Information systems for dam safety: Evolution through AI

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Abstract

The paper describes the results of a project which aims at improving the capabilities of an information system that supports the management of dam safety. The improvement has been achieved through additional components developed using artificial intelligence concepts and technologies.

We describe the pre-existing information system, identify users' requirements driving the evolution of the information system and explain how AI concepts and technologies may contribute.

We describe the functions, the architecture and the AI features of two systems (MISTRAL and DAMSAFE) added to the information system.

Finally we give some information about the users' acceptance.

1. The context

The management of dam safety can be considered as an arduous task both for the need to guarantee the safety of such structures in a country so densely populated as Italy and because of the value of hydroelectric energy.

From its establishment ENEL (the Italian Electrical Company) has devoted considerable resources to dam safety for the design and the installation of instrumentation for the collection, storage and analysis of information concerning dams as well as for the development of methodologies and control systems[1].

Automatic instrumentation and data acquisition systems are used to monitor the real time behaviour of dams. The output of monitoring systems is presented locally to dam wardens to alert them to possibly dangerous situations. Telemetry systems are used to send the information to a central data base where experts evaluate the status of the structure through the interpretation of data.

The difficulty associated with this data interpretation is due to different factors, such as the large amount of data, the uncertainty and incompleteness of information, the need for engineering judgement, knowledge of the particular structure, experience of the behaviour of dams and a background of general engineering knowledge.

The safety evaluation of dams cannot be based on numerical analysis of data alone, since many physical phenomena cannot be adequately modelled at present[2]. ICOLD[3] stated that "the phenomena which start long before total failure [...] are still extremely difficult or inaccessible for analytical modelling"; and, "in most cases, computation of the overall probability of failure of a given dam would require so many assumptions, affected by such a high degree of uncertainty, that the final figure would not be of any practical value for project design and a judgement of its safety". This implies that a safety assessment has to fuse numerical analysis, probabilistic assessment and engineering judgement, based on experience.

AI concepts and technologies can assist engineers in safety management[4,5,6] by providing additional components to the existing information system such as real time interpretation systems linked to the data acquisition units and *intelligent* data bases supporting the off-line analysis.

The paper reports the results of the work done in this field during the last decade at ISMES, that led to the development of two decision support systems - named MISTRAL and DAMSAFE - which are now operational and help dam managers to face safety problems.

In these systems artificial intelligence provided powerful tools for the design of intelligent modules: causal networks of processes, qualitative modelling, model-based reasoning, hierarchical object-oriented representations were largely used. Moreover, AI techniques, such as rule-based systems, pattern matching, and neural networks, in conjunction with conventional ones, were also exploited for implementing those representation and reasoning schemes.

2. The pre-existing information system

A basic requirement of managing dam safety is the monitoring of the structure in order to collect data which are then interpreted so as to understand the state of the dam. In Italy, this is done through a two level organisational structure: a first level identifies and manages possible alarm conditions and, if necessary, activates the second level; the second level manages the information concerning the dam and evaluates the safety of the structure on a periodical basis or when requested by the first level.

To provide for the requirements stated above, ISMES developed an information system that comprises a real time automatic *monitoring* system, a *telemetry* system and a central *data base* with associated processing and representation functions.

The monitoring system (INDACO) collects data such as displacements of the dam, basin level, seepage losses, uplift pressures and tests them against thresholds or values predicted by theoretical models (*on-line* checks). The resulting warnings and associated data are presented to the people working at the first level of the organisation (e.g. the warden of the dam).

The data collected by the monitoring system are sent through a telemetry system to a central computer and are loaded, together with manually collected data, into a data base (MIDAS), which allows the subsequent analysis and interpretation of the behaviour of the structure (*off-line* check).

MIDAS has been operational since 1985 and is used by several organisations in Italy and abroad to manage the data of more than 200 dams. MIDAS runs in UNIX, VMS and DOS environments. INDACO, a PC-based system, has been installed at 35 sites for dam monitoring.

3. User requirements and AI contribution

The limits of the technology described above and the user requirements for its improvement belong to two different levels: local level (management of warnings) and central level (periodical safety evaluation or *deep analysis on demand*).

At *local level*, monitoring systems currently available enable two kinds of checks on the values gathered by each instrument:

- comparison of the measured quantity and of its rate of change with pre-set threshold values;
- comparison of the measured quantity with the corresponding value computed by a reference model.

Therefore, these checks neither deal with more than one instrument at a time, nor with more than one reading at a time for each instrument. In addition, any behaviour (either of the structure, or of the instruments) that is not consistent with the reference model generates a warning message. Because of the limited interpretation skills of the on-site personnel, false alarms cannot be identified and, hence, they require expert attention.

At this level, AI may contribute in collecting the expert knowledge related to data interpretation and delivering it through a system linked with the existing monitoring system. The system can evaluate the measurements and classify and filter the anomalies by using different types of knowledge (e.g. geometrical and physical relationships). It can take into account the whole set of measurements to identify the state of the dam and to explain it. This enables on-line performance of part of the expert interpretation, a performance that reduces the requests for expert intervention and the associated costs and delays, and increases the reliance upon the safety of the dam.

At the *central level*, the existing system contains quantitative data coming from the monitoring systems. Nevertheless, the safety evaluation requires also the availability of additional types of information (qualitative data coming from visual inspections, results of experimental tests, design drawings, old interpretations) and different types of knowledge (empirical relationships, numerical models, qualitative models), related to different areas of expertise (structural behaviour, hydrology, geology).

