Professional Decisions: Responsibilities

David G. Elms
University of Canterbury, Christchurch, New Zealand

Colin. B. Brown
University of Washington, Seattle, U.S.A.
Oregon State University, Corvallis, U.S.A.

The responsibilities which civil engineers, and particularly the engineer of record, accept are considered. The interaction with other decision makers such as the owner, stakeholders, the law and contractors results in complexity that can be partially resolved by the introduction of protocols in the form of regulations and codes of practice. However, uncertainty always exists and can result in surprises that can produce both beneficial and bad results. The sections entitled the cast, protocols and reality, advocacy and surprise, and complexity cover these topics. The nature of responsibility is analysed. Professional engineers work within an increasingly complex environment and have a responsibility to acquire and use skills beyond those applicable to traditional technical issues.

Key Words: responsibility, systems, decisions, stakeholders, surprise, complexity, uncertainty.

1. Introduction.

Examples of decision-making are included in judicial verdicts, medical prescriptions and in military combat. It is a common characteristic of professional life. In a formal circumstance decisions are made deliberately in response to posed situations or to ongoing situations where they are immediate responses to ongoing circumstances. Of particular interest here are decisions made with respect to civil engineering work. For instance in structural engineering, decisions to be made include whether or not to build a bridge, the geometry and type of structure to be adopted, the technical design, the selection of contractor, construction activities, revisions, acceptance and operation. In each of these decision modes responsibility has to be accepted by various named individuals and organisations. Thus owners, stakeholders and public authorities are decision participants where the engineering views may be subsidiary to the main concerns, whereas the engineers and contractors have much more focused engineering worries.

Decisions punctuate the process leading from an initial idea to a finished and functioning artefact. The interlinked decisions occurring during the process provide a framework within which the various activities are carried out. Decision-making is central to planning, design and construction, and thus it is essential to the success of the project that decision-making is done well. This is not always the case. Almost all major structural failures can be shown to result ultimately from poor decisions. To be sure, major failures are few in number. However, poor decision-making also leads to less spectacular though costly inefficiencies. This paper is a contribution towards the making of better engineering decisions. In particular it focusses on that aspect of decision-making revolving around responsibility and responsibilities – the two are not the same, as will be explained below. Other aspects of engineering decisions are reviewed in two companion papers (Elms and Brown 2012; Brown and Elms 2012).

