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The Reliability Aspects in Dynamic Engineering

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SYNOPSIS Strides in dynamic engineering need to be accompanied by developments in risk appraisal of designs so as to respond to rapidly increasing sensitivity to and awareness of hazards. A practical, reliable and engineer-friendly methodology for design is presented in light of the critical review of the various current practices. An example is presented to illustrate the advantages of the preferred approach to improving, unifying and rationalising design.

INTRODUCTION

Considerable progress has been made in the area of soil dynamics over the last three decades (Das, 1993). Dynamic engineering, essentially, recognises the need for acknowledging the differences in soil properties under dynamic as against static loading as well as for acknowledging the stochasticity of these dynamic loads, specially seismic.

While impressive strides have been made in the area of soil dynamics, the consideration and treatment of the inherent stochasticties have not kept pace in design, albeit, some useful work has been published (Tang 1993; Singh et al, 1994).

A good engineering design is, necessarily, a case of providing a level of reliability that is commensurate with the consequences of failure and/or loss of life. In assessing alternative designs it is the hazard rating (probability of failure x consequences of failure) which should be taken into account. This can result only from a rational comparison between resistance or capacity of the structure and the imposed loading with respect to various conceivable modes of failure and service limits.

Soils and rocks are highly variable and display very complex behaviour which can change with time. Even with nominally homogenous soil layers the engineering properties exhibit considerable variation from point to point. As the loads and responses are never known exactly, the engineering designs are undertaken under considerable uncertainties. To engineer is to venture (Singh and Das 1995) and to manage the associated risks. There has been a considerable movement toward reliability/probability based methods with a motive to rationalise and unify design, (Frangpol and Nakib 1985, Joint Committee CEB-CECM-CIB-FIP-IABSE-RILEM, 1981). The Royal Society (1992) now recommends that "quantified-risk should be treated as a serious academic subject".

MOTIVATION FOR RELIABILITY APPROACH

The prevalent methods, based on concepts of factors, are not only deterministic and irrational but they also discourage clearer understanding of the relative importance of the various influencing factors. On the other hand the reliability approaches encourage a healthy scepticism towards assumptions in modelling and design as well as towards the test data and other design inputs. Figure 1 is a simple illustration of irrationality of methods based on concepts of factors; even when these factors use "characteristic", as against average or likely, values of load and capacity. It is obvious that the two cases of design are assumed to be of equal safety standard when measured by the factor criterion, yet the probability of failure of design (b) is dramatically higher. There are recorded examples of failure of geotechnical structures where the calculated safety factors were well above 1.0. Uncertainties in this field can be classified into:-

- Physical: including variability of soil, loads and dimensions
- Statistical: including limited sampling; soil disturbance and testing methods
- Model: idealisation and simplification of reality
- Human: errors in design, construction and use of structures

The deterministic approaches are widely used because of historical reasons, for the simplicity of computations and because of lack of exposure of designers to reliability based approaches to analysis and design. These deterministic approaches are satisfactory for low criticality structures, provided the values of the parameters used in design are realistic and that the safety factors themselves are rationally derived and calibrated using the best available reliability analysis.

REVIEW OF CURRENT APPROACHES TO RELIABILITY ASSESSMENT

Assessment of any system begins with the assessment of the

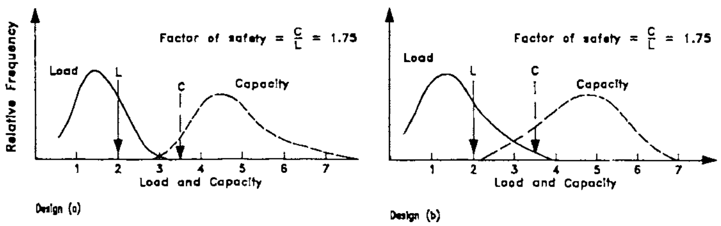

FIG.1. Designs With Identical Factors of Safety But Entirely Different Reliabilities.

elements in that system. There are basically three approaches: Fuzzy Set Theory (FST), Analytical and Monte Carlo simulation. FST has been used in risk analysis apart from other fields such as machine/robot control. The probability of failure (P_f) found using the approach would not be a single value but a set of values, each having a corresponding degree of belief that it belongs to the set. An example of such a set would be:

