Diagnostic reasoning in monitoring of civil engineering structures

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Objekttyp: **Article**

Zeitschrift: **IABSE reports = Rapports AIPC = IVBH Berichte**

Band (Jahr): **72 (1995)**

PDF erstellt am: **22.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-54665

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Diagnostic Reasoning in Monitoring of Civil Engineering Structures

Exploitation des données pour la surveillance des ouvrages d'art

Diagnostische Datenauswertung in der Bauwerksüberwachung

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SUMMARY

The paths of diagnostic reasoning implemented in two in-service real-time systems for monitoring the structural safety of monuments and dams are presented. They are based on multiple representations of the physical system through multiple state spaces. Each state space include possible, desirable and undesirable states. Various paths of reasoning may be used through different spaces. The use of multiple spaces and paths allows to exploit the available information and to accumulate evidence on the safety of the structure. These types of reasoning are typical in monitoring of civil engineering systems because they help to manage the fundamental problem of incomplete knowledge.

RÉSUMÉ

L'article présente les cheminements utilisés dans deux systèmes de surveillance, en temps réel, de la sécurité structurale des monuments et barrages. Ils sont basés sur des représentations du système physique dans l'espace et dans le temps. Des situations possibles, désirables et indésirables sont considérées. Les cheminements varient selon les espaces. Il est possible d'exploiter l'information disponible et d'évaluer la sécurité de la structure. Ce genre de raisonnement est typique dans la surveillance de systèmes en génie civil car il pallie la connaissance toujours incomplète.

ZUSAMMENFASSUNG

Es werden die Pfade für die diagnostische Datenauswertung vorgestellt, wie sie in zwei Echtzeitmesssystemen zur Ueberwachung der Standsicherheit historischer Bauwerke und Staumauern implementiert sind. Sie basieren auf Repräsentationen des physikalischen Systems in mehrfachen Zustandsräumen, die jeder mögliche, erstrebenswerte und nicht erstrebenswerte Zustände beinhalten. Dank mehrfacher Räume und Pfade können aus unvollständigen Informationen Anhaltswerte für die Standsicherheit eines Bauwerkes zusammengetragen werden.

1. INTRODUCTION

Monitoring is an important activity related to the management of structures in service. Networks of sensors and data acquisition systems allow engineers to collect data from structures such as dams or monuments. Engineers interpret data by mapping them into states and behaviours of structures and evaluate those states against some reference model to decide actions. They use various types of knowledge and follow paths of reasoning through these types of knowledge.

In the following the reasoning paths common to two A.I. applications to structural monitoring are presented. The first system (KALEIDOS) supports the real-time interpretation of a net of 120 sensors installed on the Cathedral and six medieval towers of Pavia. It is operational from February 1994 [3]. The second system (MISTRAL) helps with managing the safety of an arch-gravity dam. The system interprets data coming from 40 sensors and is operational from mid 1992 [4]. A second instance of the system is going to be installed on an other arch-gravity dam.

The reasoning paths of the two systems are defined in the context of a common conceptual framework which is based on multiple descriptions of the monitored structure using multiple state spaces.

Various reasoning paths are used inside a state space representation or between different state spaces. Each reasoning path contributes to the evaluation of the safety of the structure. We argue that these types of reasoning are typical for this kind of problems. The main reason is that they are related to the management of incomplete knowledge, which is a fundamental problem of the diagnosis of civil engineering systems.

2. REASONING PATHS

An expert engineer is able to use different types of knowledge, such as empirical associations and causal models, compiled knowledge, qualitative and quantitative models and hierarchical descriptions. He is also able to organise and use the above mentioned knowledge through reasoning processes related to the specific tasks to be performed.

A model of this kind of expertise is presented in [5]; different layers of knowledge are described:

① *domain level*;

② *inference level*;

③ *task and strategic level*.

The *domain level* contains concepts, relations among concepts, models of processes or devices.

The *inference layer* describes which inferences can be made on the basis of the previous level. Examples of possible inferences may be:

Abstract	(deletes attributes from a concept)
Match	(compares structures of concepts)

Different inferences may be linked together in different ways, according to specific tasks (*task and strategic level*). This generates different paths of reasoning. An example of a path may be:

data → (abstraction) → evidence → (association) → diagnosis

3. STATE SPACES

Different reasoning paths may be used to solve interpretative problems. In the following we will relate all these reasoning paths to a common system view.

