RESEARCH IN EARTHQUAKE ENGINEERING: A CHALLENGE TO IMAGINATION

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Introduction

Of course there is room for more and better research along conventional lines. There is for vast improvements on our strong motion instruments and on our criteria for interpreting the records we obtain; for experimentation with prototypes and models of structures whose behaviour we are still far from predicting; and for a large variety of projects of analytical and numerical nature. In most instances there is more than room: there is pressing need for high quality research on these subjects.

But the benefits to be derived from more imaginative research will often be orders of magnitude higher. Suppose that reinforced concrete were still unknown on our planet. Just compare the benefits that would be derived from inventing this material with those from improving our knowledge about the load-deformation relationships of steel frames.

I submit that the time is ripe, and has been over several years, for a shift of emphasis toward the development of new materials, new uses of materials we know, new shapes of structures, and a more imaginative assail on earthquake engineering; not for a neglect of the majority of traditional lines.

When research funds are scarce or dwindling it is essential that they be spent thriftily on projects whose returns are high. When those funds are plentiful or growing it is essential that they be so spent to help forestall disenchantment.

Lest a tinge of disrespect for past achievements be construed from these remarks let me rush to say that the very nature of earthquake engineering has forced research in this field to be quite imaginative. Indeed, the process of earthquake generation has hitherto been evasive and we are barely beginning to get glimpses at the events at play; ground motions are still almost totally unpredictable; their detailed characteristics are among the most irregular phenomena known to man; structural behaviour under these disturbances still involves uncertainties of hundreds percent; such matters as nonlinear behaviour, hysteresis, low-cycle fatigue, water compressibility, soil-structure interaction, and slenderness effects, which can often be ignored when designing against gravity loads, often become paramount in earthquake resistant design; and notwithstanding our ignorance and the complexity of the phenomena in which earthquake engineering delves progress has undoubtedly been forthcoming; knowledge and ease of calculation have perforce been replaced with imagination. Let us have more of it, then!

Seismicity

To produce an optimal structure we should design for earthquake forces that increase with the expected consequences of failure and decrease with the

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sensitivity of the structure's initial cost to the magnitude of the design forces. Accordingly the return periods of optimal design disturbances for underground hydroelectric plants and, even more so, for nuclear power plants are extremely long -- of the order of ten thousand years. Practically as a matter of definition, statistical data are wanting in this range; the oldest historic accounts of earthquakes are biblical.

It is customary to represent the rates of earthquake occurrence in a semilog graph as the one in fig. 1, which corresponds to the whole world and is based on data in ref. 1 for a time span of 49 yr., with magnitudes corrected as in ref. 2. Here M is earthquake magnitude while $\lambda(M)$ is the average yearly number of times that M is exceeded. Similar graphs are obtained for earthquakes originating within a limited volume of the earth's crust or over a different time span. Indications are that in most cases empirical data can be approximated by a straight line down to magnitudes at least as small as -2 and down to rates of occurrence of about 0.1 yr^{-1}, that is, recurrence periods of about ten years. However, the straight line cannot be extrapolated indefinitely in the range of longer return periods, for it would predict infinite seismic energy release per unit time (3). Statistical data already indicate a pronounced drop-off in the rates of occurrence relative to the straight line for return periods exceeding some 50 yr. On the other hand, data in this range are indeed scarce.

There is one other reason against the extrapolation of statistical data. The objection is exemplified by the New Madrid earthquakes of 1811-12 and by the sequence of severe shocks which began in northeastern Turkey in 1939 and have continued to the present date. Both groups of events took place in otherwise quiescent areas, although there are indications of seismic activity in that region of Turkey around 1500 BC (4). In any relatively aseismic area in which we may identify geologic features similar to those in either of these regions we may expect, be it with a small probability, a sudden, perhaps short lived, burst of seismic activity (II). Hence, extrapolation from statistical data may err seriously on the unsafe side, but the situation can be recognized in an approximate probabilistic treatment. Perhaps the best way to do this will be to postulate that earthquakes are not independent events as would correspond to a generalized Poisson process, but rather that they are governed by a branched process (5) in which certain tectonic events, which we are just beginning to understand, take place randomly in time, that each event of this nature gives rise to an increase in seismic activity, and that the latter declines thereafter. The model would permit incorporating such features of earthquake occurrence as time correlation (6,7) space correlation (8,9), and aftershocks. This type of treatment has begun to receive attention, for example in an excellent paper by Vere-Jones (10). There is still need for a physical interpretation of the parameters of the corresponding distributions. The model advanced by Burridge and Knopoff (11) may help provide this basis. In it earthquakes are conceived as caused by the sliding of a number of visco-elastic bodies fixed to a bar which is being displaced at a constant rate relative to the plane of sliding. Analytical solutions of the model are intractable but a simulation study may serve as basis for the desired physical interpretation of the stochastic processes that produce non-Poisson sequences of earthquake shocks.