$P_f = 10^{-6}|0.1, 10^{-5}|1, 10^{-4}|0.4, 10^{-3}|0.1$ and means that P_f could take a value of 10^{-5} with a probability of 0.1, 10^{-4} with certainty, 10^{-3} with 0.4 probability etc. The authors do not regard FST to be a suitable method because the implications of the calculated set membership are unclear, the propogation of probabilities is based on unacceptable and unclear assumptions and the solicitation of personal or group probabilities from experts is ad hoc (Baecher, 1983). The ANALYTICAL approach includes numerical integration, maximum entropy distribution and second moment methods. Most engineers are ill-at-ease with these and experience difficulties even with very simple problems - leading to demotivation. Unfortunately this approach is by far the most popular with the exponents of the reliability studies who resort to unjustifiable simplifying assumptions to make the analysis tractable. The results are "exact" but unreliable. In many designs of even modest complexity this approach may not even be possible (Singh and Gowripalan, 1988). Singh and Chung (1991) have demonstrated that notionally "exact" results (such as reliability index β), obtained from unquestioned application of statistical theories are of little value, and even misleading. MONTE CARLO SIMULATION is the preferred approach. The methodology is given in Figure 2. It has been used in a variety of situations (Singh, 1987; Singh and Das, 1995). It is not only more attractive to engineers but can handle complex problems without resorting to distortion of the actual problem or input probability distributions, and with full consideration of the corelations between variables in a model. Sensitivity of the design reliability to these variables (stochastic) as well as to the various models can be easily studied. Singh et al (1994) describe features which are desirable in a rational approach. Their work pursues and achieves these features through a powerful combination of table-top hardware and a robust and friendly software, features of which are described by Singh (1985, 1987).

ILLUSTRATIVE EXAMPLE USING THE PREFERRED APPROACH

Consider a concrete foundation subjected to a vibratory force of 3000 lb. The weight of the machinery mounted on this block is 15216 lb; the nominal (mean) breadth (b), length (L) and height (H) are 6, 20 and 7.8 ft respectively. Average unit weight of soil (γ_s) and concrete (γ_c) are 115 and 144 lb/ft^3. The mean shear modulus of the soil (G) is 3000 lb/in^2; Poisson's ration (μ) = 0.4. The operating frequency (f_o) is 200 cpm.

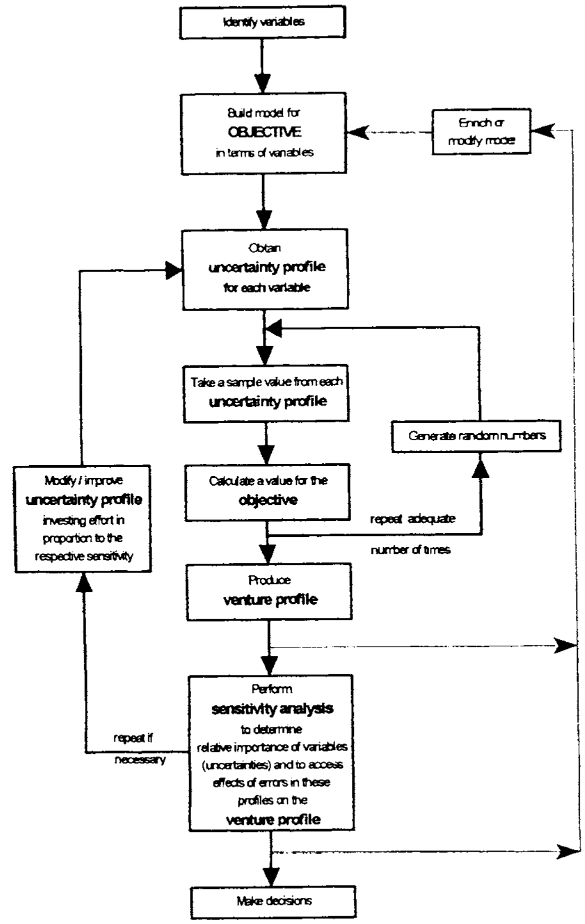

FIG.2. Monte Carlo Simulation Methodology

For the sake of the illustration we take the following models for resonant frequency (f_m) and amplitude of vibration (A_z) from Das (1993, page 200).

$$f_m = \left(\frac{1}{2\pi}\right)\left(\sqrt{\frac{G}{\rho}}\right)\left(\frac{1}{r_o}\right)\sqrt{\frac{B_z - 0.36}{B_z}} \qquad (1)$$

where $r_o = \sqrt{\frac{BL}{\pi}}$; $\rho = \gamma_s \div 32.2$; $B_z = \left(\frac{1-\mu}{4}\right)\left(\frac{weight}{\gamma_s r_o^3}\right)$

$$A_z = \frac{Q_o(1-\mu)}{4Gr_o}\,\frac{B_z}{0.85\sqrt{B_z} - 0.18} \qquad (2)$$

The Deterministic analysis yields f_m = 405 cpm (therefore $f_m/f_o > 2$; OK!) and A_z = 0.00244 inches.

