3.2–CONSEQUENCES OF FAILURE (INCLUDING HUMAN REACTION)

by

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SYNOPSIS

There is a trend towards a broader view of earthquake engineering: as the control of a large system, here called the SHC (seismic hazard complex). The SHC is, in turn, part of the natural hazard complex. Consequences of failure (SHC mal-performance) are briefly described as physical events plus their social, economical and political consequences. The complexity of human reaction, viewed from the need to provide a measure of system performance, is discussed. Optimal control using this measure is the ultimate goal. Current status of some available procedures ("paradigms") for seismic design decision making, and future research needs, are also reviewed.

1. INTRODUCTION

1.1 *Complexity of the Earthquake Hazard.* Earthquake resistant design presents some of the most complex problems within engineering. Structural failure produced by an earthquake begins a tree of loss events generally terminating by injury, loss of life, social disruption and economic damage. The total system involves many mechanical, physiological, psychological, social and economical components. Uncertainty in stimulus and system behaviour augment the difficulties, aggravated by system size and the diversity of the elements.

The problem is complex, but the conflict it reflects is simple. Man accepts hazards to gain opportunity. The fundamental earthquake engineering problem is the relative value placed on economic opportunity and the risk of earthquake-triggered loss. This risk depends on the assessment of the probabilities and the magnitude of the loss.

1.2 *Trends in Problem Formulation.* Our first response to this complexity has characteristics of myopia and tunnel vision, as could be expected. Earthquake engineers have mostly studied small, physical elements (dynamic response of idealized structures) of this problem in isolation. Decisions have been based on such studies, patched together with results from work of a similar kind in seismology, economics and practical politics.

Only in the last few years has there been a change (paralleled in other disciplines) to study the overall system - even at the expense of some detail, if necessary - to provide a firmer framework within which to fit more detailed studies. These *system studies* focus on method and socio-economic overview, a promising development for the solution of natural hazard problems. The papers by Grandori and Benedetti (7) and Vanmarcke *et al.* (28), are examples which attempt a global view of the problem. Other studies (13,14,19,20) seek to go even further, relating also to design against other hazards, natural or man-made.

These studies provide what some authors call a "methodology". Other terms are: "procedure", "conceptual framework" or "rationale" – these terms are jointly synonymous with what Kuhn (11) has called a *paradigm* and has studied in great depth. A paradigm serves as a pattern or rou-

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tine for cognition and problem solving. Both a paradigm and the data relevant to it are necessary ingredients of solution. Paradigms in science and engineering are objects of constant scrutiny for performance and are replaced when better paradigms become available (11).

When a paradigm for a class of problems (such as "Earthquake Engineering") is being constructed, a dual difficulty often arises. For the lack of relevant data, the paradigm has limited value at first, but data (in the form needed) cannot be generated efficiently until the paradigm has been established. This apparently trivial point is emphasized here for two reasons. First, because much intrinsically invalid criticism ("since you don't have the data, your approach is useless") in this period of rapid paradigm development must be combated with patience. Second, because paradigm development is an intellectual effort that cannot easily be speeded up by merely allocating more funds. Many problems in structural engineering (for example "progressive collapse") illustrate this point. Paradigm development requires time and a conducive atmosphere, but without paradigms the value of research production won't be proportional to the research allocation.

1.3 *Data.* Paradigm development is followed by a period of data generation. In reality, the process is cyclic. In earthquake engineering, data collection presents special problems; data on damage and consequences of failure can only be collected after the occurrence of earthquakes. Much of the old data from past earthquakes is rather useless for modern paradigms which, for example, require strong motion seismograms ("one seismograph in Managua is worth ten on the moon"). Reports on damage lack important detail (such as age distribution and design basis of structures, reports on undamaged structures, sufficiently detailed analysis of how injuries or loss of life occurred, and so on). The total effort of data gathering has been quite haphazard, until recently lacking international co-operation and pre-disaster planning.

Some of the investigations following individual earthquakes have been thorough. Yet without a paradigm, the data become encyclopaedic and costly, or else useless.