There is a wealth of indirect geologic information awaiting examination and interpretation. One matter we should try to infer therefrom is the evolu-

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[II] This reasoning has been advanced by C. R. Allen.

tion of seismicity over long periods of time, since we wish to describe present-day (or present-century) seismicity with accuracy. Our interest in very long recurrence periods does not imply a marked concern about earthquakes of the next ten thousand years but mainly the need accurately to compute the characteristics of events whose severity will be exceeded with a probability of about 10^{-4} per year during the next 50 to 100 yr.

It takes the joint efforts of geophysicists and geologists to discern which are geologic indications of large earthquakes and to evaluate the presence or absence of these signs. C. R. Allen has begun doing work of this nature using information from geologic fault slips (12). Other signs are more indirect. The churning of boulders against each other, which can only be ascribed to earthquakes, might be reproduced in the laboratory and by trial and error combined with sophisticated applications of probability theory; thus, appreciable improvement could be achieved in our estimates of regional seismicity. The opposite type of indication consists in capriciously eroded rocks that stand as though performing spectacular stunts. Their history can be traced back a few tens of thousand of years. Their study in physical or numerical models should afford upper bounds of intensity-related earthquake parameters.

Considerable imagination will be required for a satisfactory gathering and processing of this type of information, even if some would prefer that imagination not be allowed to run too freely.

Much would be gained if we had a model of the earth, reproducing its seismotectonics. Initially the model would be conceptual; it would evolve into an iconic model, and would eventually become a computer version capable of simulating these processes. The iconic stage already seems like a very real possibility in view of recent advances in geophysics.

Rare phenomena that are properly regarded as irrelevant when dealing with short and moderate return periods are likely to become significant with relation to very long return periods. It is especially difficult to find potential sponsors that will take us seriously when we talk about the need for research on esoteric subjects. Thus, we ought to be looking into earthquakes generated by the impact of meteorites on earth. The moon offers a beautiful record of such events, and it is easy to translate the rates of meteorite arrivals on our natural satellite into rates on the earth's surface taking into account the difference in gravity between the two bodies (13,14). Preliminary computations indicate that this cause may raise the overall seismicity of the earth roughly as shown in fig. 2. The increase is significant for return periods exceeding a few thousand years. In proportion it is more significant in seismotectonically inactive regions than in the earth in toto. And there is also the matter of meteorite-generated tsunamic, which may be quite important in the design of coastal nuclear power plants.

In seismicity as in all other branches of our discipline we may expect imaginative research to be fertilized to a major extent by contributions from scientists in other fields.

Earthquake Control

There is some glamour attached to the goal of predicting the occurrence and characteristics of earthquakes. Yet, most earthquake engineers feel that our research efforts are better spent in learning how earthquakes can be adequately resisted than in forecasting them. An even more attractive effort would concern the prevention of major earthquakes. There has been speculation on the possibility of attaining this aim by producing series of explosions in active faults, which would presumably release strain energy in a chain of harmless events thus preventing the occurrence of catastrophic ones. It is conceivable that such a scheme would be successful although few would be surprised if it turned out to be excessively expensive and some would not be startled to learn that the process achieved an effect opposite to the one sought, since the non-Poisson nature of earthquake occurrence bespeaks of positive correlation between these events. Testing of the theory in a computer-simulation model as the one I mentioned earlier would be indispensable before the decision were adopted to implement this scheme.

Earthquake Recording

We continue to lose the initial portion of strong-motion records because of the trigger mechanisms in our accelerographs. We are beginning to use closed-loop tape recorders with an erasing procedure but these instruments are still being debugged while physiologists solved a similar problem years ago.

The day is still to come when we record space derivatives of strong earthquake motions, including their rotational components. We know they are probably very important, even more than the three components of translation for some structures. Techniques for obtaining accurate records of this type have long been available and have already been used for recording the rotational components of mild shocks (15).

Earthquake Simulation

To continue in the interdisciplinary vein I will mention only one aspect of earthquake simulation which would have occurred to us many years ago had we associated with physicists. It is rather widely acknowledged now that large earthquakes in many places of the world originate in successive foci along a geologic fault. In a stochastic numerical model that simulates the process with remarkable success foci are treated nearly as a single focus moving along the fault at the rate of $0.78\ v_s$, where v_s is the velocity of shear waves (16). This model will automatically produce main features due to the travel of the source. But the most commonly used methods for earthquake simulation do not. Evidently they fail to incorporate the Doppler effect associated with the direction of focus travel relative to the station of interest. It is likely that this effect has been responsible for the surprisingly high content of high frequency components in the records of some earthquakes whose epicenter was located at a long distance from the station as in the 1966 Lima earthquake (see data in ref. 17).