In this view the state space of a system is the set of possible (and not possible) states of the physical system. Moreover the state space includes, within the area of possible states, two sets defining desirable and undesirable states.

Note that the set of possible states is not the union of the desirable and undesirable states. The reason is that, while (im)possible states express the semantics of the model, (un)desirable states express the pragmatics (we want that the system behaves as near as possible to the desirable states and as far as possible from the undesirable ones). This is a common way to try to control systems which are not completely known (i.e. the system may reach not optimum states or not well known states but has not to reach critical states). Based on the space state, different tasks are possible:

- identify, using the available information, the current state of the physical system in the space state;
- compare the current state with the desirable ones to evaluate the distance between the current state and the border of the desirable states area;
- predict the evolution of the current state (identify one or more paths starting from the current state);
- explain the reason of the current state in term of the past evolution of the state (identify one or more paths to the current state);
- compare the current state with the not desirable ones and evaluate the distance between the current state and them;
- predict possible evolution of the current state, due to particular external events (e.g. earthquakes or floods) to evaluate if the system state could reach some undesirable state.

The same physical system may be described by many different state spaces. For instance, a first space may by defined using a data model: possible states are defined through possible values of a set of variables; the current state is described by the current set of values, while desirable and undesirable states are defined through thresholds derived from past observations.

A second state space may use a statistical model derived from past observations or a model of the design behaviour of the structure: possible states are defined through possible values of input and output variables of the model; the relationship identified by the model defines desirable states while thresholds define undesirable states.

A third state space may use a causal net of possible physical processes [2]; possible states are possible activation states of the processes, while desirable or undesirable states are specific activation states.

The reasoning in interpretative tasks is a path through a state space or through many state spaces described by different models and data. Different paths are possible depending on the specific goal, the available knowledge and the existing constraints.

4. PATHS OF REASONING IN MONITORING OF CIVIL ENGINEERING STRUCTURES

Typical paths of reasoning in monitoring of civil engineering systems are described in the following. These reasoning paths are used by two in-service systems (KALEIDOS for monitoring of monuments and MISTRAL for monitoring of dams) which will be shortly presented in the next chapters.

4.1. Reasoning about single measurements (RP1)

The state space is identified by effect variables (e.g. displacements of dam blocks are effect variables, while level of basin and air temperature are cause variables) which are measured by the monitoring system. Each variable has real values and is considered separately.

Desirable and undesirable states are defined through thresholds. Each variable has a set of thresholds which are derived from past history. They split the possible states into subspaces (from normal to highly anomalous).

The reasoning path is as follows: each measured value is filtered, then the result is compared with the relevant thresholds and the location of the current state in the subspaces (normal, low anomaly, medium anomaly, high anomaly, very high anomaly) is identified.

Moreover, not only the original measurements may be processed in such a way, but also their derivatives. The reasoning path is described in the following graph:

data	→	(filtering)	→	current state	→	(comparison with thresholds)	→	desirable / undesirable state
[data space]				[single measurements space]				[single measurements space]

According to [5] the *domain level* contains the following concepts: *data, states of the type "single measurements"* (classified in current, desirable and undesirable) and *thresholds*; the *inference layer* contains *filtering* and *comparison with thresholds*; the *task level* links domain concepts and inferences generating the above written reasoning path.

4.2. Reasoning about cause-effect measurements groups and associated models (RP2)

Groups of causes and related effect variables are considered. For each group (a set of causes and one effect) desirable and undesirable states are defined using quantitative models and thresholds. The models may be derived from past observations or from the design behaviour of the structure. For instance, a model may describe the relationship between water level of the basin and air temperature (causes) and displacement of a point of a dam block (effect).

For each group all the measurements are filtered, then the model is used to compute the effect from the measured causes. Then the measured effect is compared with the computed one. Possible situations may be

- the value of the measured effect variable is outside thresholds defining in any case an anomalous state;
- the value of the measured effect variable complies with the computed one (considering a possible range of variations defined by thresholds) and is not outside the above mentioned thresholds defining anomalous states. The state is normal;
- the value of the measured effect variable does not comply with the computed one, nor is outside the above mentioned threshold defining anomalous states. In this case the model and the measurements are inconsistent. This is usually regarded as a dangerous situation

(something is happening which we are not able to explain). The state is considered anomalous.