Soon, however, a fairly robust paradigm for earthquake engineering should emerge. If the problem complex and the paradigm are roughly as outlined in sections 1.4 and 1.5, some meaningful efforts could be made now to plan the data gathering. This work will first involve studying the optimum resource allocation in general hazard adjustment. Next comes natural hazard research (a comprehensive study is available (32)). Finally, specific studies of earthquakes as one of the natural hazards, and "engineering" (which in a broad sense, includes research into earthquake risk, structural behaviour and its socio-economic impact, building codes and their enforcements) as one of the adjustments. Rosenblueth (24) has provided a preliminary earthquake engineering research resource allocation study, exemplifying this work.

Once the optimum resource allocation has become better defined, the actual data collection can be planned; networks of strong motion recording equipment, establishment of permanent well-prepared teams empowered internationally to investigate earthquake disasters, and measuring their engineering and socio-economic impact. In all this activity planning it must be hoped that the care and feeding of paradigms is not neglected; data gathering is confused with research, as often as testing is confused with experiment.

There is also a real risk of gathering too much data. Fortunately, ways are being explored to limit the data gathering (as well as other efforts) to what is economically justifiable. Interesting systematic attempts of this kind are the pragmatic *screening* procedures described in section 3.4.1.

1.4 *The Seismic Hazard Complex.* The consequences of failure are the output of a system which we choose to call the *Seismic Hazard Complex* (SHC). Earthquake engineering is the process of control of this system. Consequences of SHC failure and the measure of these consequences is discussed in section 2. How we try to optimize the control of the SHC system is finally considered in section 3.

The earthquake engineers of the past had an assignment that (in hindsight) was relatively simple: Design a structure to survive earthquakes without damage. The profession has by now developed the necessary skill - indeed a great achievement. Yet, from the viewpoint of society needs, it is just a first step.

Increasingly, the public is holding professionals accountable for the consequences of their actions. There is a growing awareness of social organization, reflected in many countries in increased group and class litigation; also, individual professional responsibility is being expanded into a responsibility of the profession as a group, held accountable for their code of ethics and for the consequences of their craft. An increasing degree of liability for the satisfactory performance of technology regulators (such as building codes) is incurred by engineers and elected public officials.

The job now facing the earthquake engineering profession has stepped up. If it can be assumed for a moment that society has a well defined system of values, the job is to see that the right amount of society's resources is invested, at an optimum rate in the best way, into providing safety against earthquake hazards. The task requires that we are prepared to look at the entire physical system exposed to earthquake hazard, and also that we are prepared to balance the risk, relative to other hazards, in an optimum fashion in collaboration with other professions: economists, politicians, transportation engineers, industrial hazard engineers, etc.

To make matters more specific, let us describe the system at risk (the SHC). First, there is the *physical* system: inventory, buildings, utility and transportation networks, dams - encompassing all man-made objects and many natural objects: navigable waterways, slopes and embankments, cattle, and so on - including even police, firefighters and bakers.

The physical system (insofar as this matter is concerned) serves as a tool in the pursuit of human needs. To guide the deployment of the physical system we have the *economic* system, the *socio-economic* system, the *legal* system, and the *political* system in increasing levels of hierarchy. Certain subsystems of these are affected by seismic events or involved in the adjustment to limit the hazard. These relevant subsystems together form the SHC (seismic hazard complex). Similarly, everything affected by natural hazards in general may be called the *natural hazard complex* (NHC).

1.5 *The Paradigm.* A fairly coherent body of ideas for earthquake hazard management has emerged in the past few years and is forming into a firm paradigm. Co-ordinated studies in social sciences (31,32) are accessible. A new earthquake engineering "methodology" has been stated in great generality by Vanmarcke *et al.* (28) and with much practical detail by Whitman *et al.* (33). The work by Lee and Collins (13) illustrate integration of these rationales.

