Limitations in Decision Making and System Performance

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Abstract: Failures, understood in a broad sense as the poor performance of a system, can be analyzed from different perspectives. A top level view finds human cognitive characteristics determining performance. While cognitive psychology is frequently mentioned in the literature of varied fields (from artificial intelligence to civil engineering), its findings are seldom noted. In this paper, a summary of the most relevant human biases and limitations is presented and exemplified with civil engineering cases. Alternative means of reducing their effects are then discussed.

Introduction

Failures can be analyzed from different perspectives. Expert engineers try to determine the physical causes, the "triggering mechanisms"; in the process they extract technical lessons which can be used to improve new designs (Leonards 1982). Others take a wider view, looking at the overall system, of which the structure is just a part (Perrow 1984). But it is still possible to take an even more global approach and consider failures as events that can be statistically studied. Depending upon the perspective taken, different causes of poor performance may be detected.

Statistical analyses of the occurrences of failures, including catastrophic failures, poor performance, and malfunctions, show that, for the following systems, the actual probability of failure or of unexpected performance is between 1% and 5% (i.e., sometimes two or three orders of magnitude higher than is theoretically predicted):

1. Buildings severely damaged during the 1985 Mexico earthquake (high-intensity area in Mexico City).
2. Nuclear power plant systems (Ford [1986] offers an interesting account of these systems).
3. Space rockets (including the Space Shuttle program).
4. Embankment dams. (Note: several investigators have studied statistical data on the failure of dams, in most cases originating from ICOLD. They all agree [Peck 1981] on an average historical value of 1%. Tavares and Serafim [1983], Penman [1986], and Schnitter [1979] state that an important improvement of about one order of magnitude may have taken place recently. However, Ingles [1984] shows that, at least in Australia, the rate of failures has remained constant.)
5. Bridges.

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Similarly, Harr (1987), on the basis of simple probabilistic considerations, showed that the expected reliability of most civil engineering systems is between 0.95 and 0.99, which corroborates historical records. The diversity of systems, and the variety of historical, geographical, and economical contexts leave man as the only common element in all these events, and lead one to look at human cognitive limitations and willingness to accept risk as the determining factor for performance (see also Ingles 1984 and 1979, for similar arguments). There are today a large number of books (Salvendy 1987) and journals (*International Journal of Human Reliability*, and *Human Factors*) dedicated to these issues, as well as the Human Factors Society. Engineering began to pay more attention to human factors in the 1950's, in the field of industrial engineering. Even though civil engineering's interest is fairly recent (Grigoriu 1984; Nowak 1986), there are already attempts to study and model the effect of human errors in design and system reliability (Stewart 1987; Nessim and Jordaan 1985).

As part of their work in the development and use of knowledge systems in geotechnical engineering, and also because of their interest in geotechnical failures, the writers were led to review the literature and evaluate some of the characteristics of human decision making that can lead to errors. Some of the biases and errors in decision making, with examples from civil engineering, are summarized in this paper. The intent is to bring to attention aspects of human behavior that affect the training and education of individuals, the development of expertise, and problem-solving strategies, communication patterns, as well as specific tasks such as design, analysis of failures, and the development of knowledge systems, among others.

Model of Decision Maker

Man can be idealized as a transfer mechanism that takes a certain problem or stimulus as input and processes it, giving a response as output. This simple model is presented in Fig. 1. Although it is a simplistic version of reality, it represents the main components of decision making, emphasizing its dynamic nature: feedback is continuously affecting the transfer system to adjust it to the observed natural relations between facts and their corresponding

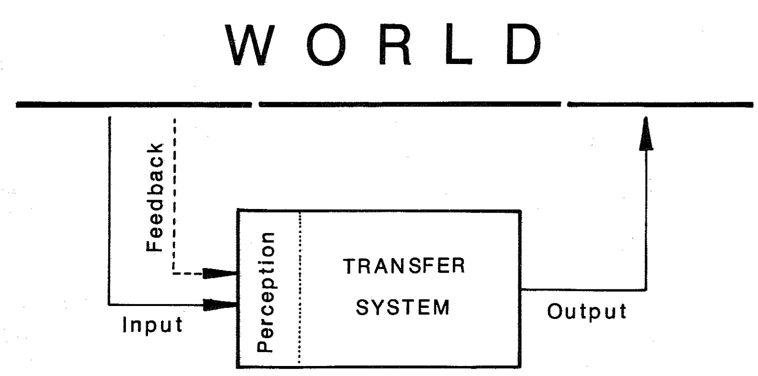

FIG. 1. Simple Model of Decision Maker

outcomes. This incremental adaptation to the phenomena is the development of expertise. The perception of feedback is affected by the characteristics of the transfer mechanism itself. The circularity of this process forces any natural bias or limitation to become deeply embedded, affecting all levels of the decision process: the gathering of information, its processing, the presentation of results, and the analysis of the feedback.