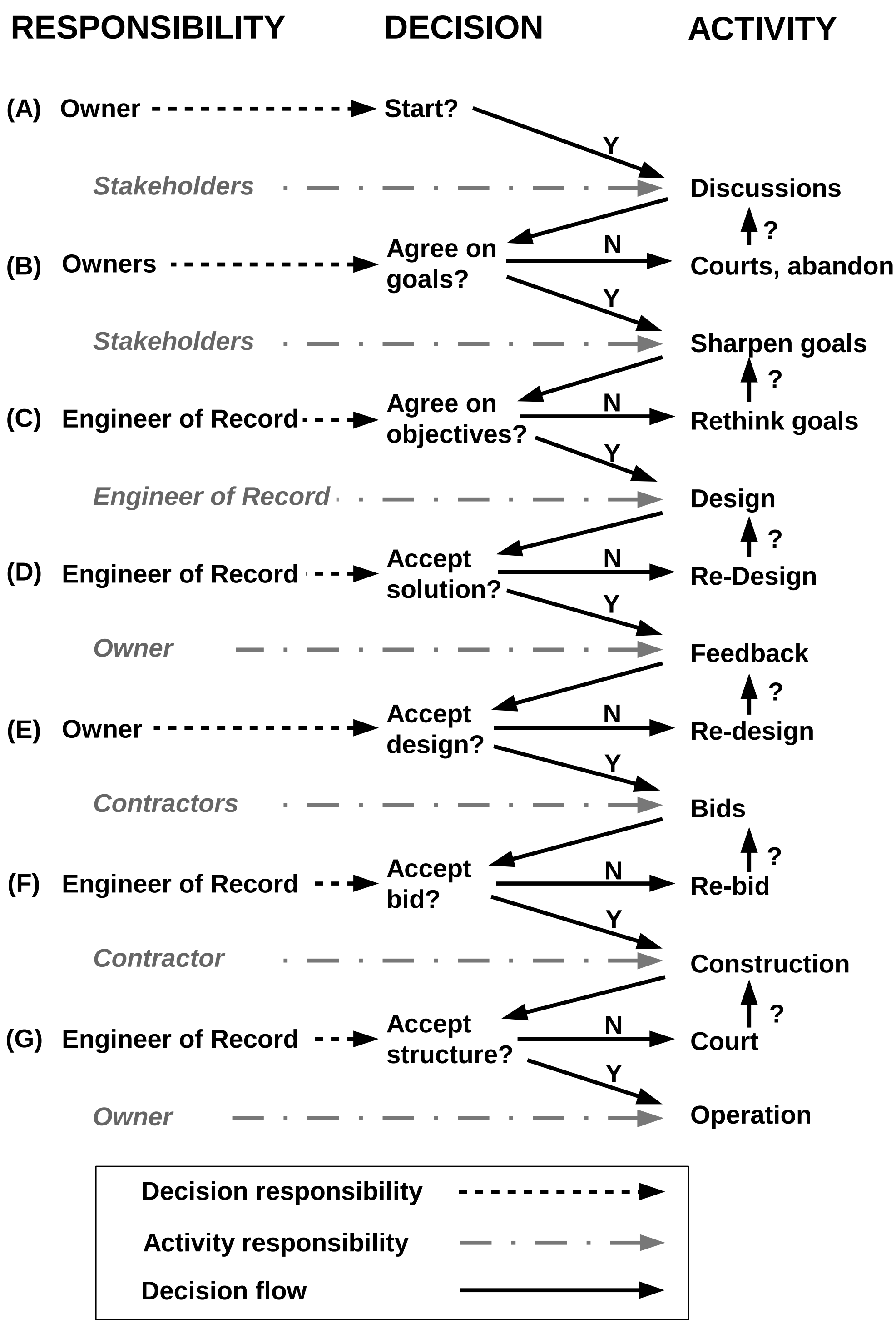

Fig. 1 Responsibilities and decisions

Fig. 1 shows a plausible, but not generic, example of a decision scheme applied to a civil engineering project. This scheme is intended to result in an operational facility. Responsible parties are shown on the left, with major decisions in the centre column and resulting actions on the right. The responsible parties or actors are of two sorts. Those designated (A) to (E) are the decision-makers and are shown connected to the decisions for which they are responsible. The decisions are either positive or negative (Y or N), and, in either case, result in activities. The second set of actors, shown in italics, are mainly advisory participants. They have input to and influence on the activities resulting from the decisions. These inputs can be opinions, as in the case of stakeholders and owner, professional knowledge provided by the engineer of record, and the actual construction by the contractor. By providing these inputs responsibilities are accepted. In some cases they will have primary responsibility for carrying out the actions. The arrows from Responsibility to Activity record this input. The responsible professional engineer, at least in an advisory capacity, will be evident at all stages in such a scheme. Many of these interactions will produce material needed to proceed with each decision. The civil engineer should anticipate being involved with the public, through the legal and political system, as well as the owner and stakeholders.

As well as determining the framework that meets the objectives, efforts must be made to identify hidden consequences that may affect the resilience and robustness of the project. Only by this critical approach can the objectives be attained. These objectives can be realized by various possible actions, which, in turn, produce new states with their associated consequences that can be characterized by the risks involved. Decisions provide answers to the questions posed by these procedures. They are choices amongst the possible actions that meet the objectives in a satisfactory or possibly optimal way, satisfy the constraints, and do not result in undesirable, unintended consequences.

The scheme in Fig. 1 indicates that the origin of the decision problems changes throughout the undertaking. Thus the establishment of goals (B) by the owners occurs in a different environment from the design by the engineer of record (D). Different decision makers are in place and the considerations provided by background activities have different emphases. However, there are varying forms of civil engineering input necessary at each level of decision-making. The professional input changes as the work progresses and the manner of decision-making may be dictated by calculations, experience, or at the other extreme, by an accepted protocol or code of practice.

Of particular concern is the successful involvement of the civil engineering professional as the process illustrated in Fig. 1 proceeds. The next section, **The Cast**, examines the various actors with whom the engineer of record may have to engage. A distinctive feature of civil engineering is that every facility, structure or scheme is considered to be unique and yet there are common standards that exist which are often legally binding. These standards are contained in codes of practice and other protocols. Although usually appropriate, these standards are often limited and have to be augmented and broadened by experience. The section **Protocols and Realities** provides a discussion of these matters. The input into this discussion will come from interested factions such as stakeholders and the owner, (B) and (D) in Fig. 1, as well as from the engineer of record, (C). The section **Advocacy and Surprise** considers these sources and the possible pertinence of the opinions. A main thrust of this work is to establish the realities of the environment within which civil engineers will make decisions. The section on **Complexity** explores this aspect of the making of decisions. In this way the background is established for considering the decision making and responsibilities of practicing engineers. Finally the section on **Responsibility** examines issues involved in being responsible, and having responsibilities.

The aim in this paper is to consider the place and nature of the responsibilities of professional civil engineers in a scheme such as proposed in Fig. 1. The emphasis is on the broader professional objective to change the existing world and not just to describe the work environment. The major conclusion is that the civil engineer requires a sensitivity and understanding of issues beyond those provided in the usual technical education if a responsible role in professional decision making is to occur.

2. The Cast

Figure 1 indicates the various interactions that may be necessary in a scheme for a facility that involves civil engineering. The main concern in this study is the part played by the *engineer of record*. This title identifies the responsible person with respect to the *owner*. The engineer of record acts for the owner with respect to engineering matters and, by signature, is responsible for these matters. If buildings are involved then the leading role will usually be played by the *architect*. The engineer of record, in common with other *professional engineers* such as those involved in environmental control and elevators, will be a creature of the architect. Inevitably the civil engineer of record will interact with these and with *lawyers* and *business managers* who represent the owner. The engineer of record will be aided by *assistant engineers* and by *specialists*, such as geotechnical engineers.

Stakeholders will certainly include government agencies. Much of the interaction will involve satisfying legal requirements and other obligations. These dealings with government bureaucracies are obligatory and a usual part of professional life of the engineer of record. Other stakeholders provide viewpoints that may be different to those of the owner. The interaction here is with citizen groups, other professional engineers, lawyers, business activists and individuals. The engineer of record has the responsibility of determining and explaining the civil engineering consequences of these often conflicting views to the owner.

The *contractor* is selected from competitors on the basis of cost or, in some professional and social environments, on the basis of special associations and competencies. When selected on the basis of the bid price the engineer of record has to maintain a continuing relationship, as the representative of the owner, until the acceptance of the completed facility. Inevitably changes from the bid design will be necessary and have to be agreed with the contractor. These are usually technical in nature and involve revealed differences as well as requested changes to account for the equipment and experience of the contractor.

3. Protocols and realities

Much that is completed in the activities associated with decisions (C), (D) and (E) in Fig. 1 invoke protocols such as codes of practice that establish necessary targets that must be attained if the finished facility is to be satisfactory. Protocol requirements are attained by the use of procedures, which are forms of models. They can be as simple as a checklist used by a technician to determine whether definite requirements have been completed, to as complicated as the complex and often difficult calculations needed to ascertain that technical code provisions have been satisfied. Confidence is placed in the protocols and procedures: they are intended to ensure that facilities perform according to the objectives and at safety levels that are professionally and socially acceptable. However, overconfidence has been known to lead to hubris (Sibly and Walker 1977) and an unprofessional attitude to responsibilities. The consequences can be calamitous.

