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Human Influences in Quality Assurance

Influences de l'homme sur l'assurance de la qualité

Der Einfluss des Menschen auf die Qualitätssicherung

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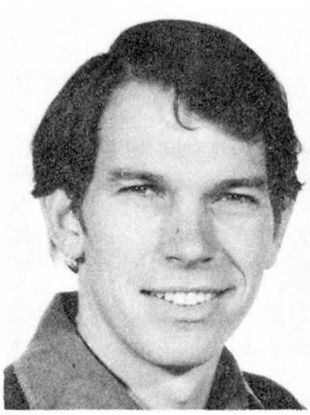

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SUMMARY

The effectiveness of quality assurance depends largely on the effectiveness of the facilitative measures it provides and the control measures it imposes. These are related to structural safety and structural performance through human error. Both empirical data about human error and models are selectively reviewed herein and directions of some ongoing research outlined.

RÉSUMÉ

L'efficacité de l'assurance de la qualité dépend essentiellement de la simplicité des mesures retenues et des contrôles exigés. L'assurance de la qualité, au-delà des erreurs humaines, est en relation étroite avec la sécurité et le comportement des structures. Des valeurs empiriques sur l'erreur humaine ainsi que des modèles sont présentés et analysés. La direction de certaines recherches en cours est indiquée.

ZUSAMMENFASSUNG

Die Effizienz der Qualitätssicherung hängt weitgehend ab von der Einfachkeit der eingeführten Massnahmen und von den geforderten Kontrollen. Sie steht über menschliche Fehlhandlungen in enger Beziehung zu Tragwerkssicherheit und Tragwerksverhalten. Erfahrungswerte bezüglich menschlichen Fehlverhaltens sowie geeignete Modelle werden besprochen und die Zielrichtung einiger laufender Forschungsarbeiten angedeutet.

1. INTRODUCTION

In order to achieve an acceptable level of quality for a given structure, a necessary, but not sufficient condition is that the structure is "safe". Safety is conventionally measured by factors of safety, load factors and now by partial factors of Limit State Formats. It can also be measured by a "nominal failure probability", or its transform, the "safety index". The data for a failure probability calculation is usually objective, that is, measured data, but its interpretation is subjective. Also the conditions defined as "failure" are subjective in interpretation.

The traditional (additional) measures used to attempt to ensure the achievement of safety (and other requirements to be met by the structure) have been various forms of "control", such as checking, inspection, sanctions. From a purely global societal point of view these measures are probably adequate [1]. However, their cost-effectiveness is open to question. The effect of these (and other) measures on actual, rather than nominal, structural safety and serviceability, and more generally on "structural quality" is of interest, but at present understood in a qualitative rather than quantitative way.

It has always been understood that some organizations appear to be more effective than others; Pugsley [2], for example, listed organizational attributes in his famous "climate" factors. Perhaps partly because of the traditional "them and us" attitude generated by the division of design and construction functions, the importance of inter- and intra-organizational behaviour appears sometimes to have been lost sight of by civil engineers, although its importance is well appreciated in other circles [3], and is evidently a factor in some major cases of structural failure [4]. Organizational adjuncts such as adequate information flow, adequate communications, conducive work environment, competence, selection and training personnel, etc. may all be regarded as "facilitators" in achieving the objective of adequate structures. It is well recognized that the formal organization structure as an operational system is almost one of last resort; real and effective operation tends to transcend such formalism [5].

Effective Quality Assurance must be able to accommodate and utilize each of these three strands, namely (i) nominal safety and serviceability, (ii) various "control" measures, and (iii) the "facilitating" factors. There are probably many ways in which this might be done. One intuitively appealing approach is to maximize the expected net benefit of a project [e.g. 6]

$$\text{Max } [B - C_T] = \max [B - C_I - C_{QA} - C_C - C_{INS} - C_M - p_f C_F] \tag{1}$$

where B = benefit(s) of project

C_I = initial cost

C_{QA} = total cost of quality assurance = $\sum_i C_{QAi}$

C_C = cost of consequences of quality assurance

C_{INS} = cost of insurance

C_M = maintenance cost

C_F = cost of failure

and p_f = probability of failure of the project.

Apart from C_F, it is likely that all the costs will be related to p_f, and in the case of C_{QA} rather strongly so. This is in accordance with findings for failed structures [7,8,9]. To use expressions such as (1) in an operational sense, p_f and its relation to C_{QA} (and the other costs) is required. This means that the relationship of the "control" measures and the "facilitators" to p_f must be known. A review of attempts to develops such relationships is the main thrust of this paper. Alternatively, of course, the knowledge of p_f relative to other risks in society might be sufficient for decisions about the quality assurance measures required.