The reasoning path is described in the following graph:

data	→	(filtering & grouping)	→	current state	→	(computation of effects & comparison through models & thresholds)	→	desirable / undesirable state
[data space]				[causes / effect groups space]				[causes / effect groups space]

4.3. Reasoning about families of measurements (phenomena) (RP3)

The state space is identified by sets of effect variables belonging to the same type of instruments (e.g. the set of extensometers installed on a dam).

Each set identifies a global behaviour of the physical system which we call *phenomenon*. The identification of a phenomenon means that we are not able to identify a particular physical process in the structure (e.g. a highly anomalous rotation of a dam block). Nevertheless we may identify a more general and uncertain situation (e.g. highly anomalous movements of the structure). In some cases the available information could be not sufficient to identify a particular process, but the general behaviour of a family of instruments may provide sufficient evidence for an abnormal situation.

The desirable and undesirable states are defined though sets of empirical rules which take into account the significance and the reliability of each instrument. The values of each set of variables are filtered and then interpreted as possible evidences for a particular state (from normal to highly anomalous) and the rules are applied to find if sufficient evidence for a particular state holds. The reasoning path is described in the following graph:

data	→	(filtering & grouping)	→	current state	→	(association through empirical rules)	→	desirable / undesirable state
[data space]				[phenomena]				[phenomena]

4.4. Reasoning about processes (RP4)

The state space is identified by a set of possible physical processes which may be active in the structure (e.g. rotation, translation, seepage).

Each process has a state, from a desirable one (normal) to a highly undesirable (very high anomaly). This state is defined through qualitative models expressing relations among effect variables. The models describe physical or geometrical constraints among measurements. The values of the variables are abstracted from real values to qualitative descriptions (e.g. the rotation process of a dam block may be not active, low, medium, high, very high. A high downstream displacement of a plumbline installed on the block and a high compression of a strain gauge in foundations under the block imply a high downstream rotation process of the dam block).

The reasoning path is as follows. The measured quantities are abstracted from real numbers to a suitable quantity space. Then, for each possible process, the associated qualitative model, which is used as a set of constraints, is applied. If some constraint is true, the relevant process status is asserted.

Note that in some cases also quantitative models are used, but their meaning is different than in RP1. In RP1 a model is a relationship between causes and effects which is used to compute the latter, given the former. In RP4 models are constraints among effect variables which may be used to verify the existence of evidences for a possible physical process. The reasoning path is described in the following graph:

data	→	(qualitative abstraction)	→	qualitative data	→	(verification of constraints)	→	desirable / undesirable state
[data space]				[qualitative data space]				[processes space]

4.5. The integration of different reasoning paths

Monitoring systems such as KALEIDOS or MISTRAL use more than one reasoning path. An obvious problem arises: how to integrate different paths and the different interpretations they provide?

A first consideration is that all the measurements, models, phenomena or processes are referred to a common physical structure which may be split in parts (e.g. a dam system may be composed of dam blocks, basin, foundation).

The interpretation system maintains an object-based description of the physical system and every attribute or reasoning is referred to a specific object (e.g. the whole dam or a block of the dam).

Nevertheless, different reasoning paths are used together because the knowledge of the physical system behaviour is incomplete. For each object composing the system as well as for the whole system itself, different paths may be applied. Each of them provides a state which may be interpreted as evidence for the global state of the object.

Influence rules are used to describe the contribution of each state to the global one. These rules are used to summarise, through a conservative approach, the interpretation results for warning purposes. Moreover, the whole available interpretation results coming from the different reasoning paths are presented and explained to the user, because each of them may be used to support a human decision providing different types of evidences for the evaluation of the safety of the structure.

5. FIRST APPLICATION: MONITORING OF MONUMENTS

An application of the previously presented paths of reasoning is the KALEIDOS system which has been developed for the on-line management and interpretation of the measurements gathered on monuments. The first version of the system was delivered for the management of the safety of the Cathedral of Pavia and of six towers in the same town.

