SEISMIC SAFETY ASSESSMENT OF DAMS AND APPURTENANT WORKS FOR AREAS OF LOW TO MODERATE SEISMICITY

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SUMMARY

The seismic safety assessment of dams and appurtenant works in areas of low to moderate seismicity presents some significantly different philosophical and technical issues to those encountered in assessments in areas of stronger seismicity. For example, in the UK, which can be described as a region of low seismicity, some engineers question the need for any seismic assessment. However, the public perception of the hazards posed by dams to the community is becoming more acute, due to the efforts of interested pressure groups. As a result, it is difficult to justify that seismic safety assessment is unnecessary. On the other hand, the costs of performing a detailed seismic assessment as would be done in regions of high seismicity are also difficult to justify, and meet understandable resistance from dam owners.

This paper outlines a systems framework that enables these issues to be identified and addressed in an incremental fashion, using both traditional and new techniques, so that the assessment process is focused on the key issues, uncertainty is managed, and resources are applied to best effect. A major benefit of this approach is the establishment of a logical hierarchy of performance objectives for the dam system. At the top of the hierarchy is a broad statement defining the performance objectives of the overall system. Lower levels of the hierarchy identify the assessment processes of the key components of the dam system and their associated performance objectives. The latter derive from those of related components above them in the hierarchy. The performance objectives may be stated generally, or in terms of codified rules. The components may include human related issues as well as technical engineering issues. The systems framework is explained using an idealised example intake tower for a hydroelectric power plant.

INTRODUCTION

Assessment of the likely seismic performance of dams and their appurtenant works is a problem faced by dam owners throughout the world. It forms one aspect of the overall asset management process. In general terms, dam asset management can be considered to be concerned with promoting and protecting the dam owner's enterprise, while at the same time protecting human life. The seismic issue is one of many that affect enterprise and life safety, and must be balanced against the other safety issues, which place similar demands on the available resources. Successful asset management recognises the often complex and conflicting interactions between safety issues, and seeks ways of modelling these interactions in order to support effective decision making.

Somewhat paradoxically, seismic issues are particularly problematic in areas of low to moderate seismicity, such as the UK and northern Europe. Here the seismic regime is such that damaging earthquakes are very rare (in the UK the 1 in 10,000 year event is about magnitude 6.0). As a consequence, the public perception, and until relatively recently that of many dam engineers, has been that seismic effects can be ignored. Indeed, many dams constructed in such regions prior to the 1980's were at best designed to the most rudimentary seismic requirements. However, more thorough research into the seismic hazard, coupled with the growing realisation of

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the serious impact of even moderate earthquakes on unprepared enterprises, and the continuing desire to protect life, are changing perceptions. Dam owners in areas of low to moderate seismicity are now considering seismic risks in their asset management, but most seismic assessment techniques that are currently available to them were developed for new build in strongly seismic regions rather than for assessing existing structures. The dam owners need tools to help guide and justify expenditure on the seismic assessment process.

The processes of design of new structures and the assessment of existing ones differ in many respects. In the former, the engineer has control over all aspects of the performance of the structure, and can ensure that suitable safety margins are included. In the latter, the assessment generally starts from the standpoint of maximising the available performance of the existing structure such that any remedial measures can be minimised. This often involves problem specific risk assessments, which may also seek to establish acceptable performance requirements that differ from those adopted for new build. Furthermore, the technical understanding of the seismic behaviour of non-seismically designed dam and appurtenant structures is still relatively immature. Assumptions and techniques adopted for new build might not necessarily be appropriate for existing structures. The seismic performance assessment process must recognise this.

The nature of seismic loading is that it affects everything in the shaken region. This leads to complicated interactions between physical and human systems. Earthquakes are unerring in finding the weakest links in and between these systems. The essence of successful earthquake engineering is the identification and elimination of these weak links.

This paper outlines a seismic assessment methodology that is based on systems modelling. It draws on concepts and methodologies that have recently been developed and applied to coastal management [Hall and Davis, 1998], oil reservoir management, and the seismic assessment of a hospital [Sanchez Silva et al, 1996]. The apparent diversity of these application areas demonstrates that the systems modelling concepts are generic. The latter is an essential feature if the methodologies based on these concepts are to be successful in integrating the many differing technical and human issues in safety problems.