Reliability analysis was performed with the following input:

G ranging from	2100	to	4800 lb/in^2
γ_s	108		118 lb/ft: dependent on G
H	7.6		8.0 ft
L	19.75		20.25 ft
B	5.9		6.1 ft
γ_c	140		148 lb/ft^3
μ	0.25		0.45: dependent on G

To demonstrate ability to handle correlations (dependencies) the following equations were used:-

$$\mu = 0.45 - 0.000055\,(G-2100) \quad (3)$$

$$\gamma s = 113 + 0.00223\,(G-2100) \quad (4)$$

Also recognised were the dependencies of weight on L, B, H and γc and of radius (r_0) on B and L (simultaneously). For example, the model for mass ratio (B_z) became:

$$\frac{\{1-(0.45-0.000055(G-2100))\}\times\{(BLH\gamma_c)+15216\}}{4\{113+0.0022(G-2100)\}\times\{\sqrt{BL/3.141}\}^3} \quad (5)$$

The software allowed direct screen entry of the models (Figure 3) without needing access to source codes, and using meaningful variable names. The probability distributions (Venture Profiles) of f_m and A_z are shown in Figures 4 and 5. All the input variables were deliberately given near-normal or normal distributions (Uncertainty Profiles) so as to demonstrate that even then the objective function is not necessarily normally distributed. It is interesting to note that there is a very high probability that f_m/f_0 will be less than 2. These figures also show that there is an unacceptably high chance that the movements will become "troublesome to persons" standing on the block (Richart, 1962). The Sensitivity analysis was easily performed. Figure 6 shows Sensitivity Profile of mass ratio with respect to G, B, H and γ_c. The lengths of the lighter bars show, with reference to RHS scale, the relative influence of these variables on the mass ratio.

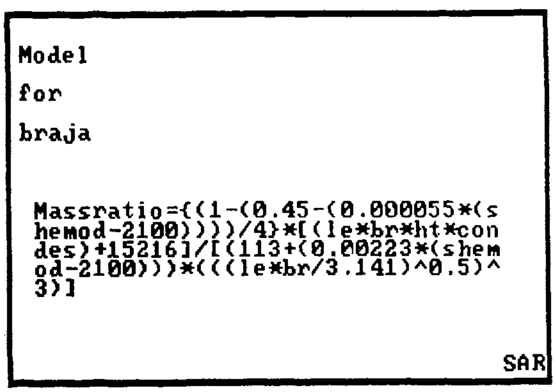

FIG.3. Direct Screen Entry of Model: Example for Mass Ratio

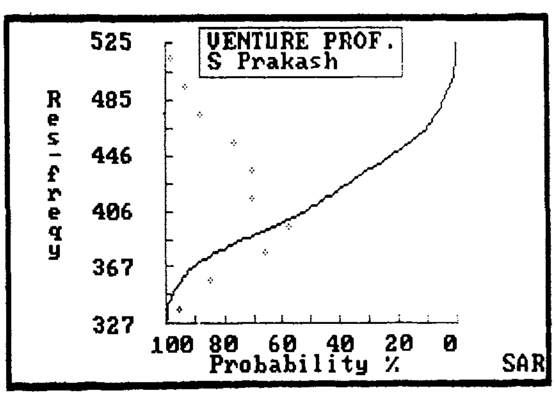

FIG.4. Probability Distribution (Venture Profile of Objective Function) of Resonant Frequency, f_m.

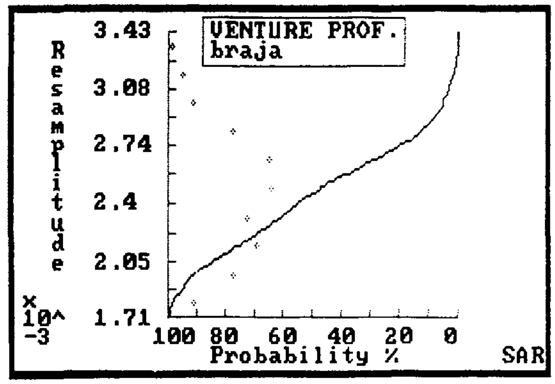

FIG.5. Probability Distribution (Venture Profile of Objective Function) of amplitude of Vibration, A_z.

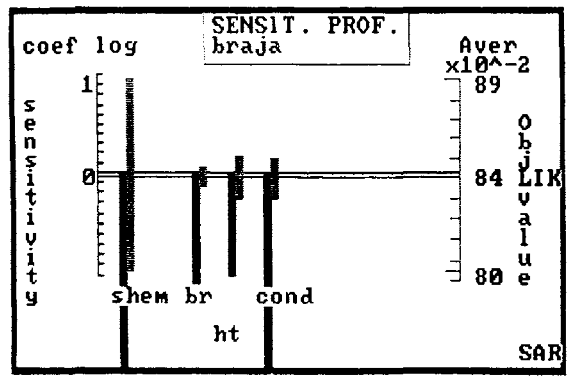

FIG.6. Sensitivity Profile of Mass Ratio to Variations in Shear Modules, Breadth, Length and Height as well as Concrete Density.

