A RATIONALIZATION OF EARTHQUAKE ENGINEERING STRUCTURALISTIC, PROBABILISTIC AND BAYESIAN

DEPREM MÜHENDİSLİĞİNDE RASYONELLİK, YAPISAL, İSTATİSTİKSEL VE BAYESİEN YAKLAŞIM

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ABSTRACT

The unpredictability of earthquake ground motion, the nonlinear character of structural response and the present inexperience in defining collapse conditions and in quantifying states of damage invites the establishment of conceptual frameworks where some open problems in seismic design may be reformulated and solved. Such a task is attempted in the present paper. The resultant conceptualization of earthquake engineering is called a rationalization because purpose, principles and methods are clearly identified and concatenated. It is structuralistic because its elements are to be understood in terms of their global structure and of their interrelationships. It is probabilistic because it uses probability theory to represent the states of knowledge and it is bayesian because it uses the theorem of Bayes as the main principle of inference.

1 - INTRODUCTION

Seismic design is one of the more demanding of all engineering branches because: i) the occurrence of a strong earthquake presents an extreme randomness, is impossible to forecaste for pratical purposes and its onset is so suden (unlike windstorms and floods) that emergency protective action is hopeless; ii) increases in the seismic reliability of buildings are deemed expensive and opposed to architectural license and customary engineering practice; iii) in strong earthquakes buildings are generally stressed beyond the elastic range and "non-structural" elements [2] often have a determinant influence; iv) public opinion is both scientifically uninformed and keenly sensitive about earthquake safety issues in seismic regions. Earthquake engineering, in consequence, must deal explicitly with questions that other engineering branches can afford to ignore.

Despite the substancial advancements made since the first World Conference on Earthquake Engineering in 1956, in every strong earthquake, recent engineered constructions have collapsed or have been heavily damaged, which necessarily has to be attributed either to an underestimation of the seismic hazard or to an overestimation of the structural resistance or to both causes. In consequence,

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[2] like masonry infills in reinforced concrete frames.

it is surely important to examine: i) the acceptability of this situation and ii) the possible corrective measures. The assessment of the second subject is the objective of the present paper.

2 - PURPOSE AND METHOD IN EARTHQUAKE ENGINEERING

It is assumed that the purpose of earthquake engineering is to provide, with high reliability, safety against earthquakes. The need for an high reliability level arises because a single earthquake can act simultaneously on a large number (e.g. greater than 10^4) of structures; hence, for the total number of collapses to be small, the reliability of the resistance must be very high (e.g. greater than 0.999). Against this assumption stands the traditional opinion that earthquake resistance is expensive; but recent and detailed analysis of the effective cost majoration in reinforced concrete buildings due to increases in the design level of earthquake forces have shown those majorations to be really small (Costa, 1990). But the price of earthquake resistance involves more than monetary or monetary-equivalent costs, like limitations to architectural configuration and other difficulties in satisfying certain functional requirements. The acceptance of this price is a truly cultural problem that surely must be discussed in wider circles than the engineering profession, and would clearly demand an analysis of the relationship between earthquake engineers and the societies (professional, political, social,...) to which they belong. This analysis is, however, outside the scope of the present paper and may found elsewhere (e.g. [6] and [19]).

In a given place, strong earthquakes are rare events and the management of the associated risks poses special problems (Svenson and Karlsson, 1989). Moreover, recent studies (Wildavsky and Dake, 1990) indicate that the acceptability of risks or of the measures needed to their mitigation have strong cultural components. In consequence decision-making theories for risky situations (Machina, 1987) are controversial because of the existence of "mental ilusions" (Bierman, 1989). It seems or, at least, it is here claimed that it is so, that the appropriate strategy to deal with those problems is to present a clear picture of the fundamentals of earthquake engineering, or of what it should be, and that this picture should be rational, structuralistic, probabilistic and bayesian.