As a consequence, a supporting system is needed to help people manage such heterogeneous data and the complexity of their evaluation. We will show in the following that Artificial Intelligence can provide new ways to model the behaviours of the physical systems (e.g. a qualitative causal net of possible physical processes). This modelling approach is a useful way to integrate different types of knowledge providing a global scenario to understand the physical system behaviour. Moreover AI may be helpful in collecting and formalising different types of knowledge from different experts for data interpretation and evaluation of the dam state.

4. MISTRAL and DAMSAFE

To improve the capabilities of the information system in accordance with the above stated requirements, we developed two systems using AI concepts and technologies.

The first system, MISTRAL, is linked to the existing monitoring system and provides on-line interpretation and explanation of the dam state.

The second system, DAMSAFE, is essentially the evolution of MIDAS. It integrates MIDAS (database and graphical and computational tools) and adds new types of information, such as design records, photographs, design drawings, test and monitoring data, qualitative assessments. DAMSAFE provides additional models of the dam system and tools to support the interpretation of data and the evaluation of possible scenarios.

In the following we describe in some detail the functions, the structure and the AI concepts and technologies related to MISTRAL and DAMSAFE[7,8,9].

4.1. MISTRAL

MISTRAL is a knowledge-based system that supports safety managers when dealing with the interpretation of monitoring data gathered on dams.

MISTRAL receives data from the automatic monitoring system of a dam, identifies the state of the structure and generates natural-language explanations of the results of the evaluation. The result of the evaluation is a set of qualitative indexes, which express the state of the entities which have been assessed (instruments, dam blocks, foundation, physical processes, ...) in terms of values ranging from *normal* to *very high anomaly*[❶] .

A man/machine interface allows the user to access the results of the computation. It draws on the screen graphical representations of the objects which have been assessed and displays them using a colour scale based on their state. The interface has been carefully designed to help the users immediately understand the current state of the structure.

MISTRAL provides the users with a database collecting all the data related to the control system (measurements, evaluations, explanations). It is possible to select a situation from the data base and show on the screen its graphic representation and explanations. The users may also insert comments about the situation whenever they have some additional knowledge which could help understand what is going on.

Since its first conception, MISTRAL's evaluation process has been based on empirical and model-based reasoning: application experts and developers of the system defined heuristics and models of the dam behaviour, which use monitoring data as evidence of the state of the structure. More recently, the idea of using additional information related to specific situations assessed by experts in the past led to the development of a *database* of interesting cases and *tools* to detect possible *analogies* between the situation to be evaluated and those stored in such database. In such a way, MISTRAL provides the users both with its standard evaluation, based on general criteria, and with pointers to past situations which can be regarded as significant to the management of the safety of the structure.

4.1.1. MISTRAL's architecture

MISTRAL comprises the following modules (see Figure 1):

- *communication module*: manages the data communication from the monitoring system to MISTRAL;
- *numerical pre-processor*: checks the measurements against thresholds and recognises trends in data;

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❶ Currently, at most five values are used: normal, low anomaly, medium anomaly, high anomaly, very high anomaly; for some objects, only a subset of these values is appropriate.

- *evaluator*: identifies the state of the structure and highlights analogies with past situations;
- *explainer*: generates a natural-language explanation of the deductions carried out by the evaluation module;
- *man/machine interface*: allows the user to access the results of the computation;
- *database management module*: manages an internal database of measurements and evaluations.

The communication module calls the monitoring system and receives the data gathered during the last acquisition (normal real-time procedure) or collected while MISTRAL was, for some reason, not active.

The numerical pre-processor checks the measurements and their rate of change against thresholds; moreover, it computes the expected values for (some of) the instruments by means of theoretical models and checks against thresholds the displacements of the measured values from the expected ones and their rate of change.

Note that the whole set of thresholds used within MISTRAL has a different meaning from that used by INDACO when the two systems are coupled: while the former are safety thresholds, individuated by safety experts on the ground of their knowledge of the structure and of the past measurements, the latter are purely regarded as instrumental thresholds, used to verify the correct behaviour of the instruments.

Moreover, the numerical pre-processor applies mobile average algorithms to highlight trends in readings of the monitoring instruments.

Two *reasoning agents*, the evaluator and the explainer, process these data and store their results in the internal database, which is used as a *blackboard*: each reasoning agent uses the blackboard to read/write the concepts related to dam safety that it manages.

Essentially, the evaluation is a process of evidential reasoning, which transforms data states into dam states and interprets them in terms of alarm states. Then the explainer maps data and dam states into the proper messages.

The first step of the evaluation synthesises the results of the numerical processor, defining a *qualitative state index* for each instrument, that might range from *normal* to *very high anomaly* (and that, for computational purposes, sometimes is mapped into an integer value); moreover, MISTRAL sets also a parameter to record the *direction* of each measure.

Then the evaluator executes different types of checks on groups of measurements:

1. *checks on sections*: readings from instruments within the same section of the dam are composed (e.g. vertical blocks);
2. *evaluation of physical phenomena*: readings from instruments which measure the same quantity are examined (e.g. displacements, under pressures);
3. *evaluation of physical processes*: readings from instruments which allow the identification of ongoing processes are examined (e.g. rotation of the dam body).

The evaluator acts on a hierarchical model of the dam and uses information chaining techniques in order to establish the current state of the structure starting from local knowledge of the state of the instruments. This is done using several kinds of representations for codifying relationships between the data and the states[8]:

- *numerical functions*: empirical formulas define relations based on the alarm state of single instruments and on their reliability and significance; for instance, the empirical index for a dam block is a linear combination of the state indexes of the instruments belonging to that block, weighted on the ground of the reliability and significance parameters of the instruments. In this way, the most important instruments have a major impact on the definition of the empirical index, whilst alarms from the least reliable instruments may be attenuated or even filtered, when not supported by other ones; therefore, the empirical evaluation acts as an implicit congruency check on groups of data.
- *production rules*: starting from the values of some attributes of the system, rules can be fired, which set other values as well as the activation state of currently ongoing physical processes;
- *constraint based techniques*: constraints among variables define possible states of the system; process identification is driven by the satisfaction of those constraints. An example is shown in Table 1: a rule describes a part of the space state of the process *rotation* of a dam block. If the rule is fired (that is, all the conditions are true), then the activation state of the process is set to the value defined by the conclusion of the rule. In the example, the high downstream displacement of a plumbline installed on a

dam block and the high compression of a strain gauge in foundations under the block imply a high downstream rotation process of the dam block.