To illustrate the order of magnitude of this form of Doppler effect consider the situation depicted in fig. 3. Under the assumption that fault slip propagates at a rate of $0.78\ v_s$ and taking the velocity of P waves, v_p, as $1.70\ v_s$ and that of surface waves, v_r, as $0.92\ v_s$, we find that the prevailing frequencies in these three phases will be modified as in the following table, which gives values of the prevailing frequency at the station divided by the one for a fixed source.

Phase	Station A	Station A'
Longitudinal waves	0.69	1.83
Transverse waves	0.56	4.54
Surface waves	0.54	6.57

The effect certainly deserves exploring.

Behaviour of Materials

We have made little progress in our ability to predict the behaviour of soils and structural materials under earthquake loadings.

Arthur Casagrande showed 35 years ago that every noncohesive soil possessed a critical void ratio. A soil in a looser state would lose its shear strength when deformed under constant volume: it would liquify; in a denser state it would increase its shear strength (18). Work by Castro (19) has confirmed Casagrande's findings, establishing also the dependence of the critical void ratio on confining pressures. However, Seed et al. (20-22) have found that every noncohesive soil will eventually liquify, whatever the initial void ratio, after a sufficient number of loading cycles under test conditions used in the laboratory. Liam Finn and collaborators have found a strong dependence of the number of cycles to liquefaction on the boundary conditions and history of the test specimens; previous liquefactions make the specimens alarmingly prone to liquify (23,24). When trying to use laboratory results for predicting soil liquefaction in the field we find a contradictory situation: presumably all soils can liquify, whatever their void ratio, when subjected to a sufficiently long earthquake if field drainage conditions are sufficiently unfavourable. On the other hand, if we accept Casagrande's ideas, we conclude that only soils in a looser-than-critical state are susceptible of liquefaction, but they do not undergo this change of state under a sufficiently short quake or with favorable drainage. And we cannot properly evaluate the drainage conditions. An imaginative breakthrough is needed for our understanding of the phenomenon of liquefaction and the possibility of our predicting its occurrence.

We continue testing traditional walls, partitions, beams, and columns under increasingly realistic laboratory simulations of earthquake loadings and this is very well since there is yet much to learn about the behaviour of conventional structural members. But it would be much more profitable to devise new types of walls and of other members which would use new materials or new ways of assembling materials currently in use. Some U.S. universities have launched research programs to explore the possibility of developing a low cost concrete having high tensile strength and other attractive variations of construction materials now in use. These endeavors point the way for worthwhile progress.

Buildings and Other Structures

I have mentioned the need to record rotational components of ground motions. Data on angular accelerations about a vertical axis would constitute the basis for computing part of what is known as "accidental torsion" in buildings, that is, torsional oscillations of nominally symmetric structures during earthquakes. This portion of the torsional excitation acts even in truly symmetric buildings. Unforeseeable differences between actual and computed stiffnesses, yield forces, and masses cause the rest of accidental torsion in structures that are nominally but not truly symmetric. For the evaluation of the corresponding torques there is need for statistical information on these discrepancies in structural parameters and for a probabilistic treatment of structural response to earthquakes. A step in the latter direction has indeed been given by Benjamin (25) but it refers only to a particular example of shear walls.

There is no doubt that all this research is worth doing. Yet a much more significant contribution will be found in Newmark's recommendation for example, which was made over 20 yr. ago, appreciably before any paper had called attention to these phenomena and before any building code contained provisions for accidental torsion, to the effect that the 43-story Latino Americana Tower in Mexico City be provided with a peripheral reinforced spandrel beam in every story to give torsional strength and stiffness to the nominally symmetric tower. A large dose of comparable insight is now much more urgently needed than the gathering and interpretation of data.

Research in some areas in which we are badly in need of information deserves high priority even if it does not take us far from traditional projects. Thus, we should learn more about the effects of deterioration on structural behaviour, particularly in the range near failure of damaged structural members. Most of what we know concerning the behaviour of earthquake damaged structures is confined to the range of small deflections: changes in the natural periods and in the small-amplitude degrees of damping. But if mere plastering and minor repairs restore a seriously decreased fundamental period practically to its original value (26) it is evident that we have generally not been measuring the structural parameters most significantly affected by earthquakes.

