Geotechnical monitoring system based on the analysis of geospatial data

Losier, L.M., Dors, C., Mahler, C.F. & Mansur, W.J.
Department of Civil Engineering – Rio de Janeiro Federal University, Rio de Janeiro, Rio de Janeiro State, Brazil
Desgagné, E., Garchet, P.M., Portela, M. & Schuler, A.R.
Geovoxel, Rio de Janeiro, Rio de Janeiro State, Brazil

ABSTRACT

With the recent technological developments, significant advances were made improving geotechnical instruments and their ability to generate and transmit data. However, a consequence of the speed of innovation is the arising of new technological gaps. One of the shortcomings identified are directly associated with integration and processing capacity of such a complex set of information available which, in turn, complicates the final analysis of the professionals involved in the decision phase. In this context a highly innovative application integrating Geomatics with Geotechnics has been designed and implemented. This implementation brings together several geotechnical tools that offer data acquisition, processing and analysis capabilities of field information through dynamic charts integrated with satellite imagery and geospatial information in the form of interactive maps. This monitoring platform allows the decentralization of decision, generating interaction among the engineers involved. By its integrator character, this platform can be used for the monitoring of complex heavy engineering works, mining operations, oil and gas explorations, sanitary landfills, in addition to the prevention of natural events that conduct many cases to disasters and their severe consequences.

RESUMEN

El actual desarrollo tecnológico ha traído consigo avances significativos mediante el uso de instrumentos geotécnicos, así como también por su capacidad para generar y transmitir datos. Sin embargo, con esta rápida innovación han surgido también algunos inconvenientes. Uno de ellos está directamente asociado con la integración y la capacidad de procesamiento de complejos conjuntos de información disponible. Esto complicando a su vez, el análisis de los profesionales involucrados en la fase de toma de decisiones. Por ello, una aplicación altamente innovadora que integra la Geomática, ha sido diseñada e implementada, la cual reúne diversas herramientas geotécnicas que ofrecen tanto capacidad de adquisición de datos, como también de manipulación y de análisis de información *in-situ* a través de información dinámica, integrada con imágenes satelitales, e información geoespacial en forma de mapas interactivos. Esta plataforma de monitoreo permite descentralizarla toma de decisiones, generando interacción entre los ingenieros involucrados. Gracias a su carácter integrador, esta plataforma puede ser utilizada tanto para monitoreo de trabajos de gran complejidad en ingeniería pesada, como también en operaciones mineras, exploración de petróleo y gas, rellenos sanitarios e inclusive para prevención de desastres naturales y sus nefastas consecuencias.

1 INTRODUCTION

Recently, significant advances were made with geotechnical instruments and their ability to generate and transmit data. Now that geotechnical projects have access to a potentially huge quantity of field information, the actual issue may not be situated in the generation or transmission capacity of information, but more on the integration, organization, manipulation and distribution of the raw data in order to help and support the decision making. Moreover, parts of these raw data (as the georeferenced position of field components like instruments or boreholes) have a spatial dimension that needs geomatics skills to be exploited adequately. Geomatics is a multidisciplinary science that provides tools for acquiring, integrating, processing and analyzing spatial data.

Gomarasca (2009) defines Geomatics as a systemic, multidisciplinary, integrated approach to select the instruments and the appropriate techniques for collecting, storing, integrating, modelling, analysing, retrieving at will, transforming, displaying and distributing spatially georeferenced data from different sources with well-defined accuracy characteristics, continuity and in a digital format.

A first prototype of a geomatic application applied to the geotechnical field was tested during the construction of a tunnel in an historic district in Brazil which was listed by the IPHAN (National Institute of Historical and Artistical Patrimony of Brazil). This site was particularly complex as, there were old buildings showing signs of cracks and crevices. This prototype used ArcGIS from ESRI, the world leader in Desktop Geographical Information System (GIS) and Rockworks, a well-known software for 3D modeling of geological environment. A GIS is a powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world (Burrough, 1986). The ArcGIS

software used by this prototype allows exporting database and GIS layers to a free ESRI Viewer, ArcReader that was distributed to the client users giving them a full access to the project database, thematic maps and static graphs. ArcReader files were produced every day and available to download from a web portal. This portal was offering information and functionalities like historic access control recording ,blog for fieldwork diary, online calculation of rock mass rating (RMR) (Bieniawski, 1989), Q-system rock classification (Grimstad and Barton, 1993) and isocontour settlement graph produced from settlement pins and benchmarks/tassometers data using geostatistical technique named ordinary kriging. The tunnel construction project has shown several interesting results. Among them, there is the integration and centralization of information in a single GIS environment and web portal. It has also helped reducing construction time and risk during the construction process resulting in a better return on investment for the constructors. Since then, several changes were made to improve the system and solve some problems such as the lack of automation for huge quantity of manual data process; the difficulty to maintain synchronized the client database, the lack of a web based GIS solution, the impossibility to fill online forms for managing instrumentation requirement, etc... To resume, a much more friendly solution was needed for the end users.