The discussion of consequences of failure in the sequel, oriented towards this kind of paradigm, shows that many difficulties remain to be resolved. The work ahead is, however, now quite clearly defined. For example, the problem complexity must be reduced to the point where any further simplification would significantly affect the outcome of the design process. Screening models (3) and other tools to do this are under development (section 3). The final bottleneck in this work is likely to be philosophical, centering on the role of government in hazard adjustment.

2. FAILURE CONSEQUENCES

2.1 *Earthquake Damage* propagates through the SHC system hierarchy as discussed by White and Haas (32). For example, in their "natural event system", the earthquake is the *primary* hazard, possibly generating one or more of the *secondary* natural hazards: tsumani, avalanche, landslide, flash flood (from dam failure) and, of course, fire. The primary and secondary natural hazards produce structural (mechanical) failure in the physical system. Structural failure in turn, may trigger subsequent natural or other hazards (e.g. breakage of gas pipes may cause fires). The consequences propagates in an event tree, stretching into the economical, socio-economical, and sometimes even political and legal systems, and back down again through the system hierarchy. A good example is the far reaching consequences of the 1933 Long Beach disaster, producing the Field Act of 1933 which, in turn, has influenced the consequences of subsequent earthquakes.

Physical system damage is, unfortunately, not a good measure of the consequences of failure. Relatively light physical earthquake damage may well produce serious damage to a system of higher level. For example, some of the smaller communities in Alaska survived the 1964 earthquake with few casualities, but they collapsed economically. The 1755 Lisbon earthquake produced widespread physical damage. Yet, its greatest short term impact was perhaps political namely a consolidation of Pombal's power (6). This, in turn, produced repercussions onto the social and economic system of the city, the country and its colonies. The long term effects of these changes would today seem of far greater significance than the direct effects.

These examples suggest that the consequences of failure will generally transcend the bounds of what can be measured, even if attention is limited to strictly physical and economical consequences. A suitable boundary in space (physical, economical, etc.) and time remains to be devised before a rational measure of failure consequences is obtained. A first attempt to assess the economic expected damage components for a 1974 replication of the 1906 San Francisco earthquake (4) provides a good insight into part of this problem. A regional economic analysis of the linear Leontief type was made in this study. About half of the total loss was found to be indirect, i.e., due to reduced economic activity. The total expected economic loss component was, incidentally, estimated to lie between US $13,000,000,000 and $52,000,000,000. These amounts are by no means incredible, when compared with the recent (September 1976) press estimate of US $8,500,000,000 for the 1976 North Italian earthquakes.

2.1.1 *Physical Damage.* The physical damage to be expected in an earthquake of given intensity is an interesting problem in engineering science which (relatively speaking) is well resolved now (13,19,20). Nevertheless, Rosenblueth has concluded in a pilot study that further resource allocation to study structural behaviour deserves high priority (24).

There are some problems of adjustment to earthquake hazard that can be resolved in terms of just the physical system: earthquake insurance (1,27,29), disaster planning, and perhaps also design of vital, lifeline, and public facilities (Field Act). Hasofer and Lomnitz (8) have estimated a "reasonable maximum amount" one should spend against a repetition of the 1972 Managua earthquake; since this estimate was considered adequate to cover the added cost of [effectively] safe design and construction, they were able to make a recommendation for adoption of earthquake damage prevention (up to 15% of normal construction costs) in the reconstruction of Managua.

2.2 *The Loss Measure.* The quantified damage is called the *loss*. It can be represented by a vector of finite dimension. A suitable measure of this vector is necessary in decision making (14).

Cost-benefit analysis requires a real-valued measure of loss. This raises the old question about the monetary value of a human life, a notion still rejected by many on epistemological or moral grounds. It may be instructive to consider it in the following alternative form, circumventing some of the moral objections. The evaluation of loss is ultimately and exclusively to be made in terms of human response, if indeed "man is the measure of all things". "The value of a thing is the amount of ... life which I am willing to exchange for it" (Thoreau). A dollar, then, has a well-defined price in "real money": its *individual* life equivalent. The question is therefore rather: Can a life *lost* be measured in terms of this life measure as well?

