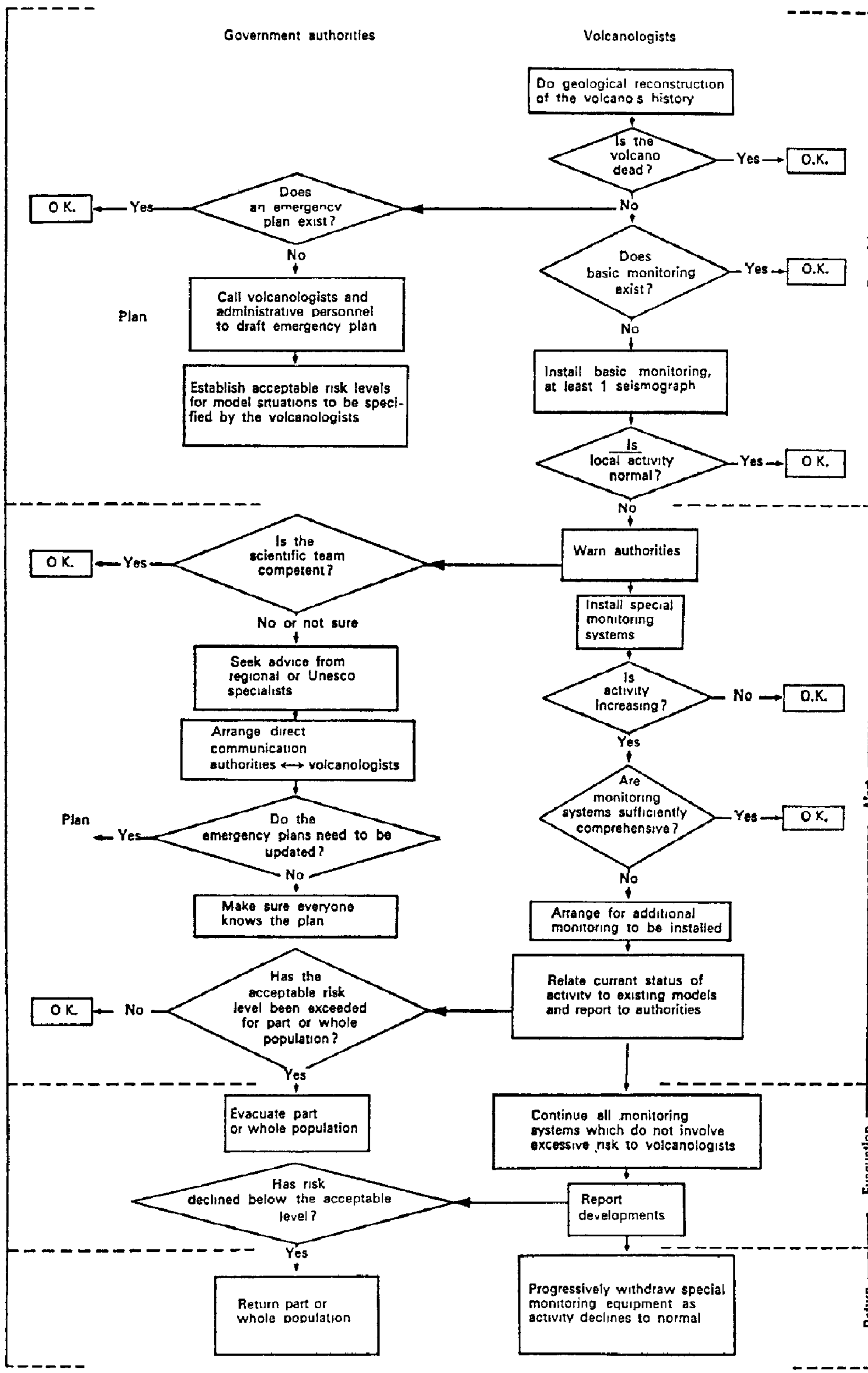

FIG. 1. Volcanic emergency planning: a flow diagram.

sides the making of basic policy decisions on the level of acceptable risk in advance of any crisis, will alleviate some of the uncertainties and anxieties which arise during a crisis. They may also halt what appears to be a world-wide tendency of increasing unwillingness, on the part of governments, to take any risk for the population in the face of abnormal volcanic or seismic phenomena.

Finally, advanced planning provides the important opportunity for scientists to be directly exposed to the public and the news media, and from this to learn the need to use simple language and to avoid the temptation of placing too strong an emphasis on the more spectacular and sensational aspects of earthquake or volcanic hazards. □

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To delve more deeply

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