Desktop GIS and web-based GIS have been used in several recent civil engineering applications: tunnel construction (Choi et al., 2009; Nejatbakhsh, 2008); slope stability problems (Gabriele et al., 2009; Lan et al. 2009; Xie et al. 2006); automated seismic microzonation (Antoniou et al. 2008); excavation operation (Hashash and Finno, 2008); earthquake-induced hazard prediction (Sun et al. 2008); hazardous conditions in near-real-time (McCarthy et al. 2008); borehole data management (Chang and Park, 2004). Nowadays, Geographic Information Systems (GIS) and Computer-Aided Design (CAD) systems are widely used in the tunnelling industry and play important roles in the process of subsurface characterization (Choi et al., 2009).

From field sensors, satellite images and weather information, the GEOVOXEL develops customized systems GVX for each type of need, integrating data automatically (depending on the nature of the instrument if it is manual or automatic lecture), allowing storage and processing of historical data for instant previews on WebGIS and dashboard. Just by clicking on an icon that represents an instrument, it can display data table of the spatial database, or a dynamic graph on the WebGIS and the join files (pictures, pdf report, and other kind of files format).

The GVX users have immediate access to structured information and quality over any Internet connection, using computers, cell phones and other mobile devices, and also receive alerts from the instruments on the devices.

Another kind of system in few similar aspects to GVX was developed by Gabriele et al. (2009) for landslide monitoring, collecting and processing data from heterogeneous sensors as GPS, inclinometers, ground rain gauges, piezometers, and extensometers in real time and immediately made available on the web through a special user-friendly portal (including a WebGIS).

In addition, the **technological benefits** related to the project development were on three levels: (i) **strategic level** - Reducing the Risk involved in the operation and maximization of investment, (ii) **tactical level** - Great contribution to decision making by integrating external technical staff relevant to the process and keeping in a single environment all the information of the enterprise, and (iii) **operational level** - easy learning tool, available 24X7, centralizing all documents, files, pictures, readings and transforming the role of human resource functions involved in operational management.

Another technological advantage of the GVX is that it can be used to monitor several phases of engineering projects: characterization, construction and operation.

2 PROJECT CONSTRUCTION PHASES

2.1 Characterization

Site characterization or Pre-Construction phase is the first step in geotechnical assessment. It begins with a geological mapping during prefeasibility studies and progresses through exploratory borings, permeability measurements, laboratory testing, and perhaps large scale in situ rock mechanics tests during the feasibility and design phase of the project. The purpose is to understand the geology of a site, to estimate geometries and material parameters for engineering analysis, and to ensure that details of the site geology that might adversely affect facility performance have been identified (Merritt, 1981).

The exploratory borings can usually be a Standard Penetration Tests (SPT) at regular depth intervals. This type of exploration provides an indication of the soil or rock types and relative density or consistency at the depths and locations tested. Bulk samples, Shelby tube samples, core samples, etc. may be utilized to obtain samples for specific types of laboratory tests.

The use of Kriging, a geostatistical technique, on SPT allows creating a subsurface model of lithology layers. Kriging has the ability to honour a true value at a sampled site and to provide estimates from data points in close proximity and its uncertainties, at unmeasured sites. This procedure estimates unsampled values by calculating the weights assigned to the individual neighbouring points. These weights depend on the spatial relationship between values and distances between the sampled and unsampled data points. These spatial relationships are quantified by constructing a semivariogram, which is fundamental to geostatistical analyses.

