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Autor: Comerford, J.B. / Lazzari, M. / Ruggeri, G.

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Causal Models and Knowledge Integration in System Monitoring

Modèles et base de connaissances intégrées pour la surveillance

Kausalmodelle und integrierte Wissensbasis für die Ueberwachung

J.B. COMERFORD
Civil Eng.
ISMES
Bergamo, Italy

M. LAZZARI
Computer Scientist
ISMES
Bergamo, Italy

G. RUGGERI
Civil Eng.
ISMES
Bergamo, Italy

P. SALVANESCHI
Physicist
ISMES
Bergamo, Italy

M. FANELLI
Civil Eng.
ENEL/CRIS
Milano, Italy

G. GIUSEPPETTI
Civil Eng.
ENEL/CRIS
Milano, Italy

G. MAZZA
Civil Eng.
ENEL/CRIS
Milano, Italy

SUMMARY

In this paper, an expert system is presented that aims to assist engineers in the management of dam safety. The proposed system uses qualitative causal models, hierarchical object-oriented structures, and other knowledge representations linked in an integration environment, for evaluation of data from monitoring and inspections of dams.

RÉSUMÉ

Les auteurs présentent ici un système expert visant à venir en aide aux ingénieurs chargés de gérer la sécurité des barrages. Le système utilise des modèles causaux qualitatifs, des structures hiérarchiques à orientation objet et d'autres représentations de la connaissance liées à un environnement d'intégration. Il permet d'évaluer les données de mesure provenant de la surveillance et de l'inspection des barrages.

ZUSAMMENFASSUNG

Der Beitrag stellt ein Expertensystem vor, das Ingenieuren bei der Beherrschung der Talsperrensicherheit helfen soll. Das System benutzt qualitative Kausalmodelle, objektorientierte hierarchische Strukturen und andere Darstellungen von Wissen in einer integrierenden Umgebung. Es dient der Auswertung von Messwerten aus der Überwachung und Inspektion von Talsperren.

1. INTRODUCTION

This paper derives from a project in progress at ISMES and supported by ENEL/DSR/CRIS that aims to investigate the application of Artificial Intelligence techniques in the field of dam safety.

In order to carry out this task it was necessary develop a conceptual framework within which the techniques of AI could be employed. The approach to dam safety adopted in this project is founded on the view that safety of structures is a problem of continuing management from design through construction to operation and that this management of safety is a quality management procedure (for a more detailed discussion of our view see [2,4]).

AI is seen as contributing to the problem of managing structural safety through providing new methods and approaches to modelling physical systems, such as qualitative physical models (models expressed in non-numerical terms) which can be integrated with conventional engineering models, to provide descriptions of a system at different levels of detail and from different points of view [5]. Knowledge arising from different sources, such as domain theories, codes of practice and experience can be integrated and used to interpret and manipulate on the qualitative and quantitative data of interest [3]. AI environments can provide extensive communication between the user, the models, and the reasoning mechanisms to produce a type of cooperative system of user and machine.

The approach described above to dam safety and the use of AI techniques have led to the design and development of an expert system (DAMSAFE), that uses qualitative causal models, hierarchical object-oriented structures, and other knowledge representations linked in an integration environment, for evaluation of data from monitoring and inspections of dams.

The system harnesses these knowledge structures to evaluate the state of the dam and its near environment through interpretation of these data. The results of this evaluation may be used in making judgements concerning the safety of the structure.

The system may be used in a variety of roles, such as on-line handling of alarms arising from dam monitoring, off-line management of safety of particular dams, assistance in decision making about the allocation of resources in safety improvement programmes, and training of junior safety managers.

2. DAMSAFE

DAMSAFE is a system being developed at ISMES as an environment to implement the approach described above to dam safety, using the tools of artificial intelligence. It is a system in which different types of information (design records, photographs, design drawings, test and monitoring data, qualitative assessments of condition) concerning a dam and different types of models of the dam system (numerical structural models, data models, normative models for behaviour) can be united to assist the engineer in carrying out the procedures of dam safety management. The system provides a platform in which the state of the dam system can be represented and then tested against a variety of normative models. The system is intended as a *cooperative management tool.*

The system developed so far is a prototype that enables hazard audits to be carried out on descriptions of the dam and behaviour of the dam coming from monitoring. The structure of the system is based on three main entities contained within an integration environment:

1. models of the physical world

   These models can be divided into:

   - those which describe the present state of the physical world;
   - those which describe desirable states of the physical world;
   - those which describe undesirable states of the physical world.