On March 17, 1989 the Civic Tower of Pavia collapsed. After this event, the Italian Department of Civil Defence appointed a technical-scientific committee to analyse the causes of the collapse and to check the state of other monumental structures of the town. The work of the Committee included a plan of monitoring surveys and interventions to be carried out on the Cathedral of Pavia and on six towers. This plan led to the installation by ISMES, in 1990, of an automatic monitoring system linked via radio to a control centre, located at the University of Pavia.

The instrumentation (120 sensors) installed on the Cathedral and on the towers allows to acquire the most important measurements on each monument, such as opening/closure of significant cracks, displacements, stresses and also cause variables, such as air temperature, solar radiation, groundwater level and so on.

The data gathered on the monuments are checked by the monitoring system to evaluate the reliability of the measures and to highlight any anomaly. Then, the data are periodically transferred into the historical data base MIDAS, which allows the off-line analysis, post-processing and plotting of data.

In such situation, two kinds of risk were identified, which suggested the development of an *intelligent* system for the monitoring of the structures.

First of all, the monitoring systems currently available allow the carrying out of checks on single values gathered by each instrument. 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) which is not consistent with the reference model generates a warning message. Because of the limited interpretation skills of the people on-site, false alarms cannot be identified and therefore require expert attention.

On the other hand, off-line expert analysis on series of data may require delays not compatible with the needs of the safety management of the structures.

The use of artificial intelligence techniques allowed to improve the capabilities of the monitoring system. AI contributed in collecting the expert knowledge related to data interpretation and delivering it through a system linked with the existing monitoring system. The system, called KALEIDOS (Fig 1), can filter and classify the anomalies by using different types of knowledge (e.g. geometrical and physical relationships). It can take into account the whole set of measurements and warnings to identify the state of the monitored structures and to explain it. This allows a part of the expert interpretation to be performed on-line, and therefore to *reduce* the requests for expert intervention and to *increase* the level of safety of the structures.

KALEIDOS is comprised of the following modules:

- ☐ *communication module*: manages the data transfer from the monitoring system;
- ☐ *evaluation module*: identifies the state of the structure;
- ☐ *explanation module*: generates natural-language explanations of the deductions of the evaluator;
- ☐ *man/machine interface*: allows the user to go through the results of the computation;
- ☐ *database management module*: manages a database of measurements and evaluations.

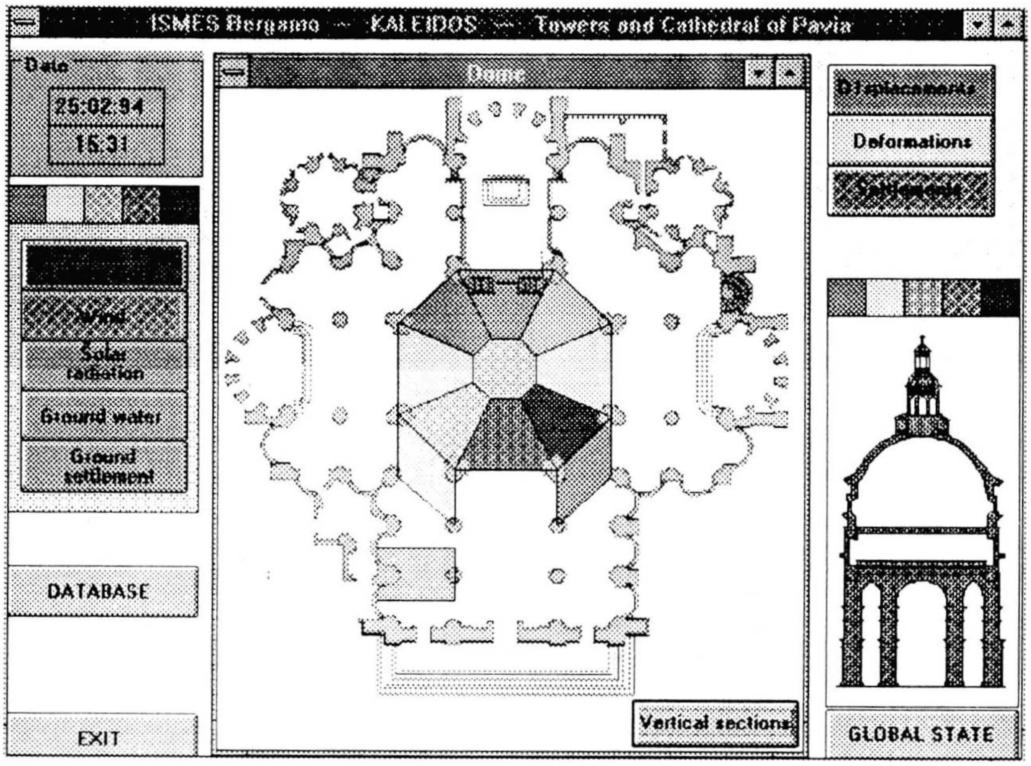
The communication module calls the monitoring system and receives the data gathered during the last acquisition (normal real-time procedure) or collected while KALEIDOS was, for some reason, not active.