The three-dimensional geological and geotechnical model (Figure 1), based on boreholes, shows on the cross-section (Figure 2) extracted from the 3D model that: for future phases of work of the tunnel, granular soil will be found, especially in the vault. Those cross-section can be performed anywhere on the 3D model.
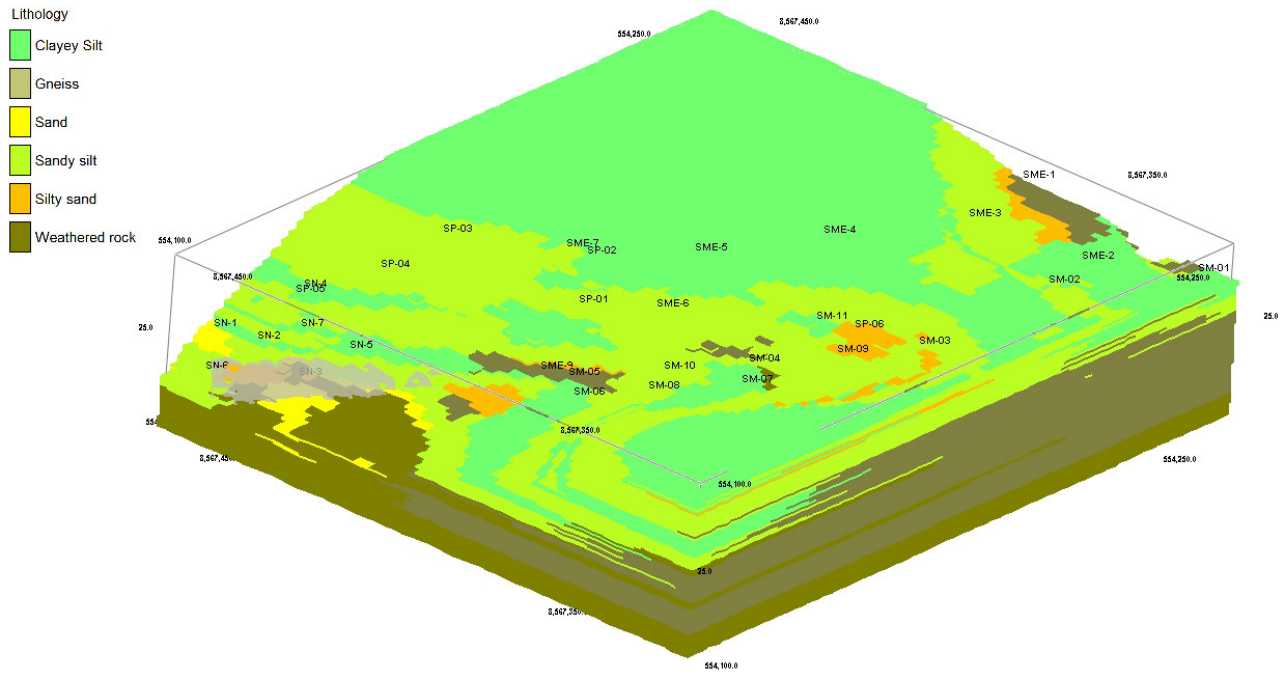
Figure 1. 3D subsurface modeling of lithology layers of the tunnel region using geostatistical interpolation of borehole data.
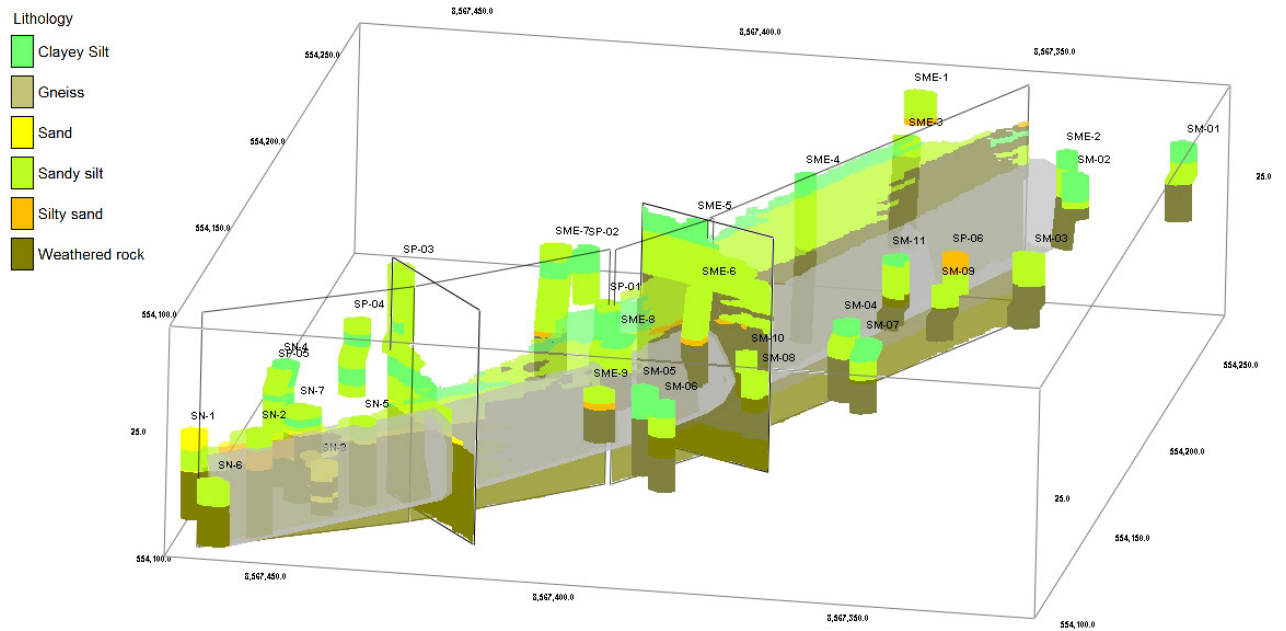