The dire picture sketched is not the normal outcome in civil engineering work. The protocols are nearly always sufficient to ensure that the finished projects are successful, and the process can be termed satisfactory. It may not be the best of all possible solutions, but it will be a satisfactory one. Although it is claimed that each civil engineering project is unique, there are common features that ensure that the protocols and procedures continue to be successful. The common and continuing features include objectives, materials, geometries, environments and uses. Under these continuing circumstances there is a tendency to believe that the protocols and models replicate reality. However, it is when these features change that the protocols and procedures are most vulnerable. It is then that it is necessary to understand the real situation and perhaps develop more appropriate models (Elms and Brown 2011, 2012). Protocols provide constraints either explicitly as in the case of codes or implicitly in the manner of contemporary practice.

Many contemporary specifications for structural design employ the language of probability. The literature consistently cautions that these probabilities are nominal and therefore should not be confused with the actual chance of an event occurring. Indeed studies that attempt to determine the actual failure rate of structures show that these nominal probability values are two or three orders of magnitude smaller than the real occurrences. The difference occurs due to different underlying models; it is not entirely due to the unrealistic character of the nominal values (Melchers 2007, Brown et al. 2008) which may in fact be correct with respect to technical issues. However most failures are due to reasons that are beyond the usual domain of technical considerations. The model used in the preparation of specifications has a technical and narrower focus than that considered when all failure states are involved. Be that as it may, the failure rate of typical structures is socially acceptable and the protocol provided by specifications is appropriate. It has been argued (Nethercot 2008) that the complications in understanding required by specifications based on nominal probability considerations do not invite professional use and that non-reliability based protocols are more widely employed. As far as design outcomes are concerned it is not likely to matter in as much as the probability based codes (or protocols) were calibrated against the safety levels achieved by earlier deterministic ones. Thus there are available parallel design protocols that are applicable to an identifiable class of structure (precast~~,~~ reinforced concrete high rise construction in non-seismic locations for instance) with satisfactory results. Only when real evidence conflicts with this sense of optimism is the protocol and its underlying model re-examined. An example is the real evidence provided by the partial collapse of the 24 storey Ronan Point apartment block in London in 1968 (Griffiths et al 1968). The failure was initiated by a gas explosion in an eighteenth floor corner apartment that blew out an exterior load-bearing wall. The resulting collapse killed four and injured seventeen residents. The reality of professional interest was not the middle aged cake maker lighting her oven, but the level of internal pressure that can exist in residential construction and the progressive collapse that can be initiated in structures. The existing model was clearly inappropriate and as a result the attention of specification writers was directed to these matters. Contemporary codes address these additional features. There is a critical question for the engineer of record: how can unjustifiable confidence in accepted protocols be avoided?

Protocols are established to provide security to the designer and to ensure the integrity of that class of structure. The viewpoint is of examining the safety level (S) rather than failure (F) with the presumption that the normality axiom of probability theory, namely,

$$P(F) = 1 - P(S) \tag{1}$$

applies and that a safety level, S, ensures a failure rate of P(F). However, the underlying model does not match reality. These probabilities are nominal and the equivalence will not apply when the actual situation is outside the range of applicability of the protocol. This was recognized by Stephens (1998) when considering the inadvertent launch of nuclear tipped ballistic missiles. When the attention was exclusively on safety, as displayed in protocols, the failure rate, based on Equation. (1), was acceptably low. However a concentration on what could go wrong, as opposed to what had been provided to improve safety, produced an ominous picture. Essentially, concentrating on F and constructing realistic scenarios could, in this case, avoid the misuse of protocols. The engineer of record would have to think about the project in a different way from the designer and ask the question "What could happen?" as opposed to "Is the safety level that of the protocol?". On these technical matters the engineer of record has to view the project with different eyes from those of the project engineers. Protocols usually consider the safety of elements or substsems within a system and not the total system. The engineer of record has to adopt a wider model. As well as ensuring that both element and system safety exist, a holistic view of the project must be adopted.

In the cases cited the engineer of record acts in a narrow, professional capacity; the concerns are with technical topics and an interaction with a wider community is seldom required. When interactions occur with owners, stakeholders, advocates, lawyers and others the engineer of record has to have developed views that may be beyond the technical. The decisions in (A) and (B) in Fig. 1 depend on human, social, judicial and political views as well as physical reality. However, whatever their outcomes these external views can affect the effectiveness of protocols..

The public discourse concerning the consequences of any civil engineering project can lead to changes in the goals and objectives. The technical consequences of these changes have to be explained to others. This requires a communication model that shows sensitivity to others engaged in the discussion. However, victory in the technical sense may be elusive. Unambiguous decisions are available in legal verdicts (Heiberg 2007) Such cases are clear cut but more often adjustments have to be made to the objectives that affect civil engineering activities and decision-making. These adjustments may make the previously accepted design protocol inapplicable. It has been suggested (Brown 1960) that by changing specifications to be less safe more structures could be built for the same money. This simplistic view has been studied (Sanchez-Silva and Rosowsky 2008) with respect to prescribed safety levels in developing countries~~,~~. In addition to technical matters, economic and cultural issues of a local nature were introduced into the scheme. This informed discussion places the subsequent structural design into a different context from that in the developed world. One word that appears frequently in these broader discussions is “sustainability”. This is a reminder of the changing objectives in public works projects. The saving of lives was central to coastal protection schemes and to designing for seismic safety. At one time the deaths caused by North Sea flooding and in earthquakes numbered into the hundreds and thousands. Now the fatalities can be orders of magnitude smaller and the objective in design has moved away from personal safety to maintaining economic viability. The inclusion of sustainability into the goals and objectives of a project introduces a possible conflict if the Brundtland Commission definition of sustainability, namely, “Meeting the needs of the present without compromising the ability of future generations to meet their needs” is accepted (World Commission on Environment and Development 1987). One view of civil engineering work, especially of public works, is that the project changes the world for the better. Such changes have long term effects that will impact future generations in often unpredictable ways. There is no doubt that the civil engineer must obtain an understanding of the application of the Brundtland Commission definition to the project. The definition as a statement of general purpose is a splendid goal, but in order to proceed to professional decision-making, specific objectives, usually expressed as quantitative attainment measures, have to be stated. The civil engineer has to be fully involved in the discussions that lead to these measures and consequently has to be widely informed on topics beyond the technical.~~.~~

