GEOMAN: A Knowledge Based Expert System for On-Line Monitoring of Nuclear Structures

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ABSTRACT

The paper presents an innovative approach to the problem of the surveillance of Nuclear Power Plant sites in terms of structural settlements and groundwater regime, which is based on remote sensing and artificial intelligence techniques.

For a continuous control of the structural behavior, in terms of absolute and differential settlements, and for a real time check on piezometric levels, a remotized instrumentation system was installed at the Caorso Nuclear Power Plant, consisting in level indicators (for settlements) and electric piezometers, whose readings are centralized in a computer for data acquisition and processing. The control and primary interpretation of such readings, which are collected several times a day, cannot rely on a long period interpretation, in order not to loose the benefit of the "real time" data acquisition. Thus, a Knoledge Based Expert System (KBES), named GEOMAN, has been developed, to carry out those task and complement, on a frequent basis, the engineering interpretation of the data, that can be performed for instance on a yearly frequency.

By using knowledge derived from theoretical analyses performed for the evaluation of the time-related building settlement and from the forecasted levels of water-table, the KBES evaluates the actual behavior with respect to predictions, detecting any mismatch with the expected behavior and identifying the possible causes. That is, mismatches are interpreted firstly as the possible result of changed boundary conditions (e.g. river level) of known effect, and only if they remain unexplained warnings are given. Finally, the system may suggest actions to be taken to restore the design situation.

INTRODUCTION

Instrumentation systems are extensively employed to monitor the performance of soil and building foundations in Nuclear Power Plant (NPP), where both alignment of equipment and differential settlements between adjacent foundations may be critical to safety.

Effective monitoring involves long-term readings from many instrument points, making available a large amount of data in various formats that need to be processed and analyzed to detect if any unexpected phenomenon is taking place (Cremonini et al., 1986). The instrumentation data are usually stored on a data base and processed by means of computer techniques. The interpretation by the experts of the stored data leads to an evaluation of the site behavior, comparing the actual behavior of both soil and structures with the design assumptions, and eventually updating the design predictions.

In the following it is firstly discussed how a Knowledge Based Expert System (KBES) can be successfully employed in performing an uniform and real-time evaluation of measured data, allowing also for immediate detection of any vulnerability which may affect the behavior of the soil-structure system under control. In the second part of the paper, the results obtained through the proposed approach to the surveillance of the Caorso NPP in Northern Italy are presented, showing the details of the developed KBES.

EXPERT SYSTEMS FOR MONITORING

Geotechnical monitoring interpretation traditionally has not been highly computerized, since the geotechnical engineer usually relies on case histories, his own experience and his professional judgement. However, today's monitoring techniques provide detailed information on the behavior of geotechnical or structural systems, usually in the form of a large amount of data. Thus, evaluation and interpretation of the collected information can result rather complex and time consuming, especially when a continuous monitoring is required.

In the primary interpretation phase KBES can incorporate the expertise of a team of geotechnical engineers in order to achieve uniformity and efficiency of results, since they solve complex problems using heuristics, decisional factors and a wide and specialized knowledge in addition to the traditional algorithmic procedures. The development of monitoring expert system allows the engineer to efficiently evaluate large amount of instrumentation data on a real-time base. As a consequence, if discrepancies in the expected behavior of the system are detected, immediate warnings are given and appropriate contingency plans suggested by the KBES can be activated.

INSTRUMENTATION DATA INTERPRETATION PROCESS

The process of evaluating and interpretating instrumentation data implies two phases (Figure 1): a) a preliminary geotechnical site characterization and b) a periodical instrumentation data interpretation.

In the first phase the soil behavior is thoroughly analyzed, including both the geomechanical aspects (soil settlements due to the Plant live loads) and the hydrogeological aspects (piezometric regime in the subsoil) (Module A, Figure 1). At the end of this phase a number of behavioral and forecast models are available, which is verified through a preliminary analysis of the instrumentation data.

The second periodical phase is subdivided into three sequential steps:

- o the analysis of the data of each instrument within the functional group in order to exclude any anomalous reading unit (Module B1, Figure 1);
- o the analysis of the behavior of each instrument group, with reference both to the available models and the design limits (Module B2, Figure 1);
- o the presentation of the interpretation results for site control (Module B3, Figure 1).

