The Acceptability of Geotechnical Risk

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By selecting me to give the Third Geomechanic Lecture my New Zealand geomechanical colleagues bestowed a high honour and for that I was and am deeply grateful. Now the Organising Committee for this Regional Conference have honoured me again by inviting me to essentially repeat that lecture with much the same material, perhaps with a little less local allusion, since they felt it would suit a rather wider audience. Much if not all which I wish to say has been well said before by Casagrande (1965), Peck (1967) Lambe (1973), Wu (1974), Vanmarcke (1979) and others and more recently by Ingles (1979), Lind (1979) and Slovic (1978). The proceedings of the three ICASP meetings, especially the third in Sydney last year, are a fruitful source of important material. If I have failed to make due acknowledgement to all those authors whose publications have influenced my outlook, may I publicly apologise.

Engineering, especially geotechnical engineering, is concerned with risk - the making of many decisions in the presence of uncertainties - of insufficient information, and of inconsistent information with design methods of uncertain accuracy. Thus an engineer lives with probabilities rather than certainties, overtly even if not expressed as such. However, in the lecture I have no intention of delving too deeply into purely technical matters such as probability methods of risk analysis, cost/benefit analysis or decision theory. I shall not mention the Monte Carlo method, Pearson distribution functions, Markov processes, or Bayes theorem, but will content myself with a few observations on the assessment of risk and its acceptability to society.

When I last discussed these matters in the Third New Zealand Geomechanics Lecture last year, I took a quotation from Shakespeare as an appropriate text:

> "Out of this nettle, danger, we pluck this flower, safety."
>
> Shakespeare, Henry IV

But it was suggested to me that if I must preach I should use a Biblical text, and offer you:

> "I returned, and saw under the sun, that the race is not to the swift, nor the battle to the strong, neither yet bread to the wise, nor yet riches to men of understanding, nor yet favour to men of skill, but time and chance happeneth to them all"
>
> Ecclesiastes, 9:11

Did not J.K. Galbraith call the present time "the Age of Uncertainty"?

Introduction

Until the publication of "Of Acceptable Risk" by William Lowrance (1976) there was a meagre literature on the subject of social benefit versus technological risk. Earlier, Rachel Carson (1973) Chauncey Starr (1969, 1971) and a few others were prominent 'voices in the wilderness' pointing the way. But in the last few years there has been a rapidly increasing world wide interest in the matter, given great impetus by the nuclear energy debate, as well as by major catastrophes such as the Flixborough Chemical Plant explosion in the UK, and dam failures in the USA, not to mention the more recent Three-Mile Island nuclear plant with its near core melt. Lord Rothschild's Dimbleby Lecture on BBC Television in November 1978 was described by the New Scientist as 'an extremely significant event' being 'the first serious attempt by an establishment thinker to present to a wide public the thorny problem of risk'. Because of his audience he was forced to cover the subject a little superficially, but he brought forward the viewpoint that we should compare the risks 'before being put into a panic by some apparently authoritative utterance'. His theme was good, though I have some reservations concerning the reliability of some of his quoted data.

As in most subjects, to avoid confusion, a few terms should be defined, which have acquired a variety of meanings in debate and published literature, and I will follow the suggestions of the Council for Science and Society (1977) Report "The Acceptability of Risks":

> "Hazard" refers to a situation with the potential to cause harm to people, property or the environment. It thus implies that something of value is exposed to potential harm or loss.

> "Risk" refers to the probability that the hazard will be realised, though following common usage it may also be extended to

cover the combination of the probability and the severity of the harm itself. There has been a recent tendency to restrict the term 'risk' to those hazards involving human life - distinguishing between cost/benefit and risk/benefit, perhaps because of difficulties of defining a common scale.

There is no general term to describe adequately when harm is sustained, though in the context of geotechnical engineering "accident" will probably serve.

"Safety" is an absolute, probably never attainable in real life. Lowrance defined a 'safe' situation as one where 'the risks are judged to be acceptable' but this leads to the paradox that a situation may be 'safe' to one ignorant of the hazards, yet 'dangerous' to another who is aware of them. In the CSS Report it is suggested that 'a thing is provisionally categorised as safe if its risks are deemed known and in the light of that knowledge judged to be acceptable' and perhaps we should use the word in this sense.