BIASES IN DECISION MAKING

The versatility of human thinking in processing different stimuli is demonstrated by the large variety of tasks a human can undertake, for example numerical manipulations, gambling, driving in a big city, and designing a major engineering system. These achievements may create a state of overconfidence in man's cognitive capabilities, neglecting the limitations that result in failures. This section gives a summary of the most important sources of biases, errors, and misconceptions in human decisions.

Misuse of Heuristics, Tversky and Kahneman (1974) describe three common heuristics: "representativeness," "availability," and "adjustment and anchoring" (see also Kahneman et al. 1982). The first heuristic, representativeness, states that the probability that event A is related to event B is evaluated by the degree to which A resembles B. Two biases linked to this heuristic are referred to as "illusion of validity" and "insensitivity to predictability." The former relates to the unwarranted confidence induced by a good fit between prediction and its outcome, and the latter involves making predictions solely in terms of the favorableness of the description, regardless of the reliability of the evidence. This is a common bias in experts investigating civil engineering failures: they tend to concentrate on supporting evidence and to disregard negative evidence (see Popper [1965] for a more scientific approach). The Teton Dam failure provides an illustrative example. During the post-failure investigations, "wet seams" were discovered within the embankment fill. Several hypotheses were proposed by leading experts to explain their presence, such as arching and hydraulic fracturing, frost action, and construction placement. However, none of these suggested formation mechanisms was fully supported by all the evidence known to date regarding this failure (Leonards 1987). Contradictory evidence exists in every case, a "falsification" of the hypotheses in Popper's words.

The "availability" heuristics states that instances of large classes are usually recalled better and faster than instances of less frequent classes. There are several possible biases resulting from this heuristic that depend on the facility to retrieve instances, the methodology used in recalling them, and, perhaps most commonly, the imagination in establishing possible scenarios. Fischhoff et al. (1978) suggest the following reasons for the availability heuristic in relation to risk assessment: (1) Ignorance; (2) failure to consider all the possible ways in which human error can "mess up" a system, (see Ford [1986], for numerous examples in the nuclear plant industry); (3) insensitivity to the assumptions regarding the consistency of the context (in which the system is embedded); (4) overconfidence in current technology; and (5) failure to comprehend how the system functions as a whole. Not realizing the potential consequences of a design modification is an example of a bias due to this heuristic, as illustrated by the 1981 collapse of the suspended walkways in the Kansas City Hyatt Regency Hotel.

The third heuristic, "adjustment and anchoring," states that individuals develop their belief by starting from a particular reference and adjusting it according to the remaining information. The adjustment process is often faulty. Slovic and Lichtenstein (1971) list four common errors induced by this heuristic: (1) Conservatism or the insufficient adjustment of posterior probabilities; (2) primacy or recency effects, which refer to the relative influence of old or recent information, respectively; (3) inertia effect, i.e. the more information a subject has, the more the resistance to change; and (4) commitment effect; the disposition to bind to one's decisions or ideas (Janis and Mann 1977). The last of these errors, commitment, may be caused by personal constraints (one's self-esteem and self image; the threat of perceiving oneself as weak or unreliable; reluctance to be critical of a completed work, etc.), or by social constraints (pressure exerted by society; the possible stigma of being known as erratic or unstable, etc.). The same authors indicate that the following consequences can result from an increasing degree of commitment: (1) Reluctance to reverse a decision; (2) a likelihood that other alternatives will be negatively considered; and (3) a low likelihood that a setback during execution of a decision will be viewed as a real threat and motivate a change in the course of action.