There seems to have been a concentration of effort in the twentieth century to make professional protocols more and more applicable. They have become more complete, detailed, and apparently more rational. Specifications have lengthened to include additional safety measures and there appears to have been an attempt to make the protocols cover all eventualities. Towards the end of the century the difficulty of satisfying this latter intention became apparent. More recently, the relationship of the protocols to the realities they purport to represent began to be discussed. Common measures, real information and data have begun to intrude into the professional decision-making. Immediately difficulties arise involving the marriage of real and nominal information as well as some of the assumptions underlying the models used: for example, the choice of discounting factor if life-cycle analysis is attempted. It is possible that the situation is approaching that in other branches of engineering where the owner establishes a requirement specification for a product that includes legal and social restrictions, and seeks bids for the supply. This approach invites a design-build arrangement that may not be popular in some communities. Irrespective of the extent that the profession moves towards this arrangement, there is a necessity to predict future performance and thus make firm statements about the safety, economics, sustainability and behavior of a project. Such a move towards realism is incorporated in contemporary performance design, but the extent to which better results are achieved is not always clear.

4. Advocacy and surprise

Before decisions can be made by the engineer of record an unambiguous understanding of the objectives must be constructed. The owner is an enthusiast for the initial goals of the scheme but these can be varied and added to by the input of stakeholders. These participants have advocacy stances that can influence a decision scheme that seeks a solution satisfying the objectives and constraints. However, other concerns may exist which have to be identified by the engineer. Inasmuch as these concerns had not become apparent in the initial engagement with the owner, the inputs of the stakeholders can be considered surprising by the engineer. A common model for these situations is required which may appear as a constraint on the solutions that satisfy the objectives.

A responsibility of the engineer of record is to identify without ambiguity the objectives of the project and potential unexpected and surprising outcomes. Such identification is evident in (C) in Fig.1. The owners and stakeholders are likely to provide much of the evidence for these objectives, constraints and outcomes. These participants are often advocates for particular, and often conflicting, outcomes and actions. Occasionally the disputes are settled sharply in favor of one side. A case in point was the two barriers proposed by the Corps of Engineers between the east end of Lake Pontchartrain and the Mississippi (Heiberg 2007). These barriers would have closed when a flood surge threatened New Orleans and environs. This was an advocacy stance by the Corps. A contrary stance was taken by Save Our Wetlands, Inc. in the role of protecting environmental features that would have been threatened by the use of the barriers. The matter was decided in the courts and the barriers were not built. This type of clear cut resolution is unusual and compromise between the goals of the owner and the views of the stakeholders has to be made. The engineer of record must ensure that the terms of the compromise are clear, and, if possible, expressed in a quantitative manner.

The intrusion of advocates into the pre-design discussions may thus be regarded as a blessing to the engineer of record. In this way issues aired and underlying assumptions questioned are usually dealt with. Essentially the engineer is provided with the concerns of relevant stakeholders without having to seek them and hence avoid subsequent surprises. This participation of the broader community as represented by stakeholders and their advocacy is a creature of the last sixty years. Prior to then the owners established their goals by authoritative command and took little account of other interests. This certainly made it easier for the engineers of record of that time inasmuch as they were in no doubt about the source and instructions of their brief. As an example, the location of transportation routes, once decided, was enforced by laws such as eminent domain. Therefore, the engineer of record on a critical bridge had a purely technical view of the work. Today a decision about a major crossing of the Columbia River on Interstate 5 between Oregon and Washington states has been mulled over for twenty years whilst the views of stakeholders on bicycle lanes, pedestrian access, bus routes, mass transit commitments, access to adjacent communities and the visual appearance have been considered. Even with the access of contemporary stakeholders to the market place of ideas, a serious problem occurs when concerns are not evident before final objectives are established. In every completed project there are outcomes which were not anticipated in the design. In most cases they are not serious, but, in others, changes in operations have to be made to accommodate these concerns. A case in point exists in changes in operation of hydro-electric schemes to provide for the enhanced passage of fish. These requirements were not considered in the design stage and only became evident in early operations. Stage (C) of Fig. 1 would be a critical phase for a search for surprising potential situations. This is where the engineer is urged to “think outside the box”. It is suggested here that the engineer should normally proceed in a manner which ensures that potential surprises are identified and decisions made about their inclusion in the final decision-making. Such examination would happen whilst steps (C) and (D) are considered.

There will always be a small chance of any surprising situation occurring but not every unlikely situation is surprising. A usual statistical example is of a toss of a coin where the coin finishes on its edge. This is contrasted with being dealt a hand of cards. The coin can be made to such a thickness that the probability of landing on the edge is the same as receiving any hand of cards. However any random hand of cards is without surprise, whereas the coin landing on its edge is indeed surprising. The difference is associated with the probabilities of the alternatives and the extent to which a particular outcome is interesting to us. In the case of the cards the alternatives are the same as the hand dealt, but in the case of the coin they are each near 0.5 and very different to the chances of the coin landing on edge. Weaver (1948) developed a measure of surprise, A(X), at the occurrence of outcome X that accounts for these differences, namely,

$$A(X) = \frac{E(P)}{P(X)} \qquad (2)$$

where E(P) is the expected value of the probabilities of all outcomes and P(X) the probability of the outcome of interest, X. When the hand of cards is considered the numerator and denominator are equal and the measure of surprise is one. When the coin toss is considered there are three outcomes and therefore E(P) is approximately one-half and the probability of the coin landing on edge is 10^{-n} where n>>1. Then the measure of surprise is of order 10^{n}. Thus a small value of A(X) denotes small surprise compared to a high value. Note that any degree of severity of the consequence of an outcome is not considered in the definition of Eq. (2).