The *evaluator* interprets the data, using different state space representations and reasoning paths and provides the safety status of the structures. From the trace of execution, using knowledge about the behaviour of the structure and the instruments, the *explanation module* generates natural language messages. They describe the current state of the structure and the deductions of the system.

The user can go through the results of the processing through a *window-based interface*. The interface draws on the screen graphical representations of the objects which have been assessed (instruments, towers, columns, ...) and displays them using a colour scale based on the state of the object. Interactors are available to get more refined information about the state of the structures, by focusing on interesting details.

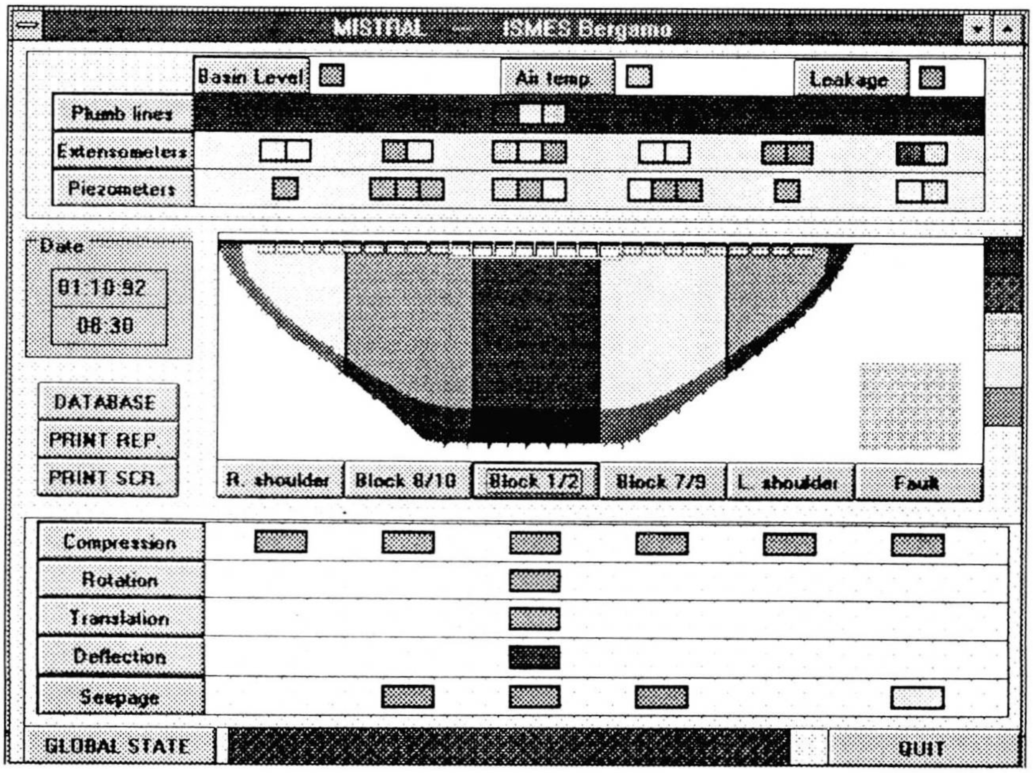
KALEIDOS provides the users with a *static data base* of test cases, and a *dynamic database* collecting all the data related to the control system (measurements, evaluations, explanations). It is possible to select a situation from the data base and show on the screen its graphic representation and explanations.