It is important to distinguish between two different kinds of reasoning: deduction and inference (Jaynes, 1988). Deduction is associated with science and inference with engineering. Or, to use more striking words, the distinction may be, as Rinne wrote in 1965, between the science and the art of earthquake engineering: *the understanding of the earthquake itself and the analysis of its effects on structures and other man-made facilities is assigned to science. The projection of this understanding to the design and construction of structures to be resistant to future earthquakes, at unknown times and of unknown intensity, is assigned to art* . To explicit those distinctions, between what strictly is science and what strictly is not science, in the following the earthquake engineer will be referred to *qua* scientist and *qua* designer.

3 - THE SCIENCE OF EARTHQUAKE ENGINEERING

Earthquake engineering uses knowledge from very different scientific areas, which should be organized to form a coherent ensemble. The pragmatic and primary purpose of the organization is to support the practice of engineering. To emphasize the artificiality of the organization it will be referred to as the *scientific construct*. The construct will be formed by models, which can be phenomenological or descriptive. A model is defined by a set of hypothesis which idealize the relevant aspects of nature [6]. Phenomenological models idealize some part of the physical processes occurring in nature. Descriptive models are mainly depictive and function as interfaces between the different phenomenological models; it will be shown bellow that descriptive models obey the above definition of model.

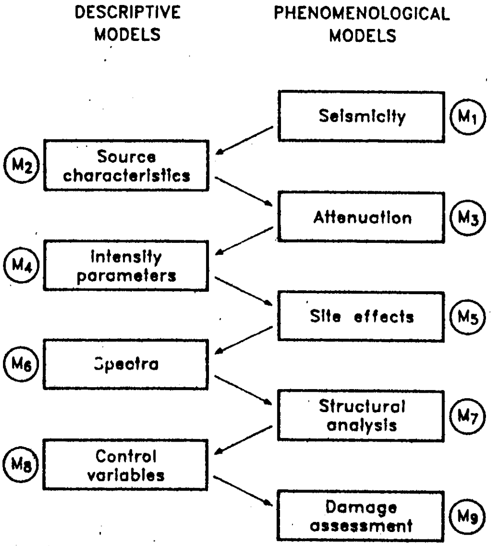

Figure 1 - The scientific construct

The scientific construct is constituted by the following models whose relationships are illustrated in the figure 1:

- A model for the earthquake generation mechanism, (M_1) which gives the occurrence in space and time of earthquakes defined by a descriptive model of the source characteristics the earthquake (M_2);

- A model for the propagation of earthquake vibrations (M_3), which transforms the descriptive model of the earthquake source into a descriptive model of the intensity of ground vibration (M_4), quantified for the reference soil conditions;

- A model for local soil conditions (M_5), which transforms a descriptive model of vibration intensity into another descriptive model of vibration severity adapted to structural analysis inputs (M_6);

- A model for structural behaviour (M_7), which transforms a model of vibration intensity into a descriptive model for the earthquake effects on a structure (M_8);

- A model for damage evaluation (M_9), which transforms the values of the control variables into assertions on the decrease of safety or on the impairment of the functional requirements of the structure.

It will be always supposed that the scientific construct is set-up for a specific structure built in a given site. This scientific construct is generally implemented through the following models, which are referred here for illustration.

The earthquake generating mechanism is modelled by some generation zones, (lines or areas) where earthquakes occur as a Poisson process in time, are uniformly distributed within each zone and are attributed a magnitude by sampling of a given probabilistic distribution. The propagation of earthquake vibrations is modelled by attenuation formulae which gives values of peak ground motion or Mercalli Intensity as a function of magnitude and epicentral distance, for the reference soil conditions. The model for local soil conditions gives the spectra (response spectra, power spectra or peak values of the motion) for the different types of soil as a function of the earthquake intensity parameters. The model for structural behaviour gives the values of the control variables (generally the maximum values of internal forces and deformations) as a function of the spectrum. This model may have extremely different degrees of sophistication [4], from a one-directional static linear model (acted by horizontal forces) to a spatial nonlinear strength-decreasing dynamic model (acted by a non-stationary stochastic model of ground motion). The model for damage assessment evaluates the results obtained in the structural analysis in respect to the criteria defining the functional requirements of the construction.

The development and understanding of the phenomenological and descriptive models is the field of activity of the earthquake engineer *qua* scientist.