In considering the level of surprise associated with failure use is made of Equation (1) where P(F) is the actual probability of failure and not the nominal value. Two outcomes are possible and therefore the numerator is approximately unity if P(F) is small and the denominator is $P(F) = 10^{-n}$, with n>0. The measure of surprise is then approximately 10^{n}.. The engineer can construct a personal surprise scale based on professional experience. For instance in considering truss bridges of the type that failed on Interstate 35 in Minneapolis values of n between 3 and 4 may be appropriate, and in the case of long floating concrete pontoon bridges that exist in Washington State a figure slightly larger than one could be used in the light of the failure of two of the six bridges built there.. In this way an engineer can construct a personal scale of surprise such as shown in Table 1.

n	Linguistic Surprise
0	No surprise
1	Not surprising
3	Mildly surprising
5	Definite surprising
7	A miracle

Table 1. Relationship between failure and surprise

It is unlikely that the surprise level can be computed with useful accuracy, but it is possible to consider the order of the surprise by comparing the chances of an identifiable event with those revealed by advocacy groups or by conventional models. A situation that has a low surprise level invites inclusion into the decision scheme. High levels of surprise call for professional judgment. The engineer of record may have to deal with hypothetical events raised by advocacy positions or by normal professional concerns. For instance, the 2011 Christchurch earthquake of Feb. 22 resulted in very high local vertical accelerations (up to 2.2 g). Such high values had seldom been experienced elsewhere and certainly not in New Zealand. Although code writers had considered including high vertical accelerations, there was little evidence to suggest that they would occur. The occurrence was indeed a great surprise. Now the codes will be rewritten and the question of their inclusion will be faced with available local evidence but still with the knowledge of the global rarity. The likelihood of the accelerations will be less surprising, but still surprising. The same worries occur in the Pacific Northwest where the Cascadia subduction zone runs just offshore from Washington and Oregon. The evidence concerning the last massive earthquake there is largely derived from the Japanese tsunami literature. The earthquake was at about magnitude 9 and occurred in the year 1700. The question now arises about the extent that a future, similar event should be catered for in codes. All experts agree that the event will occur but the spread of recurrence dates makes for a very uncertain environment for the engineers to make important and potentially costly decisions. One approach is to identify the danger and attempt to introduce resilience into the design scheme with the intention of preserving both lives and fortunes.

Surprise is neither place nor time invariant. In spite of the fact that an aircraft had struck the Empire State Building, it would have been reasonable for the engineer of record for the World Trade Center to consider that probability to be unlikely and surprising. Placed in the same situation today the surprise level would have dropped and the event would be considered as more likely. Thus surprise changes with experience, an issue which is relevant to an engineer's use of models. Also, the same scenario in different locations can excite different levels of surprise. Ice hanging over the entrance to a tunnel often can exist in the cold mountains at 5,000 ft. elevation. This is not a surprising event. The same condition at sea level in a damp, but occasionally cold, climate would be surprising. In both cases freeing of the ice and crushing of a vehicle could occur. However, the attitude of the responsible engineers addressing the same problem, but located 100 miles apart, could be different.

The engineer interacts with the contractor in stages (F) and (G) in Fig. 1.As construction proceeds surprises occur. These are particularly evident at the foundation stage and call for decisions by the engineer of record that respect the contract documents and the opinions of the contractor. Some surprises call for significant changes. For instance, confidence existed in prior geotechnical studies that showed that solid rock existed at the proposed foundation of a two-pin arch bridge. Excavations revealed that every borehole had struck a sizeable rock and that a viable foundation did not exist. In the light of this the bridge was changed to a three-pin arch. The level of high surprise provided by this situation is unusual but changing construction requires continuing alertness by the engineer of record to a possible need to change the model being used. Decision (G) in Fig. 1 dates the completion of the constructed project and determines whether any penalties for late completion or rewards for early finishing are exercised. These are not occasions for surprising any of the concerned parties.

Surprising events may be trivial in consequences, and if not so may be beneficial or adverse. The actual foundation weakness of the arch bridge previously discussed could have as easily been reversed. More satisfactory foundation material could have been found. Just because an event is surprising there is no necessity that it be serious, beneficial or important. The engineer of record will pay attention to surprising events that have important consequences. This suggests that a combination of consequences and the measure of surprise in Equation (2) be constructed and termed "shock".

5. Complexity

Complexities will be generated by the model used by the engineer as a representation of reality. The model will be constructed to attain an objective. For instance, if interest is in motion of heavenly bodies then two obvious models exist. The Ptolemy model of wheels and gears is geometrically complex but intellectually simple; the Newtonian one of gravity is geometrically simple but intellectually challenging. Both will meet the objective but the talents required of the modeler will be very different. The selection of the model is critical. The engineer can build an analytic theoretical model that represents the features that will be encountered and yet that model may be of little value. It may be difficult to solve and contain uncertainties in the constituencies and connections. It can be described as too complex. A definition of the adjective “complex” in the Shorter Oxford English Dictionary (2002) is “Intricate, not easily analysed or disentangled, complicated”. It is perhaps unfortunate that the dictionary associates intricacy with complexity. If “intricate” is taken to mean that something consists of many parts, it may or may not be difficult to disentangle. From an engineering view the idea of entanglement means that as the complexity of a model increases, the more difficult it will be to obtain useful information for decision-making, A contributing factor is that the limits of human understanding reduces as the number of constituents in a complex model increases. Miller (1956) has suggested a number of seven and this could well become a limit for the decision maker. From a practical viewpoint the engineer is required to establish a mental model or construct in which the system is limited in the number of constituents. Even with this limitation the problem may still be complex. However, a systematic reduction of the problem into subsets or subsystems, where this is possible, can make both understanding and solution easier. This is the reason why the concept of responsibility discussed below has been split into several categories.