Figure 2. Cross-section along tunnel line and few transversal cut.

The boring data and cross-section extracted from the 3D model are the first data to be georeferenced in the GVX system allowing the geotechnical engineer to consult easily those spatial data just by a simple click and will help the decision making of the geotechnical engineer. The 3D model of the rock layer is joined to

each borehole allowing to consult the Virtual Reality Modeling Language (VRML) model online in a free viewer plug-in Cortona3D (http://www.cortona3d.com/).

2.2 Construction and operation

During the construction phase of the project, instruments are used to monitor the effects of construction. The data acquisition can help the engineer to determine how fast construction can proceed without the risk of failure. Instruments can provide early warning of impending failures, allowing time for safe evacuation of the area and to implement remedial action.

Lambe (1973) has shown how designs/predictions are limited by both the method used and the data quality available and that a balance is required to maximise the accuracy of the prediction as shown in figure 4. With this figure, the author also shows that for a highly accurate data and a method of low quality or vice-versa the accuracy of the prediction will be worse.
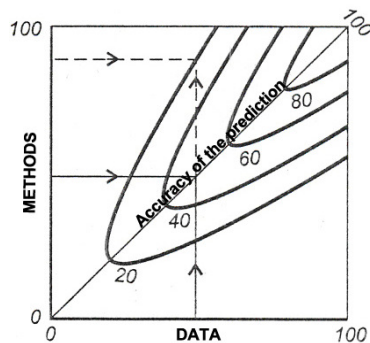

Figure 4. Accuracy of the prediction (Lambe, 1973).

Safety monitoring requires quick retrieval, good data quality, processing, and presentation of data, so that decisions can be made promptly. This was done during the tunnel construction. The instrumentation in this case used manual lecture for the monitoring of: 8 inclinometer, 31 benchmarks, 6 tassometers, 146 settlement pins, 23 Seismographs, 2 piezometers, 1 pluviometer, and 12 convergence sections.

According to Lunardi (2008), there are two construction stages: the operational and the monitoring. The operational phase is during the works for the stabilisation of the tunnel that are carried out on the basis of the design prediction. The project is monitored on the basis of a quality control programme prepared in advance. The monitoring phase is during the deformation phenomena (response of the medium to tunnel advance) where the data are being measured and interpreted during construction. The monitoring phase does not end when the tunnel is completed, but continues during its whole life to ensure that the main structure and surrounding environments are safe.

3 PRELIMINARY RESULTS

One of the main purposes of this system is to support these phases (characterization, construction and operation) to help the geotechnical engineer in his decision making process. As mentioned in the introduction, the GVX system will give answers to several gaps encountered during the prototype experimentation, in 2009. This system has entered in a production mode, in February 2011, for the monitoring of instrumentation during the construction of a mineral stock-pile on soft-soil in a strategic port of Brazil.

3.1 GVX system

The solution proposed is an innovative web platform designed to store and delivers all data produced prior to the project construction phase and all data collected and calculated during the instrumentation process. This information is designed to be accessed by various stakeholders that will experiment a specific experience based on his role in the project. For example, the field engineer will have access to forms and wizards that allow him to upload measured data as the project supervisor will concentrate on the analysis of charts and table data that give him suitable information to help him make better decisions. This adaptive interface implementation of the portal is based on a complex security and content management workflow that make possible the interaction of field workers with engineers, data analyser and decision-makers. One of the main characteristic of this system is its data access driven by a dynamic mapping widget that show all field components in the form of clickable georeferenced objects and events that bring to the user all information he needs in an intuitive approach. This information ranges from field collected raw data to real-time generated dynamics charts, pictures, boreholes lithology cross-section, daily commentaries, etc..., including historic values. This system also offers an advanced alert system that will advise users in case of any inappropriate value measured by instruments on the field.