"Acceptable" defines a level below which no specific action is deemed necessary.

Acceptability, of course, raises the question of to whom, and we immediately find the eternal triangle of those who create the hazard, those who regulate it, and those who experience it. Acceptable levels of risk will generally not be the same to each of these three parties, even when concerned with the same hazard.

In "An Anatomy of Risk" Rowe (1977) succinctly points out that the only certainty in life is death; the uncertainty lies in when and how death occurs. In the interim, we endeavour to delay its onset and extend the quality of life, and much of our activities are towards these ends. In all our human activities, there are risks. Some are assessed qualitatively, a few quantitatively, and many ignored through lack of either information, understanding or control. In a given situation, Rowe clearly distinguishes two broad categories of uncertainty:

1) Descriptive uncertainty - in which there is an absence of information on what are the significant factors to be considered in the analysis of that situation.

2) Measurement uncertainty - in which there is an absence of information on the specific values to be ascribed to parameters required by such analysis.

These are very similar to Peck's (1967) subjective and objective concept of uncertainties in foundation design. These, together with evaluation, are the essential elements of risk assessment.

1) Risk identification - in order to reduce the descriptive uncertainty.

2) Risk estimation - in order to reduce the measurement uncertainty.

3) Risk evaluation - in order to take action to reduce or avoid the risk.

Thus, we have the assessment of risk, concerned with the measurement or estimation of the probability and severity of harm, which is essentially an empirical, technical activity, whereas the judgement of safety or acceptability of risks is a values-oriented, political activity (Lowrance). Lord Rothschild (1978) suggested that we should ask ourselves or 'them' some very simple questions:

"First, is the risk stated in straightforward language that I can understand, such as 1 in a 1000? If not, why not?

Second, is the risk stated per year, per month, per day or per some period of time? If not, I shall ignore the information.

And another more sophisticated question: Are the tolerances on the figures or the uncertainties associated with them given or said to be known? If they are not then the information must be of questionable value unless it comes from an acknowledged authority who knows so much that he can make an informed and reasonably accurate guess."

While I would regard his response to his second question as being a little sweeping, especially for those risks which show marked variation with time and exposure, I believe he is basically right, since without time many expressed risk/probabilities are at least ambiguous. Many authors, not only in the geotechnical field, are guilty of omitting time from their risk assessments.

These are important questions which should always be asked when people begin to talk about risk. In accordance with Rothschild's admonition and for consistency, I shall try to compare risks on the basis of per annum per unit, whether the unit is per person, per structure, or whatever. In this way a scale of risk can be presented. But judgement of acceptable risk is more than numbers, as Kasper (reported by Barnaby 1978) dramatically describes:

"Near Santa Barbara, California, plans have been made to construct a large liquid natural gas terminal ... A small group of American Indians is protesting the siting of the plant, contending that the chosen location is the most sacred spot of their culture, the Western Gate, where the Indians say the souls of their people must pass after they die to join the spirits of their ancestors ... One can envision a Rasmussen-like report, examining the probability that a soul would be unable to migrate past a liquid gas terminal. The report would, no doubt, conclude that risk was very small, perhaps 10^{-9} for each soul. To technical experts the risk seems negligible; to the Indians the risk is unthinkable..."

Here in New Zealand, would we contemplate interference with Cape Reinga?

Assessment of Risk

In the design of geotechnical works there are three broad areas of uncertainty which must be examined in the assessment of risk or overall reliability:

1) The uncertainty in applied loads

2) The uncertainty in analytical design methods

3) The uncertainty in soil properties

Of these, the last-mentioned is by far the greatest uncertainty, even with an extensive soil exploration and testing programme, rarely more than about 1 part in 10^5 of the soil is known. Boring and sounding may well not disclose the most -un favourable conditions, especially the important weak zones and erratic discontinuities. Interpolation between test locations and unavoidable sample disturbance add their uncertainties, before the laboratory determines specific soil parameters with their own uncertainties, for use in design. Unless sufficient funds are made available to make an adequate investigation of site conditions, and the designer clearly outlines the questions to be answered by the site investigation, we may find that the pertinent questions are unanswered and the designer is forced simply to assume, or to extrapolate on an assumed basis, the values needed for the problem at hand, with generally a gross increase in uncertainty.