There is also need for quantitative basis that will allow calculating the probability of occurrence of the various modes of damage and failure, particularly in multidegree structures, and predicting the losses caused thereby. At what set of values of the ductility factor does a reinforced concrete or steel frame become useless and when does it collapse? Moveover, a simple description of the severity of cracking of walls and concrete frames and of the extent of local buckling in steel members is of little use when we seek a rational derivation of design reliabilities, or, to put it in more usual terms, a rational derivation of allowable load factors and base shear coefficients. We need descriptions in terms of the cost of damage, including in this cost such components as phychological effects and loss of rentability.

There are some timid efforts aimed at the assignation of quantitative values to losses due to gravity loads (27). This type of research has been carried out by interdisciplinary teams in which the participation of a psychologist has been crucial for the design of questionnaires that permit estimating reductions in rentability and the amounts that tenants would be willing to pay to repair the damage. A comparable attempt is worthwhile in connection with earthquake damage. Ideally the research team would also incorporate the advice of architects and experienced contractors.

Fine, let us continue to find out how conventional masonry panels behave under earthquake loading. But let us also embark in the development of new types of wall satisfying criteria based on behaviour under low-cycle fatigue, acoustic and thermal insulation, appearance, ease of fabrication and installation, and cost.

An interesting innovation in shear walls is due to Muto (28). By casting vertically slit, reinforced concrete shear walls tied to a tall steel frame the excessively high stiffness of ordinary walls is reduced without appreciably impairing their strength, provided they are adequately reinforced around the slits. Variations on this theme seem worth exploring.

Two promising lines of research that are going on at present refer to damping devices in buildings and devices to reduce building compliance to ground motion.

Early attempts at providing artificial damping (29) were not very successful. The damping devices used dry friction to absorb energy in towers. Good maintenance was required for proper functioning but the structures were located far from where they could easily receive that type of maintenance.

Ordinary dashpots have been used in powerhouses (30). The ease with which these structures can be adequately maintained makes this solution fit for them even if it would not be advisable for other types of construction.

From the viewpoint of maintenance the use of confined inserts (fig. 4) made of rubber or certain plastics (31) holds promise. The same is true of devices that dissipate energy through hysteretic deformations, as the patented "damping band" (32) depicted in fig. 5a. The band limits the shear that a framed structure can transmit to a shear wall, much as a fuse would limit the electric current intensity that it allows through, but the band continues to transmit an approximately constant force after reaching its maximum. The device is easily hidden from view. A different version is displayed in fig. 5b.

Several arrangements have been proposed, and some of them analyzed or tested, partially to isolate a building from the oscillations of its base. Proposals include the use of hard rubber between column bases and the foundation, as shown in fig. 6 (33); very flexible columns restrained by bumpers when undergoing large deflections, as in fig. 7 (34); rollers in two orthogonal directions, as in fig. 8a (35); and columns suspended by means of hangers, as displayed schematically in fig. 9 (36).

The hard-rubber pads provide limited freedom and their durability is open to question.

The flexible columns have to be extremely flexible to induce appreciable reductions in seismic shears. This poses the problem of instability under the combination of shear and overturning moment, which can be obviated by limiting the lateral deflection of the columns, but such a limitation works against the desired reduction in shears. This combination of factors is still to be solved in a satisfactory manner.

Use of rollers introduces the need for lateral restraint and damping plus the duplication of some foundation elements. Yet it is claimed to constitute an economical solution. Bearings have also been suggested in combination with elastoplastic steel bars (37). A variable lateral stiffness can be accomplished by using noncylindrical or nonspherical rollers or bearings (38) as in fig. 8b.

Suspended columns used in conjunction with lateral damping devices constitute one of the most practical proposals, since they are not beset with serious problems of instability or of maintenance.

With one or two exceptions the foregoing solutions have not been incorporated in actual buildings and there is as yet no experience with their performance in prototypes during a strong earthquake. Some doubts assault the skeptical observer, particularly with respect to the effects of rotational components of ground motion about horizontal axes, for none of the isolation systems described is designed to curtail the effects of such components. Yet this type of solution is so attractive that one would like to see more research done to overcome such doubts.

There are many things we could learn from mechanical, electrical and electronics engineers, such as concern for ease of repair and replacement of system components that damage frequently.

It was stimulating to witness the anchor-bolt detail similar to the one shown in fig. 10 at the bases of steel stacks in Huachipato, Chile (39). After the bolts elongate plastically during an earthquake, they can be replaced without difficulty. The damping band I spoke of earlier is not of simple repair or replacement. It would be encouraging to hear that research is being carried out to produce devices of these characteristics, perhaps flexible or ductile walls whose deformations would cause local damage of such a nature that the walls could be set right at low cost and without annoyance to the occupants.