The above three activities can be efficiently implemented and then automatically performed by means of a KBES. This can be integrated with the geotechnical monitoring system and can examine (in real time or at specified time intervals) the settlements data and the ground water level at a NPP site, as shown in the following sections, to produce a reliable and timely primary interpretation of the site behavior.

THE EXPERT SYSTEM GEOMAN

The innovative approach to the problem of the surveillance of NPP structures and subsoil presented above has been successfully employed at the site of the Caorso Plant in Northern Italy. Some details about the site characteristics and the instrumentation system installed are given first. The subject KBES is then described, and the features of the adopted remote sensing and artificial intelligence techniques are shown.

Site Information

The Caorso NPP, with an 880 Mwe BWR (Mark 2) reactor, is the largest in activity in Italy and is in operation since 1981. The site subsoil comprises two separated alluvial aquifers, whose piezometric regime is controlled by the nearby Po river.

The heavy buildings of the Plant and the massive soil embankment have produced large settlements (Cremonini et al., 1987), which require continuous monitoring: the average settlements of the buildings vary in the range 20-35 centimeters. Only five centimeters of settlement have been recorded since June 1977, after the end of construction activities: this settlement is due to the consolidation of cohesive layers, as confirmed by the almost uniform average settlement of the plant buildings. An additional few centimeters of settlement are predicted for the next 30 years, based on the long-term settlements statistical forecast (Biondani et al., 1987).

Foundation elevations for the Main Buildings are more than seven meters below the average groundwater table in the upper aquifer, and dewatering activities were hence required for construction. The dewatering system consists in a plastic diaphragm of cement-bentonite, deepened to the aquitard separating the two aquifers, and deep wells operated inside the diaphragm. Dewatering activities were extended to the Plant operation phase as safety precaution, thus requiring also a careful surveillance of the piezometric levels in the area.

To monitor in a continuous and automatic way the settlements of the foundations, a system of level indicators has been installed on the Main Buildings of the Plant. The system is based on the principle of communicating vessels and gives electrical signals proportional to the elevation difference between the vessels. Groundwater monitoring is performed by a remotized and automated piezometric system of Casagrande and Wellpoint piezometers, installed within both aquifers inside and outside the diaphragm, and by a remotized sensor system (water level/pumping rate) installed in the dewatering wells.

The Expert System

The periodic and frequent evaluation and interpretation of the instrumentation data have been automatized by the KBES GEOMAN (GEOtechnical Monitoring ANalyzer), which performs all steps previously described simulating the reasoning process of the geotechnical experts.

The KBES has been developed within the DAISY programming environment (Righetti and Cremonini, 1988), a rule-based KBES developing tool featuring ample computational capabilities, partability on commercially available hardware and software and direct interfacing with external programs and data collection systems.

The knowledge base is parted into six major groups of rules (Figure 2): a) the GEOMAN module, which activates the system reasoning process and includes the data structure; b) the GENERAL module, which manages the other moduli and contains the user interface and interacts with the site information data base; c) the module PIEZOM, which performs the piezometric data analysis and evaluation; d) the module PUMP, which evaluates the dewatering system data; e) the module SETTL, which performs the settlement analysis and evaluation for the Plant buildings; and f) the module REPORT, which plays as the interpreter of the anomalies found, combining the results coming from c), d) and e), and outputs the results of the interpretation session.

The knowledge base, subdivided in 24 submoduli, consists of more than 600 rules. For data management and evaluation, and for the user interface, this large set of rules has been integrated by more than 100 external routines in FORTRAN77. Figure 3 outlines the complex internal structure of the KBES, identifying the submoduli in which each modulus is subdivided. The same figure also shows the control transfer between the various moduli and the commands (circles in the left position of the figure) available in the user interface.

Settlement Data Evaluation

In the process of settlement data, the KBES evaluates either groups of instruments installed on the same foundation, or couples of instruments placed at the ends of rigid connection (piping systems) between adjacent buildings.

In a first phase, the system analyzes each instrument a) searching for instruments whose readings result anomalous with reference to the average settlement behavior of the foundation and b) searching for instruments whose readings disagree with the forecast values.

In a second phase, the system analyzes each group of instruments and evaluates the settlement measurement by a) evaluating the foundation average settlement, tilt and tilting direction with reference to the measured vs. the predicted values and b) comparing the amount of differential settlement in correspondence of the rigid connections between adjacent buildings to the design limits.

