Landslide monitoring and analysis using GIS technology

D. Jean Hutchinson, Geological Sciences and Geological Engineering, Queen's University, Kingston
Mark S. Diederichs, Geological Sciences and Geological Engineering, Queen's University, Kingston
Rob Harrap, GIS Laboratory, Queen's University, Kingston

ABSTRACT
Landslide stability analysis poses special challenges to engineers faced with monitoring and remediation: geotechnical data is variable and contingent on geological, meteorological, and built-infrastructure factors that are generally poorly characterized. The objective of the sensor network analysis is to provide a manageable stream of information that can be evaluated in near-real-time so that critical decisions can be made. The Geotechnical In-Situ Technology Network (GIST) project combines geotechnical process modeling, case study development, and Geographic Information System implementation to provide a stored geotechnical framework of site knowledge and heuristics for analysis. A Decision Support System (DSS) forms the core of the system, using site knowledge and spatial and temporal reasoning approaches to manage the information flowing to a DSS display. Using techniques from digital library design, the DSS display also provides local context, historical data access, and tools for rule development. Ongoing research includes tool development and testing, and case study analysis for the development of the geotechnical rule base.

RÉSUMÉ
L'analyse de la stabilité des sols offre des défis particuliers aux ingénieurs faisant de la surveillance et de la remédiation: Les données géotechniques varient et dépendent de la géologie, de la météorologie, et des infrastructures déjà en place, facteurs qui sont généralement mal caractérisés. L'objectif de l'analyse du réseau de détecteurs est de fournir un flux d'information maîtrisable pouvant être évalué en temps quasi-réel afin de permettre la prise des décisions critiques. Le projet du Réseau de la Technologie Géotechnique In Situ (TGIS) combine le modelage de processus géotechniques, le développement d'études de cas, et l'implantation de systèmes d'informations géographiques, afin de pouvoir fournir, pour analyse, une structure géotechnique d'euristiques et de connaissances de sites. Un système de support de décisions (SSD) forme le coeur du système, utilisant la connaissance de site et le raisonnement spatiale et temporels afin de gérer l'information affluant vers un afficheur du SSD. En utilisant les techniques de *digital library*, l'afficheur du SSD fourni aussi le contexte local, l'accès aux données historiques, et des outils servant au développement de règles. La recherche en cours comprend le test et le développement d'outils, ainsi que l'analyse de cas servant au développement de la base de règles géotechniques.

1. INTRODUCTION

Landslide stability analyses include a wide variety of approaches, depending in part upon the level of understanding of the geological, meteorological and geotechnical factors influencing the stability, which in turn depends upon the stage of the engineering evaluation as well as the hazard posed by and consequence of failure of the unstable slope. Assessment approaches range from those based on empirical classification and evaluation of past history, through semi-quantitative, multivariate analysis of parameter maps, to heavily instrumented, monitored and modelled slopes. In all cases, geotechnical engineering analysis of the potential for slope instability is required. Confidence in the outcome of such analyses depends upon the quality and quantity of data available.

The subject of the research project reported in this paper is the enhanced evaluation of slope instability, where the ongoing collection and interpretation of data from geotechnical instruments provides the basis for a more rigorous site analysis, as well as the ability to establish thresholds for sounding early warning alarms and for activating emergency plans. Effective linkage between these components depends upon development of a geotechnically sound rule base to interpret and make decisions based upon the instrumentation data. Case history analysis forms the core of the development of the geotechnical rule sets, and the basis of demonstration cases which display the approach and the tools (for example, see Kjelland et al, this conference). Rule sets can describe the combination of multiple variable input data sets (for example, see Figure 1), or can quantify the basis for interpretation of data collected from instruments, and consequent warning levels and action arising from data interpretation.