4 - THE ART OF EARTHQUAKE ENGINEERING

4.1 - The uniqueness of earthquake engineering

Before attempting to characterize what should be the grounds of expertise of the earthquake engineer *qua* designer it is convenient to explicit the differences between seismic design and design for other actions.

Present civil engineering practice is essentialy based in a code format which was a direct development of classical structural safety theory (CSST). This theory has the particular advantage of being based on very elementar results of probability theory, but has not evolved to incorporate more powerful probabilistic and statistic methods as can be readily appreciated by the study of the so-called level 2 methods. The essential assumptions of CSST is that actions and structural behaviours are described by a small number of independent variables[3] and that structural behaviour is linear or linearizable. Those assumptions are not appropriate for seismic design because of the complex and markedly nonlinear nature

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[3] In most case in CSST literature probabilistic variables are generally set-up as independent or in a form that may be easily transformed into a set of independent variables.

of the structural behaviour expected in a strong earthquake event.

In earthquake engineering, problems have always a large (potentially infinite) number of dimensions because actions are represented by time-histories of vibration and the resistances also must be formulated in terms of time-histories of action effects. Although several approaches for simplification were moderately successful it have not been possible so far to identify a small set of earthquake intensity measures (peak ground acceleration, velocity and displacement, duration, Arias intensity...) and damage indexes (maximum ductility, dissipated energy, strength degradation...) that would give reliable results for a significant number of cases of practical interest. In consequence, the effective problems of earthquake engineering are extrapolation problems (the number of data points for interpolations shall be at least equal to the total number of variables plus one) and thus much more difficult than the interpolation problems usual in non-earthquake engineering.

In linear problems, the distinction of actions from action effects (essential in CSST) and the separation of design methods (ignored in CSST) from safety verifications is essentially arbitrary because it can be formulated in a rigorous way. In nonlinear problems, the overall accuracy is very dependent on the division of the global problems into separate elementar problems. In earthquake engineering, in particular, the clear distinction between design methods and safety verifications is very important [6].

4.2 - The grounds of expertise

By *grounds of expertise* is here indicated that part of the skill of the earthquake engineer that is no longer science but is not yet wisdom. A possible alternative is to use the name *praxiology* [4] but since a very specific application is intended the use of a special denomination may be accepted. The present development of the grounds of expertise is based on the complementary concepts of *parametrization* and *randomization.*

It is supposed that for each of the nine models in the scientific organization of earthquake engineering (figure 1) there will be a family of models which will be symbolized by $M_{ix}, i = 1, 2, ...9, x \in X$ where x is not necessarily integer[5]. It is useful now to consider two illustrative examples of those families. The first example is a discrete and finite family of source characteristics models: $M_{21} = \{\mathcal{M}, d\}; M_{22} = \{\mathcal{M}, h, d\}; M_{23} = \{\mathcal{M}, h, \sigma, d\}; M_{24} = \{\mathcal{M}, \sigma, h, d, m\}$; where $\mathcal{M}$ is the magnitude, σ is the stress drop, h is the focal depth, d is the epicentral distance and m is a fault type indicator: m = 1, underthrust fault; m = 2, overthrust fault; m = 3, extensional fault; m = 4, strike-slip fault. The second example is a non-discrete non-finite family of attenuation functions which have the general form $M_{3x} \equiv F_x : M_2 \rightarrow M_4$. This example considers $M_{21} = \{\mathcal{M}, r\}$ and $M_{41} = I, I \equiv$ Mercalli intensity. Then, one may have:

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[4] Which means science of efficient action (Kotarbinski, 1960).

[5] The meaning of x in M_{ix} and in M_{jx} with $i \neq j$ is not the same.

$$M_{3x} = \{I = \alpha\mathcal{M}^{\beta}r^{-\gamma}, 0 < \alpha, 1 < \beta, 1 < \gamma < 2\}$$

It is assumed now that each family of models has a partial ordering which means that it is defined a transitive and reflexive relation $<$ between pairs of models such that

$$M_{ix} < M_{iy} \quad M_{iy} < M_{iz} \quad \Rightarrow \quad M_{ix} < M_{iz} \qquad M_{ix} < M_{ix}$$

The relation $<$ indicates that one model, the coarse model is less detailed than the other, the fine model. The essential assumptions made here are: i) the coarse model is viewed as a subset of the fine model; ii) a mapping, the coarsening mapping, is defined between the fine model and the coarse model, so that every "point" of the fine model is associated to a "point" of the coarse model; the mapping defines a parametrization of the fine model.