   These models are constructed using object-oriented modelling techniques.

2. models of human reasoning (reasoning agents)

   These are models of reasoning about the problem domain, including identification of data features or mapping of data states into dam states.

3. communication mechanisms

   The communication mechanisms take the form of interfacing software components, which enable the user to cooperate with the system through an object-oriented man/machine interface.

The whole system can be used in two different ways:

- as a *diagnostic tool*: there is a sequence of operations of the reasoning agents that allows to translate data into dam states;
- as a *knowledge integrator*: the system assists in the management of safety by facilitating the integration of information about the dam. Drawings, maps and pictures of the dam form part of the information base. Databases of past measurements of the dam can be integrated with the reasoning and modelling system described above. The system functions as an integration tool for different types of knowledge about the dam system, such as theory, regulations and expert knowledge. In such a way the system can be seen as a *virtual expert,* that reflects the knowledge of many different experts (civil engineers, hydrologists, geologists, ...) interviewed during the knowledge elicitation phase of the development process of the system.

3. STRUCTURE OF THE PROTOTYPE SYSTEM

The structure of DAMSAFE is based on the *object-oriented* metaphor. The different types of knowledge represented within the system are integrated using a hierarchical model describing, through objects and attributes, the main components of the system.

The hierarchical structure is comprised of two physical world models and three reasoning agents (figure 1). The *models* make up the problem domain: the *data world* represents all the relevant concepts related to data received from monitoring, while the *dam world* contains all the relevant concepts related to the physical world of the dam. The *reasoning agents* act on the physical world models, and contain the knowledge required to reason about the concepts of these models. They perform a variety of tasks, the most important being that of relating the concepts in the data world to those in the dam system world.

Each model represents a view of the physical world, while each reasoning agent represents a function of the data interpretation process performed by dam safety managers.

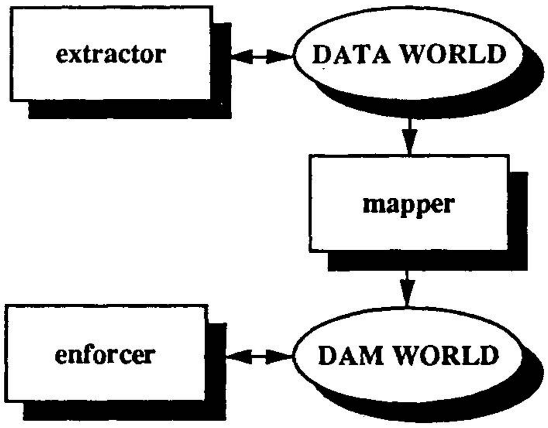

Figure 1: The structure of DAMSAFE

The system is also a data base: attribute values can be saved at the end of a session by using *multiple inheritance* and deriving the attribute to be saved both from a data-object class and from the special *persistent-object* class.

3.1. Data world

The concepts which constitute the data world are those used by engineers in discussing and interpreting the data for dam safety. Some of these concepts are expressed quantitatively, that is, numerically, others are expressed qualitatively. Within this model are the features of data which are significant for identifying particular behaviours and states of the dam system.

Therefore this model contains several *objects*; each of them represents the data related to a single instrument of the monitoring system. These data are *attributes* of the object; they can be time series of instrument readings, as well as details of the type of variable represented. Features such as peaks, trends, steps and plateaux, identified in different types of time series are recorded in this model.

Through the man/machine interface the icon representing the data world can be expanded and the icons representing the objects of the data world appear on the screen. Each object has *methods* to deal with it, which allow the user to access the knowledge linked to the object. In such a way one can read the values of the attributes of the object, or show a time series on the screen. It is also possible to assign values to attributes; this allows the user to act directly on the data world, by-passing the filtering of the reasoning agents.

3.2. Dam world

This world contains a model of the physical world of the dam and its environment, concepts describing the possible states of this world and a set of concepts modelling the possible behaviours of the dam and its environment. The physical dam model describes the dam and its environment as a hierarchy of objects (a hierarchical object-oriented model).

Five objects are currently represented within the prototype: the dam body, the foundation, the curtain wall, the basin, the foundation drains. These objects have attributes which, taken as a set, describe the state of the system. The attributes can be *quantitative* (e.g. the basin level), *qualitative* (e.g. the concrete quality), or *complex* (e.g. the undepressure profile, that is obtained by superimposing the readings of three piezometers to a design drawing of the dam and its foundation, using the representation of the piezometers within the drawing as axes for the measures, and connecting the three points corresponding to the readings on the axes).