2. HUMAN ERROR

The link between the facilitating factors and control measures on the one hand and structural performance and structural safety on the other is through "human error".

Precisely what constitutes "human error" and how it actually affects structural reliability is at present rather poorly understood. There are considerable efforts being made to collect documented cases of structural failure and to somehow extract from these useful lessons or guidelines for avoiding future failures - a process which took place rather less formally in former times [9]. Of course, not all human error is equally likely to cause structural failure (however defined), and not all structural errors are of equal importance. There are, no doubt, many existing structures which contain one or more "errors", yet which are perfectly adequate in service, even though their reliability may not be adequate according to the design criteria originally adopted.

As shown by empirical studies [4,9] human errors are typically discrete events (e.g. incorrect choice, omission) with an associated magnitude (e.g. size of error). The size of the error, and in particular the size of its effect, is of particular importance for structural engineering.

Human error may be considered to be of three types: random variability in performance of well-known and well-understood tasks, errors in the performance of these tasks and errors due to various forms of "unknowns"; see Table 1 [10].

Error Type	Failure Process	Mechanism of Error
variability V ↓ gross A	In a mode of behaviour against which the structure was designed	One or more errors during design, documentation, construction and/or use of the structure
gross B	In a mode of behaviour against which the structure was NOT designed	Engineer's ignorance or oversight of fundamental structural behaviour
		Profession's ignorance of fundamental structural behaviour

Table 1 Classification of Errors (adapted from [10])

3. MODELS FOR HUMAN ERROR

3.1 Relationship between Error and Failure Probability

The earliest work attempting to model the importance of human error assumed a linear relationship between the error content in a project and its probability of failure due to human error [11,12]. The precise nature of the errors themselves, their possible effects and any possibility of cancelling effects or automatic detection were not considered. It was recognized that there are two components to the failure probability - that due to gross errors (or uncertainty effects) and that due to gross-error-free material, loading and workmanship variability, the so-called theoretical failure probability. These two components are approximately independent in most situations [10,14].

A more precise statement between error and failure probability can be made if the relationship between probability of failure and error in resistance is explored separately from the occurrence probability of resistance errors. For the first of these, the standard limit state equation formulation can be rewritten as [10]:

$$Z = ER - KS \tag{2}$$

where E represents a random variable of error applied to the random variable of resistance R and K represents a discrete-valued model uncertainty (such as might occur when extrapolating beyond existing knowledge).

The error variable E should strictly be viewed as the structural outcome of a human error or errors, such as the misplacement of reinforcement, or incorrect location of a bolt, etc. A variety of human error(s) may have caused this particular outcome (e.g. omission, incorrect number, etc.). There is thus room to explore the dependence of safety (expressed, for example, through Z) and its dependence on structural errors [15] as well as the latter's dependence on human errors. This distinction has not always been made clear.

Formulation (2) allows for the magnitude component of human error of type V and type A, but does not account for type B errors. The latter can be introduced as follows. Let the probability of error occurrence be p_E. Then the failure probability represented by (2) without and with this error is $p_o = \Phi(-\beta_o)$ and $p_1 = \Phi(-\beta_1)$ respectively, where $\beta = Z/\sigma_Z$ and the subscript o denotes $E = K = 1$ in equation (2) and the subscript 1 refers to equation (2) as written (i.e. with human error) [16,17].

The resulting total failure probability is then given by

$$p_f = (1 - p_E)p_o + p_E\, p_1 \tag{3}$$

or more generally:

$$p_f = \sum_{i=o}^{r} p_i\, p_{f|i} \tag{4}$$

where p_i is the occurrence probability for the error state and $p_{f|i}$ is the failure probability given state i, with i=o denoting no error content.

Naturally, the limit state equation (2) represents only one possible failure mode. A further possibility is that not all random loads or resistances may have been properly considered in the analysis. It follows that the above formulation can be extended simply by considering more than one failure mode and errors in formulation of limit states [18].

Another approach, which considers the interaction of error occurrences, error detection, error correction and structural failure as separate events, has been formulated [19], as well as those in which the involvement of architect and builder is also included [17,19].

3.2 Error Occurrence

In order to apply the above formulations, information is required on error occurrence probabilities. It is here that problems begin to arise. Very little empirical information is available with which to construct models.