Groundwater Data Evaluation

In the process of the piezometric instrumentation and dewatering system data, the KBES evaluates the recorded measurements within either one of the two aquifers, inside or outside the diaphragm wall area.

In a first phase the system analyzes each instrument a) searching for instruments whose readings are considered anomalous with reference to the average piezometric surface pertaining to the group and b) searching for instruments whose readings appear anomalous compared to the past-history of the sensor (e.g. anomalous trends, evident peaks or frequent oscillations of the signal). These instruments are then excluded from the analysis.

In a second phase, the system analyzes each group of instruments and evaluates the groundwater data by a) a comparison of the measured average piezometric level and hydraulic gradient to the values predicted by the hydrogeological model of the site (Cremonini et al., 1989); b) a comparison of the average piezometric level to the design limits (e.g. minimum level inside the diaphragm, maximum level outside the diaphragm with respect to its upper edge, etc.); c) a comparison of the dewatering monthly pumping rates to the design limit of each well and to the past average values and d) a control of the water level in the pumping wells, with reference to the design limits.

Instrumentation Data Interpretation

The expert core of the KBES GEOMAN has been implemented to simulate the methodology that experts apply in the interpretation of instrumentation data. All abnormal situations, i.e. any inconsistent or improper instrumental behavior in the period, are compared and correlated in order to obtain useful information about the causes of the anomalous behavior. Whenever the KBES is not able to find a satisfactory explanation of the anomalous situation, due to lack of implemented knowledge or available information, the system signals the anomalous situation.

Any reached conclusion is provided with a certainty factor (variable in the range 0 to 1), which represents a relative measure of the confidence in the conclusion reached through the logical reasoning process. Such a certainty factor starts from an initial value associated with any abnormal situation found in the data evaluation phase, is modified during the session by weighted relationship associated with any applied logical rule and reaches a final value related to the reasoning conclusion.

Besides the clear indication of any sensor or instrument functionning improperly, the KBES states at the end its interpretation about the absolute and differential settlement trend shown by the monitored location on the Plant structures, making hypotheses about the possible causes (e.g. variations of live loads during the refueling activities, elastic effects due to changes in the piezometric level in the foundation subsoil, etc.). Moreover, the KBES evaluates and interprets the piezometric regime in the aquifers with respect both to known seasonal variations of the average piezometric levels and design limit situations. The effects related to the dewatering activities are also taken into account, evaluating the effects of the pumping activities on the aquifers and the efficiency of both the pumping wells and diaphragm wall sealing.

Several checks are performed, for instance, possible anomalies with respect to predictions are cross-checked with the groundwater levels to identify whether a change in piezometric levels may have caused the anomaly.

Expert System Performance

The KBES GEOMAN has been successfully installed and employed for the evaluation and interpretation of the geotechnical instrumentation data collected on a continuous base at the Caorso NPP and stored on a large data-base. System performance was very effective allowing for a continuous and real-time surveillance of the site. However, the processing time was found of over 24 hours when the whole instrumentation data set was processed with reference to an extended period of time (i.e. an year of data), using a HP-9000 for the expert system. The session related to only three months of data required about six hours.

The KBES interpretation resulted as close to the expert's conclusions within a sample period of two years (1986-1987), where "traditional" reports from geotechnical experts were available. All available data were processed, regardless the typical selective approach used by experts in the analysis of large data-bases. Moreover, the interpretation was performed in an automatic way, thus applying an uniform reasoning process to all data.

CONCLUSIONS

Innovative developments in the field of the structural and geotechnical monitoring of nuclear power plant sites have been presented, as applied to the surveillance of the Caorso Plant in Northern Italy.

Continuous monitoring of selected controlling parameters plays a primary role in the surveillance of the Plant safety. The engineer can take great advantage by the use of KBES in decision-making supported by a large number of instrumental data: firstly, control of the plant site and structures by a safety point of view is provided in real-time; secondly, hazard detection and warning procedures are introduced in the knowledge-base; thirdly, interpretation and updating of the site behavior parameters is performed by the KBES in an uniform, homogeneous and thorough manner throughout the whole life of the Plant.