The methodology is illustrated by developing a systems model of an idealised intake tower for a hydroelectric power plant (Fig. 1). This tower has a reinforced concrete shear wall structure, which houses at its base the inlet to an aqueduct that feeds the hydroelectric power plant. The aqueduct inlet can be closed off by lowering a stop gate, which is normally suspended at the top of the intake tower in the control house. An electrically powered winch is used to lower the gate, but the winch can be wound manually if necessary. The tower is accessed from the shore by a reinforced concrete, multi-span bridge, over which the main electrical power supply cable is run. The performance requirement of the tower is that it should permit closure of the aqueduct inlet by lowering the stop gate in the case of a downstream emergency after the Design Basis Earthquake (DBE).

THE PROCESS OF SEISMIC SAFETY ASSESSMENT

The proposed systems methodology for seismic performance assessment adopts a hierarchical process model (Fig. 2), which assembles the evidence for and against the assessment outcome. At the top of the hierarchy is the overall performance assessment process (in this case that the intake tower can satisfy the performance requirements for the DBE). Beneath this are two branches of sub-processes, dealing with the performance of the main structure of the tower and of the aqueduct stop gate. Each level of the hierarchical structure becomes more focused on specific aspects of the tower, with appropriately detailed performance requirements (Fig. 3). The process hierarchy shown is deliberately simplified to aid clarity. In practice, it would be much richer and more complex.

The process model must handle a number of key issues [Hall and Davis, 1998]. Central to the assessment is the handling of *uncertainty*. Uncertainty arises from the accuracy of the systems model and the data that are fed into it. Both the model and the data are abstractions of reality. They are an *incomplete* and possibly biased representation, and therefore may have considerable uncertainty associated with them. Uncertainty also arises from the many non-technical issues that are involved in safety assessment. In general, these are extremely difficult to quantify numerically, which is why they are often ineffectively handled in conventional probabilistic risk assessment (PRA). Thus, there is a danger that conventional PRA may be biased towards issues that can be readily quantified and away from those issues that really matter. Whatever the issue, there will be imprecision in its definition, referred to as *fuzziness*, which is another source of uncertainty. *Randomness*, which is the lack of a specific pattern in observations or a series of measurements, also gives rise to uncertainty.

The hierarchical model of the process is built down from the top process to some appropriate level of detail. Each process (or holon) has a set of attributes drawn from an overall set. This ensures *consistency* in the specification of the processes. A real understanding of the process comes from a clear specification of the attributes. A specimen set of attributes is listed in Table 1.

The attribute list can be linked to common Quality Assurance procedures, which help consistency and *transparency* of the assessment process. The latter aspect is particularly important, since it helps to ensure that all 'actors', be they engineers carrying out the performance assessment or external reviewers, are aware of the extent of the contributions made by other actors and how these relate to their own contributions. In this way, it is possible to identify omissions or duplications in the assessment process, and make justifiable statements about the dependability of the assessment.

Table 1 Specimen attributes for a process holon

Attribute	Description / Purpose
Title	Process identifier
Objective	Objective of the process
Performance requirement (or success criteria)	Statement of the performance requirement, which could be from a code of practice
Client	The person/organisation for whom the assessment is done
Owner	The person who is responsible for the process
Actors	The people who are involved in the process
Timing	When the process occurs
Inputs and outputs	Inputs and outputs to the process
Resources	Resources required by the process
Hazard	Identified uncertainties affecting the process
Evidence FOR	Accumulated evidence in support of the success of the process in meeting its performance requirements
Evidence AGAINST	Accumulated evidence against the success of the process in meeting its performance requirements

The methodology uses Interval Probability theory [Cui and Blockley, 1990] as a means of acquiring expressions of the uncertainty about the success of a process and then combining them. An interval number, on the range [0,1], is used to represent the belief in the dependability of a concept.

$$P(E) = [S_n(E), \qquad S_p(E)] \tag{1}$$

where

$P(E)$ is the measure of belief in the dependability of a concept E,

$S_n(E)$ represents the extent to which it is certainly believed that E is dependable,

$1 - S_p(E) = S_n(\overline{E})$ represents the extent to which it is certainly believed that *E* is not dependable, and

$S_p(E) - S_n(E)$ represents the extent of uncertainty of belief in the dependability of *E*.