Commitment is common and frequent, affecting all decision makers from novices to experts, including scientists. Kuhn (1970) notes that because of commitment, fundamental inventions have most frequently been made by young individuals or those who were new to the field. The writers believe that commitment was a significant factor in the decision not to evacuate the downstream area of the Vaiont Dam, in the continuation of the experiment that ended in the Chernobyl catastrophe, in the launching of the Space Shuttle Challenger, and in the selection of the site for the Teton Dam. With regard to Teton Dam, Duck et al. (1979) state that: "The final location of the Teton Dam was largely based upon factors not directly related to the foundation conditions at the site nor the type of materials available for the construction of the dam" and that "the project passed through the separate reconnaissance, feasibility, and final design stages common to all Bureau work. Each of these stages involves an increasing amount of investigation and design commitment."

Man and Uncertainty

To a certain level, all civil engineering decisions are made under uncertainty. Hogarth (1975) hypothesized that "most people do not evaluate uncertainty; subjectively, they act to reduce or avoid uncertainty which they consider to be a property of the environment rather than to lie within themselves." Indeed, uncertainty relates to one's limited comprehension of a phenomenon and its complexity (Chameau and Santamarina 1987): only an uncertain abstraction, a model of the real world, is perceived by the decision maker (see Fig. 1).

Most researchers have focused on random uncertainty (the psychological study of other forms of uncertainty, like "fuzziness," is recent and limited). They have found several common fallacies which confirm that man is a poor intuitive statistician: (1) Sample size. Subjects tend to disregard the effect of sample size on the variance of the mean; (2) "Gambler's Fallacy": The tendency to believe that, in a random process, the overall probability of an event must manifest itself in a short series of trials; (3) Randomness and

Patterns: Hogarth (1975) reports that subjects are unable to produce random sequences of two or more events and that there is always a desire to discover patterns; (4) High and low probabilities: Individuals are poor at estimating the probability of events with either a very low or a very high probability of occurrence; (5) Conjunctive and Disjunctive Events: There is a tendency to overestimate the joint probability of conjunctive (chain-like) events and to underestimate the probability of disjunctive (funnel-like) events (Tversky and Kahneman 1974); (6) Illusory Correlation: Concluding that two or more events are always concurrent because they are frequently observed together; (7) Regression Towards the Mean: Repetitions of an event that initially gave extreme results are more likely to give subsequent values closer to the mean; although this phenomenon is often observed, it goes against man's intuition; (8) Law of Small Numbers: Tversky and Kahneman (1974) have observed that both naive and experienced individuals tend to accept intuitively that small samples are representative of a population. These biases affect all decisions when frequency and chance are involved, for example, earthquakes, hurricanes, floods, traffic, and jointed rock mass.

Limited Capacity

Several studies reported in the literature have tried to determine man's limitations in perceiving and processing information. Miller's rule (Miller, 1967) states that an individual's capacity for processing information (i.e., distinguishing between pieces of information or objects) is limited to 7 (± 2) objects. Slovic and Lichtenstein (1971) observed that three clues are usually sufficient to account for more than 80% of the variance in an individual's response. They also noted that increasing the amount of data increases the individual's confidence with relatively no increase in the quality of the decision. This is a common fault both when specifying and when processing in situ and laboratory tests used in the design of foundation systems.

Task Characteristics

The characteristics of a task can affect individuals' responses. Some of these characteristics are (1) Variability of the data; (2) consequences of an incorrect decision; (3) order of presentation; (4) payoffs; (5) amount of information; (6) vividness of information; (7) context; (8) speed of presentation; (9) simultaneous presentation; (10) units; and (11) range of values. Experience and awareness can reduce the sensitivity to these characteristics; still, they make subjects vulnerable to external manipulation.

Biases and Expertise

There are several stages in the development of a skill. Anderson (1985) distinguishes the following three: cognitive, associative, and autonomous. "Tuning" is an inherent characteristic of this skill development process. It consists of recalibrating one's decision-making approach (see the transfer mechanism in Fig. 1) on the basis of feedback from previous experiences.