Rational deliberation in decision making appears to produce the most satisfactory choices when the number of constituents is three or less, unconscious thought or intuition, where there is an absence of rational deliberation, may be preferable in decision-making when more constituents exist (Dijksterhuis, et al. 2006; Gigerenzer 2007). Information entropy levels will tend to increase as the number of constituents increases. Low entropy is an indicator that the few constituencies and connections are amenable to careful analysis from which useful outcomes can be expected. Precision becomes elusive and dependence on experience, memory and intuition becomes valid when more constituents, higher entropy and uncertainty exist, Zadeh (1973) captured this separation in the following manner:

> Essentially, our contention is that the conventional quantitative techniques of system analysis are intrinsically unsuited for dealing with humanistic systems or, for that matter, any system whose complexity is comparable to that of humanistic systems. The basis for this contention rests on what may be called the *principle of incompatibility*. Stated informally, the essence of the principle is that as the complexity of a system increases, the ability to make precise and yet significant statements about the behavior diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics.

However, it is not only a matter of the degree of sparseness of the components of a system. Different network architectures reveal surprisingly different properties (Barabasi 2002; Watts 2003).

An examination of Fig. 1 reveals that the civil engineer will have to deal with humanistic as well as technical complexity. The approach where many constituents and connections exist and where analysis may be of small significance seems to be at odds with the extensive literature on optimization in decision making. Such analysis would only seem to be fruitful when few constituents are involved. However, it is possible that these analyses may be valuable as confirmatory evidence and as an examination for omissions, even when the decision is made intuitively (Gigerenzer 2007).

The vagueness inherent in complex and humanistic matters is often alleviated by the establishment of protocols. For instance the managerial complexity of discretionary railroad gauges in the 19th century was clarified by national laws that established standard gauges, Much of civil engineering is constrained by such protocols and professional engineers have to not only accept them, but also have the responsibility to make sure that the other participants in Fig. 1 are aware of the limitations and constraints that they place on objectives, and hence decisions. These protocols come in the form of laws, codes and regulations, and it is difficult to imagine the complexities that would exist without them. The extension of codes of practice in the last century can be partially attributed to an effort to standardize practice and with the resulting uniformity, reduce complexity in design and construction. The movement towards performance based design may be a step to reduce the uniformity induced by obligatory codes.

6. The nature of responsibility

Any decision has associated responsibilities. The concept of responsibility has several different though related meanings. Klein (1995) suggests four: causal responsibility, legal responsibility, moral responsibility and role responsibility. "To be causally responsible for a state of affairs is to bring it about either directly or indirectly. … To be legally responsible is to fulfil the requirements for accountability under the law. .. The term 'moral responsibility' covers (i) the having of a moral obligation and (ii) the fulfilment of the criteria for deserving blame or praise." Finally, role responsibility refers to "the duties … which are attached to particular professional or societal roles." (Klein 1995). All four concepts apply to the professional involvement of engineers in decision-making. Broadly they can be summarised as responsibility *for* doing something, responsibility *to* someone or some body, and the moral *state* of being responsible. The decision-maker has both responsibilities and also an obligation to behave responsibly. Klein's categorisation can be expanded as follows:

Causal responsibility is the responsibility for doing something. Often, many people are involved in a decision, but ultimately there is only one owner responsible for that decision. The owner might be an individual such as the engineer of record, or a defined group of people such as a committee. This is the unit responsible for making the decision. Accordingly, this is also the unit accountable or liable if the decision was poorly made.

Someone has to be responsible for carrying out whatever actions have been decided on. Very often it will be the decision-maker, perhaps the engineer of record. In other circumstances the decision-maker will be acting within a framework which gives authority to the decision-maker and also takes responsibility for subsequent actions. A judge, for instance, might sentence a person to imprisonment, but the legislative and administrative framework within which the judge is operating will take responsibility for subsequent actions. Therefore, there are two distinct responsibilities involved: responsibility for making the decision, whose results must be given to the body authorising the decision-maker, and responsibility for taking the results of the decision forward to achieve some action. Both are important. One cannot exist without the other for a proper decision-making framework. The important thing is not to confuse responsibility for decision with responsibility for action.

There is also a causal responsibility for providing appropriate information and advice. This relates closely to role responsibility, discussed below. The role of the engineer is not always that of the decision-maker.

Legal responsibility. "Legal" is used here in a broad sense of accountability. A decision-maker is authorised to make the decision by an authority, who again might be either an individual or a group. The decision-maker is responsible to someone. Here again the need arises for a defined framework within which the decision must sit – "framework" is used here to mean an administrative entity having responsibility, authority and ownership. The decision-maker is responsible to the framework that provides the mandate for making the decision. Thus, in authorising the decision-maker, the framework also takes on responsibility for the decision. In turn, the framework is responsible to a wider framework, such as finance providers or society. Causal and legal responsibility can be thought of as two related ideas: responsibility upwards, and authorisation downwards in a hierarchy.

The decision-maker can be an agent of the authorising framework for that decision. The authorising framework may itself be an agent for some higher framework such as a board of directors. An agent will normally have a limited range of autonomy – a limited mandate for action. Any decision-making must be within this authorised range, within which the decision-maker has authorisation to decide or act.

Moral responsibility and role responsibility. In the context of professional decision-making, moral and role responsibilities are not readily separated. Both relate to the way one acts, or should act. They can be thought of as personal and professional obligations respectively. Thus "moral" is used broadly. It can be seen as an ethical issue, as an imperative for a professional engineer to behave ethically in what is done, but beyond traditional ethics there is also an imperative for an engineer to do a job as well as possible within the constraints surrounding it, such as time or funding. In this case, the requirement is to make as good a decision as possible, where the word "good" is related to a moral imperative. Here there is a need for the engineer to be as good at the job as possible. This means attention to the real needs of the problem, and also to the need for the engineer to be competent and informed. Beyond the way in which a good result is helped by the attributes of the engineer, there is the further issue of what might be meant by a good result – a high-quality design or completed artefact, for instance. The word "quality" is a useful alternative to "good" in an engineering context. Be that as it may, there is a need to consider the skills required of an engineer in order to make a good decision.