Moreover, MISTRAL performs pattern recognition on time series: the results of the numerical pre-processor are processed by the evaluator to check relationships between cause and effect quantities (e.g. basin level and displacements) and to explain trends of the time series.

Eventually, MISTRAL applies case-based reasoning by checking the situation under examination against past reference situations, which are regarded as significant in respect of safety management[0]. For this purpose, we have defined a subset of the state indexes, which we consider the most significant ones; MISTRAL applies algorithms and metrics to these parameters to define the degree of similarity between the current situation and those stored in a reference database. Links to the closest-matching cases within the reference database are built on-the-fly and shown to the user through the interface, so that the user can access their evaluations, mainly to take advantage of the additional comments provided by the experts, which might lead the current evaluation.

From the trace of execution, using knowledge about the behaviour of the dam and the instruments, the explanation module generates natural language messages. They describe the current state of the structure and the deductions of the system.

Users can access the processing results through a window-based interface (Figure 2, Figure 3). The interface draws on the screen graphical representations of the objects that have been assessed (instruments, sections) and displays them using a colour scale based on the object's state, by mapping the indexes belonging to the scale *normal - very high anomaly* into colours ranging from green to red, using grey for representing missing information (for instance, malfunctioning instruments).

Figure 2 shows how MISTRAL gives the user information from its interpretation. Small squared lights atop the screen codify the state of the instruments; these squares lie on coloured strips, whose colours represent the state of *families* of instruments of the same type, which are interpreted as the activation states of relevant phenomena, such as movements with reference to plumb lines, deformations with reference to extensometers, seepage with reference to piezometers.

Rectangular lights in the lower part of the screen codify the processes' activation state, such as rotation or translation of a block. The colours of the dam blocks (right shoulder, block 8-10, etc.) and of the strip at the bottom of the screen (global state) summarise the state of the physical system's structural components and the state of the whole structure.

Interactors are available to get more refined information about the dam state, by focusing on interesting details. For instance, when a user presses the grey button 'Block 1-2' in Figure 2, the window shown in Figure 3 appears on the screen: this window presents the current readings recorded by the instruments on the block 1-2 (main section of the dam), a picture of the block, the current state of the instruments (on the right) and of the whole block (on the left) and the explanation of the current state.

Via the interface, the user can also activate functions, such as print screen, and access the internal data bases.

MISTRAL provides users with three data bases, which collect all the data related to the control system, that is measurements, evaluations, explanations and users' comments.

These data bases have different purposes: the first one is dynamically upgraded with the information related to the case under evaluation (historical data base); an other data base stores reference cases to be used by the analogical evaluator (reference data base); the last archive provides the users with test cases, generated through simulation, which show how the system would interpret limit situations (test data base; note that the situations shown here belong to this archive).

Users can select a situation from a data base and see on the screen its graphic representation and explanations. Moreover, several data management functionalities are available to deal with the measurements stored within the data bases, such as statistical functions, export formats, visualisation tools.

4.2. DAMSAFE

DAMSAFE is intended as a *co-operative management tool*, in which different types of information concerning a dam and different types of models of the dam system can be united to assist the engineer in carrying out the procedures of dam safety management (Figure 4).

The system developed so far enables hazard audits to be carried out on descriptions of the state and behaviour of the dam coming from monitoring and from experts' judgement. Moreover, the system interfaces several external data bases. The structure of the system is based on three main entities contained within an integration environment:

1. models of the physical world, which describe both the present state and the desirable or undesirable states of the physical world; they are constructed using object-oriented modelling techniques;
2. models of human reasoning (*reasoning agents*), which are models of reasoning about the problem domain, including identification of data features or mapping of data states into dam states;
3. communication mechanisms, which take the form of interfacing software components, that enable the user to co-operate 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 the translation of data into dam states;
- as a *knowledge integrator*: the system facilitates the integration of information about the dam. Drawings, maps and pictures of the dam form part of the information base.
  Several databases are linked to the system: a database of past measurements of the dam, a database of laboratory and *in situ* tests and an archive of documents and cadastral information. The system functions as an integration tool for different types of knowledge about the dam, such as theory, regulations and expert knowledge. In this 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 gathering phase.

The structure of DAMSAFE is based on the *object-oriented* approach. Different types of knowledge are integrated using a hierarchical model describing the main components of the system. The hierarchical structure includes two physical *world models* and three *reasoning agents*. The models make up the problem domain, while the reasoning agents contain the knowledge required to reason about the 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 world.

4.2.1. Data world and dam 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.

The data world contains several *objects*; each object 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.

Each object has *methods* to deal with it (in the object-oriented sense), which allow the user to access the knowledge linked to the object. In this 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.

The *dam 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 its possible behaviours. The physical dam model describes the dam as a hierarchy of objects (e.g. dam body, foundation). These objects have attributes which, taken as a set, describe the state of the dam. The attributes can be *quantitative* (e.g. reservoir level), *qualitative* (e.g. concrete quality), or *complex* (e.g. underpressure profile).

The model of the behaviours of the dam contained within the dam world is represented through a causal net of processes and is described in the following.