A transformation of site-based engineering practice is underway, which should result in a complete rethinking of both the theoretical and pragmatic aspects of hazardous-site monitoring, analysis, and remediation. This transformation is centered around the evolution of new integrated sensor communication devices and the corresponding development of tools that are capable of accepting, translating, analyzing, and reporting on the data coming from sensor webs (Delin, 2002; Nickerson and Lu, 2004). "Sensor Webs collect information and interact with the environment, based on what they detect"

(Delin, as quoted in Rupley, 2003). This new technology of smart sensor webs integrates methods from sensor design (principally electrical engineering), from geographic information science (GIS), from computer science (principally artificial intelligence and network theory) and, in the case of this research project, from geotechnical engineering. Together these systems contribute to the construction of Decision Support Systems (DSS) for site investigation and monitoring. Decision Support Systems aim not to replace human experts and their hard-earned decision making ability, but rather to extend what the human can do, both in terms of efficiency and the range of factors considered in a decision, as discussed by Clancey (2004) for other applications. The system will support use by geotechnical experts and by instrumentation technicians.

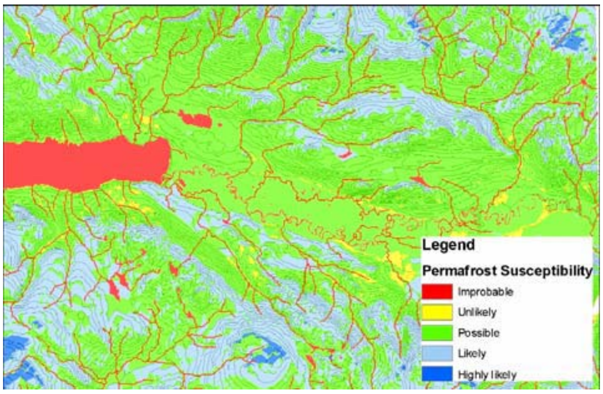

Figure 1: Susceptibility map based on multi-variate analysis within GIS (Lyle, 2004).

Little work has been done to date on combining geotechnical sensor data with GIS and DSS techniques, and especially on using the significant spatial analysis and visualization capacity available in GIS which would support rapid decision making for geotechnical domains, such as unstable slopes. The objective of the Geotechnical In-Situ Sensor Network (GIST) project is to combine sensor network monitoring tools with the results of geotechnical modeling and intelligent systems technology, to capture aspects of the geotechnical decision making process and thus support experts via a DSS. The basic framework is shown in Figure 2. The goal of the GIST DSS interface is to provide spatial analytical tools for operator-driven use, as well as an interface for programming decision rules, and furthermore to build these on commercial off-the-shelf GIS technology, to support flexible and potentially widespread use. The application of these approaches to slope monitoring programs is discussed in this paper. Further discussion of the development of the GIST tools can be found in Hutchinson et al (2004), and application to case study analysis in Kjelland et al (2004b).

The “Library of models” sector of the DSS shown in Figure 2 is of particular interest to geotechnical engineers. This sector includes a well-illustrated library of slope instability cases, allowing operational personnel to identify potential slope instability modes, based on guided review of field observations, using the slope classification scheme proposed by Cruden and Varnes (1996). Technical personnel will also use the model management portion of the DSS to carry out mechanistically appropriate slope stability analyses. It is intended that integration of the modelling tools into the GIST platform will encourage technical personnel to conduct sufficient analyses to improve their understanding of the sensitivity of the process to parameter variation, and to produce a probabilistic model of the potential for slope instability.

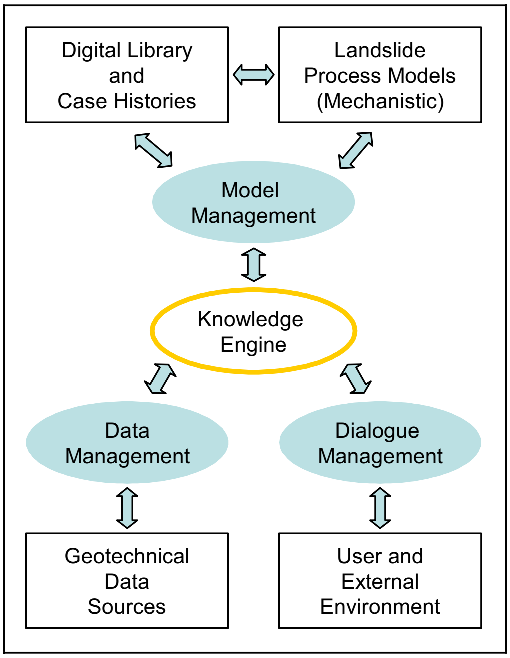

Figure 2: Decision support system framework. Geotechnical components of the system include the geotechnical instrumentation data linkage and sources, the case history library and the mechanistic landslide process modelling. The user and external environment will support both technical and expert levels of use.