Besides feedback, another condition that controls the change from one stage to another is task repetition. In Fig. 2 the average time required for students to solve simple strength-of-material problems correctly is plotted against the estimated number of repetitions of similar tasks. This figure is based on limited data; extrapolations for large number of repetitions relied upon subjective information from graduate students and professors. Never-

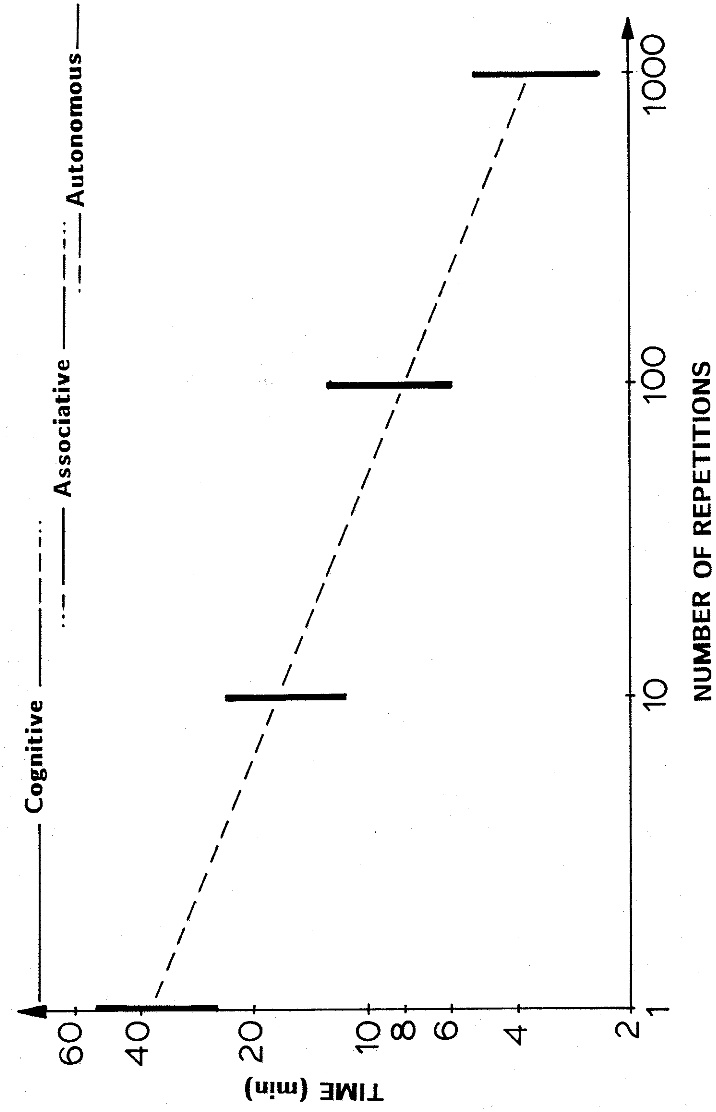

FIG. 2. Expertise and Repetitions

theless, the trend agrees well with data presented by Anderson (1985), who also showed a log-log relationship between time of execution and number of repetitions for quantitative tasks. Furthermore, when the individuals were asked how they performed the task, the different stages in the development of the skill became apparent (the horizontal bars in the figure).

In civil engineering, the number of repetitions of major design tasks is limited since many structures are one of a kind. How many dams has an "expert" dam designer actually designed? Or how many nuclear power plants has an "expert" constructor built? The answer in most cases is very few, and most likely the experiences took place in varying contexts, with an important time delay intervening in the feedback.

In addition, there are also biases in the processing of feedback that affect the consequent development of expertise. Hogarth (1980) lists the following: (1) Reliance on outcomes only (observed outcomes provide partial information). For example, the good performance of a selected foundation may lead to the unjustified confidence in one's own decision capacity, while other types of foundations may have behaved better and/or at lower cost; (2) misperceptions of chance fluctuations, i.e., a frequent event, not recently observed, seems to have greater chances of occurring; (3) success/failure attributions, i.e., the tendency to blame failures on chance and attribute successes to one's skills; (4) logical fallacies in recall, i.e., the tendency to feel confident in a "logical" reconstruction of an event (for example, confidence is gained when the few available clues are put together in analyzing a geotechnical failure, whether or not the real cause of the failure is known); and (5) hindsight bias, i.e., individuals show a lack of surprise after the occurrence of an event.

Besides the benefits of know-how, experts have other advantages over non-experts. They are less sensitive to the characteristics of the data (format, sequential order, amount, units, etc.). They also tend to minimize conservatism, and are more consistent in their decisions. Nevertheless, it is not uncommon to find instances where "naive individuals" provide better solutions than the experts do. Such occurrences can be explained by some of the decision-making characteristics discussed earlier: (1) Automatic expert decision making versus the awareness required by less experienced persons, which may improve their decisions; (2) the inertia effect; (3) the availability effect; and (4) biased processing of feedback.