Factors of safety

I support the thesis that the application of conventional overall factors of safety has never been completely appropriate in geotechnical engineering, and I suspect in some other branches of engineering too, yet our text books continue to propagate the concept. Only in the simplest systems, where loads and material strengths are known quite accurately, is it reasonable to take the ratio of either the available strength to the mobilised strength, or the applied loads to cause failure to the design loads, as a measure of safety.

Either or both of these ratios are used in various areas of geotechnics to indicate 'safety'.

$$F_1 = \frac{\text{Available shear strength}}{\text{Mobilised shear strength}}$$

$$F_2 = \frac{\text{Load to cause failure}}{\text{Design load}}$$

In the general case such factors are more factors of ignorance derived from simple formulae to cover all the unknowns of very complex situations, because neither the resistance to failure, nor the unbalanced forces causing failure, can be determined sufficiently accurately in advance.

However, a great many structures continue to be built, apparently successfully, on the basis of factors of safety derived from experience several decades ago, despite major changes in analytical design, construction techniques, and soil sampling and testing methods. Rarely do we know soil properties and behaviour well enough to justify a computed factor of safety of say 1.3 for cuts and fills or 1.5 for earth dams yet these values are used in normal design. One is left with the feeling that these values are accepted because a factor of say 2.5 would make the cost so high that the structures would not be built, and further, for the successful structures, either the soil conditions were better than anticipated, the design loads have not been reached, or the analytical model is conservative.

Further evidence supporting my concern is the recent paper by Haurylkiewicz (1979) where he shows that use of the two conventional expressions for factor of safety, based on either forces or on strengths respectively, leads to grossly different assessments, by up to a factor of 2, in a strip foundation bearing capacity problem.

Further, depending upon the design loads and the strength parameters used in the calculations, there is no consistency, and one method does not always produce factors of safety higher than the other.

In the present discussion, a problem with the factor of safety concept is that it allows no ready assessment of the risk of failure. We do not know the relationship between the factor of safety and the probability of failure which may apply in a given geotechnical situation, except that an increasing factor does imply a decreasing probability. Even near the single point representing a factor of safety of 1.0, we do not really know the probability of failure, though estimates and rough calculations have been made.

No competent geotechnical engineer would suggest that a factor of safety of 0.95 implies certain failure and 1.05 certain safety, yet listening to them, a layman could well be misled into believing that this was the case. It has been suggested by Sherman (1966) that in some situations a geotechnical factor of safety of 1.0 may imply a 50 percent probability of failure, presumably within the normal expected life of the structure. Should this be even remotely true, it hardly fits with my earlier definition of safety. Perhaps because of the dramatic changes which occur when a material ruptures, the factor of safety approach tends to condition us to a safe/unsafe sharp boundary outlook and to the belief that a high enough factor of safety implies true safety. Perhaps because of this, the consequences of failure may not always have been examined as fully as would be demanded by a probabilistic approach.

Soil Variability and Probabilistic Design

As soon as it is admitted that the strength of a soil stratum is not constant, but varies in space and time, simple overall factors of safety are no longer applicable. Further, if we plot the frequency distribution curves for soil strength and applied load, it is not hard to see that the tails of the curves may cross, giving rise to some value of probability of failure. Small factors of safety (small differences between mean strength and mean load) and large variabilities will clearly give rise to a larger probability of failure than large factors of safety and small variabilities. Probability of failure can be obtained by integrating the frequency of pair values whose ratio is less than unity.