Evidence or belief is mapped onto interval numbers using membership functions similar to those used in fuzzy set theory. Three extreme cases illustrate the meaning of this interval measure of belief:

$P(E) = [0,0]$ represents a belief that *E* is certainly not dependable,

$P(E) = [1,1]$ represents a belief that *E* is certainly dependable, and

$P(E) = [0,1]$ represents a belief that *E* is unknown.

The interval $S_n(E) = S_p(E)$ implies that there is no uncertainty in the evidence and corresponds to the theory of classical probability. Thus, whilst Interval Probability Theory is founded on the axioms of probability theory, it allows support for a conjecture to be separated from the support for the negation of the conjecture. It can therefore handle situations where incompleteness is an important issue, because the problem domain need not be completely specified in order to obtain meaningful inferences.

The user inputs a judgement for each of the bottom level processes of Fig. 3 in the graphical form illustrated in Fig. 4. This input can be viewed in three ways. It is either the evidence 'for' and the evidence 'against'; or the 'necessary' evidence for and the 'possible' evidence for; or the probability with uncertainty about that probability.

In building the structure of the model, account has to be taken of the relationships between the processes. Firstly, there is the matter of *sufficiency* and *necessity*. The weight given to the contribution from a sub-process is a measure of sufficiency. If the parent process (i.e. the one immediately above) cannot succeed without the sub-process, then that sub-process is necessary. The relationship between processes at the same level is considered through the *dependency*, which is expressed using an explicit parameter. The more dependent two sub-processes are, the less information they add to the parent process. The process modelling and probability calculus is implemented in a graphically orientated software package, which becomes effectively an uncertainty simulator. These ideas have been put together with a non-additive probability calculus [Hall et al, 1998] in a software tool called JUNIPER.

Fig. 3 shows an example hierarchy for the intake tower developed using JUNIPER. The processes are titled and the interval uncertainty shown as a pair of numbers under the title, and graphically as coloured bars at the bottom of each process box. The left bar is coloured green to represent the *evidence for* the success of the process. The right bar is coloured red to represent the danger of *evidence against* the success of the process. The white gap between the red and green bars relates to the uncertainty of the process. The evidence may result from inspections, detailed finite element analyses, physical testing etc. The dependency between sub-processes is shown by the large number at the node, while the sufficiencies are shown adjacent to each link from the sub-processes.

Left clicking on the process box allows the uncertainty values to be entered (in the range 0.00 to 1.00), while right clicking allows the attribute list to be edited. A typical dialogue box for entering the uncertainty values is shown in Fig. 4. The *evidence for* and *evidence against* bands may be dragged using the mouse, or entered explicitly in the appropriate box. As the dialogue box data are changed, the coloured process boxes and associated numerical values in the main hierarchy diagram are calculated dynamically. The propagating effects of changing parameters can be seen instantaneously, which gives powerful and often surprising insights into the problem. It is straightforward to identify sub-processes that have the greatest effect on the overall process and, hence, to justify the concentration of remedial measures on these processes. In many cases, it is not possible to express the uncertainty values as precise numerical values. Fig. 4 shows how linguistic descriptions, such as 'Low', 'Moderate', 'High', 'Irrelevant', etc. can be employed instead.

Experience of the use of JUNIPER in a wide variety of situations has shown that it provides a first level sensitivity analysis of the problem domain, showing where the main uncertainties lie in the decision making process. Case studies have also shown how such an approach tends to the generation of debate as well as elucidation of the problem. Once a satisfactory hierarchy has been developed, it can be used as a template for similar problems. Thus, it can become a systematic repository of good practice, which is readily maintained and accessible. This could be of considerable benefit in the training of future generations of dam engineers.

INTAKE TOWER EXAMPLE

The principles outlined above are illustrated in the example hierarchy of Fig. 3. The top process is the overall assessment of whether the intake tower satisfies the DBE performance requirement, defined as the ability to close off the inlet to the aqueduct using the stop gate if required after a DBE. For simplicity, the hierarchy branches into two to consider only the main structure of the intake tower (the left branch) and the stop gate (the right branch). A proper assessment hierarchy would have many more branches, and would represent a much richer model of the intake tower assessment process. The parameters used in Fig. 3 have been chosen to illustrate the key features of the methodology, and are not necessarily representative of a real tower assessment.