The mapping capability of this monitoring system is due to the spatial database management system that the monitoring system is based on. This allow the integration and attachment of all the history of data measured and generated during a heavy engineering project to his relevant georeferenced components as the buildings, the instruments, the boreholes, the seismic zone, the mining concessions, the mineral or tailing piles, the hydrographical elements, the communication ways, etc... The GVX platform gives access to all this spatial information along with its descriptive properties in a unique, friendly and fast Web interface (figures 5 and 6).

Also, by its generic character, GVX platform allows any type of field instruments from any brand to be configured and monitored. Specific constants used in charts generation calculation or instrument calibration may be specified as input values to allow accurate calculation. The functionalities of this system may be successfully applied to any project of any sector where geotechnical monitoring is needed.
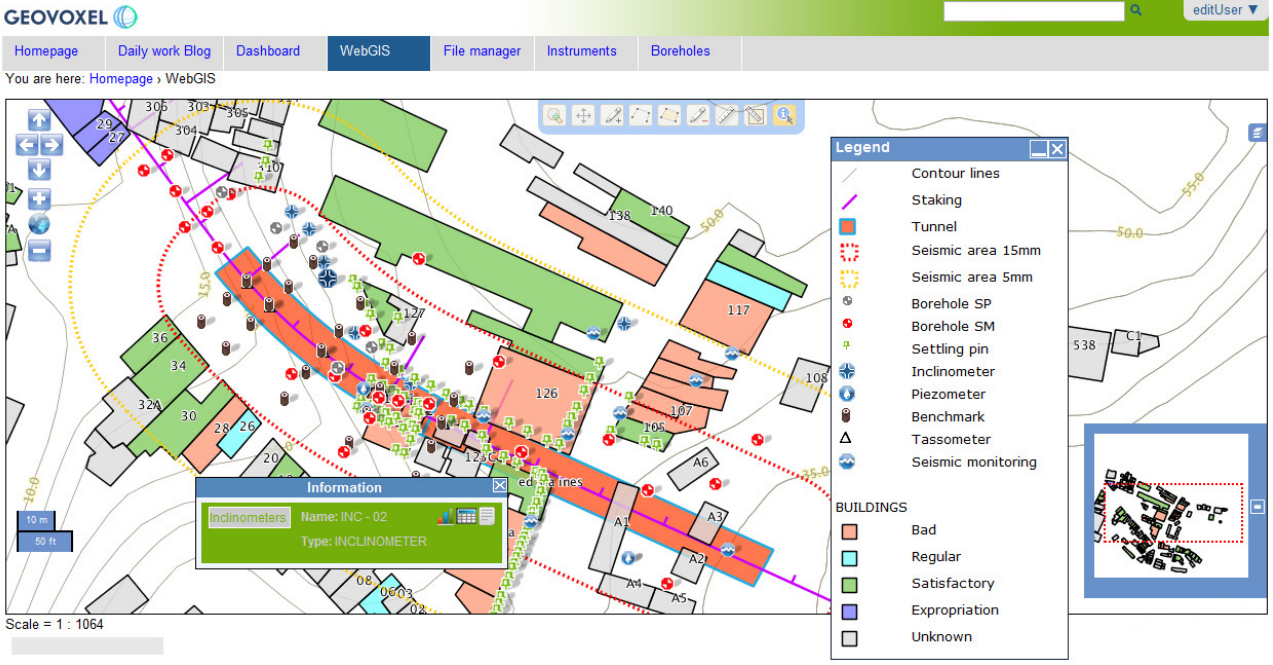
Figure 5. WebGIS of tunnel area.

Figure 6. Dashboard of dynamic graphics showing data of geotechnical instrumentation (inclinometer at the left; and settling pin graph at the right).

4 DISCUSSION AND CONCLUSIONS

This paper discusses how Geomatic sciences combined with recent information technologies can help Geotechnical Engineering in a decision making process. Geomatics has a systemic, multidisciplinary and integrated approach that allows georeferenced information to be processed, managed and presented with its corresponding alphanumerical data in a friendly way so that users from a variety of disciplines can take advantage of the extra value offered by this kind of system.