Other desirable lines of endeavour in building research include the invention of new structural solutions which would permit increasing the optimum intensity of seismic design without cost increase; the development of computer programs for analysis and direct design of recently introduced structural solutions for tall buildings, such as precast panels and large precast three-dimensional units, hollow walls, and staggered truss sytems as well as of whatever new systems are indeed invented; and the comparison of alternatives from the viewpoints of cost and performance in all pertinent aspects.

Building Codes

We probably agree that rational behaviour is tantamount to optimization processes. But the formats of contemporary building codes seem to pursue a different end. It is as though we knew the optimum values of design parameters and stated in our building codes "thou shalt not produce structures whose safety or level of performance is so low that the utility lies more than these many units below optimum." This is illustrated in fig. 11, which makes it clear that we establish only lower limits. Rather than giving the approach for granted and assuming that we are in possession of the correct numerical values it would be healthy to ask if we should not fix upper limits as well. Do we really know what the optimal values of design parameters are? How much is it proper to allow the utility to drop below its maximum possible value? Let us take these questions one at a time.

It will be argued that in countries enjoying free economy we cannot forbid an individual from investing absurdly. Actually we are forbidding just that when we stipulate lower limits of safety and performance since, quite frequently, most of the loss due to failure or damage will be the owner's. This is particularly evident when we consider such matters as allowable deflections, drift, and crack widths. If these clauses are violated society will only suffer the consequences of a greater-than-allowable loss to the owner in repair and maintenance costs and in lowered rents. If this function of our building codes is sanctioned there is no valid argument against establishing upper limits of safety and performance so as to prevent wasteful expenditures. Capitalistic countries do often forbid the exodus of capital and its investment in gold; they could equally dictate measures against the hoarding or burying of structural materials in structures and foundations. Ideally, then, a building code would provide means for calculating optimal values of design parameters and allow margins of under- and overdesign.

Taking little for granted we may as well ask if it is best for building codes to set allowable limits at all. The point is that specifications attached to some building contracts have begun replacing tolerances on concrete strength with a table or graph from which are obtained bonuses or penalties to be applied to the price of concrete depending on how well the specified strength has been met. The bonus or penalty that should be specified so that the owner's expected utility be independent of the concrete quality supplied can be computed rationally under the assumption that design has been optimized, that is, that the specified strength requirements are optimal (40). There are several advantages in this style of specification over the more conventional one, since the structural members having defective concrete need not be torn down or strengthened unless their strength lies so far below the specified value that they would call for excessively large penalties; thus, unnecessary delays and excessive losses to the contractor are obviated while at the same time providing the builder with a stimulus to supply better quality. The same approach could be used in building codes, at least in connection with control cylinder strengths and with appearance and serviceability requirements.

No, we know neither what the optimum values are nor how much it is proper to deviate from them. This is a fertile and fascinating field for research.

One of the most challenging tasks ahead lies in devising ways for the implementation of codes that tend to produce optimum designs and are worded in optimization formats. If out of naivete or overzealousness we produce codes that satisfy this criterion but are unpalatable to the profession at large we defeat our purpose: our behaviour is not truly rational. The best efforts of researchers would profitably be directed toward the planning of an evolutionary process pointing to ideal building codes.

Earth and Rockfill Structures

In precomputer times we seemed to reason thus: the assumption that earth and rockfill structures are in a state of plane strain makes them amenable to approximate static analysis; anything more complex than this is unmanageable. Let us then build these structures as though our chimeras were real and, since we are to err, let us err on the safe side by treating every transverse section as though it were the most unfavorable one. Today there is no need for such oversimplifications. Failure of cohesive slopes under gravity loads take place along doubly curved surfaces centred around the tallest section, as illustrated in fig. 12. Under dynamic excitation noncohesive models of rockfill dams vibrate deforming approximately as in fig. 13, with the largest crown accelerations in the neighborhood of the tallest section. Hence we would do wisely if we varied the slopes of earth and rockfill dams, perhaps as indicated in fig. 14. The same applied to cuts and fills of variable height in highways.

One of the most significant innovations in earth and rockfill structures during recent years consists in the use of reinforcement (41). We must find out how various kinds of reinforced structures behave under seismic disturbance and develop criteria for designing them.

Common Sense

Experience has shown us that some structural solutions are far superior to others; that some types of structures are virtually earthquake proof; that some types fail without inflicting more than minor injuries to human beings while others are deathtraps; and that certain structural solutions and details systematically behave in a poor fashion. But man has been defined as the only animal that stumbles twice against the same stone. With or without much research we would do well not to repeat our mistakes.

In this context the first difference in performance that comes to mind is between tied and helically reinforced columns. Scanning the literature we find hardly a failure of helically reinforced columns as against thousands of failures of tied columns. The difference in performance indicates a vast difference in toughness and in shear strength.