To illustrate those ideas, on a descriptive model, consider $M_{21} < M_{22}$ with $M_{21} = M_{22}$ (h = 30 km), that is, the coarse model M_{21} is obtained from the fine model M_{22} by disregarding the variability of the focal depth and atributing to M_{21} the values of M_{22} for the focal depth of 30 km. The coarsening mapping may be defined in a simplistic way by making $M_{22}(\mathcal{M}, h, d) \rightarrow M_{21}(\mathcal{M}, d)$ or in a more sophisticated way $M_{22}(\mathcal{M}, h, d) \rightarrow M_{21}(\mathcal{M}, \sqrt{d^2 + h^2 - 900})$. It is now clear that descriptive models are indeed models according to the definition given above, because they represent only the aspects of nature considered relevant; but the limit of a succession of descriptive models of increasing perfection will not be a model if it perfectly mirrors nature. For further development of the theory of descriptive models the reader may identify them with the *frames of discernement* of the Dempster-Shafer theory[6] and consult appropriate literature (e.g. Shafer, 1976). To illustrate now those ideas on a phenomenological model consider $M_{71} \equiv \mathcal{L} : \mathcal{M}_{61} \rightarrow \mathcal{M}_{81}$ and $\mathcal{M}_{72} \equiv \mathcal{N} : \mathcal{M}_{61} \rightarrow \mathcal{M}_{81}$ where $\mathcal{L}$ and $\mathcal{N}$ are a linear and a nonlinear model of the structure, M_{61} is some ensemble of accelerograms and M_{81} are the peak values of the displacements. The coarsening mapping may be defined by $\mathcal{N}(\eta) \rightarrow \mathcal{L}$ where η is the ductility factor used in allocation the limit elastic strengths. Further developments of this theory may be found in Muncaster[7] (1983). The above examples show how the general concept of parametrization can relate simple and sophisticated models: but they also allow to antecipate that in some situations the coarse model may give much better approximate solutions than in other situations. Hence, it is attractive to weight differently the situations of good approximation from the other situations; this is obtained by randomization of the domain of the models. The randomization technique has the additional advantage that it makes available existing inference tools if the corresponding statistical inference principle is selected as the basis of inference. In particular, the relationship between coarse and fine models may be

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[6] From which the term "coarsening" was borrowed.

[7] From which the terms "coarse" and "fine" were borrowed.

used to *regularize* the estimates; the concept of regularization is a fundamental one for statistics in abstract spaces (Grenander, 1981). Note that the evaluation of the seismic behaviour of a structure (as far as this evaluation is amenable to analysis) is a statistical problem in the space of structural behaviours.

The use of random models may be also advocated because they can represent uncertainties. Those uncertainties may arise either on account of partial ignorance of the physics involved (as is the case in evaluating future ground motions) or because a deliberately simplified model is used which only approximately represents a better model which is not used e.g. because of economic constaints. The appropriate interpretation of the concept of probability in this framework is the subjetivistic one (Apostolakis, 1990). The use of probability methods in the evaluation of the earthquake risks is reasonably established [9]; thus, it is only necessary to present here the basics of the probabilistic evaluation of structural behaviour; the need for that evaluation results from the uncertainties associated to the ultimate capacity of structural elements (Park, Ang and Wen, 1985).