4.2.2. Causal net of processes

The model of the behaviours of the dam and its environment is a set of processes connected in a causal network, that models how the behaviours of the dam can interlink in a causal way, resulting in various scenarios as one process leads to another (Figure 5 shows a fragment of the network).

The full net includes ninety different processes describing possible dam behaviours (e.g. translation, chemical degradation of foundation). We derived this network from published case studies of dam failures and accidents, and from discussions with experts on dam design and safety. We have included the conditions under which one process can lead to another, and documented each of these processes along with descriptions of how evidence of these processes might be manifested in the monitoring data or in visual-inspection reports.

The network can be used in different ways:

- as a *data base*: each process has attributes that describe the process itself (e.g. start time, rate of change); among these attributes, the activation state expresses whether the process is within physiological thresholds or over them; both users and automatic reasoners may access and modify the attributes' 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 the user an immediate synthetic report on the dam's current state. DAMSAFE represents other attributes besides the activation state (for example, reversibility, speed) by coloured areas of the box associated to the process;
- as an *inference tool*: automatic reasoners can use the causal links to build event paths for simulating the system state's future evolution or identifying the possible causes of an active process. In the first case the net acts as an oriented graph, where a causal flow propagates through the net from the cause processes (e.g. rainfall, earthquake) to the effect processes (e.g. structural cracking) via activation rules. With these rules, DAMSAFE sets the state of each process on the basis of some conditions on its input (the links from its causes) and defines how each process influences its effects. In the second case, DAMSAFE applies consistency rules to chains of processes, using the activation state of some processes as evidence for the state of those processes that cannot have any direct evidence from the available data;
- as a *knowledge base*: each process has *hypertextual* links to its written documentation, that describes the process and its connections to other entities (processes and objects). Therefore, users can easily access the system's theoretical foundations through the user interface.

4.2.3. Reasoning agents

Three reasoning agents have been developed. The first one (*extractor*) operates solely on the data world to manipulate data and extract features from the data sets. It uses the graphical interface to show to the user a time series plot and to interactively identify *features* of the plot which are considered relevant to dam safety. 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.

The second reasoning agent (*mapper*) performs the task of interpretation identifying 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 *production rules* defined by experts, which link data values to dam states (Table 2). These links are defined by using a formal language designed to allow non-programmers to easily write and read rules (Table 3). When a rule is fired, 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 the mapper over the model of the dam and its environment. thus highlighting possible causal chains.

4.2.3. On-the-fly creation of objects and interface

A dam's entire information set might be inserted into the system by providing DAMSAFE with a description written in a special language, called ADAM. We have designed ADAM so that users unfamiliar with programming languages can easily build their own data management environment (Table 4).

Through ADAM descriptions users inform the system about the components of the dam currently under evaluation (for instance, blocks) and about the data sources to be linked (for instance, the database of monitoring measurements and its access code).

At run time, DAMSAFE interprets ADAM descriptions and sets up the necessary objects and links to databases, as well as a hypertextual interface based on HTML scripts (HyperText Markup Language). In this way, DAMSAFE can manage links to other databases or procedures (used as reasoning agents) on a net of computers via the hypertext transfer protocol (HTTP).

Furthermore, DAMSAFE translates ADAM descriptions of physical entities, processes of the causal net and links among them into a hierarchy of C++ objects, which are then managed and accessed by the reasoning agents.

5. Status of the implementation and results

MISTRAL was developed on a personal computer. The first version of MISTRAL has been installed since October 1992 on a personal computer linked via serial line to the INDACO monitoring system of an arch-gravity dam (length about 500 m., max. height about 100 m.) and is currently in use providing the interpretation of data coming from 40 sensors. In 1994 the system was extended to manage six new instruments.

The system obtained very rapid acceptance by the user. It reduced the effort required for the management of warnings, allowed better exploitation of the power of the monitoring system and, most importantly, improved the quality of the safety management procedures. Users appreciated both the interpretation capabilities of the system and its man/machine interface, that highlights the system's state in a user/friendly and effective way.

At least two classes of users of the system exist:

- *dam managers and dam safety experts*: they use MISTRAL as a *control panel*, that shows the current state of the structure, and as a *decision support system*; the internal dynamic data base helps the dam managers understand the evolution of the dam state, in order to start necessary actions (e.g. inspections, retrofitting);
- *junior safety managers*: they use MISTRAL as a *training tool*, to understand past evaluations of the behaviours of a dam.

Subsequently, new versions of MISTRAL have been completed for three other arch-gravity dams. Since each dam has its own original features, the development of these versions required a large effort to gather the relevant knowledge, while codifying this knowledge into MISTRAL's data structures was rather simple, since it implied essentially the re-definition of the declarative code that describes the objects to deal with, and the tailoring of the relevant rules. In fact, from the programming point of view the largest effort was required for updating the graphical interface.

The applicability of the approach is much wider than the safety management of dams. It is related to the application of monitoring systems to structural and environmental problems. For example, we developed a version of MISTRAL devoted to the real time interpretation of the structural behaviour of the Cathedral of Pavia, as well as of six medieval towers in the same town. This new release of the system has been installed since January 1994 and is currently operational. Moreover, in 1996 we derived from MISTRAL a system for the interpretation of landslide monitoring in Valtellina (Northern Italy); this release integrates also a geographic information system to display data through its cartographic facilities[11]. In this case MISTRAL gets its input data from a data sever on a local area network.