2.3 *Human Response.* Man is involved in many different roles: bystander or victim; as an individual or in groups; during or after the earthquake; as decision maker before the earthquake; and as an intelligent, competitive species adapting to the consequences of the earthquake. No subject has received more study - and yet, no comprehensive model of human behaviour is in sight. Human reaction as a consequence of failure may require many *ad hoc* models. Unfortunately, social scientists have also many other interesting phenomena to study. The burden of communcation of research needs for efficient earthquake loss reduction and interpretation of the results must be borne by the engineers.

2.4 *Individual Response During Earthquake.* For example, "Everybody runs outdoors" during earthquakes of MMI intensity VII. Some people with much earthquake experience, however, seek shelter in interior door openings or under furniture; this helps them to avoid injury. Lomnitz (16), however, found that foreshocks and daytime occurrence of earthquakes both tend to reduce casualties greatly because it gives people the chance to run outdoors. The discrepancy can perhaps be ascribed to geographical differences in earthquake frequency and in modes of construction - enough to jeopardize either the credibility or the simplicity of any model. Individual human behaviour in hazardous situations is best dealt with as an unpredictable and uncontrollable quantity.

2.5 *Influence of Social Organization.* Comparisons of earthquake response of societies with different types or degrees of social organization also reveal significant differences. Kates *et al.* (10) conclude from the 1971 San Fernando and the 1972 Managua earthquakes that adjustments in folk society as well as in modern industrialized society are effective in comparison with societies in transition which, combining organizational features of both, are peculiarly vulnerable to natural disasters. For a seismic event a unit of magnitude lower, Managua's property losses were roughly 15 times greater, and injuries 10 times, and deaths 100 times more numerous than for the San Fernando Valley.

Human group disaster response deserves careful sociological study which may eventually result in workable decision models.

2.5 *Local Attitudes to Earthquake Hazard.* Jackson and Mukerjee (9) polled the residents of San Francisco for perception and adjustment to the SHC. They reported a 78 percent interview refusal rate compared with 10-15 percent in Cornwall, (Ont.), Los Angeles and Anchorage. This (possibly innocent) discrepancy alone would suggest that there is much to be learned before a rational adjustment policy can be prescribed. They conclude that those few San Franciscans who are willing to talk about the hazard give it a low priority and have adjusted poorly to it. Should building code decisions be made on the basis of a democratic political process under such circumstances? This is discussed in section 3.4.1.

3. CONTROL OF THE SEISMIC HAZARD COMPLEX

3.1 *The Control Problem.* The consequences of failure are more fruitfully viewed as consequences of the *state* of the SHC at the time of the earthquake, as well as of *chance*. That the earthquake occurs, and does so at a particular time of day, and many other matters, are the aspects of change. But the state of the SHC is mainly the outcome of policy, strategy, implentation and other *adjustments* to the hazard. Adjustments are subject to control. They can be made in some eight or nine different ways (earthquake reduction or control; earthquake-resistant construction; land use management; forecasting; warnings; insurance; community preparedness, drills, etc.; disaster relief, rehabilitation; and "loss bearing by inaction") (19,20). The range of possible human adjustment is very great. Loss bearing by inaction is not necessarily irrational - it is a reflection of one aspect of human adaptability. We would think it irrational if we could not adapt at least to some losses through "loss bearing by inaction" (e.g. taxes, etc., to obtain the mutual benefit of society). An adobe house is an excellent adaptation to nature, if the earthquake hazard is small (or misjudged, or neglected).

The decision problem is: What is the most *rational* mix of adjustments to the SHC? The allocations may vary with time, and the problem is one of *optimal control*, strictly speaking

3.2 *Existence.* First: Need an objectively rational solution exist? Human preferences differ, and apparently indispensable concepts of justice (23) appear to lead into the Arrow voting paradox (17). In effect, a *social welfare function* does not exist and the adjustment options cannot necessarily be preference-ordered rationally and justly. One alternative is *negotation* (3).