Some information has recently become available for design related tasks (see below), and some data on simple cognitive and psycho-motor tasks (e.g. button-pushing, dial reading, etc.) exists in the human factors literature [e.g. 20]. Data banks exist for tasks related to the aircraft industry [e.g. 21], but it is doubtful if these are appropriate for structural engineering tasks. For design errors, it has been suggested that they might be modelled as random events over some task or (time) interval. In this case a Poisson process over time interval t and with average rate of error occurrence per unit time, λ, is appropriate [22,23].

$$P_{N|A}(n,\lambda) = \frac{e^{-\lambda t}(\lambda t)^n}{n!} \qquad n = 0,1,2, \ldots \qquad (5)$$

where $P_{n|A}(n,\lambda)$ denotes the probability that the number of errors N is n, given that the average rate of error occurrence Λ is λ. The latter is usually uncertain due to variations between tasks, between persons or teams, etc., and may also need to be modelled as a random variable. Unfortunately, it is very doubtful that errors are completely random.

4. MODELS FOR ERROR DETECTION AND CHECKING

In principle, the combination of the error occurrence models and the models tying error to failure probability, allow prediction of the effect of human error on structural reliability. In practice, however, some detection of error is almost inevitable. Designers may check their own work, or detect mistakes later in the design; associates or supervisors similarly may detect errors, as may either or both an "in-house"check of the design and a formal independent check as part of building permit issuing procedures.

The earliest models assumed a linear relationship between error content and control [11,12]

$$x_j = (1 - \gamma_j)x_{j-1} \qquad (6)$$

where x_j = proportion of errors after control j

x_{j-1} = proportion of errors before control j

γ_j = effectiveness of control j.

Values for γ from inspection effectiveness of electrical and other small components in factory production suggest a range 0.3 - 0.9 with 0.75 for simple visual tasks under good conditions and with trained inspectors [24]. The relevance of such figures to the more complex tasks in civil engineering design and construction is not immediately obvious and more directly relevant data would be appropriate.

Before control measures can be applied, the errors must be detected. Because error rates or error detection levels were not known, the earliest studies [11,12] did not specifically deal with actual error counts, or their probability distributions. Only recently has a model for error detection been proposed [23], with particular reference to design checking.

In this model, it is supposed that the act of checking some work can be regarded as a series of trials, with the encounter of each error being an individual trial. Only if the error is detected is there a "success". If there are L errors in the work checked (i.e. L trials) and the probability of detection for each error is p, using the binomial distribution, the probability of detecting k errors is:

$$P_{K|L,P}(k,\ell,p) = \binom{\ell}{k} p^k (1-p)^{\ell-k} \qquad k \text{ integer} \tag{7}$$

By plotting $P_{K|L,P}$ against $k|L$, a distribution function for the overall checking effectiveness ($\gamma = k|L$) can be obtained. This overall measure is only of use if all errors are assumed to have equal influence on the structural failure probability. As already noted, this is unlikely to be the case.

More generally, the overall effectiveness of checking, γ, and the probability, p, of error detection for each error, are each functions of a number of variables. The most important of these is checking effort, which may, as a first approximation, be represented by time spent on checking. With this assumption, it is known from search theory [22, 23] that the detection probability increases with the time spent on searching for an error; this phenomenon can be described asymptotically by the exponential distribution:

$$\gamma(e) = 1 - \exp[-\alpha e] \tag{8}$$

where γ = detection probability
e = time or effort spent on searching
α = a parameter, which is a function of the degree of detail examination, inversely a function of size of task and also a function of controller (checker).

It is assumed that the checkers or controllers are completely independent of those whose task is being investigated; if not, the detection probability will be lower.

The exponential nature of (8) reflects the fact that any one controller will recheck his own work given sufficient time, and this may be repeated with more time available. Hence an optimal scheme would invest only a limited time search for one controller, followed by another, independent, controller, etc.

Instead of time as the parameter in checking, the cost of checking might be used. One such formula is [23]:

$$\bar{\gamma} = 1 - \exp\left[-\alpha \frac{C_c}{C_{io}}\right] \tag{9}$$

where $\bar{\gamma}$ = mean checking efficiency;
C_i = cost of checking;
C_{io} = initial cost of error free structure; and
α = parameter as before.

The ratio C_c/C_{io} for design checking has been estimated [13] to be in the range of 0.004 to 0.006. However, the associated checking efficiency is not known.

A somewhat different model for error reduction has been proposed by Lind [17], working from the plausible suggestion that large errors are more likely to be detected than small ones. Unfortunately it is restricted to errors modelled as additive to the resistance R, which seems unlikely to be completely appropriate in view of the empirical data available.

5. EMPIRICAL DATA

It is evident that most of the models proposed are quite primitive in that only gross, or overall, effects are considered. They do, however, give an idea as to the type of data that is required. With data will, hopefully, come better understanding and better modelling.

As already noted, data on human variability, human error and human intervention is scarce. Some basic results related to design have been reported [25] and a few further results will be given below.