The new GVX web portal was presented as an innovative tool to help improve and support complex Geotechnical fieldwork offering specific and useful Web tools like blog, dashboard, geographic information system (WebGIS), dynamic charts, intelligent forms, events and content management, etc. This experience has shown that theses functionalities are very useful in supporting complex monitoring and investigation projects. This web portal has shown significant improvement compared to the first prototype, solving, among others things, the lack of automation for huge quantity of data, worksheet type calculation and generation, the difficulty in maintaining synchronized the client´s database, the lack of a web based GIS solution, the impossibility to fill online forms for instrumentation data input, etc.

At this moment, this GVX Geotechnical monitoring platform is in use in a construction of a mineral stock-pile on soft-soil and it already has demonstrated his help to the fast decision making. In addition to being a useful tool to organize and manage in a unique integrated environment all data obtained and generated in all phases of the construction process, it can improve the safety of the construction work.

Some development is still in progress to improve the user's decision-making process. A new set of functionalities will be implemented to manage heterogeneous data sets in 3D and 4D (3D + time).

REFERENCES

Antoniou, A.; Papadimitriou, A.; Tsiambaos, G. 2008. "A geographical information system managing geotechnical data for Athens (Greece) and its use for automated seismic microzonation". *Natural hazards*, v. 47, n. 3, p. 369-395.

Bieniawski, Z.T., 1989. *Engineering Rock Mass Classifications*. Wiley, New York, USA, 272pp.

Burrough, P. A. 1986. *Principles of Geographical Information Systems for Land Resource Assessment.* Oxford: Clarendon Press.

Chang, Y. S. and Park, H. D., 2004, Development of a web-based geographic information system for the management of borehole and geological data: *Computers Geosciences*, Vol. 30, No. 8, pp. 887–897.

Choi, Y.; Yoon, S. Y.; Park, H. D. 2009. "Tunneling Analyst: A 3D GIS extension for rock mass classification and fault zone analysis in tunneling". *Computers & Geosciences*, v. 35, n. 6, p. 1322-1333.

Chung, J. A. E. W. O. N.; Rogers, J. D. 2010. "GIS-Based Virtual Geotechnical Database for the St. Louis Metro Area". *Environmental and Engineering Geoscience*, v. 16, n. 2, p. 143.

Gabriele, S.; D'aquila, G.; Chiaravalloti, F. 2009. "A Distributed Real-Time Monitoring System for Landslide Hazard and Risk Assessment". *GeoSpatial Visual Analytics*, p. 387-394.

Gomarasca, M. A. 2009. *Basics of Geomatics*. New York: Springer Science.

Grimstad, E., Barton, N., 1993. Updating of the Q-system for NMT. In: *Proceedings of the International Symposium on Sprayed Concrete*, Fagernes, Norway, pp. 44–66.

Hashash, Y. M. A.; Finno, R. J. 2008. "Development of new integrated tools for predicting, monitoring, and controlling ground movements due to excavations". *Practice Periodical on Structural Design and Construction*, v. 13, p. 4.

Lambe TW. 1973. Prediction in soil engineering, *Geotechnique*, 23(2), 149-202.

Lan, H.; Martin, C.; Froese, C.; Kim, T.; Morgan, A.; Chao, D.; Chowdhury, S. 2009. "A web-based GIS for managing and assessing landslide data for the town of Peace River, Canada". *Nat. Hazards Earth Syst. Sci*, v. 9, n. 4, p. 1433-1443.

Lunardi, P. 2008. Design and construction of tunnels: analysis of controlled. Publisher: Springer - 576 pages

McCarthy, J. D.; Graniero, P. A.; Rozic, S. M. 2008. "An integrated GIS-expert system framework for live hazard monitoring and detection". *Sensors*, v. 8, n. 2, p. 830-846.

Merritt, A. H.; Baecher, G. B. 1981. "Site Characterization In Rock Engineering"..22nd U.S. Symp. on Rock Mechanics, pp. 49-66.

Sun, C. G.; Chun, S. H.; Ha, T. G.; Chung, C. K.; Kim, D. S. 2008. "Development and application of a GIS-based tool for earthquake-induced hazard prediction". *Computers and Geotechnics*, v. 35, n. 3, p. 436-449.

Xie M, Esaki T, Cai M. 2006. GIS-based implementation of three-dimensional limit equilibrium approach of slope stability. *J Geotech Geoenviron* Eng ASCE 132(5):656–660.