Harr (1979) discussed this concept in terms of capacity and demand - perhaps to avoid the problem of differences between the forces and the strengths approaches - and showed that, with the degree of overlap likely to occur in a real geotechnical situation, the area of overlap is a good estimator of the upper limit to probability of failure. Hill (1979) subsequently criticised Harr's approach and showed that it was approximately true only where the differences in the means (small factors of safety) were comparable to or less than the standard deviation of the data. As the factor of safety increases, Harr's method grossly over-estimates the probability of failure. If it had been as simple as Harr suggested, the method would have been widely used.

Provided we know the shapes of the tail distributions of capacity and demand functions, we can readily assess failure risk. But except for reasonably uniform soils in major geotechnical works, we rarely know even the mean soil strength parameters well enough, let alone the shape of the low strength distribution tail.

However, recent studies of variability of several soil parameters have been made by various authors, particularly Lumb (1968, 1970, 1971, 1975). These show that intrinsic variability of strength parameters is likely to be between 5 and 50 percent (expressed as a coefficient of variation), with the cohesion variability being several times that of the frictional component, and normally distributed. Such data have been used by Singh (1971) to assess the reliability of conventional factors of safety in slope stability and bearing capacity calculations. He concludes that typical confidence levels lie in the range from 90 to 99 percent, a similar conclusion to that reached by Pender (1977) in a probabilistic assessment of a cut slope.

I have some difficulty in really understanding such statements without mention of time, not only because of Rothschild's admonition. If we presume that a confidence level of 90 percent or a 10 percent probability of failure means that, of 100 identical structures, 10 are likely to fail within the normally expected design life, and if we then assume a design life for such structures of say 50 years, with the risk averaged over that period, we might expect the probability of foundation failure to be 2×10^{-3} to 2×10^{-4} per year per structure. If foundations of structures do not 'fail' at this frequency, it may indicate that true factors of safety are rather higher than computed ones indicating that our measured soil strengths are not as high as those which actually exist in the ground, or that the design procedures are conservative, with the actual loads experienced by the structures being much less than allowed for in design.

Statistical interpretation and probabilistic modelling of soil properties and behaviour should provide a better insight and assessment of the reliability of design than a simple safety factor, though there is a need to keep procedures simple. As with other new procedures, the more complicated it is, the more likelihood there is of misinterpretation and misuse.

The increasing literature on probabilistic methods in geotechnical engineering will, I hope, finally lead to acceptable methods. The use of the computer to handle the tedious calculations has permitted and encouraged a wider use of statistics and probability in engineering, though too often I fear, without a concomitant increase in understanding.

The importance of this change in approach is that it leads directly to an assessment of risk of failure, to a better recognition of the possibility of failure and hence, perhaps, to an examination of consequences.

Design Parameters

One way of reducing the probability of failure, even with low conventional factors of safety, is to select design parameters rather less than the measured/expected characteristic or assumed parameters, and this is commonly done. How it is done is part of so-called 'engineering judgement' and there are not too many guides in the literature. Even the recent 7th European Conference on Soil Mechanics and Foundation Engineering at Brighton (Design Parameters in Geotechnical Engineering) failed to produce many papers of direct value to the practitioner in this regard. If we select minimum values, we risk falling into Peck's (1977) pitfalls of over-conservatism, yet higher values clearly mean higher risks of another kind. One of the fascinating parts of Casagrande's (1965) outstanding Terzaghi Lecture is the insight given in his fictitious example of 'calculated risk'. He suggests that, having investigated the foundation conditions adequately for an embankment to be built over deep clay, the designer concludes that the in situ shear strength ranges between 1.0 and 2.0 tons per square foot. The designer may then decide to use a conservative 0.6 tons per square foot allowable (design) value if failure may lead to catastrophic loss, but be willing to accept a greater chance of failure with a design value of 1.2 tons per square foot where the potential economic loss is modest and greater economies can be achieved in construction. He thus adjusts his probability of failure by widely varying his 'factor of safety' depending on the consequences of failure.

This type of approach is widely codified in Scandinavia, with clear distinctions being made between characteristic and design strength values. The Danish Code of Practice (1978) Helenelund (1977) (Swedish) and Friis and Roti (1979) (Norwegian) outline practice in their respective countries. When the Norwegian Geotechnical Society release their report 'Safety Principles in Geotechnics' in English, it will be widely appreciated, since it offers such clear guide lines, with factors linking failure, characteristic and design parameters depending on the nature of the soil and the consequences of failure.