The integration of KBES in monitoring systems appears as an effective new way for the analyst to interpret instrumentation data, and to provide insight in the behavior of engineering systems.

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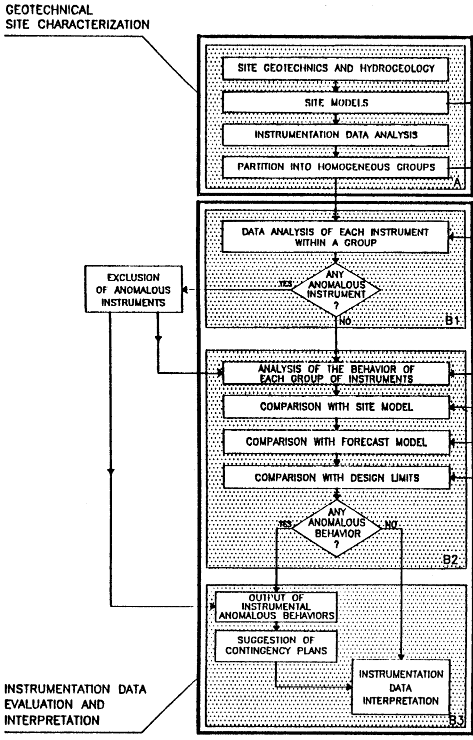

FIGURE 1 — INSTRUMENTATION DATA INTERPRETATION PROCESS

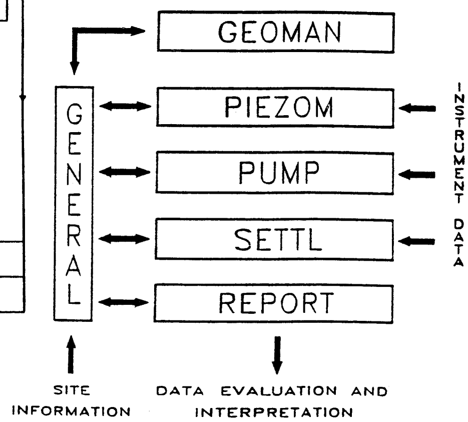

FIGURE 2 — GEOMAN STRUCTURE

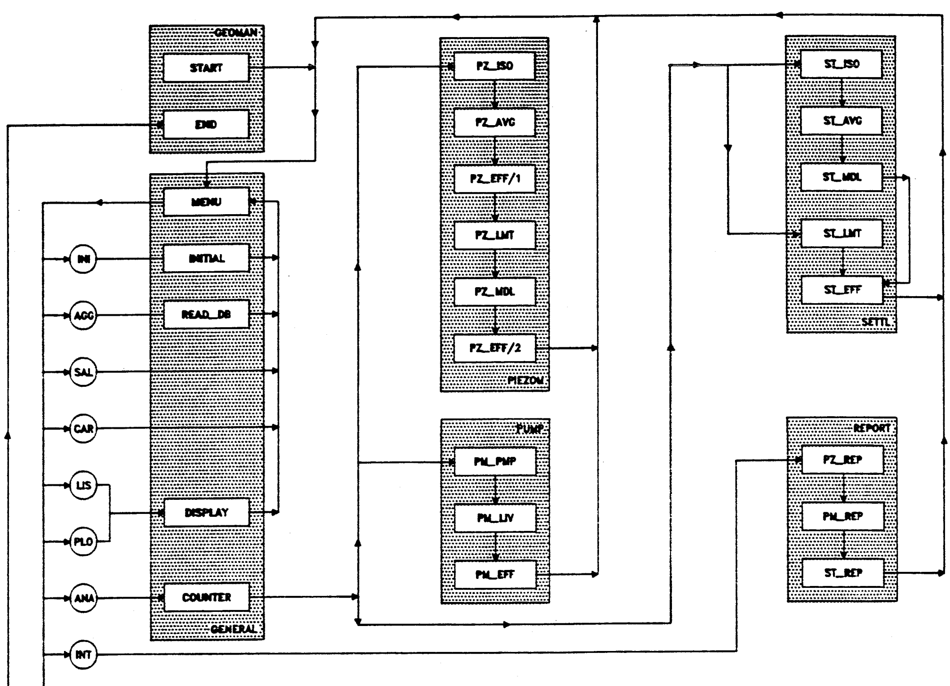

FIGURE 3 — GEOMAN FLOW-CHART