Final Comments

This paper summarized the human biases and limitations that affect engineering decisions. The well-known examples that were cited clearly illustrate the importance of these factors, and they show that they are certainly a major cause for nonoptimal decisions and sometimes poor performance in civil engineering systems. Similarly, Faust (1984) studied biases and limitations in the context of scientific reasoning and concluded that cognitive restrictions are the greatest obstacle to the progress of science.

It would be appealing to organize these biases and limitations in a flow chart that individuals could use to avoid the resulting pitfalls. However, due to the complexity of human decisions, such a scheme does not appear feasible if it is to retain any sense of reality. Other alternatives have been suggested to reduce these human factors or their effects, including modification of regulation and legal systems, improving education (e.g. training with large number of cases to provide an immediate feedback), complementing man and machine, and replacing man. A trend seems to exist at the present to favor the latter approach. Meehl, for one, (1984) indicates that the history of the more developed sciences does not reflect "a positive 'building in' of the human element, or even 'correcting for' it, so much as a systematic 'elimination of' it at every stage where it tends appreciably to determine the protocol results."

Finally, it is relevant to recall Peck's observation (1981) following a study of dam failures: "Nine out of 10 recent failures of dams occurred not because of inadequacies in the state-of-the-art, but because of oversights that could and should have been avoided. . . . The necessary knowledge existed; it was not used." (See also Walker [1980] for similar observations.) In addition Peck pointed out:

1. Most causes are events that are unthought of.
2. Sophistication in the analysis cannot help.
3. The best engineering judgment is needed.
4. Problems are nonquantitative.
5. Solutions are nonnumerical.

Although one could object to some of these statements (for example, the effect of improved analytical and physical models), these observations indicate that engineering practice, and thus the performance of civil engineering systems, can be improved by providing decision makers with tools that systematically remind the engineer of all the facts to be considered, give easy access to state-of-the-art knowledge, stimulate the use of best judgment, and help make allowance for nonquantitative parameters. A number of Artificial Intelligence techniques, such as decision support systems, may play an important role in this regard.

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Restoring an Impaired Concrete Silo

By German Gurfinkel,[1] Fellow, ASCE

Abstract: A rectangular reinforced concrete grain silo, supported by mill building columns, was impaired by cracking and spalling, as well as major distortions in the walls. A close inspection revealed major exposure and corrosion of the reinforcing bars. Failure of the silo was possible under service conditions; repair was required. Placement of a conventional shotcrete concrete liner was considered but discarded because it required thick walls and double layers of reinforcement that made it heavy and costly. Instead, a welded steel liner made up of continuous horizontal frames, and a composite steel plate for walls, was used because of its light weight, less expensive construction, and smoothness of its walls. Design of the remedial steel liner is discussed at length; various details, such as connections at the corners to achieve continuity and attachments to the concrete silo walls, are given. This innovative solution is ideally suited for repair of silos that are subjected to combined axial tensions and bending moments.

Introduction

A reinforced concrete flour mill building was constructed in 1972 at the port of Point-à-Pitre, the capital of the island of Guadeloupe, in the West Indies. The structure included a set of silos (see Fig. 1) that was built integrally within the building and was supported by its columns. The silos were used to contain blended wheat and flour and were provided with multiple suspended hoppers. The capacity of the silos was rated at 396 tons.

Major distortions of the walls of silo No. 8 were discovered in early 1987. After emptying the silo, an inspection by plant personnel revealed concrete cracking and spalling, as well as major exposure and corrosion of the reinforcing bars. These observations were confirmed by the writer during an onsite inspection. Because failure of the silo was a distinct possibility, the owner was advised not to use the silo again until it was strengthened as required. The owner asked the writer to design the necessary strengthening that would restore the silo to service.

The conventional solution for strengthening impaired concrete silos consists of building a shotcrete concrete liner inside, using the existing walls for hanging the required reinforcement and for spraying the concrete pneumatically, at high velocity, against them. For a rectangular silo, however, calculations showed that a steel liner would be more economical, easier to fabricate and erect, and much lighter in weight. The lighter weight developed into an additional advantage that was greatly appreciated because the silos did not rest directly on an independent foundation but were supported instead by columns of the building. The actual steel liner was not only much lighter than the equivalent concrete liner, but it was even lighter than the amount of grain that it displaced; this resulted in a net reduction in total weight for the fully loaded silo.

The merits of a welded versus bolted connection system for the repair were

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