Risk comparison

When comparing the relative risks of human fatality subject to various hazards, it is convenient to take the average risk of death due to disease or natural causes as a reference, say 10^{-2} per person per year. Only in the 10-30 age groups is the average accident rate actually larger than this. A few lists of fatality risk have been compiled, and, by being repeated in various publications, have acquired an aura of authority which may not be justified. (Kletz (1977), Ingles (1979)).

The following table gives a selection of the values quoted.

VOLUNTARY HAZARDS	DEATHS PER PERSON PER ANNUM
Motor cycling	2×10^{-2}
Smoking 20 cigarettes per day	5×10^{-3}
Car racing	1×10^{-3}
Car driving	2×10^{-4}
Drinking a bottle of wine/day	8×10^{-5}
Young woman taking contraceptive pills	2×10^{-5}

INVOLUNTARY HAZARDS	DEATHS PER PERSON PER ANNUM
Influenza	2×10^{-4}
Pedestrian	5×10^{-5}
Dam failure (USA)	1×10^{-6}
Train travel (UK) } Bush fire (Australia) }	5×10^{-7}
Lightning strike (UK) } Falling aircraft (USA) }	1×10^{-7}
Chemicals transport (UK)	2×10^{-8}
Meteorite	6×10^{-11}

It seems clear that we accept quite high risks voluntarily and that we accept those forced on us if they are much smaller. As Starr (1972) put it so well, 'we are loath to let others do unto us what we are happy to do to ourselves'. Apart from the high risks of travelling in motor vehicles, a very rough generalisation might be that risks of 10^{-6} are of no great concern to the average person (except for nuclear plant disasters). When the risk rises to 10^{-4} the public are willing to incur expenditure to reduce the risk, unless the risk is voluntary. At 10^{-3} it becomes unacceptable to the public, and there is strong pressure to have it reduced. Such a generalisation is, of course, greatly affected by the benefits which people get (or think they get) from the risk, as pointed out by Ashby (1977).

Human Error in Structural Failures

In his analysis of some 800 cases of structural failure, Matousek (1977) concluded that more than half could be attributed to gross error and that 'the causes of failure should be seen in human mistakes, errors, carelessness etc during planning, analysis and design, erection and use...'. Similar sentiments have been expressed by Lind (1979) and other authors, with the proviso that 'human error ... is defined with respect to what another competent person most likely would do in the same situation, and not with respect to someone infallible and omniscient'. Lind also points out that an error does not cause failure by itself, but that there is generally a congruence of errors in concept, design, material, workmanship, inspection and so on.

An analysis of failure of large bridges in Australia showed a failure rate of 3×10^{-3} which is several orders of magnitude greater than expected from probabilistic models of extreme or chaotic errors. Ingles (1979) asks whether such errors should be regarded as negligible beside human errors, and Matousek makes the following observations:

a) Failures occur much more frequently than suggested by established rationales, neglecting gross human error.

b) Failures are few, but almost invariably associated with human error.

c) Commonly, multiple human errors are found when a failure is investigated.

d) Presumably, human errors are also frequently present in structures which do not fail.

We have perhaps too tolerant an attitude to human errors, and should markedly increase our inspection systems to combat them. Costs may be high, but we should attack this large source of uncertainty in our assessments before seeking improvement in other areas.

Perception of risk

It is the perceived risk rather than the true risk which influences decisions, attitudes and anxieties, and it may be difficult to differentiate between the benefit from reducing the number of deaths from some hazard and that from increasing people's feelings of safety. Anxiety is a disbenefit even if the risk is much smaller than believed.

Familiarity tends to dull perception of risk. What has become an established activity of society seems less of a risk than unfamiliar activities. If there is a substantial time lag between exposure to hazard and occurrence of injury, perception is also reduced.

With very low probabilities there is the great problem of advising the public, who would regard an 'extremely unlikely' event as one that is really not going to happen. When it does occur, the experts are castigated.