In general the action effects on the structures may be measured by control variables that are defined in a suitably general form as functionals on the histories of the structural variables [7]. The case when those functionals are damage indexes (i.e. take values between 0 and 1 and increased values corresponds to increased damage) is of special interest, because it allows a compact definition of the ultimate state. For example, if a frame has N collapse mechanisms and d_{ij} is the damage index for the i-th hinge in the j-th collapse mechanism the collapse criteria is simply: $max_j\ min_i\ d_{ij} = 1; 0 \leq j \leq N; 0 \leq i \leq N_j$ where N_j is the number of plastic hinges in the j-th mechanism. It should be noted that, due to the multi-dimensional character of structural behaviour, it does not makes sense (at this level of theorization) to define damage functions for the structure because too many functions are acceptable. In effect, any function of the form $1-\Pi_j(1-(\sum_i d_{ij})^y/N_j^y)^x$ with $x, y \in (0, \infty)$ would qualify for the above case. The main mathematical result in this domain is that if the structural damage index is an increasing function of the damage indexes of its elements and is transitive (i.e., if state s_1 corresponds to more damage than state s_2 and s_2 corresponds to more damage than s_3 then state s_1 corresponds to more damage than s_3) it has a weighted linear representation (Fishburn, 1988)[8]: $D(p) = u(p)/w(p)$ where D is the structural damage index, p is a vector containing the structural elements damage indexes and u and w are linear functionals; then $D(p) > D(q)$ means that the state represented by p corresponds to greater global damage than the state represented by q. The major problem associated to the probabilistic definition of a limit state by some set of values for the different control variables lies in the quantification of their mutual probabilistic dependence. However, the assumption that they are independent may be acceptable in many cases; but this is a subject where experimental data is clearly needed.

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[8] This result has some mathematical qualifications which are irrelevant for the present purposes.

4.3 - The rules of decision-making

The arrangement of models, through the use of parametrization and randomization, needs a last elaboration before they can be used as the support for engineering decisions. This consists in the definition: i) of a transitive partial ordering in the ensembles of the nine models by $\{M_{ix}, i = 1,2,...9\} < \{M_{iy}, i = 1,2...9\}$ if and only if $M_{ix} < M_{iy}, i = 1,2,...9$; ii) of an absolute minimum $\{M_{io}, i = 1,2,...9\}$. This minimum arrangement of models corresponds to the more simple analysis that is admissible; higher order arrangement corresponds to the use of more sophisticated analysis methods. It is possible now to formulate the activity of the earthquake engineer *qua* designer as a climbing (in a 9-dimensional space, at least) from the minimum arrangement to an arrangement of models that gives an adequate reliability. This "climbing" may be thought of as a sucession of steps, in which two models are compared. The main point in this comparison is the assessment of the *predicative novelty* [3] of the higher order arrangement. This assessment shall be made, in the present rationalization, in terms of the probability of failure. The present rationalization of earthquake engineering is called structuralistic[9] because of the important role played by the "structuration" induced by the partial ordering in ensembles of the nine phenomenological and descriptive models.

5 THE BAYESIAN APPROACH

It must be admited that it is not presently possible to explore in convenient detail the range of the different models that may be integrate the different arrangements. What is possible, and is dealt with in this last section, is to show the possible contribution of bayesian inference for this class of problems. This bayesian approach was developed to optimize numerical structural analysis in the nonlinear range [18]; but its applicability is more general and it is presented here in this way. It is assumed that the source of the action is described by some probabilistic distribution, that the action effects are given by a vulnerability function and are assessed by comparison with random resistances. Presuming total absence of information about system behaviour, the vulnerability function may be any nondecreasing function, since it is reasonable to expect that an increase of the action would not correspond to a decrease of the action effect. Hence a complete ensemble of nondecreasing functions is a first step to the representation of our knowledge about system behaviour. Completeness means that given the vulnerability function of any system, there should be in the ensemble a function which is equal to that vulnerability function. From a practical viewpoint, it is not necessary, to find the value of the probability of failure with great accuracy. Thus, it is not needed to identify the vulnerability function with much sharpness. Hence, completeness may be understood to be attained if in the ensemble there is always a function which is sufficiently close to any possible vulnerability function.

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[9] This term was borrowed from literary theory (e.g. [8]).

This fact suggests that a not very large number of ensemble functions V_i may be used ($i<1000$) if during the analysis it is investigated if this number should be increased.