The problem is not as academic as it might appear. Increasingly, public interest groups are essential factors in technological policy problems, and many projects have failed or bogged down on this point.

Screening procedures (section 3.4.1) may provide a third alternative (if they are politically feasible). They lead to "solutions" which may or may not satisfy the constraints of rationality, justice and efficiency.

3.3 *Decision Theory*. The engineer usually assumes *a priori* that economic opportunity can be assessed rationally (benefit-cost analysis of projects) and that our assessment of probabilities is objective (or at least "true" when subjective). These assumptions are the basis of the *optimization theory* of decision making under risk. The theory is built on axioms of *utility* that seem to be indispensable attributes of rational beliefs, value systems and behaviour. The theory is *normative*.

To what extent is this theory also *descriptive* of actual decision making? A recent summary of this empirical question from the viewpoint of adjustment to natural hazards is available (25).

As alternatives to the optimization theory, several *bounded rationality theories* are available (25). A real decision maker (because of his cognitive limitations) operates on a much simplified model of the real problem. Rather than striving to optimise, he is content to *satisfice*, i.e. to strive to maintain or attain some acceptable (rather than maximum) level of achievement. It has been argued that optimization, while primarily normative, has some relevance for describing actual decisions, while the notion of bounded rationality has normative as well as descriptive implications.

There is much evidence that the optimization theory is not descriptive of decision making in the context of adjustment to natural hazards. The full range of alternatives is often not available to the decision maker because of limitations of culture and awareness. Homeowners are sometimes unaware that earthquake damage insurance is available, and their adjustment to the hazard is limited to loss bearing. There are also misperceptions of risk and denial of uncertainty (section 2.6) and "crisis orientation" (disaster needed as stimulus for action). Bounded rationality models appear to be useful a description of actual decision processes (25). Kunreuther (12) has proposed an *ordered choice* model neglecting, roughly speaking, all smaller risks with joint probability less than a certain threshold level (compare the adobe house example in section 3.1).

3.4 *Metarational Decision Making*. Most people apparently have non-linear value functions (5,18), placing a premium on avoiding a large loss all at once over the same loss spread out as many individual events. De Neufville (5) concludes from experiment, moreover, that different professional and interest groups have quite different degrees of non-linearity: "Developers" and "Tenants" do not seem willing to pay any substantial premium to avoid possible seismic damage, while "Structural Engineers" and Government Officials" do.

One may speculate over the reasons: catastophe aversion is weakest for those who only incur a personal risk but have to pay out of their own pocket, while it is strong when the decision is made on behalf of many, using public funds. This appears in general agreement with Chauncey Starr's observations of acceptable levels of voluntary and involuntary risks.

The results raise a very important question: If people are so irrational in their values, should the decision maker act as their delegate (try to faithfully represent their irrationality), or should he act *in loco parentis* (optimize a utility function, somehow fitted to human preferences)? Some recent contributions (5,13) suggest a political mechanism equivalent to the delegate theory. Yet, our tolerance for irrationality (admittedly variable) is low. People will normally revise their stated preferences if they are shown to be inconsistent. This would suggest *loco parentis* decisions. But if an entire society is unanimously shortsighted, misjudging the "present value" of an uncertain hazard (such as nuclear gangsterism, oil depletion, or the big Boston earthquake) in the view of the decision maker only, on what grounds is he entitled *not* to act as a delegate?

Analogy suggests that people actually prefer imposed rationality via some *forgiving control system* compensating errors of aim (for example, the shotgun is preferred over the rifle for bird-hunting - at least by those that depend on it for survival). What is required, then, is a theory of *metarational decision making,* i.e. how to bias the "rules of the game" (e.g. building codes or insurance rates) such that those with irrational subjective preferences by "free choice" are led to act in their own best interest. Bringing up children provides many examples of intuitive metarational decision making. Assuming that a satisfactory theory could be developed, there may still be convincing arguments against implementation - has the state a right to do so (22)?