There is also an obligation for the professional to understand and abide by the requirements of accountability referred to above, and also to be clear about the objective of any decision. In this respect there are two modes of proceeding which could be called the rational and the humanist. The first is objective. Besides being clear as to the aim of the decision and its surrounding constraints, the engineer needs to have all the necessary information to hand, which may require prior analysis of basic data, and an understanding of the uncertainties contained in the information. A common measure is necessary for comparing alternatives.

In parallel with this, a humanist approach is necessary. This is holistic and largely unconscious information processing, "feeling" what a result should be subjectively rather than objectively processing the information to hand.. Jung contrasted thinking and feeling as two different and complementary means of dealing with information (Jung 1964). It has been shown that for decisions involving simple choice, a rational method of proceeding produces better results than a humanist, but where the nature of the choice is complex, the reverse is true (Dijksterhuis et al 2006; Gigerenzer 2007). It has been shown that people with brain damage such that they cannot empathise and their emotional reactions are damaged in some way, cannot make any decisions even though they might in other way, such as analytical skills, be intelligent and capable. The implication of this is that emotions are involved in decision-making (Damasio 2003).

It is normally the case that engineering education deals carefully with rational approaches, but not at all to the same extent with the humanist. This might lead to the unhelpful situation of an engineer actively seeking to suppress intuitive leadings with the thought that somehow they are not "proper". One can learn intuitive approaches, of course. They can be picked up by experience, but there is a danger here that unguided (or unthinking) experience can also narrow the bounds of what is seen as normal professional activity. Research shows that intuitive approaches can be learnt (Goleman 1996), but they need both practice and a will to apply them.

One disadvantage of any use of intuition in decision-making is that the results are a personal thing, and it is difficult to form a defensible audit trail, which would often be required in a potentially litigious situation. But we are not arguing for the sole use of intuitive decision-making. Rather, we see the rational and humanist approaches as complementing each other in an environment of mutual support. This position could also be stated the other way around: neither the rational nor the humanist approach to decision-making would be adequate alone where a complex decision has to be made.

7. Discussion

The discussion of responsibilities revolves around labels, titles and actions. These are associated with individuals, organizations and the interactions between them. Essentially this reflects the modeling that has been accepted. The involved cast has been identified in a reductionist manner and the associated models are constructed on that basis. In this way the description of the entities and connections is established. This non-causative state is like a study of kinematics; it tells you locations and motions without providing any sense of causes for getting there or for going elsewhere. These next steps are within the province of dynamics. Fig. 1 is the demonstrative model used here and shows the cast as entities and the connections that are presumed to exist as lines. The causative part is indicated vectorally by arrows and various actions. This is the chosen representation of a holistic reality, namely the establishment of a functioning facility. The responsibilities are assigned to the actors but there are other entities, like the law, which, as illustrated by the Lake Pontachartrain barrier example, can stop the intended activity. A question in modeling is how far to go in establishing entities and connections. Rodriguez-Nikl and Brown (2011) have provided a scheme that depends on decision invariance and accounts for the limited number ideas that can be accepted in thinking and rational decision-making. This can help to establish the model boundaries. However, the success of this procedure depends on the inclusion of all critical entities and their connections. Any omission invites surprises. A search for omissions suggests the necessity of a holistic overview of the reductionist model. This is the “big picture” action which has so many advocates A claim here is that both the reductionist and holistic views are necessary in any successful decision scheme. The reductionist view identifies obvious responsible parties and their connections, the holistic one provides insight into what might have been missed.

The choice of model can provide complexity to the scheme. This model driven complexity is a creature of human actions and can be similarly reduced. An example provided here is the introduction of protocols. There is a chance of surprise if the efforts at simplicity omit critical entities. Again it may be necessary to impose a holistic overview to detect these omissions. The actor with a mandate to carry out these holistic over-views is the engineer of record for whom it is an understood responsibility.

Uncertainty haunts all stages of decision-making. The goals of the owner have to be translated into definite objectives and there will be doubts in the mind of the engineer of record about the completeness of this operation. The various concerns of stakeholders are often difficult to convert into sharp resolution. Again it will not always be clear that the engineer has caught the full intentions of these advocates. Protocols are intended to resolve many ambiguities but it is understood that codes and regulations can be variously interpreted and are therefore subject to tests in the actual use of a facility or by court action. The model chosen to represent the critical aspects of reality has uncertainties associated with the entities and connections selected, their properties and processes, and incomplete information on loads, materials, geometries and other conditions. The use of computer methods can provide some control in these matters but there is always a possible conflict between precision and accuracy. Usually precision is of little interest to the civil engineer. Although the moments, shears and hence stresses in a continuous bridge beam can be predicted with precision for prescribed code loads, prescribed material properties, and stated geometries and support conditions, the engineer knows that these are but models of real conditions. The resulting answers are useful guides but no significant decision will be made that depends on purportedly precise results. In all these concerns about uncertainty the civil engineer has to keep an open mind about the various ingredients of the decision mix. A balanced approach is required in which all aspects are given consideration. Elms (1985, 1992) has treated this required balance under the title of a *principle of consistent crudeness*. The intention is to attain a state whereby all significant issues receive appropriate attention.