In tropical climate it is customary to supply school buildings with cross ventilation by adopting a structural solution like the one in fig. 15. The longitudinal row of short column stubs marked d in the figure are practically doomed to fail under earthquake (42). It is not so much a question of torsion but one of these columns having to resist too high a shear due to their high relative rigidity and of their failing in shear in a rather brittle manner. There are several ways in which this situation can be obviated at a very small increase in initial cost.

Also in tropical climate bajareque walls (mud walls on a timber frame) are often used with light-weight roofs, such as those made of palm leaves. Houses built in this fashion collapse easily under earthquake but their failure is almost harmless. The same type of wall with roofs built of heavy earth fills fails more easily and is lethal. And this is also true of unreinforced multistory adobe dwellings, almost half the dead in the 1970 Peruvian earthquake to wit. And it is so simple to correct this situation!

The list of examples could be greatly extended.

Choosing the Research Project

The process of selecting research projects for sponsorship can be represented by a decision tree, as shown in fig. 16 (43). The "experiments" in the tree may be actual experiments to be performed in the laboratory or on prototypes or they may constitute lines of analytical investigation or of observation and interpretation. "Results" are the possible outcomes of such "experiments". Considerable imagination is required to foresee these outcomes, the possible states of nature, and the corresponding utilities.

Notice that the tree may be interpreted as the representation of a game of the decision maker against nature. The black circles mark the beginning of alternatives from which the decision maker may choose. The white circles mark "decisions" taken by nature.

Branches of the tree may be regarded as representing various stages of a research project, in which case the "experiments" are the pilot tests and preliminary analyses whose results guide in the definitive stages of the project, or "actions", or it may be taken as representing both a set of alternative projects as experiments, and their effects on practical design as actions.

Once the tree has been drawn, the costs of experiments estimated, and the utilities assigned, we can traverse the tree from right to left to find the expected utility associated to each experiment and choose the one with highest expected utility.

A net showing the steps of a research project in greater detail can also be drawn. The process of selecting the optimum project has been programmed for digital computer (44). The scheme permits dealing with groups of projects some of which may have branches in common. What has been done, however, is practically trivial. The main task will consist in assigning values to the probability of success of each step in every project and to the utilities of the possible outcomes.

Without going through a formal treatment of the subject we can use qualitative considerations on utility to make rapid decisions of the type of research that it is worth sponsoring. For example, in the neighborhood of the optimal number of tests that form part of a research project, or point of diminishing returns, the utility is rather insensitive to this variable. A research project exploring a different matter, such as the development of new construction materials, may be much more profitable. If we still have doubts of hundreds percent concerning an important phenomenon, we probably do better in continuing along the same lines than in starting an original project which may be associated with a lower utility curve but very often the utility gain associated with improved accuracy is orders of magnitude smaller than that corresponding to the quest for new solutions.

The two most valuable guides we have in devising new research projects and assigning utilities to their outcomes are imagination and intuition, and this will remain so independently of the computer programs we develop to aid us in decision making.

What I have said against the unimaginative expenditure on laboratory tests to refine our knowledge of behaviour, and hence our prediction formulas, may sound old fashioned in the light of the amount of work going on with the use of computers to refine our analyses. Updating the remarks can be done by merely changing the word "tests" into "analyses".

Summary

This address is an invitation for imaginative research.

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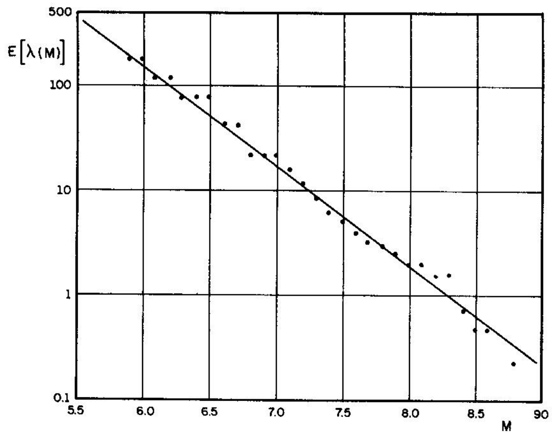