3.4.1 *Screening.* "What right does the state have ..." must also be asked in a relative context. Byer (3) and de Neufville have developed pragmatic *screening techniques* to reduce the number of variables in a decision problem to manageable proportions. Their "fairly strong" conclusions are that both monetary costs and loss of lives must be considered explicitly in building code design (neither can, unfortunately, be "screened out"). Further work is under way to develop pragmatic screening techniques for reducing the number of interested parties to be considered in public technology decisions.

These techniques are promising, but their implementation can hardly be justified merely by expediency. A theory of choice among the best *possible* (however imperfect) decision theories would seem necessary.

4. CONCLUSIONS

Earthquake engineering problem formulation is tending towards more complex and more realistic system representation. The consequences of failure as a system performance measure requires, correspondingly, more detailed and accurate representation. The precise form of the data required is only defined when a paradigm is available, representing the system in analysis. Research planning must strive to maintain a data collection process in harmony with paradigm development. The greatest current paradigm need is to find the minimum complexity required for an adequately robust problem formulation. Paradigms must be philosophically open-ended: they should be adaptable to a variety of philosophies of economics and the role of the state. Adequate representation of the huma reaction component of the consequences of failure requires extensive research in the social sciences. The burden of spurring this research must be borne by engineers. Humans, including decision makers, are not rational. It is not in the public interest to delegate code design decisions to the political domain. Rather, a metarational decision model must be developed with the aim that codes, as forgiving control systems, guide designers into decisions that are rational in the public interest.

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DISCUSSIONS

Miss Pate (U.S.A.)

As far as the value of life is concerned, I think the problem of protection against earthquakes cannot be isolated from the other sectors and that an order of priority is a better way of putting things together which means marginal cost, cost of saving extra lives from similar voluntary risks.

H.C. Shah (U.S.A.)

I want to share with you some experience, we have regarding the whole concept of acceptable risk and the concept of decision making. It turns out that when you start working in this field of decision making under uncertainty and acceptable risk, usually whenever you start with a number, let us say X number of acceptable risk, no matter what number you take, you are going to be wrong by the people who are going to evaluate it. This I am telling from personal experience. However, the way they are going to come to a conclusion whether it is a good number or a bad number, is not going to be dependent on the quantification of acceptable risk but its final realisation in how the design value that you are recommending compares with what they are used to. Let me give you an example.

Supposing currently the co-efficient of design or the lateral load co-efficient a country using is 10%. Let us say that after "rational" evaluation of acceptable risk, rational decision making of socio-economic factors, everything that you come out with the final results is 30% instead of 10%, the chances are no matter how rational you were in your quantifications somebody is going to say that he does not like it. However, if that number comes out close to what they have been used to, the chances are that the people would accept it. Really the proof of the pudding is going to be how does it effect the final design ? If it is going to affect tremendously, people are going to say that the number you have quoted is not acceptable. If it is not going to affect what they have been doing, they are going to say, "Well it looks good".

Closure by Grandori

Referring to what has been said by prof. Shah, I would like to express my agreement on the opinion that a general theory is very difficult and that the results of a rationalized cost-benefit analysis could be refused by the Community. But there are research steps for which we can derive useful guidelines from cost-benefit analysis and decision theory. A realistic aim is to look for new solutions, which are probably not optimum solutions, but are simply something better than what we do at present.

For instance we do not know at present if the total amount of resources devoted to earthquake risk prevention in a country is well distributed over the country, taking into account local seismicity of different zones. This problem can be dealt with successfully, without big problems in defining the acceptable risk, and probably with substantial consensus of people. In Italy for instance the lateral force coefficient varies from 10% to 7%. Taking into account local seismicity, a cost-benefit analysis indicates that the same coefficient should vary from 10% to 3%.

Another step could be the one suggested by Miss Pate', having as aim the comparison of earthquake risk with other risks inevitable to human condition. This problem is more difficult and the results must be considered with care, but we may expect to derive some general trend: are we overestimating earthquake risk or not ? Should we consciously push for more severe codes or for the contrary?