Slovic (1978) examines some of the psychological problems of assessing risk and states that 'people systematically violate the principles of rational decision-making when judging probabilities, making predictions, or otherwise attempting to cope with probabilistic tasks ... biases on judgements or uncertain events are often large, persistent, and difficult to eliminate'.

Some of the more important biases are found in experts as well as laymen:

a) The reliance on small random samples of data, not realising that the odds against them being correct are unreasonably high. I well remember a simple statistical examination of a few triaxial test results I made during my early years at the Soil Bureau to provide confidence limits on the C and Ø values obtained. The confidence limits proved so wide that the design engineer, who shall remain nameless, rejected the limits but accepted the single value as correct. I soon learned that in those days engineers were interested only in the measured soil values, and did not want to know how little confidence one could have in them.

b) The neglect of statistical data when making predictions.

c) An unwarranted confidence in one's knowledge (the certainty illusion). Slovic points out that people are often wrong when 'certain' they were right.

   Perhaps the study of risk of embankment failure reported by Hynes and Vanmarke (1976) is an example of overconfidence. Seven internationally known geotechnical engineers were asked to predict the height of an embankment that would cause a soft clay foundation to fail and to specify confidence limits wide enough to give a 50 percent chance of enclosing the true failure height. None of the bounds specified proved wide enough.

d) The availability bias, where available information is accepted as true in the absence of anything better.

e) The anchoring bias, where - having relied on available data - there is a reluctance to change as better information becomes available.

f) The hindsight bias, which is revealed in too many reports on failures such as one on the Teton Dam fialure quoted by Slovic (1978). 'In retrospect ... this reveals a colossal misunderstanding of the fracture pattern of volcanic rocks and a serious misconception of groundwater flow systems.'

There is also the problem that the very act of discussing unfamiliar low probability hazards may increase the perceived risk, regardless of what the evidence indicates, especially if it is 'splashed' as news in the media.

Sometimes the wrong question has been asked, as John Hawley is wont to remind us with regard to the Kelburn Cable Car. After some seventy years of exemplary service, it was lost to Wellington for a long time, because a safety report was called for. It seems likely that the risks of walking in a main street such as Lambton Quay are comparable to those of using the Cable Car, but we do not seek a safety report on Lambton Quay.

Dams

Of all geotechnical works, those concerned with impounding or controlling water give rise to the greatest hazards, and the recent history of dam failures in USA must give us pause.

Dam safety became a national issue in USA in 1972, when two failures in four months left 355 people dead and $150M worth of damage. Congress passed an act calling on the Corps of Engineers to inspect and produce an inventory of all US dams, with reports of inspections and recommendations for a national safety programme. Due to a quirk in the legislation, funds were not voted so that only federal dams (some 4% of the total) were inspected. The failure of the Bureau of Reclamation's newly-completed Teton Dam in June 1976 revived national concern with 11 dead and $400M worth of damage. Independent checks on Burec Dams identified 17 others which needed modification, and an internal survey by the Corps of Engineers found 61 suspect.

Although incomplete and unreliable, the Corps inventory of all US dams over 7.6m (25ft) in height or impounding more than 65,000 m^3 (presented to Congress a few months after the Teton failure) is still the only document assessing overall dam hazard in USA. It reports that some '20,000 of the 49,329 dams are so located that failure or misoperation of the discharge facilities could result in loss of human life and appreciable property damage' and that dam safety programmes in most states are either non-existent or inadequate to protect the public from hazards created by dams' (Miles (1976)). Some 9,000 of the 20,000 were labelled high hazard, and the remainder significant hazard.

The 12m high Kelly Barnes Dam in Georgia failed in November 1977, killing 39 people. By May 1978, 600 inspections of the 9,000 high hazard dams had been initiated, but only 219 completed, with 40 declared unsafe, and 11 so dangerous as to require dewatering. One of the condemned dams had just been completed, but not filled. Even taking account of the fact that priority is being given to the most suspect structures, the assessment of dam risk is horrifying. Could it really be as bad as 1 in 5, with a design life of 50 years, giving a risk of 4×10^{-3} per dam per year? Ingles (1979) reports 2×10^{-3} for Australian earth dams and Mark and Stuart-Alexander (1977) at least 10^{-4}.