FIG 1 WORLD SEISMICITY

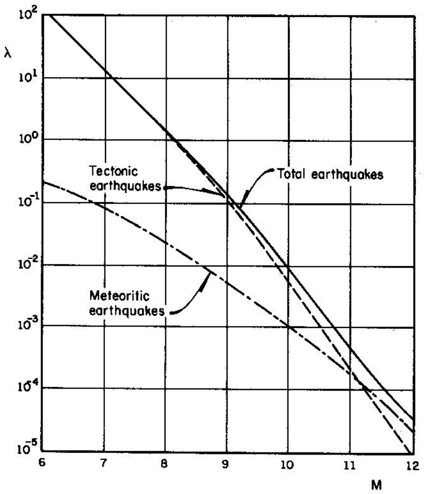


FIG 2 TECTONIC, METEORITIC, AND TOTAL SEISMICITY

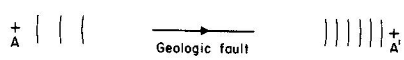


FIG 3 DOPPLER EFFECT

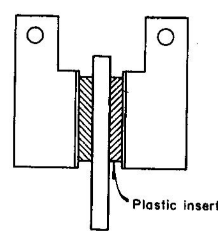
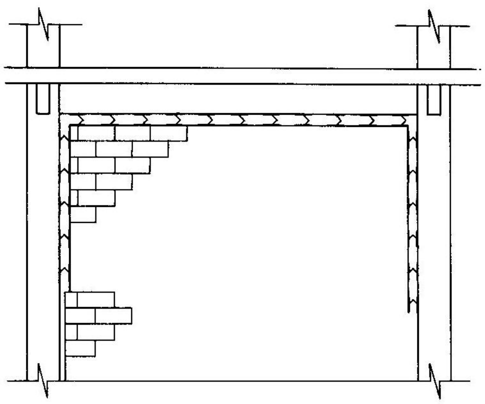