2. GEOTECHNICAL SENSOR WEB ANALYSIS USING A GIS BASED DECISION SUPPORT SYSTEM

Decision Support Systems (Turbain and Aronson, 2000) comprise software, hardware, and human process systems combined to extend the ability of a decision maker to respond to large amounts of data, rapid changes in a system, and highly complex model dynamics. DSS tools are typically predominantly software systems and increasingly link across distributed, Internet-based information sources. However, in the case of geotechnical monitoring, significant physical infrastructure is typical. Furthermore, the physical infrastructure, including extensometers, inclinometers, piezometers and surface monuments, is spatially distributed such that the location of the sensors is critically important in interpreting results, both during normal periods and during sudden changes in the monitored domain, such as would result from material failure.

A DSS for geotechnical monitoring must be able to resolve complex geological systems that are often poorly understood, with incomplete information and abundant heuristic approximations substituting for rigorous physical models. These heuristics combine rules developed from process model based parametric analyses and empirical results from case studies. While classical DSS, such as stock market trading and air traffic control systems, have excellent capacity to show rapidly changing data visually and to perform near-real-time analysis, the unbounded and uncertain nature of geotechnical domains poses special challenges.

The challenge in building a DSS for geotechnical monitoring is to provide analytical tools that can handle large amounts of current and historical data in near-real-time. The system must both summarize the ongoing monitored situation and allow the expert operator access to sensor data, to underlying spatial data for the sensor environment, to supporting information such as reports, to heuristics that combine multiple sensors into easily interpreted summaries, and to the underlying logic of those heuristics. A geotechnical DSS thus includes elements of sensor output data viewing, time-domain analysis, document libraries, rule libraries, and rule output displays, and must do this in a way that makes clear what is actually known, what is conjectural or inferred, and what the distinction is based on.

Smart sensor webs, now being designed, rely on multiple small sensors that are capable of communicating in a wireless or wired manner; in the wireless case each sensor establishes networking with adjacent sensors and via the emergence of a spontaneous communications web, with central nodes such as links to workstations, to the Internet, or to data storage. Currently realized systems often use hard-wired links between sensors, and in the geotechnical domain these sensors include, amongst others, extensometers, inclinometers, tiltmeters, piezometers and surface displacement monuments. Each sensor, whether wireless or hard-wired, contributes attributed information to the DSS; the keys to analysis are the readings taken by the device, the device identity, the time of the readings, the type of device, the location of the device, and the communications pathway. When combined with spatial information in a GIS, these allow analysis of the sensor readings in the context of the geospatial setting of the sensor. The device identity and the communications path contribute, both in terms of identifying the data source and, in the event of device failure – the destruction of a device is itself vital information when monitoring a dynamic site with the potential for rapid failure.

In the case of Decision Support Systems that need to respond quickly, or in 'near-real-time,' readings need to be analyzed not in a slow, after-the-fact fashion, but almost instantaneously. This can be accomplished via software agents that attach significant consequences to specific device readings, or to their absence, such as heightening an alert state, setting of a visual and audible alarm, and perhaps changing the monitoring state of the sensor network itself. Many existing systems for device control and site monitoring embody these types of alerts. However, given that sensor readings are ideally used to contribute to a general understanding of the evolving situation at a site, rather than as individual, disconnected evidence, sensor-monitoring agents should ideally encapsulate the full range of decision modes that multiple readings from a variety of instruments over time within a geospatial context will allow. This is especially vital when the system itself will do preliminary categorization of event significance and severity.

Individual sensors can be treated as points in a GIS context. Supporting geospatial information includes historical data values at these points, line-like features representing the surface expression of geological structures and built infrastructure, and polygon-like features representing geological units, comprising surficial deposits, rock layers, fluctuating piezometric surface(s) and weakness zones, such as faults and shear zones. Data from sensors located in the same rock mass are more relevant to one another than are data collected from sensors across geological transitions such as faults, or from different slopes. Building a system capable of intelligently grouping sensors, considering geological data, using traditional engineering techniques is not practical, since any change to the geotechnical logic of the system would require re-engineering of the DSS itself. Separating the logic from the low-level GIS operations offers a much more flexible and adaptive approach. This requires the integration of techniques from artificial intelligence, and in particular expert systems, with more traditional data- and spatial-analysis centric GIS.