The ensemble of functions is probabilized by associating to each function V_i a probability value p_i. Each set of values $\mathbf{p} = \{p_1, p_2...\}^T$ represents a state of knowledge. There is a a good state of knowledge when all the ensemble functions are associated to very small probability values with the exception of those which are close to the true vulnerability function, which have much larger probability values. Before any system analysis is performed there is no knowledge, i.e. the state of knowledge is non-informative. Absence of information must necessarily be understood in relation to some quantity, which in this paper is considered to be the probability of failure. A non-informative state of knowledge is represented, in this case, by a constant probability density in a logarithmic scale. Probability values p_i may be easily computed to secure approximately a non-informative distribution of the probability of failure.

The value of the vulnerability function is identified with the mean value of the action effect supposing a randomized action. When information is obtained (by numerical or physical experiments), necessarily using a realization of the stochastic process representing the action, the action effect value obtained is only an estimate of the true value of the vulnerability function. However, several realizations may be used and, as a result, a sample of action effect values are obtained. The sample mean value is obviously a better estimate than any individual value. If the number of sample elements is not small, the probability distribution of the sample mean value is approximately a Gaussian distribution (by the central limit theorem) with a mean value equal to the mean value of the action effect due to one realization and with a variance equal to the variance of the action effect due to one realization divided by the number n of sample elements. The coefficient of variation c may, in general, be reasonably estimated. This permits the definition of the conditional probability $P(r \mid V_i(h))$ of obtaining average action effect r for action intensity h if $V_i(h)$ is the true vulnerability function by $P(r \mid V_i(h)) = G(V_i(h), c^2 V_i(h)^2/n)$ where $G(\mu, \sigma^2)$ represents a Gaussian distribution with mean value μ and variance σ^2. Hence, after performing n computations and obtaining an average value r the *a posteriori* probabilities $P(V_i \mid r)$ may be computed by Bayes theorem: $P(V_i(h) \mid r) = p_i P(r \mid V_i(h)) / \sum_i p_i P(r \mid V_i(h))$. These probabilities represent the new state of knowledge. If the variability of the conditional probability $(P(r \mid V_i(h))$ is underestimated (due to either an underestimation of the value of the coefficient of variation or to the true distribution being not sufficiently close to a Gaussian distribution) the Bayesian analysis may present instabilities; should they be detected, a higher value for the coefficient of variation should be used. If the variability of $P(r \mid V_i(h))$ is overestimated the convergence is more slower than it could be but no other undesirable effects result.

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DEPREM MÜHENDİSLİĞİNDE RASYONELLİK, YAPISAL, İSTATİSTİKSEL VE BAYESİEN YAKLAŞIM

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ÖZET

Deprem mühendisliğinin ayrıntılarını doğrulama, yer hareketinin kısmi olarak tahmin edilememesi, yapısal davranışın nonlineer ve histerik özelliği, tariflenen hasar durumları ve çökme koşullarındaki deneyimsizliğimizden dolayıdır. Bu makale, sismik tasarımda bazı açık problemlerin yeniden formülüze edilebilmesi ve çözülebilmesi ile mevcut bilgi sınırlarının tanımlanabilirliği içeren bir çerçeve oluşturma amacıyla deprem mühendisliğindeki aktivite ve yöntemlerin bir bütününü oluşturan kavramsallaştırmayı sunmaktadır.

Kavramsallaştırmaya sadece metodları rasyonel olduğu için değil aynı zamanda amaçların toplum ilkeleri ile uyum içinde açıklanabilirliği ve tahminlerin açık olarak tanımlanabildiği için "rasyonalizasyon" denilmektedir.

Problemleri adreslendirdiği için yapısal olan bu kavramlaştırma lineer değildir ve bu yüzden elemanlarının bağımsız bir anlamı yoktur fakat aralarındaki ilişkiye ve kavramsallaştırmanın global "yapısı"na nazaran anlaşılabilirler.

Bu kavramsallaştırma, olasılığa dayanır çünkü kaçınılmaz bilinmeyenlerin yani yapısal performans ve gelecekteki yer hareketlerinin karşısında bilgi durumlarını göstermekte olasılık teorisi kullanılır.

Sonuç çıkarmanın ana ilkesi olarak Bayes teorisi kullandığı için bu kavramsallaştırma bayesiandır.

Bu makale sarsma tablası deneyi ve yapıların sayısal nonlineer analizi örneklerinin tartışması ile sunulmuştur.