3.3. Causal net of processes

The model of the behaviours of the dam system is a set of processes connected in a causal network (figure 2). The causal network models how behaviours of the dam and its environment can interlink in a causal way resulting in scenarios as one process leads to another. The full net includes ninety different processes describing possible dam behaviours. This network has been derived from published case studies of dam failures and accidents, and from discussions with experts in the field of dam design and safety. The conditions under which one process can lead to another have been included. Each of these processes has been documented along with descriptions of how evidence of these processes might be manifested in the monitoring data and also in reports from visual inspections.

The network can be used in different ways:

- as a *data base*: each process has attributes, which describe the process itself (e.g. start time, rate of change, activation state). The system provides methods for accessing such attributes, in order to show to the user their values;
- as a *control panel* of the system: each process is represented on the screen by a box, that is highlighted whenever the system infers that the process is active. Therefore the highlighted boxes give to the user an immediate synthetic report on the current state of the dam. Besides the activation state, other attributes (reversibility, speed) are represented by coloured areas of the box linked to the process representation on the screen;
- as an *inference tool*: the causal links can be used by automatic reasoners for building paths of events to be used for simulating the future evolution of the system state or identifying the possible causes of an active process;
- as a *knowledge base*: each process is linked in a hypertextual way to its written documentation, that describes the process and its connections to other entities (processes and objects). Therefore the theoretical foundations of the system itself can easily accessed through the user interface.

3.4. Reasoning Agents

Three reasoning agents were designed, and the first two have been fully implemented, while the third one is under development.