THE PROPOSED PROCESS FOR DESIGN AND ITS EVOLUTION

The ever increasing pressure from the society at large and clients in particular for greater "profitability" and safety call for reliable and cost effectively obtained designs. The models for designing geotechnical structures and the resulting objective functions play vital roles in reliability analysis. Invalidity of a model itself will make the whole design methodology useless. However, arguments can arise because models, by various researchers, are based on some simplifying assumptions and the actual phenomena involved are not fully understood. For non-critical structures the authors propose the methodology illustrated in Figure 7. This will facilitate selection of the model and development of design for a level of reliability desired by the designer. The design-charts approach will furnish reliability based designs conveniently without having to assume a theoretical probability distribution shape for the objective function. For critical structures the authors recommend the full comprehensive Monte Carlo simulation illustrated in Figure 2.

In order to obtain reliable and cost effective structures it is vital to improve existing models and accumulate reliable statistical data on the various uncertainties. This process should be carried out under the illuminating and reliable light of the Monte Carlo approach.

Sensitivity analysis, with respect to models and data, should help optimise efforts invested in the evolution of the quality of service to the client. Every time a claim is made regarding improvement in data or models this claim has to be assessed with a calibrating system. Unless the latter is itself reliable and realistic the evolutionary process will be tediously slow, and at times retrograde. It is important, therefore, that the continuing and prevalent use of the "analytical" approaches be discouraged.

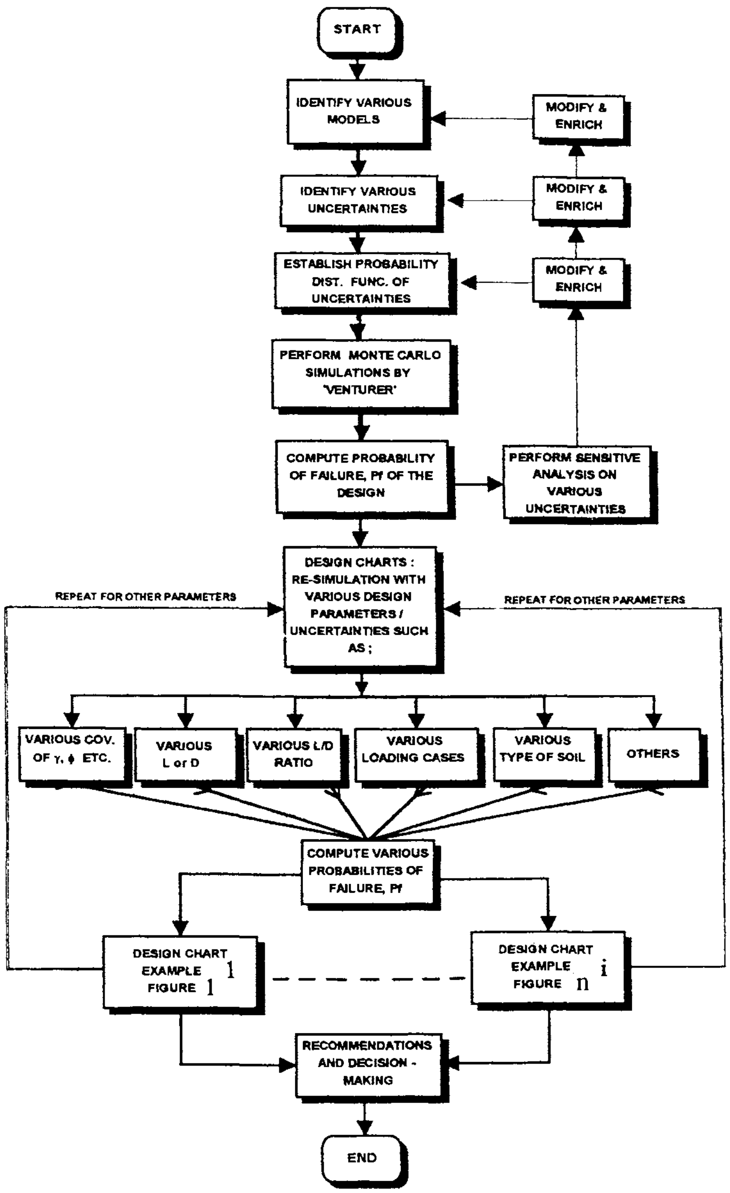

FIG.7. Methodology for Developing Reliability Based Designs for Non-critical Structures.

CONCLUSIONS

Strides in dynamic engineering should be accompanied by developments in risk analysis of designs so as to respond to a rapidly rising awareness of and sensitivity to hazards; natural and human-made.

Improvements, unification and rationalisation, called for in design, must not be carried out and assessed using unreliable calibrating approaches.

The authors recommend a reliable and practical methodology which has been made convenient and engineer-friendly with the aid of powerful combinations of Monte Carlo simulation and personal computers.

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