Few countries have an adequate inspection and surveillance system for dams, and New Zealand is no exception. At present, the safety of British dams is covered by the 1930 Reservoirs Act, passed mainly in response to a series of collapses 1864-1925, soon to be superseded by the 1975 Reservoirs Act with some improvements, but still not adequate. I understand that a dam safety inspection committee has been recently set up in Australia. One hopes that in New Zealand the Ministry of Works and Development is keeping an eye on state dams, and that, through the system of granting water rights and Loans Board finance, some control is exercised over new construction by local authorities. However, I do wonder who is watching old dams and the myriad of farmers' stock dams, some at least of which must be offering a hazard.

Dams are principally at risk during construction and filling or very soon after (infant mortality) or after a long period of satisfactory service (old age). I am sure some of our dams are in each category. If current legislation is inadequate, perhaps we should be seeking an organisation with similar statutory powers to the California Department of Water Resources.

I am sure the newly established NZ Large Dams Committee will be examining this important subject and making recommendations though we do have problems in setting up completely independent inspection committees because of the smallness of our society.

Acceptability

Having considered the scale of risks, the problems of realistically assessing risk, largely because of the human error factor, and probably the major geotechnical risk of dam failure, we may now examine 'acceptability'.

When I was asked for a title to this discourse a long time ago, I selected acceptability of risk in the blind assumption that I could clarify my concepts of acceptability before now. Unfortunately I haven't. The first step - assessment of risk - which at least theoretically should have proved an essentially technical task has proved not to be. If we have our data and probability distribution functions, then straightforward calculation gives the probability of risk, but the intrusion of the gross human error factor seems to make the calculated risk and the observed risk differ by perhaps several orders of magnitude, making nonsense of our calculations and leaving judgement from experience as the key in making predictions. The second step - judgement of acceptability - is clearly tied up with individual and social values, both for the present and for the future, and the debate is extremely wide ranging.

There are several ways that the concept of acceptable risk may be approached, as outlined by Fischhoff et al (1978). The most obvious is what Rowe and others have called 'risk aversion', in the sense of averting and turning away risk. This implies the maximum possible reduction of risk with essentially no comparison with other risks or possible benefits. Thus risks, especially new risks, should be made 'as low as possible' or 'as low as reasonably achievable'. While laudable, such an approach is sometimes carried too far, with risks sought far below the level of those derived from natural hazards. It has been said that 'our greatest risk is no risk at all'.

The next approach is 'risk balancing' implying that there is some level of risk about zero that is acceptable, and defining that level by comparison with other risks previously accepted. We have no simple scale, of course, and what is considered acceptable changes with time and with changes in society. Some risks in the comparison may have become acceptable by 'historical momentum' a passive, even stoic acceptance of what has always been. They may have become accepted because no real alternative has been found, or because of ignorance or misinterpretation. There are systematic biases in people's perception of risks, as brought out by the recent US study by Fischhoff et al. Violent and dramatic causes of death are perceived to have much higher than actual death rates, whereas most chronic causes of death are perceived to have lower than actual death rates.

Another approach to acceptability is 'cost-effectiveness' which seeks to maximise the reduction of risk for each dollar expenditure for safety. If we were to plot a relationship between risk and the cost of risk reduction, it would probably be a rectangular hyperbola. Initially, marked reductions in risk would be possible with small expenditure, but as the risk diminished, the cost of further unit reductions in risk would rise very rapidly - the law of diminishing returns. At some point a halt must be called by allocating funds among hazards so as to achieve the maximum reduction of risk to society as a whole.

The concept of safety is amorphous; and the task of maintaining that amorphous thing is theoretically infinite. The only way to be certain of avoiding wasting vast sums of money is to concentrate on tightly defined problems with a known cost and reasonable pay off.