For the intake tower to meet the DBE performance requirement, it is necessary for both the ‘Intake Structures’ and ‘Stop Gate’ processes to meet their own performance requirements. This necessity is denoted by the link lines from these processes to the node beneath the top process being shown in bold. There is an obvious dependency between the two top processes (if the tower collapses, then the stop gate will not function), and this is reflected by the dependency value of 0.74. The sufficiency of the ‘Intake Structures’ is set at 0.50 and that of the ‘Stop Gate’ at 0.66.

At the third level of the ‘Stop Gate’ branch, proper functioning of the ‘Gate Control’ process is necessary, and the link line is shown in bold. This process has two sub-processes, ‘Electric Winch’ and ‘Hand Winch’. It is assumed that these processes are independent, and, therefore, the dependency is set to zero at the node above them. Either of these processes is sufficient for the ‘Gate Control’ process to succeed, so both are given a sufficiency of 1.00.

The success of the ‘Electric Winch’ process is derived from the sub-processes ‘Telemetry’, ‘Winch Control Gear’, ‘Winch Motor’, and ‘Electrical Supply’. The ‘Telemetry’ process has been subject to rigorous seismic qualification testing, which gives a supporting evidence measure of 0.95. The ‘Winch Control Gear’ and ‘Winch Motor’ processes have been assessed against database information on similar systems, but have not been formally seismically qualified themselves. Thus, their evidential support is lower at 0.62 and 0.63 respectively. The ‘Electricity Supply’ process has not been formally assessed as yet. The assessing engineer has assigned a preliminary evidential support of 0.17 (‘None’ to ‘Low’), with an estimate of the evidence against of 0.28 (i.e. 1.00-0.72 ‘Low’). The large white bar indicates the large uncertainty associated with this assessment. This is the major cause of the uncertainty of the ‘Electric Winch’ parent process.

In a similar manner, tracing down the ‘Hand Winch’ process, it may be seen that at the lowest level, the ‘Access Bridge’ and ‘Operator Availability’ processes have the greatest influence on the ‘Hand Winch’ process. The ‘Operator Availability’ process shows in a simple way how people related issues can be included. The operator might be injured in the earthquake or might be stationed remotely from the site and unable to access it.

The ‘Gate Control’ process has evidential support of 0.64 (‘Moderate’ to ‘High’) , with evidence against of 0.28 (i.e. 1.00-0.72 ‘Low’). The engineer would have to decide whether this level of support was acceptable. By adjusting the values of the processes at the lowest levels, the engineer can determine which process or processes have most bearing on the ‘Gate Control’ process, and hence concentrate remedial efforts on these. The remedial efforts might involve more detailed studies to gather more data and reduce the uncertainty, or modifications or replacement of equipment, or revision of operating procedures.

The overall assessment of the example intake tower performance gives a measure of support of 0.43 (‘Low’ to ‘Moderate’) with a measure of evidence against of 0.21 (‘Low’). The assessment is largely controlled by the performance of the ‘Intake Structures’ process, which only has a measure of support of 0.39. Fig. 3 shows that it is the processes ‘Wing Walls’ and ‘Foundations’ that most influence the ‘Intake Structures’ process. Remedial measures should therefore focus on these two processes initially.

CONCLUSIONS

A systems based methodology for performance based seismic assessment of dam and appurtenant structures has been outlined. The methodology has considerable potential for guiding the seismic assessment process and giving the engineer deeper insights into the controlling aspects of the structure. The methodology is applicable in many areas and offers a robust systems framework for performance based engineering in general.