We wrote the evaluator and the explainer, that is the *intelligent* core of the system, in Prolog. Hence, we can rapidly prototype the first release of MISTRAL for any new site and subsequently improve it on the basis of user and developer feedback. Prolog also lets us clearly separate data and procedures within the code, so that we can quickly reconfigure the system whenever we need to add or remove objects for evaluation (such as new monitoring instruments) or functions (such as new interpretation rules). Eventually, Prolog proved very useful for developing rule-based evaluation procedures and generating natural-language explanations. We wrote the other modules in Visual Basic (interface), C (communication mechanisms and numerical processing), Access (database), FORTRAN (time series representation) and MapInfo (georeferenced data). Case-based reasoning has been implemented both via symbolic processing (Prolog) and through neural networks (NeuralWorks)

DAMSAFE was developed on workstations under UNIX using C++, the InterViews toolkit of the X-Window System, FORTRAN and CGI scripts (Bourne shell). DAMSAFE is now integrated with the pre-existing off-line system MIDAS, as well as with other data bases of tests, inspections and documents and is operational at ISMES to support a group of engineers and technicians who provide services related to periodic safety assessment of dams. Since its last release exploits the HTTP protocol and the HTML language for the interface, DAMSAFE can be run from any machine (PC, workstation, X-terminal) over our local network, by using a common web browser.

Currently, we are exploiting the experience of DAMSAFE to create a new system that aims at providing users at ENEL with access to databases and programs distributed over their geographic network.

6. References

1. **Bonaldi, P., G. Carradori, M. Fanelli, G. Giuseppetti, G. Ruggeri**
'Modern Techniques for Dam Safety Surveillance and Evaluation', Idrotecnica 2 (2), 1988 (presented at: ICOLD Intl. *Congress*, San Francisco, CA, 1988).

2. **National Research Council (U.S.) - Committee on the Safety of Existing Dams**
Safety of Existing Dams, National Academy Press, Washington, DC, 1983.

3. **International Commission on Large Dams**
Lessons from Dams Incidents, ICOLD, Paris, France, 1974.

4. **Franck, B. M., T. Krauthammer**
Preliminary safety and risk assessment for existing hydraulic structures - an expert system approach, Report ST-87-05, Univ. of Minnesota, Dept of Civil and Mineral Eng., Inst. of Technology, 1987.

5. **Grime, D., T. Phillips, M. Waage**
'The Kelly system: on-line expertise', *Hydro Review*, August 1988.

6. **Comerford, J.B., P. Salvaneschi, M. Lazzari, P. Bonaldi, G. Ruggeri, M. Fanelli, G. Giuseppetti, G. Mazzà**
'The role of AI technology in management of dam safety: the DAMSAFE system', *Dam Engineering,* **3**(4), 1992, pp 265-275.

7. **Lazzari, M., P. Salvaneschi, G. Mazzà**
'Using Prolog for the interpretation of data from structural monitoring systems', *Second International Conference on the Practical Application of Prolog*, London, UK, 27-29 April, 1994, pp 329-336.

8 **Salvaneschi, P., M. Lazzari, S. Lancini, A. Masera, G. Mazzà**
'Paths of diagnostic reasoning in monitoring of civil engineering structures', *IABSE Colloquium on Knowledge Support Systems in Civil Engineering,* Bergamo, Italy, March 16-17, 1995, International Association for Bridge and Structural Engineering (IABSE), pp 187-196.

9. **Comerford, J.B., M. Lazzari, G. Ruggeri, P. Salvaneschi, M. Fanelli, G. Giuseppetti, G. Mazzà**
'Qualitative causal models and knowledge integration in system monitoring: the DAMSAFE system', *IABSE Colloquium on Knowledge-Based Systems in Civil Engineering*, Beijing, China, 1993, Int. Assoc. for Bridge and Structural Engineering (IABSE).

10. **Lazzari, M., P. Salvaneschi, L. Brembilla**
'Looking for analogies in structural safety management through connectionist associative memories', *IEEE International Workshop on Neural Networks for Identification, Control, Robotics, and Signal/Image Processing (NICROSP '96),* Venezia, Italy, August 21-23, 1996, IEEE Computer Society, Los Alamitos, CA, 392-400.

11. **Lazzari, M., P. Salvaneschi**
'Integrating GIS and artificial intelligence for landslide hazard monitoring', *Workshop on Geographical Information Systems and Major Hazards,* Walferdange, Luxembourg, 3-6 December, 1996.

IF

state of *Plumbline1* is very anomalous AND direction of *Plumbline1* is down

AND

state of *Extensometer1* is very anomalous AND direction of *Extensometer1* is down

THEN

state of rotation of *DamBlock1* is very anomalous

AND

direction of rotation of *DamBlock1* is down

Table 1 - A rule of the evaluator within MISTRAL

```
RULE_5
    CONDITION (
        Trend OF UnderPressure1TimeSeries
        OR
        Trend OF UnderPressure2Timeseries
        OR
        Trend OF UnderPressure3TimeSeries
    )
    ASSERT ( ChangeInWaterPressureInFoundation )
    SET (
        Start_time OF ChangeInWaterPressureInFoundation TO
            MAX (
                Start_time OF Trend OF UnderPressure1TimeSeries ,
                Start_time OF Trend OF UnderPressure2TimeSeries ,
                Start_time OF Trend OF UnderPressure3TimeSeries
            )
        AND
        Finish_time OF ChangeInWaterPressureInFoundation TO
            MAX (
            Finish_time OF Trend OF Underpressure1TimeSeries ,
            Finish_time OF Trend OF Underpressure2TimeSeries ,
            Finish_time OF Trend OF Underpressure3TimeSeries
            )
        AND
        Process_speed OF ChangeInWaterPressureInFoundation TO "slow"
    )
    MAP (
        MAX (
            Gradient OF Trend OF Underpressure1Timeseries ,
            Gradient OF Trend OF Underpressure2Timeseries ,
            Gradient OF Trend OF Underpressure3Timeseries
        )
        INTO
        RateOfChange OF ChangeInWaterPressureInFoundation
    )
```