The last approach is 'cost benefit balancing'. This recognises that an acceptable risk is defined by balancing the benefits of some activity against the level of risk which it presents. The magnitude of risk found tolerable then increases proportionately with the benefits.

Values judgements are rarely straightforward or well-agreed, but probably the main criterion relates to severity of risk. It has been suggested by Dunster (1977) that on this basis we should at least identify three classes of risk - 'unjustifiable risk' when the risk is too high to be accepted irrespective of benefit; 'justifiable but not justified' when the benefits are too small to tip the scales; and 'justified' when the risk is worth accepting because of the associated benefits. Such a classification is aimed at preventing the unjustifiable risks from being subjected to a cost benefit analysis since, if they really are unjustifiable, no amount of argument about benefits can make them legitimate.

Cost benefit analyses need to be expressed in consistent terms in order for benefit to be maximised at minimum cost, and unfortunately, such terms tend to be economic. Those values of individuals or society which are not readily expressed in economic terms tend to become neglected, or at least devalued. Thus, neither all costs nor all benefits are usually considered. As one example, when human life is concerned, there is a natural repugnance to set a monetary value, but sometimes this may be the only way to put the analysis in better perspective. Various suggestions have been put forward based on:

a) A person's future contribution to society (reduced by consumption).

b) A person's future earnings.

c) Gross national product divided by population.

d) The price a community or individual is willing to pay (from health care, provision of seat belts, to kidnapping).

e) The insurance which can be purchased on the life.

f) The personal benefit of a risk accepted, divided by the risk of death (crossing the roadway, employment).

g) Infinity and zero (the limit cases not uncommonly held).

From such estimates, sums of several hundred thousand dollars in present day values are not uncommon, so that the effects of their inclusion in cost benefit analyses are not negligible. Several authors have suggested that the possible consequences of failure of major projects, like dams, are rarely included in cost benefit analyses because planning is on the basis that they will never fail. Yet in the same analysis, credit is likely to be taken for flood protection from extreme events. If the costs of dam failure were incorporated in the same way, the viability of the project could well be affected. Would this be true for New Zealand and Australian projects?

Acceptability to whom is probably the thorniest question - those who have created the hazard, those who are charged with regulating natural and man-made hazards, or those who suffer the effects of the hazard? While occasionally these may all be embodied in the same person or organisation, generally we will have three different standpoints. Do we accept Jeremy Bentham's utilitarian philosophy that the object should always be 'the greatest happiness for the greatest number', interpreting happiness in the widest sense, or do we take a more individualistic approach? Then we have the ethical problem that the only truly acceptable risk is one which is judged worthwhile following a careful examination of costs and benefits and is incurred by deliberate choice by its potential victims, in preference to feasible alternatives (CSS).

Coming through the debate seems to be the concept of 'fairness', so that we should direct our attention more towards how risks come about and how they should be controlled - that is, the procedures by which decisions are taken on the creation and persistence of risks. In the 'individualistic' approach, it would seem that the decision procedure could be simple. The risk can be offered by the creator or regulator and vetoed by the victim until his personal costs and benefits have been balanced. Theoretically, a similar approach could be made in the 'public interest' approach where the decision is made by a controller on society's behalf; but this is the rub - should the controller be guided by his experts or by concerned groups in society? Part of the solution must be the provision of facilities whereby those experiencing the risk can be competently advised by someone answerable to the group and given standing by all other interested parties to the negotiations. A move to more freedom of information is in the right direction.

Risk-taking and acceptance are essential facets of man's heritage. Risks will continue to be taken by all, including engineers. Indeed, it is a defensible thesis which follows logically from the concept that no structure is absolutely safe, that it is the responsibility of engineers to take calculated risks in the terms of Casagrande.

Without risk, there would be no innovative design. Unfortunately, frank open discussion even in a technical forum, is not really possible for many reasons, including the legal aspects and repercussions of the situation. However, we must continue to seek for some methods to ensure the wide dissemination of the knowledge of risks and their consequences. Further, we must seek from society an indication of the acceptable level of risk which it will tolerate, to ensure that safety margins are not increased to the point where innovation is lost.

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