In GIST, the ArcAgent programming environment supports the logic of sensor data fusion and analysis, and requests spatial analytical operations, data storage and retrieval, as well as display functionality from ArcGIS. The general structure of the environment is shown in Figure 3.

The CLIPS environment supports both rule-based programming (such as highly flexible rules for handling contingent sensor data) and meta-programming, where rules are generated on-the-fly or under supervision of a geotechnical engineer, allowing the system to evolve as site conditions change and more is learned about the on-site conditions. Furthermore, the rule-base can be extended through numerical modelling of slope stability, both in terms of considering existing case studies with abundant data, and to assess the influence of probable future impacts and influences on the stability, using process modelling approaches for situations out of the scope of past experience.

Rules expressed in the GIST ArcAgent system thus attach conditions to near-real-time sensor data, with conditions ranging from the presence of a sensor, through location- and setting- dependent condition-action rules, through to the use of multiple sensor data values in compound rules embodying complex condition-action situations. Since rules may include reference to current or historic values for any sensor (via the GIS database) and may furthermore perform spatial analysis on the values (via the geo-processing tools in ArcGIS), very complex spatio-temporal mechanisms can be modelled.

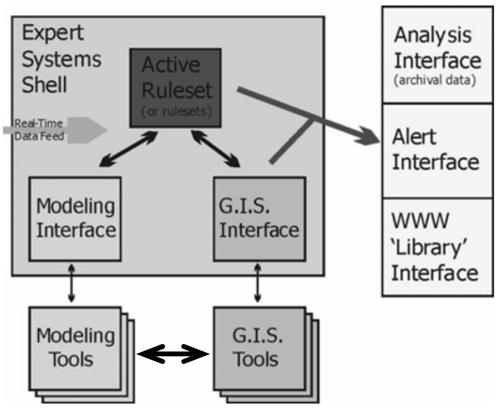

Figure 3: ArcAgent structure and interaction with the GIST system. Geotechnical data enters via the R-T data feed.

One key concept is of abstract clusters of sensors and virtual sensors; abstract clusters hide the details of multiple individual sensors under one overall alert-state sensor, radically simplifying a DSS display. Abstract clusters may be 'opened' through a simple mouse click to reveal the underlying raw data feeds, corresponding displays, and the rules that embody the abstract cluster. As a result, an interface supporting multiple scales of observation can be built, that both provides a succinct overview and access to underlying data.

Virtual sensors treat locations with existing and frequently updated geospatial data as sensors, allowing, for example, repeated LIDAR slope monitoring efforts to be combined into a number of 'watch points'. Thus, remote sensing data can be fully incorporated into a rule base and the GIST system may be used for both local data, areas dominated by multiple wired sensors, and for very large areas, where remote sensing data and indirect data such as weather measurements might dominate. The rules compress the details of this into a simpler interface, exposing only the elements that a human expert needs to be aware of; this is obviously conditional on the site character and the level of expertise of the monitoring geotechnical engineer, and thus it must be possible to reconfigure the DSS to match these changing needs. The system is being developed to present the data at the different levels of detail required for decision making by geotechnical experts and by site operation personnel.

The DSS interface that GIST provides thus includes a number of very useful utilities: cartographic elements (where sensors are, what their current alert and reading state is – Figure 4), information querying and visualization elements (profiles of sensor values for a number of sensors, grouped by proximity or geotechnical setting), access to historical data and reports in a digital library, and access to the rule-development environment. GIST will have two fundamental modes of operation: a monitoring mode, where rules fire in response to current sensor states, and a reflexive mode, where the system is used to generate new rules, based on historical data. In the reflexive mode, new rules may be developed and tested against data from a site or from an analogous case study or modelling results, without the system being explicitly 'told' that the data is not current. As such, this mode presents the opportunity for rule development and testing under the control of a geotechnical expert. GIST and ArcAgent thus provide a framework for testing sensor array configurations, new sensor analysis paradigms, automated rule generation, and linkages between numerical modelling and GIS approaches to geotechnical monitoring.