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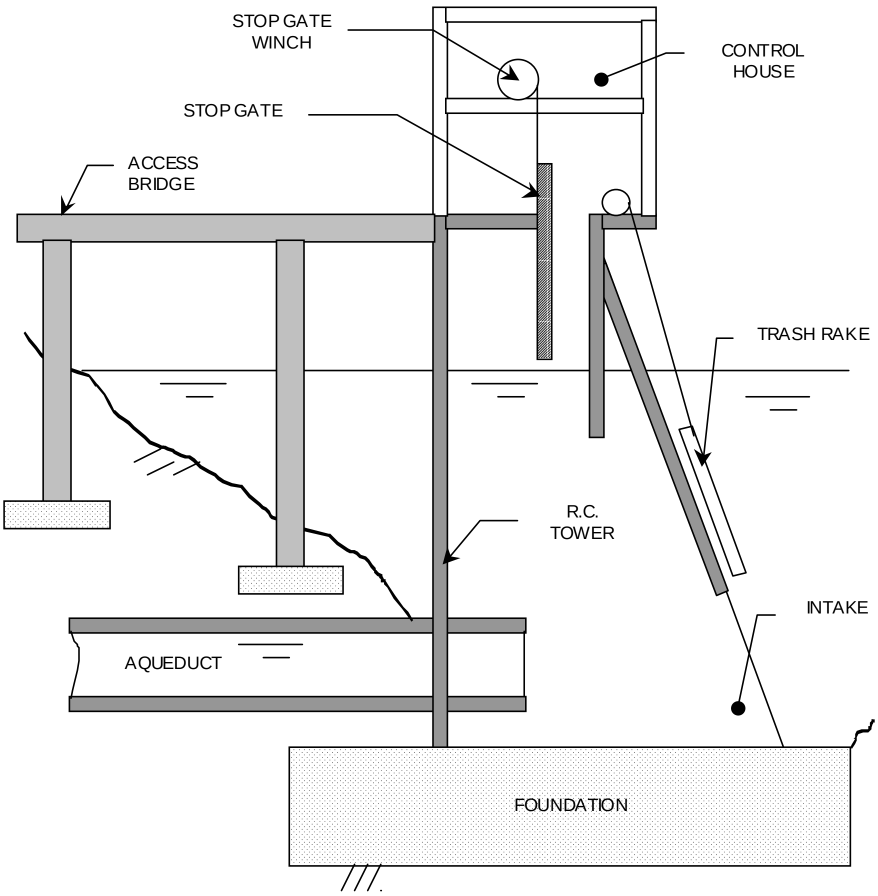