Table 2 - 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 3 - A part of the grammar of the rule-based language used by the mapper

```
<Dam>
Identifier TString AlpeZafferanaDam
system TString ALPE
description TString "Gravity dam on the Riso River"
name TString "Diga di AlpeZafferana"
MainPicture TString http://gropius/DAMSAFE/adam/AlpeZafferana/fo05redu.gif
user TString CHEF
Midas TString http://loos/DAMCGI_MDS/midas.sh?AlpeZafferana+CHEF+ALPE
CausalNet TString http://gropius/htbin/cnet_start.sh?/DAMSAFE/AlpeZafferana/AlpeZafferana.dat
Dams TString http://bramante/DamsSummary+fiaonebe54

<DamWorldElement>
Identifier TString Environment
shortdesc TString "The environment around the dam"
description TString "The environment models the objects which surround the dam and are interesting with reference
to its management"
name TString "The environment"
MainPicture TString http://gropius/DAMSAFE/adam/AlpeZafferana/fo05redu.gif

<Instrument>
Identifier TString Livellostato
description TString "Hydrostatic balance"
name TString Livellostato
ColonnaMidas TString http://loos/DAMCGI_MDS/midas_str.sh?AlpeZafferana+CHEF+ALPE+1"
</Instrument>
```

Table 4 - Statements of the ADAM language

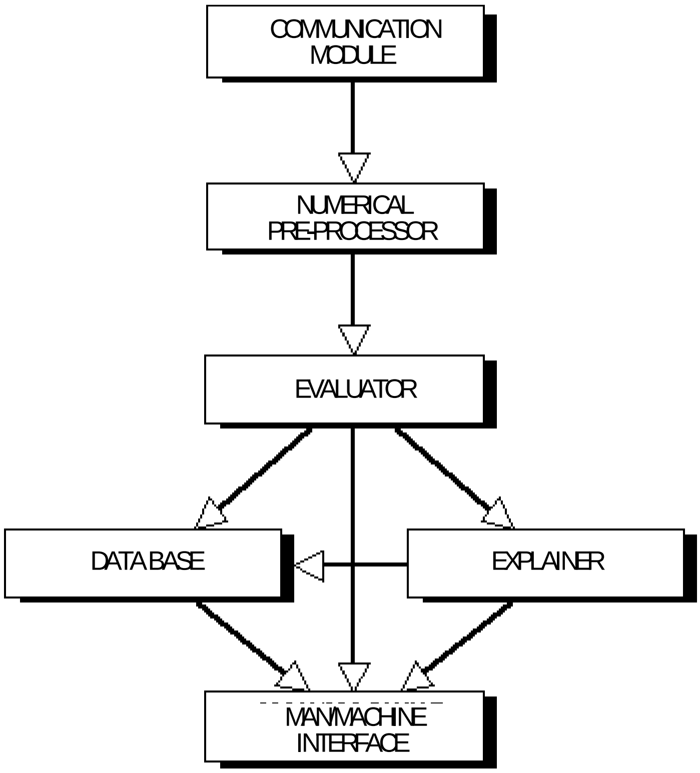

Figure 1 - MISTRAL's architecture

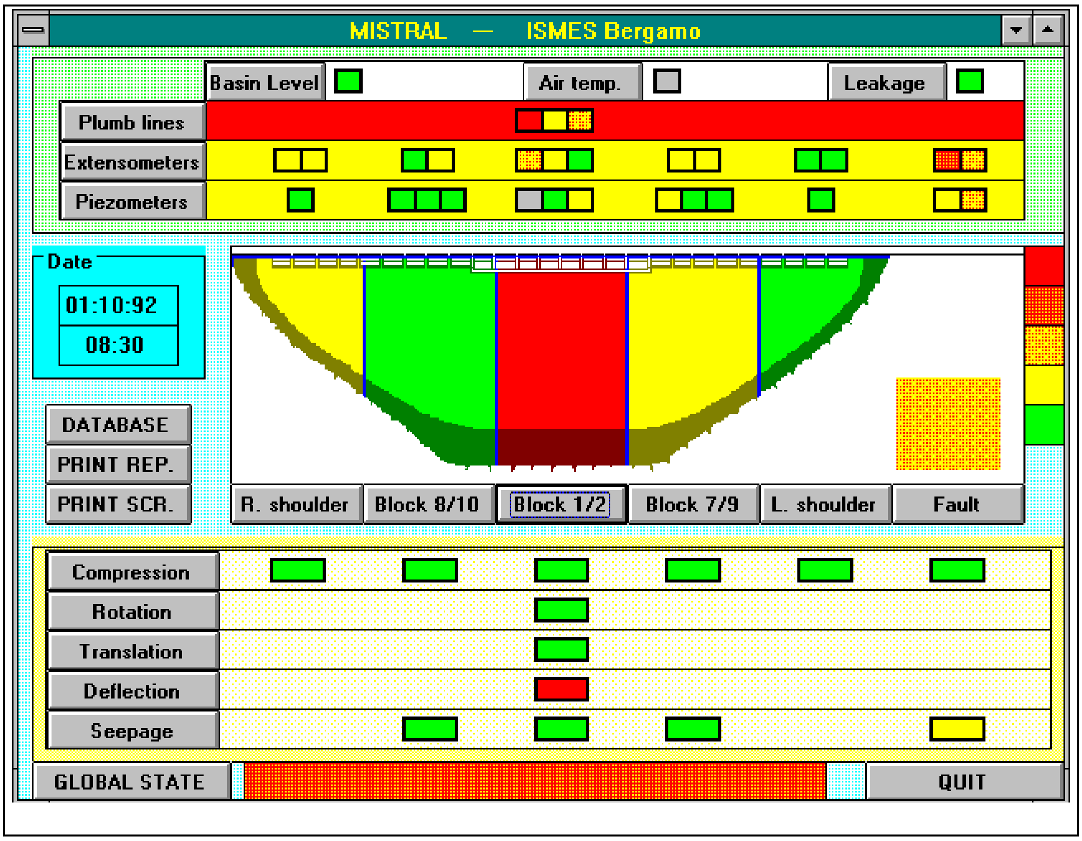

Figure 2 - MISTRAL's control panel

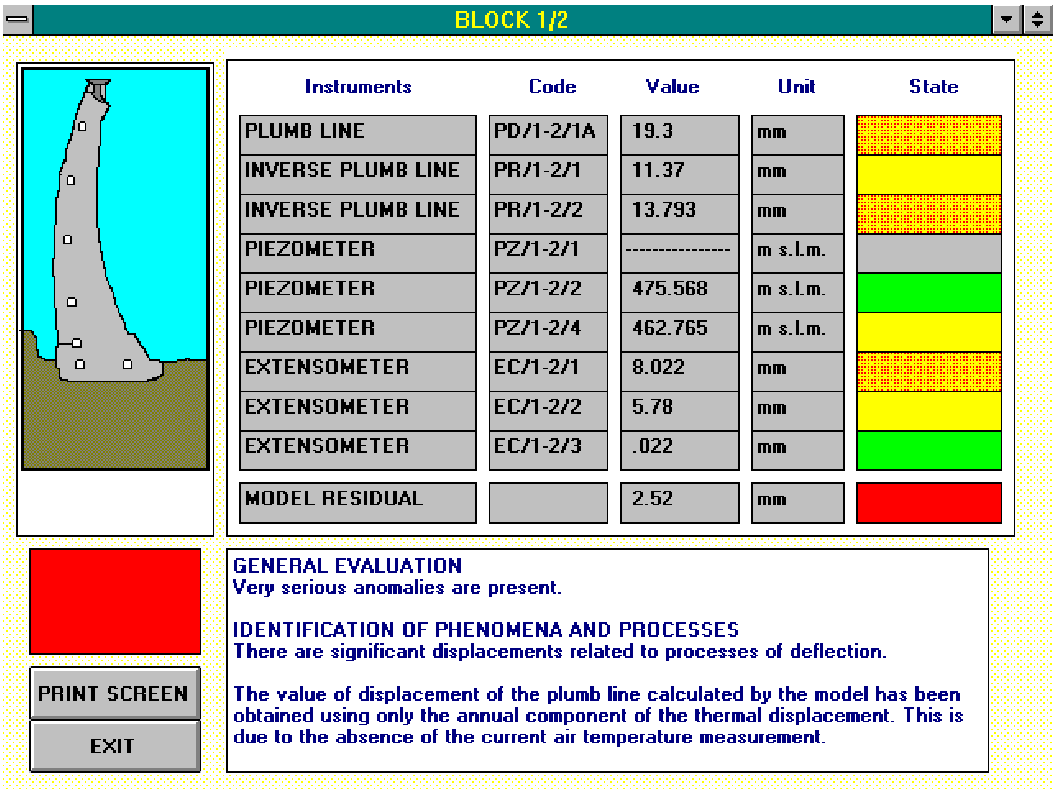

Figure 3 - MISTRAL: detailed information about the main section of the dam

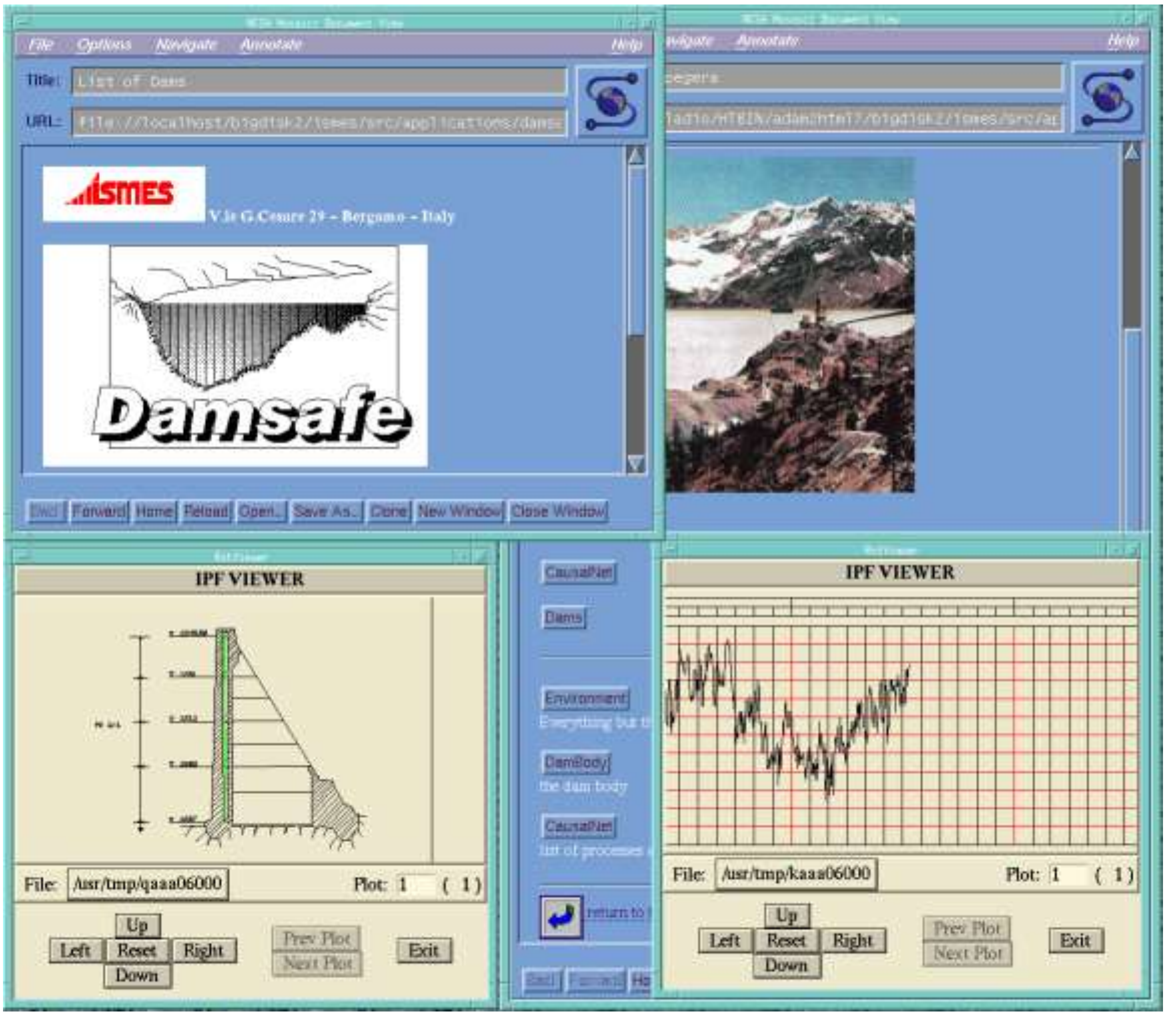

Figure 4 - Using DAMSAFE

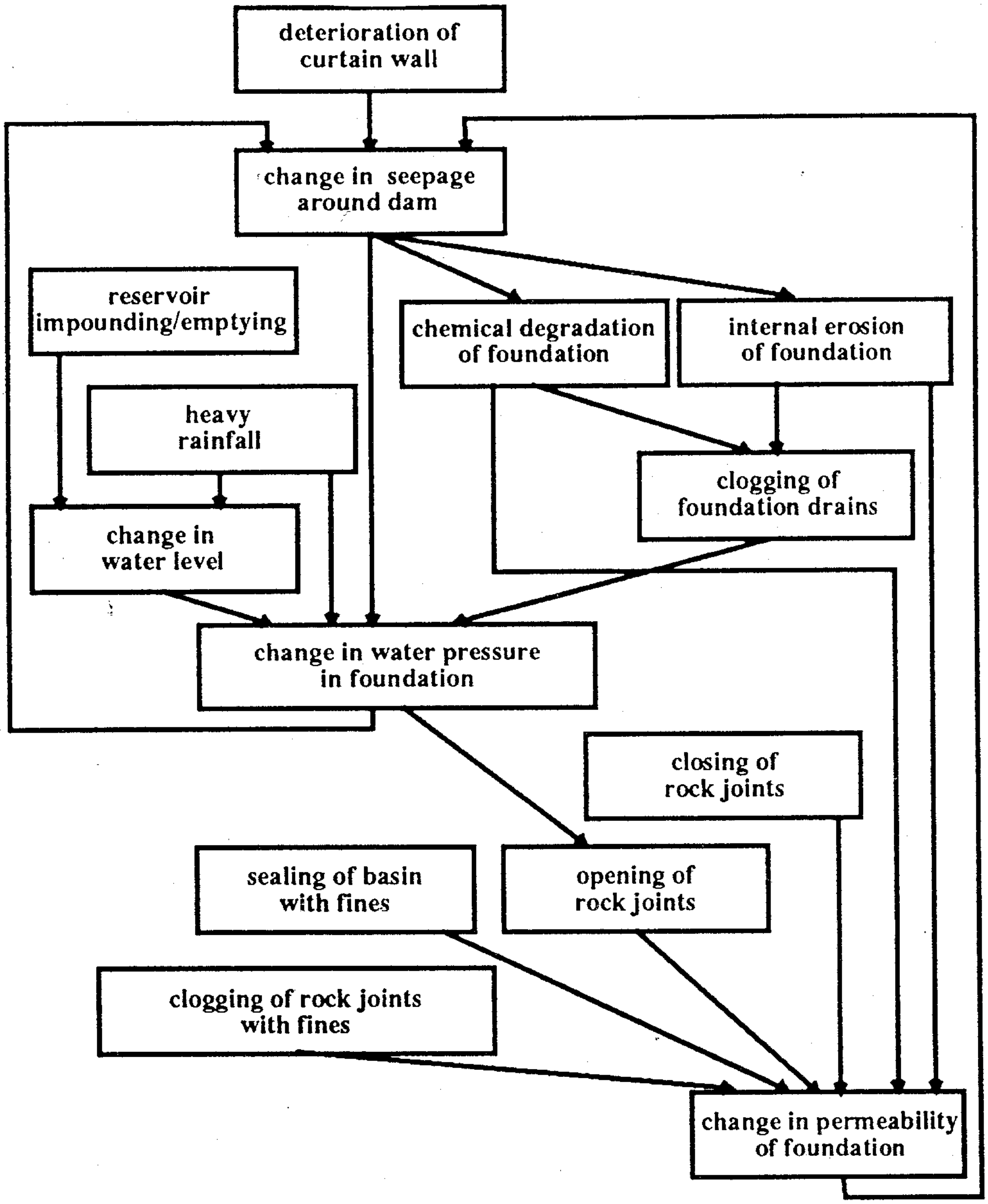

Figure 5 - A subset of the causal network within DAMSAFE