FIG 4 PLASTIC INSERT



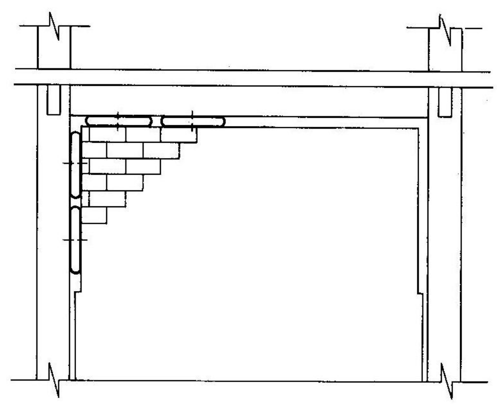


FIG 5a DAMPING BAND

FIG 5b VARIANT OF DAMPING BAND

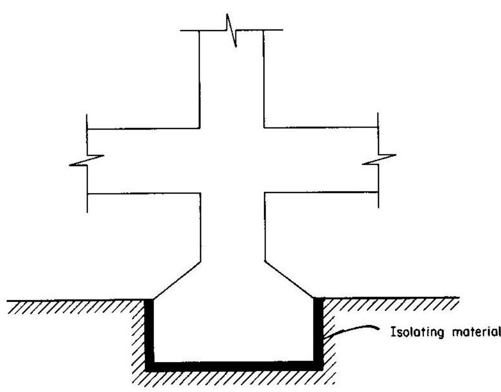


FIG 6 HARD - RUBBER ISOLATION

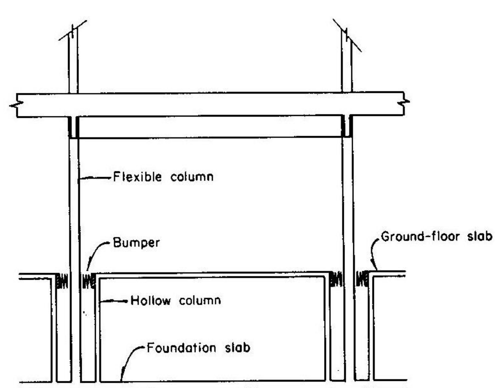


FIG 7 FLEXIBLE COLUMNS

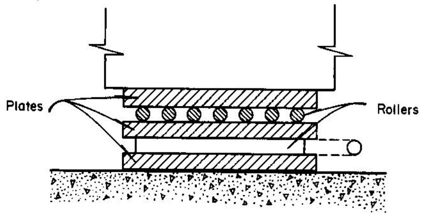


FIG 8 a ROLLERS FOR ISOLATION

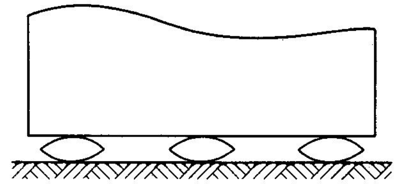


FIG 8b NONSPHERICAL BEARINGS

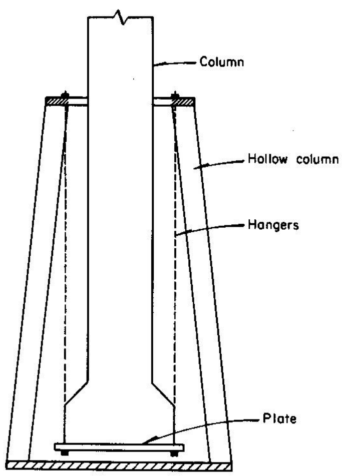


FIG 9 USE OF HANGERS FOR ISOLATION

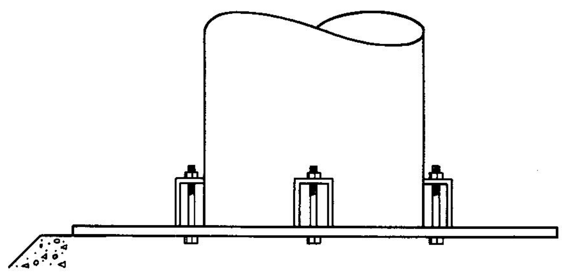


FIG 10 REPLACEABLE ANCHOR BOLTS

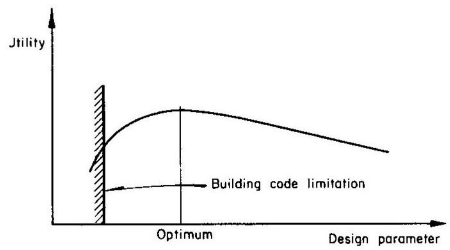


FIG 11 OPTIMUM DESIGN AND BUILDING – CODE ALLOWABLE VALUES

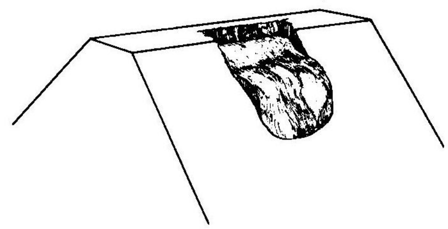


FIG 12 THREE DIMENSIONAL SLOPE FAILURE

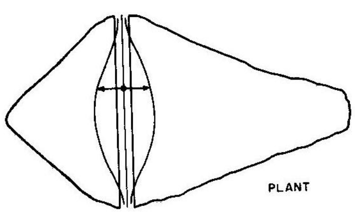


FIG 13 VIBRATION OF EARTH OR ROCKFILL DAM

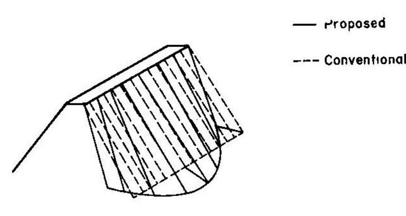


FIG 14 VARIABLE SLOPE GRAVITY DAM

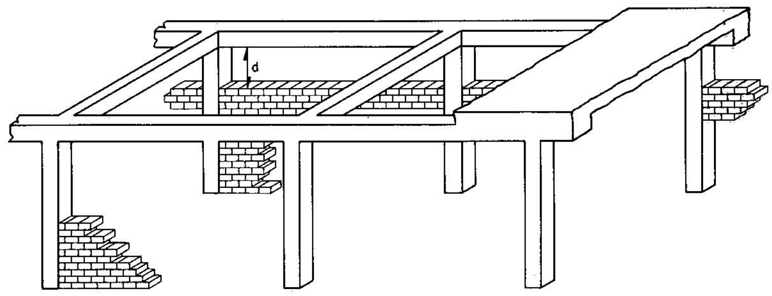


FIG 15 TYPICAL SCHOOL BUILDING

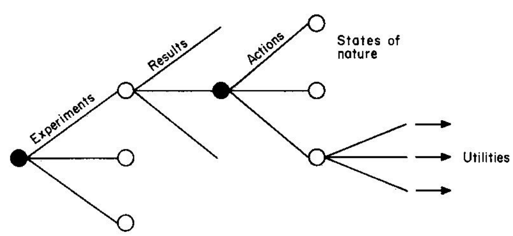


FIG 16 DECISION TREE

DISCUSSION OF PAPER NO. 1

RESEARCH IN EARTHQUAKE ENGINEERING - CHALLENGE TO THE IMAGINATION

by

E. Rosenblueth

Question by: S.Z.H. Burney

About two years ago I saw slides of the complete and total collapse of some buildings during the Caracas Earthquake. Now that the effects of the earthquake have been studied would you like to comment on the reasons for these failures, especially with respect to the design criteria?

Reply by: E. Rosenblueth

From the reports available, the main contributing factors seem to have been:

- amplification of spectral ordinates in certain ranges of natural periods in certain areas of Caracas due to local geologic conditions.
- the fact that some buildings had not been designed in the longitudinal direction to resist earthquakes.
- the rather low base shear coefficients used in design in the transverse direction.
- the reduction of design overturning moments with respect to values obtained by integrating the shear envelope.
- other causes, such as faulty details.