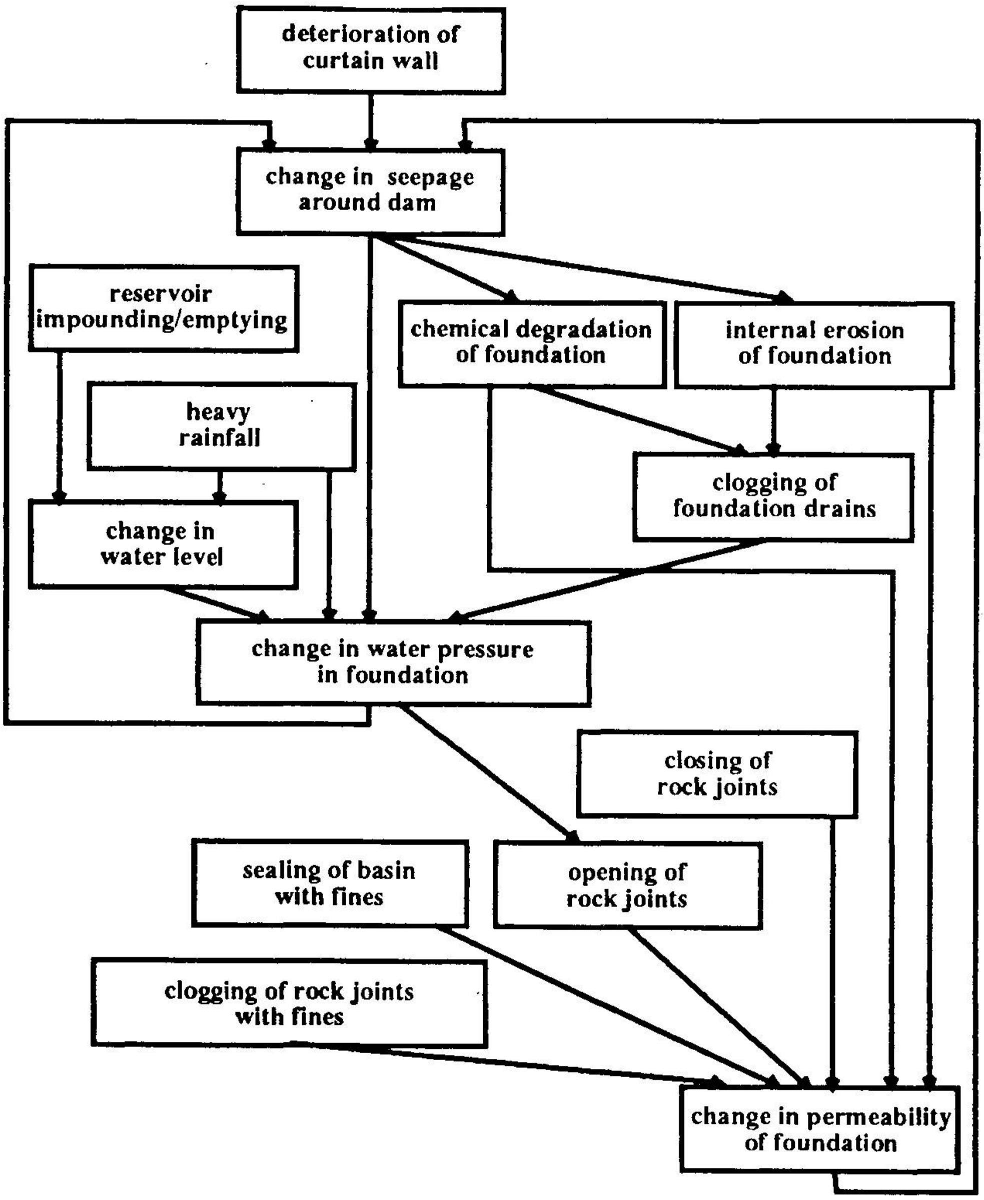

Figure 2: A section of the causal network of dam behaviours

The first one (extractor) operates solely on the data world to manipulate the data and extract features from the data sets of importance. It uses the graphical interface to show to the user a time series plot and to interactively find out a set of *features* of the plot which are considered relevant to dam safety. Possible features are trends, spikes, steps and plateaux. They are defined by qualitative and quantitative attributes (e.g. spike length, start time) and stored within the data world. These attributes can also be accessed and manipulated through methods of the data world, which may be considered as data base management utilities.

The second reasoning agent (mapper) performs the task of interpretation identifying both the possible behaviours of the dam in terms of a set of processes in the causal net, and the values of various attributes of the dam, based on evidence in the data.

This task is performed by firing *rules* defined by experts, which link data values to dam states (see table 1). These links are defined by using a formal language designed with the aim of allowing non-programmers to easily write and read rules (see table 2). The rules are translated into C++ code, compiled and then executed by the mapper. A rule is fired if a *precondition* on the values of some data world attributes is verified; in this case, the state of some dam world process is declared active and some dam world attributes receive a value. The set of active processes linked in a causal chain are highlighted by the system and describe a scenario that demonstrates the evolution of the dam behaviour.

The third reasoning agent (enforcer) acts on the dam world to extend the implications of the state identified by reasoning agent 2, over the model of the dam and its environment thus highlighting possible causal chains.

Once a model has been built of the state of the dam system in terms of a set of active processes (behaviours) and a set of attributes, this state can be tested against normative models to make judgements about the safety of the dam

4. APPLICATIONS OF THE SYSTEM

The system is aimed to be general in that it may be used (in different forms) off line to assist in investigations of safety or for training, and also on line for the generation of warnings at the dam site through interpretation of automatic measurements. The system is a decision support system and in that sense does not provide answers but assists the engineers to manage the problem. It is cooperative and interactive drawing on the relative strengths of man and machine to manage the information for safety of dams. Because of the hypertextual nature of the on-line documentation, the system can be used as a training tool for junior engineers.

An off-line version of the system is currently under validation at ISMES by dam safety experts (figure 3). It was developed on Sun workstation platforms using C++ and the InterViews toolkit of the X Window System. The system consists of about 100,000 lines of source code.

A neural network based tool was developed for supporting the feature extraction process from data and is going to be integrated with the main programme ([1]).

An on-line version of the system was developed and installed on a concrete dam in order to filter, evaluate and explain alarms coming from an automatic monitoring system; this on-line version of DAMSAFE performs a subset of the functionalities designed for the main system, since it deals only with single readings of the monitoring instruments and is able to identify a restricted set of possible processes ([6]). This system runs on a PC under MS-Windows. Both the evaluator and the explainer are written in Prolog, while the communication mechanisms with the monitoring system, the internal data base manager and the interface are written in Microsoft Visual Basic.