5.1 Calculation Errors

The aggregated error rate for calculation errors was reported as about 0.01 for engineering students [25]. A more extensive survey was conducted with calculations of differing lengths to ascertain if there was a trend with calculation length. Sampling of engineering design calculation suggests that typically only 1-3 mathematical operations are involved in calculations, but that much longer calculations do occur [26].

The results were analysed for three types of error: round-off, decimal and computational. Although there was considerable scatter in the results there was a definite trend for the error rate to increase with the number of mathematical steps in the calculation. If 5% is used to discriminate between round-off and other errors, the trend for overall error is approximately

$$p_E = 0.027\ n$$

while for 2.5% discrimination,

$$p_E = 0.0225\ n$$

where n is the number of mathematical steps. In both cases the error in these expressions can be up to 100%, particularly for low values of n.

5.2 Table Reading Errors

In the previous report [25] some error rates for table-look-up and for number ranking were reported. A further study on 15 fourth-year civil engineering students was carried out using a broad based selection of table-look-up tasks as well as table-look-up with interpolation tasks, and produced altogether 238 responses during the task time [20 minutes] with 16 incorrect responses being counted, giving an error rate of 0.067. The reasons for this quite high rate are not immediately obvious. However, it is possible that the sheer repetitiveness of the task, without much variation, in task type may be a factor.

Task no.	No. of "gross errors"	Response mean	Standard Deviation	Coefficient of Variation
1	-	161.47	2.55	0.016
2	1	34.0	1.63	0.048
3	1	87.11	1.64	0.019
4	1	80.08	1.57	0.02
5	2	36.52	1.63	0.045
6	2	20.6	0.60	0.29
7	1	688.25	21.45	0.031

Table 2 Table Interpolation Results

Table 2 gives the results obtained on 15 samples for each of seven table interpolation tasks. The number of "gross errors" in the 15 samples used for each task is shown.

A 'gross error' was in this case considered to be a response outside the interpolation range given in the appropriate table. This would therefore include the incorrect choice of location within the table. With this rather arbitrary definition, the gross error rate was found to be 0.08.

6. MACROTASKS AND MACROTASK MODELLING

The tasks described above are essentially component (or micro) tasks performed in design calculations; they do not indicate how the design itself might be affected. In order to ascertain this, two lines of research are being pursued. One of these has been to request randomly selected structural engineers to perform one of a number of reasonably realistic design (macro) tasks such as criteria selection, load calculation and member design. The returns were then analysed in detail as well as compared. As might be expected, a certain amount of the information obtained is highly specific to Australian design code requirements, but other results are of more general interest. These have been reported elsewhere [25].

The second line of research is to attempt to simulate mathematically the results obtained from the macrotask surveys, using as input (i) information obtained directly from the analysis of the macrotasks, (ii) analysis of the task itself, and (iii) microtask data of the type described in section 5. From work to date it is apparent that such simulation is feasible.

Mathematical modelling of macrotasks directly produces the structural effects of human error. In addition, the effect of self-checking can be incorporated. In the long term it may also become possible to include in the modelling the "facilitator" parameters; however, this will require rather better understanding of the social and psychological factors involved.

For the present, the development and verification of even rather crude models for some macrotasks should allow models for other macrotasks to be developed with a reasonable degree of confidence. It is hoped that in this way large scale sampling can be avoided.

7. DISCUSSION AND CONCLUSION

The human error modelling attempts outlined in sections 3 and 4 have been particularly useful in providing a framework for the type of information that is needed if progress is to be made in accounting for human error effects in the assessment of the probability of structural failure and malfunction and hence in the provision of appropriate Quality Assurance measures. The models themselves are all rather crude and simplistic but have the potential for refinement and for inclusion in the macrotask modelling of the type described in section 6.

Much depends on the availability of appropriate data. It is therefore of particular interest that the question of controls has been so dominant in modelling efforts, yet profession-related data has proved to be extremely difficult to collect.

Data collection for engineering design tasks (i.e. the microtasks of section 5) has been possible largely because engineering students have been available; the involvement of practising professional engineers has (for obvious reasons) been not nearly so easy, and is also open to possible manipulation by respondents [26]. However, their unbiased involvement would appear to be essential if the resulting models are to be meaningful.

The empirical data clearly indicates that there is no clear distinction between human variability, human error and "gross" error. The errors which may occur vary in size and in importance over a continuum. However, what counts is the eventual effect these errors have on the structure, allowing for the likely occurrence of some type of human intervention. This means that even with high quality human error and intervention models, the assessment of failure probabilities will be largely subjective.

If enough is known about human error effects they may be included directly using expression (2) to determine p_{fi} under a set of assumptions 'i' (see expression 4). Where the effect of human error is not well understood, it may be more appropriate to include it as one of the conditions 'i' in expression (4); this allows quite subjective estimates to be readily included.

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