Fig. 1 Example intake tower

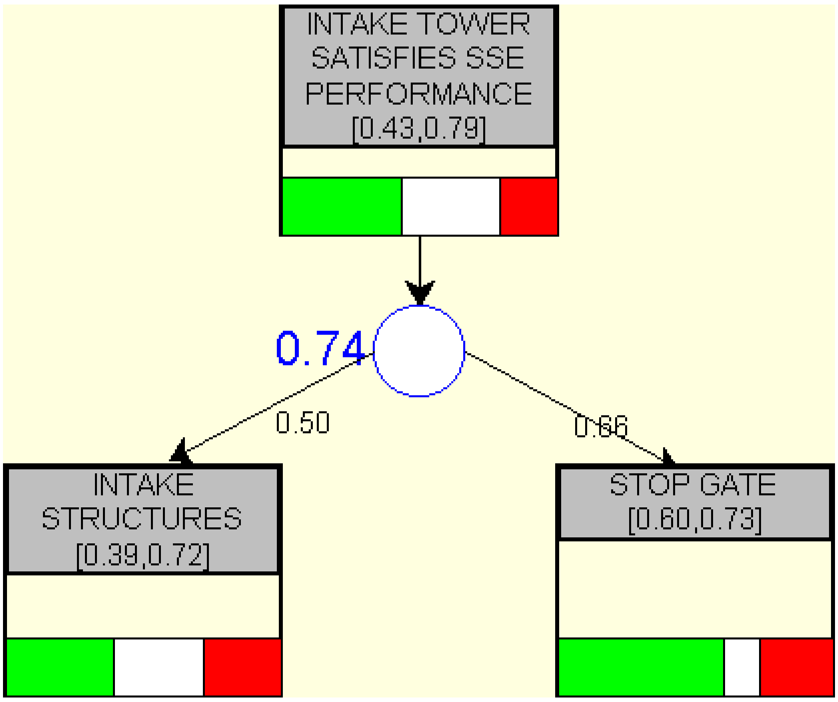

Fig. 2 Top levels of process hierarchy

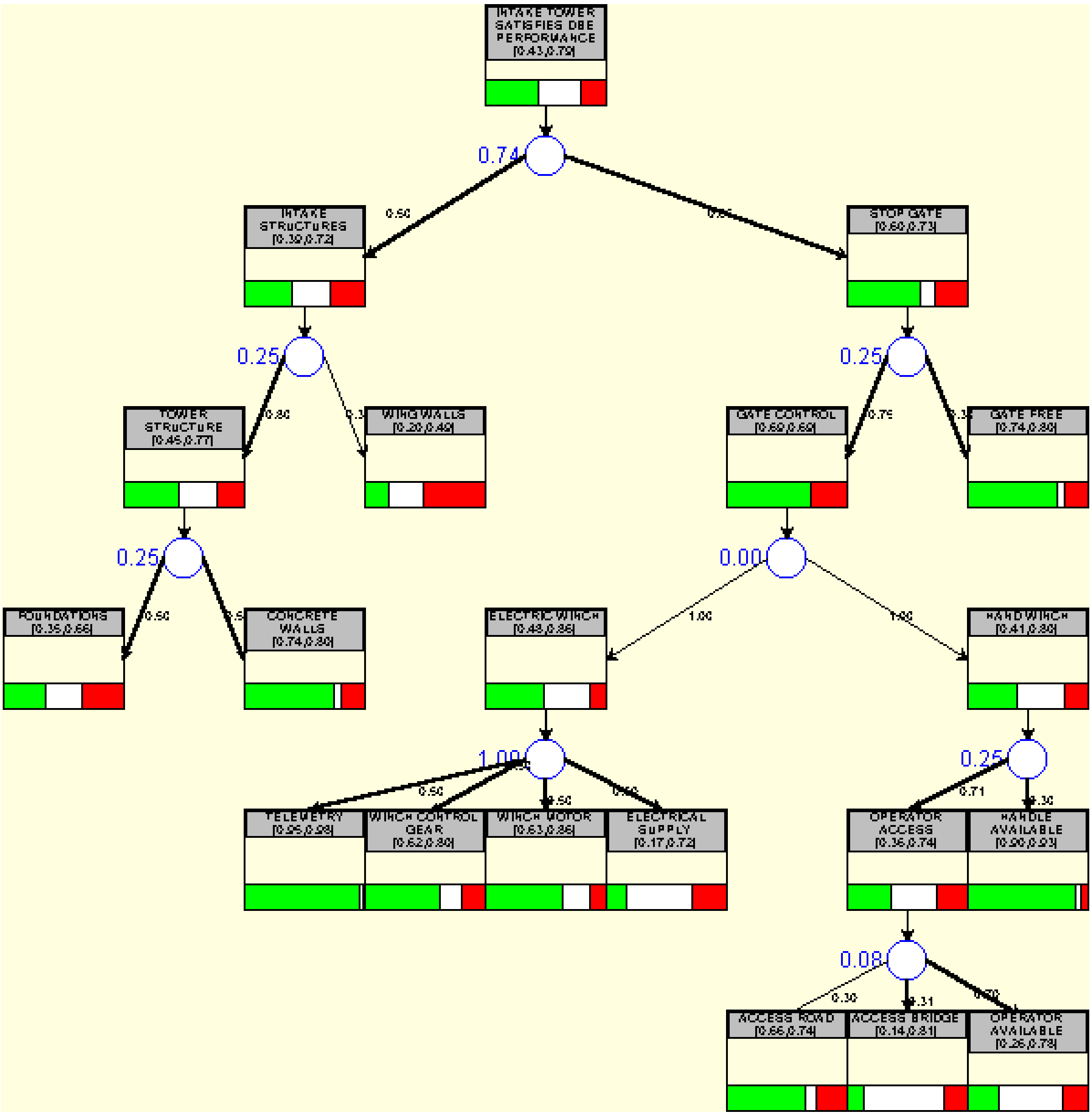

Fig. 3 Overall process hierarchy

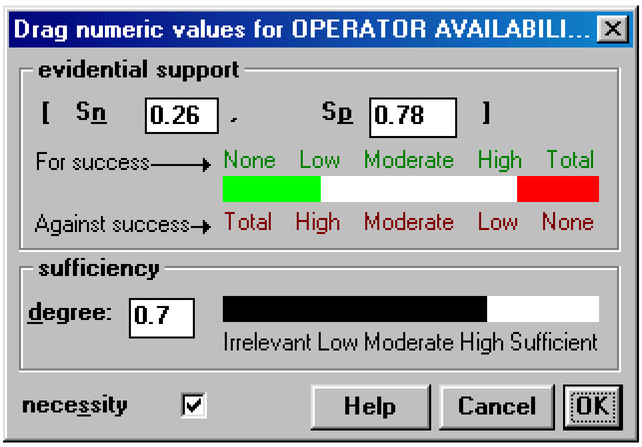

Fig. 4 Process dialogue box