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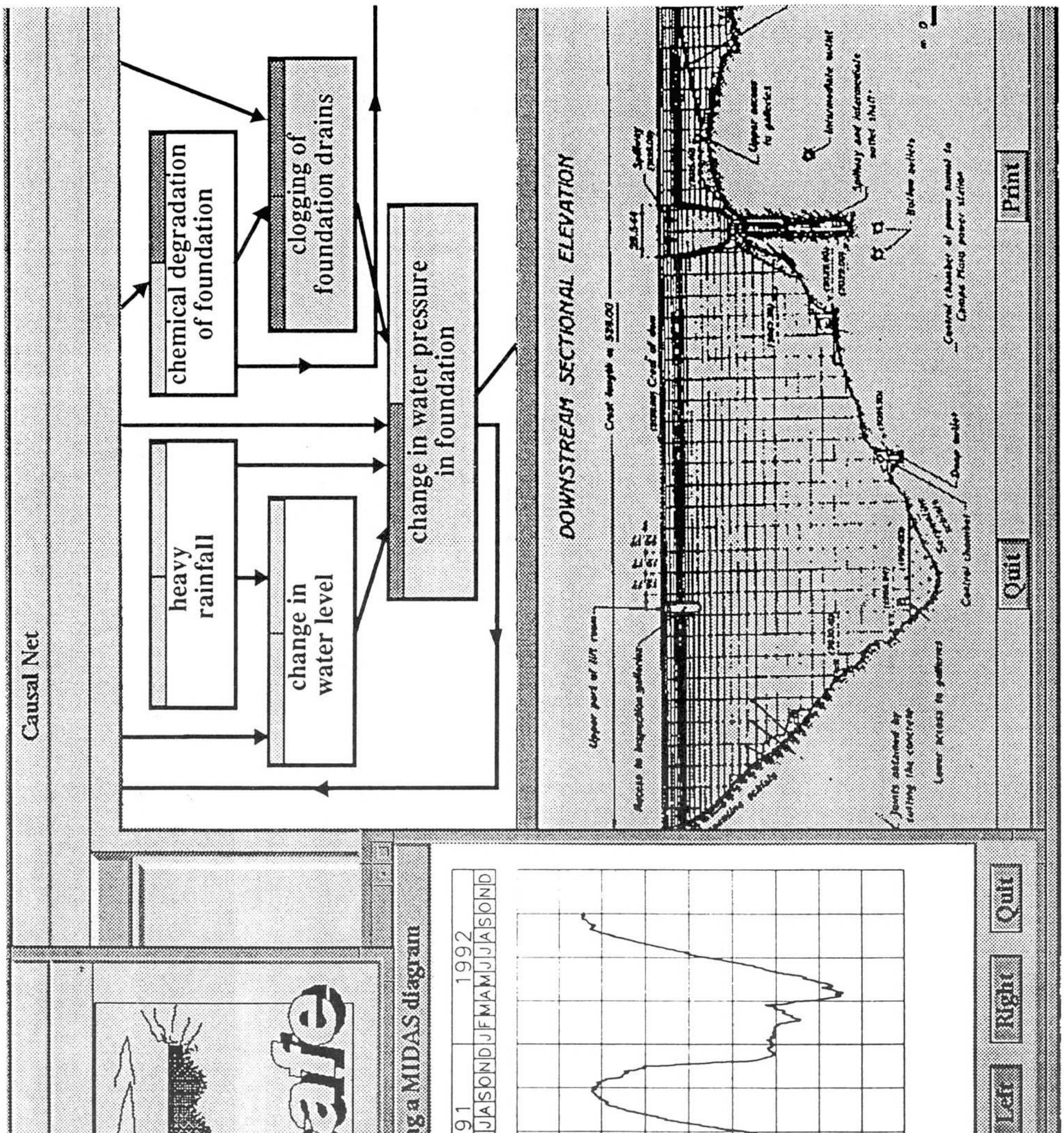

Figure 3: Information representation in DAMSAFE

```
Rule_4(
   CONDITION(Trend OF UnderseepageTimeSeries);
   ASSERT      (ChangeInSeepageAroundDam),
   SET         (
               StartTime OF ChangeInSeepageAroundDam
                  TO StartTime OF Trend OF UnderseepageTimeSeries
               AND
               FinishTime OF ChangeInSeepageAroundDam
                  TO FinishTime OF Trend OF UnderseepageTimeSeries
               AND
               ProcessSpeed OF ChangeInSeepageAroundDam TO "slow"
               ),
   MAP         (
               Gradient OF Trend OF UnderseepageTimeSeries
               INTO
               RateOfChange OF ChangeInSeepageAroundDam
               )
   )
```

Table 1: A rule of the mapper

```
<ANiceRule> ::
   (
    CONDITION( <Condition> ),
    ASSERT( <ListOfDamProcesses> ),
    SET( <SetList> ),
    MAP( <MapList> )
   )

<Condition> ::
  <ExistentialCondition> | <RelationalCondition>

<ExistentialCondition> ::
  <ListOfFeatures>

<ListOfFeatures> ::
  <Feature> OF <DataObject> [ OR <ListOfFeatures> ]
```

Table 2: A part of the grammar of the rule-based language used by the mapper