3. DEVELOPMENT OF GEOTECHNICAL RULES FOR GIS BASED SLOPE STABILITY MONITORING

The main objective of the geotechnical rule development task is to provide a semi-automated, technically sound basis for assessment of slope stability from monitoring data. Current approaches to data compilation and interpretation generally involve a significant time commitment by both operator and technical expert for examining data on a case by case basis, and few tools are available for creating queries based on geological data. The objective of this work is to develop a semi-automated analysis, based on geotechnical rules, which can post warning levels based on near real-time tracking of the data.

Generally the data available from insitu geotechnical sensors is recorded frequently enough to provide virtually continuous time series data, but is relatively sparse spatially, due to the distance between sensors, both downhole and across the surface of the landslide mass. Geostatistical approaches to analysis of sparse data, including kriging and co-kriging, are being utilized (as shown in Figure 5). At this relatively early stage of the project, substantial expert interaction with the system, to ensure that the interpolation of the sparse data is reflective of insitu conditions is required.

The natural variability of geological material properties creates another hurdle for developing geotechnical rules. Probabilistic distributions are being used to account for material property ranges. A large number of numerical simulations, using the calibrated model of the slope (see Kjelland et al, this conference), are being run to assess the effect of material property variability and combinations of trigger factors on the stability of the slope. Eventual development of a catalogue of these pre-computed results, using the calibrated model for a specific slope, will allow quick investigation of the sensitivity of the slope to changing conditions, should rapidly changing instrumentation data be encountered.

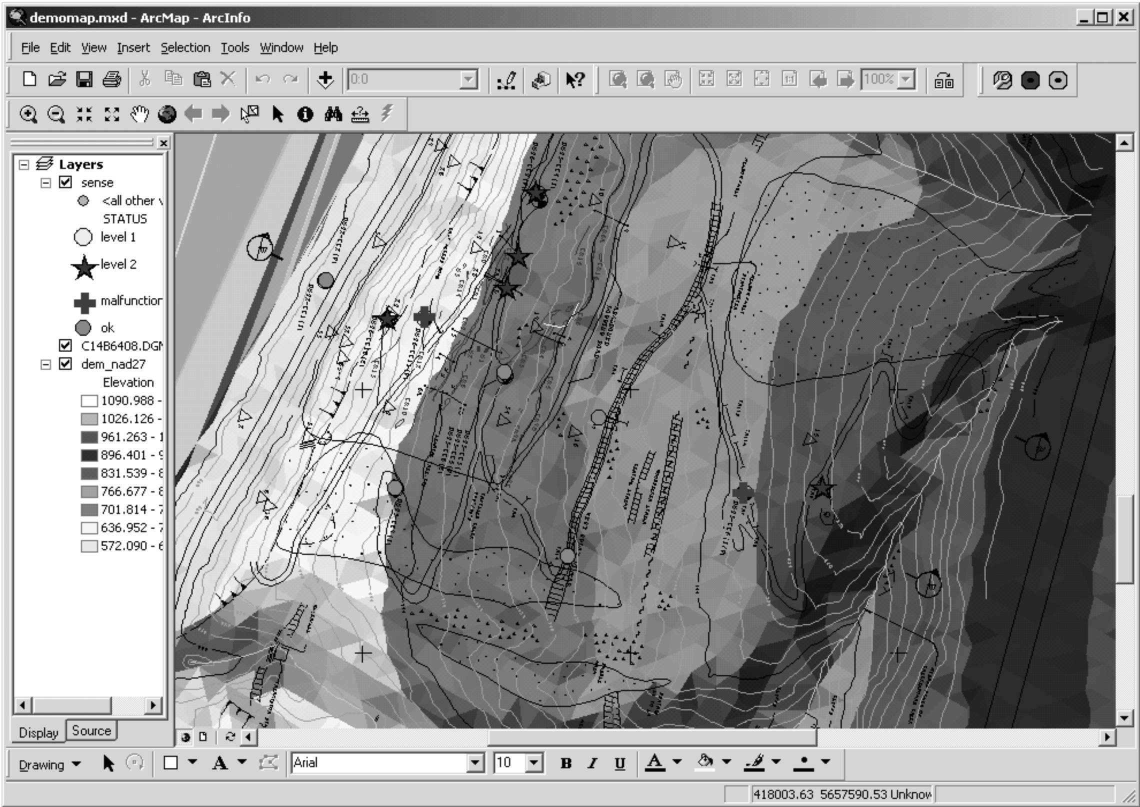

Figure 4: Plan view of sensor display for geotechnical instruments located within a slope, including status indicators for a sub-set of sensors abstracted from the data set.