KALEIDOS was developed and delivered on personal computers using Prolog, C and VisualBasic under MS Windows.



Date 25:02:94 15:31

Fig 1. The KALEIDOS system



Date 01:10:92 08:30

Fig 2. The MISTRAL system

6. SECOND APPLICATION: MONITORING OF DAMS

A second application is the MISTRAL system, which is a real-time system for the interpretation of data acquired from monitoring of dams. It shares the same architecture and technology of KALEIDOS. More detailed information may be found in [4].

Fig 2 shows how the information resulting from the execution of the reasoning paths is presented to the user. Small square lights on the top of the screen codify, on a colour scale ranging from green to red, the state of the instruments as defined by the reasoning paths RP1 and RP2. These squares lie on coloured strips, whose colours represent the state of the phenomena processed in the reasoning path RP3. Rectangular lights in the lower part of the screen codify the activation state of the processes, as detected in the reasoning path RP4. The colours of the blocks of the dam and of the strip on the bottom of the screen summarise the state of the structural components of the physical system and of the whole structure.

7. CONCLUSIONS

Previous chapters describe the diagnostic reasoning implemented in two applications of Artificial Intelligence technologies to the diagnosis of civil engineering systems.

Interpretative problems related to civil engineering structures have specific characteristics due to the types of systems they deal with. In the following, some specific aspects are listed:

1. a large engineering facility, such as a dam or a marine structure, is situated in a natural environment. The definition of the borders of the system may not be clear and depends on the goals of the interpretation problem;
2. the system is usually made of a limited number of components (on the contrary other engineering artefacts such as electronic circuits may have a very large number of components);
3. the system behaves as a continuum and is usually difficult to distinguish individual components with well defined interactions;
4. each component is known with uncertainty (e.g. the behaviour of materials is not well understood);
5. engineering facilities interact with the social environment both for operation and use of them;
6. in many cases civil engineering systems (e.g. dams) are one-off products (i.e. there is not a large population of similar artefacts which may be studied with statistical techniques as in the manufacturing industry);
7. structures are subject to uncontrolled and, to some extent, unpredictable input (for example earthquakes and floods). Moreover, it is difficult, if not impossible, to test them at full scale against design load conditions in order to verify models;
8. the characteristics of the available knowledge may be highly influenced not only by technical issues but also by economical ones. For instance, the evaluation of the possible seismic damage of an urban nucleus. needs to be accurately planned to balance the cost of the information and the value of the predictions which can be drawn from the available data.

The decisions in interpretative problems are based on modelling and reasoning with models of physical systems. Models of different types may be used: associational, causal, qualitative, quantitative and so on.

Each model describes some specific aspect of the physical system and is built or selected for a specific goal. In this sense, knowledge is in any case incomplete. Nevertheless for many situations it is possible to define the purpose and the scope of the model and then reasonably depend on the results of the model itself by assuming that it describes a complete view of a specific aspect of a physical system. This assumption is difficult in many practical interpretative problems of civil engineering systems. Engineers deal with *open world models* [1]; in this kind of models there is only partial knowledge about a system and a situation where everything is true or false does not hold. Some things are true, some false, some unknown and some are inconsistent.

Decisions are required even if the available knowledge is incomplete. Therefore the management of incomplete knowledge and the use, in a co-ordinated manner, of every type of knowledge (e.g. empirical knowledge as well as causal, qualitative or quantitative models) is a fundamental issue.

The approach above presented is based on the following aspects:

- multiple representations of the physical system;
- use of various reasoning paths through which many different types of available knowledge are used to exploit the available information and increase the evidences about the status of the structure.

These aspects are means to manage the fundamental issue of incomplete knowledge in monitoring of civil engineering systems; therefore, we think that the approach experimented in the two in-service systems above described may be widely applicable.

Finally we think that the definition of the state spaces conceptual structure and of the reasoning paths is an important issue at least for the following reasons:

- it provides a way to understand and model the expertise of engineers;
- it increases the ability to design, compare and communicate the A.I. based monitoring systems, because it provides an abstract way to model the system which is independent from the implementation.

ACKNOWLEDGEMENTS

The development of KALEIDOS was supported by the Ministero dei Lavori Pubblici - Provveditorato Regionale delle Opere Pubbliche per la Lombardia.

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