Within the decision making framework from inception to completion of a project such as shown in Fig. 1, the engineer moves between different roles and responsibilities. These apply to both making engineering decisions and contributing to decisions made by others. Good work and consistency are required in the whole project. The different roles and contexts demand versatility and, insofar as the problems are complex and demand working and communicating with others who have very different backgrounds and objectives, they require wide ranging skills beyond the technical competence previously believed to be sufficient for successful engineering practice. It is therefore a responsibility of professional engineers to understand the need for such skills and to acquire and maintain them, as well as to understand the complexity of the environment within which they work.

8. Conclusion

The concern of this paper is with the responsibilities of civil engineers, and particularly the engineer of record, in making professional decisions. These responsibilities include the interactions with owners, stakeholders, political and legal operations, contractors and protocols as especially expressed in codes of practice. There will be complexity and uncertainty in such decision procedures and chances of surprises, whether beneficial or harmful, will exist. These matters have to be included in any professional decision making procedure.

This paper has demonstrated the need to bring subjective skills into decision making, as well as a need to understand complexity and how it can be handled. The necessity of understanding clearly the problem to be addressed, often in unfamiliar and difficult contexts, has been demonstrated. Often these problems are not susceptible to conventional approaches and nowadays the competent civil engineer has responsibility to be skillful in meeting these broader needs. Clearly these matters have implications for engineering education. This paper does not attempt to provide definitive answers. However, four general requirements are suggested, namely,

to understand the framework of models within which the engineer thinks and operates

to acquire broad systems skills where the holistic thinking complements the linear causal threads of traditional rational approaches

to develop skills in subjective thinking as an essential part of decision making in complex environments to have good communication skills not only with other engineers but with the broader, involved communities.

These requirements can be thought of as defining the nature of the professionally responsible contemporary engineer.

References

Barabasi, A-L., 2002. *Linked: The New Science of Networks*. Cambridge MA: Perseus Publishing.

Brown, C.B., 1960. Concepts of structural safety. *ASCE, Journal of the Structural Division*. 86, ST12, 39-57.

Brown, C.B, Elms, D.G. and Melchers, R.E., 2008. Assessing and achieving structural safety. *Proceedings of the Institution of Civil Engineers, Structures and Buildings,* 161, SB4, 219-230.

Brown, C.B. and Elms, D.G., 2012. Engineering decisions: framework, process and concerns**.** MS submitted to *Civil Engineering and Environmental Systems*, under review.

Damasio, Antonio, 2003. *Looking for Spinoza*. London: William Heinemann.

Dijksterhuis, A., Bos, M.W., Nordgren, I.F. and Baaren, R.B. van, 2006. On making the right choice: the deliberation-without-attention effect. *Science,* 311, 1005-7.

Elms, D.G., 1985. The principle of consistent crudeness. *Proc. Workshop on Civil Engineering Applications of Fuzzy Sets,* Purdue University, Indiana, 35-44.

Elms, D.G., 1992. Consistent crudeness in system construction. In B.H.V.Topping (Ed.), *Optimisation and Artificial Intelligence in Civil Engineering,* Kluwer Academic Publishers, 71-85.

Elms, D.G. and Brown, C.B., 2011A. Tales of the unexpected. *Int. J. Risk Assessment and Management*, 15 (5/6), 387-399.

Elms, D.G. and Brown, C.B., 2012. Professional decisions: the central role of models. *Civil Engineering and Environmental Systems*. 29 (3), 165-175.

Franssen, M., 2005. Arrow's theorem, multi-criteria decision problems and multi-attribute preferences in engineering design. *Research in Engineering Design*. v16: p42–56.

Gigerenzer, G., 2007. *Gut Feelings. Short Cut to Decision Making*, Penguin Books.

Goleman, Daniel, (1996), *Emotional Intelligence: why it can matter more than IQ.* London: Bloomsbury.

Griffiths, H., Pugsley, A. and Saunders, O.A., 1968. *Report of the inquiry into the collapse of flats at Ronan Point, Canning Town: presented to the Minister of Housing and Local Government*. London: HMSO.

Jung, C.G., 1964. *Man and his Symbols.* New York: Doubleday.

Heiberg 111,E.R., 2007. Katrina provokes regret. *Civil Engineering*, ASCE., 77(8), 8.

Klein, M., 1995. Responsibility. In T. Honderich (ed): *The Oxford Companion to Philosophy*. Oxford: The Oxford University Press, p771-2.

Melchers,R.E., 2007. Structural reliability theory in the context of structural safety, *Civil Engineering and Environmental Systems*. 24(1), 55-69.

Miller,G.A., 1956. The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review*. 101(2), 343-352.

Nethercot, D.A., 2008. Reliability, responsibility and safety in structural engineering. *Proceedings of the Institution of Civil Engineers, Structures and Buildings*, 161, SB 4, 215- 218.

Rodriguez-Nikl, T, and Brown, C.B., 2011. A systems approach to civil engineering decision making, submitted to *The American Society of Civil Engineers.*

Sanchez-Silva, M. and Rosowsky, D.V., 2008. Risk, reliability and sustainability in the developing world, *Proceedings of the Institution of Civil Engineers, Structures and Buildings,* 161,SB 4,189-197.

Shorter Oxford English Dictionary 2002,

Sibly, P.G. and Walker, A.C., 1977. Structural accidents and their causes, *Proc,.Institution of Civil Engineers,* 62, Pt.1. 191-208.

Stephens, K., 1998. Using risk methodology to avoid failure, in D.G.Elms (Ed.),. *Owning the Future: Integrated Risk Management Principles and Practice*. Centre for Advanced Engineering, New Zealand. 303-308.

Watts, Duncan J., 2003. *Six degrees: the science of a connected age.* New York: Norton.

Weaver, W., 1963. *Lady Luck. The Theory of Probability*, Anchor Books, Doubleday & Co, Garden City, New York.

World Commission on Environment and Development, 1987. *Our Common Future*, Oxford University Press.

Zadeh, L.A., 1973. Outline of a new approach to the analysis of complex systems and decision processes, *IEEE Trans., Systems, Man and Cybernetics*.SMC-3(1), 28-44.