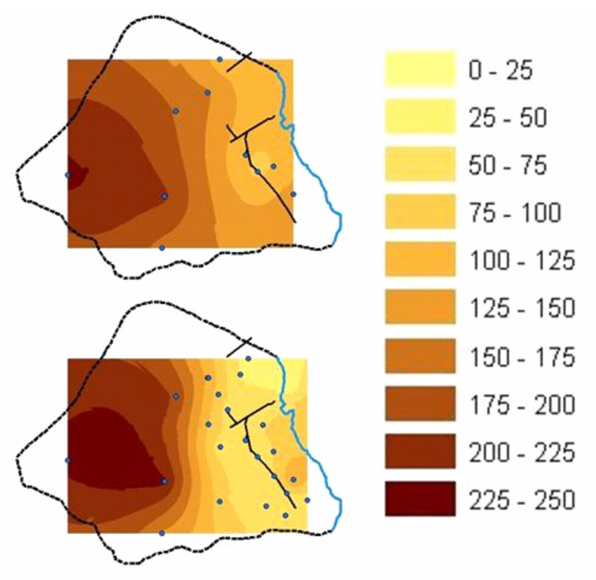

Figure 5: Piezometric elevations relative to the base of the slide, for initial readings in 1977 (top), and current readings (bottom). The change is due to the operation of a slide drainage system for many years. For more information, see Kjelland et al (2004).

Indicators of certainty in data are also being considered during the development of the geotechnical rules. More certain data is weighted more heavily in the multi-variate geospatial analysis to account for the influence of uncertainty on the data analysis. It is possible to change the weighting values as experience with the slope behaviour and with instrumentation data are gained – this assessment of the data is supported by the reflexive mode being included in GIST. It is anticipated that confidence levels will be applied to the outcome of the analyses, as well.

The geotechnical analysis required to develop the rules is facilitated by the GIST framework in several ways. Baseline geotechnical data is maintained within the system, with overlays displaying historic data and interpretation for ease of analysis. The tool provides a structured way to integrate various data sources for further analysis. In addition to these improvements in the analysis capabilities, the structure of the digital library allows examination of archived data, to provide some continuity, even with personnel change over, and potential loss or replacement of instruments within various parts of the slope. Furthermore, examination of the cases and models stored within the digital library provides the opportunity for operator training and for capturing technical expertise.

4. CHALLENGES

Development of geotechnically sound rules for interpretation of instrumentation data across a network of instruments on a large landslide, requires the compilation and evaluation of a substantial database of observations, instrumentation data and the capture of existing human interpretation and experience. This requires a detailed ‘anthropological’ study of the human expert and their interaction and interpretations, extended by process modelling using geomechanics software. While complex and time consuming, the outcome of this work should provide an enhanced analysis tool for the expert and technical support staff alike.

Most identified landslides are not as heavily instrumented as the cases under consideration during this current study. Further challenges are created by the need to support decision making about slope stability for sites where geological data and/or remotely sensed images are the only basis for stability analyses.

5. ONGOING WORK

Further work on the GIST engine will result in semi-automated rule development, based in part upon process modelling analysis for a variety of slope failure modes through case history development. As semi-automated approaches to rule development and sensor monitoring are further developed, other AI/GIS tools, as well as SCADA systems, will be considered.

Continuing research will include the extension of the GIST approach to consider railway transportation corridors and the potential for sparse sensor and proxy sensor data analysis.

6. CONCLUSIONS

GIST provides the opportunity to study the use of rule-based techniques to handle sensor network data in the geotechnical domain, well outside the traditional scope of such techniques. Specific challenges include the profound under-sampling and uncertainty of geological knowledge in nature, the highly site specific nature of engineering solutions, and the need to have reliable results, despite these limitations. GIST also provides the opportunity to understand the application of sensor webs in general to geotechnical engineering. As distributed micro-sensor webs become more common, if not pervasive, understanding how these webs can be utilized is crucial to their effective application to real situations.

7. ACKNOWLEDGEMENTS

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