INFORMATION TECHNOLOGY APPLIED TO ENGINEERING GEOLOGY

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ABSTRACT: This keynote paper describes the application of Information Technology to various aspects of Engineering Geology, from data requirements, data handling and processing to numerical and GIS modelling and visualization. It is illustrated with a number of practical examples developed in The Netherlands.

RESUME: Cet article décrit l'application de technologie de l'information à des aspects d'ingénierie géologique, depuis la demande des données, l'arrangement et le traitement des données, jusqu'à la modélisation numérique et la modélisation en SIG, ainsi que la présentation des résultats. L'article est illustré à l'aide de quelques exemples pratiques développés aux Pays Bas.

INTRODUCTION

In this keynote the following definitions are used for the key terminology:

Information Technology refers to methods of handling information by automatic means, including computing, telecommunications, and office systems. It deals with a wide range of mostly electronic devices for collecting, storing, manipulating, communicating and displaying information.

Knowledge is pragmatically defined in the context of IT as "justified true belief; as a shared human response to a complex environment".

Information can be defined as something that adds to one's knowledge and understanding, and includes data (known facts) and their interpretation.

The book of Loudon (Loudon, 2000), from which these definitions were taken, is a good introduction to the topic of IT in the Geosciences. (Figure 1) describes the relation between the elements in information technology.

IT offers opportunities for efficient handling of engineering geological information. The two most significant aspects of IT for technical geosciences are (Loudon, 2000):

The obvious ability of computers to calculate, thus opening up possibilities of more rigorous analysis with quantitative and statistical methods, and more vivid graphical presentation with visualization techniques.

The manipulation and management of information; this ranges from the ability to move elements of a picture in a graphics system to the ability to capture data, store vast quantities of information in a database management system, and retrieve specific items on demand.

IT influences the way in which engineering geologists investigate the real world, how they communicate, what they know and how they think. This can lead to better science, cost savings, increased speed and flexibility in data collection, storage, retrieval, analysis, communication, and presentation.

Since the spectacular increase of calculation power in the 1960's and 1970's through the development of computers, engineering geologists and geotechnical engineers started the development of digital methodologies to support the effective and efficient execution of their work. Initially this development focused on the application of the enhanced data handling capacity and calculation velocity to introduce more detail in conventional methods of slope stability calculation, the calculation of the behaviour of soil and rock around tunnel openings and in foundations and earthworks to obtain more refined results.

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Soon, in the seventies and eighties, however, the further growth in calculation speed and in the handling capacity of large data volumes (as well as the increased accessibility of calculation power in the form of PC's) enabled the development of new methods of geotechnical analysis (finite element, finite difference, distinct element, and particle flow methods), allowing for models of irregular forms with the third dimension, consisting of materials with more complicated stress-strain relationships (including strain softening and the like). The fourth dimension was introduced where progressive stages of excavation and/or loading, and or time dependent deformation processes introduced time as an important factor into the analysis.

Other important developments that became possible with the ever increasing calculation speed and data handling capacity at relatively low cost levels are in the field of database systems for the storage and retrieval of geotechnical surface and borehole data and in the field of 2D, 3D and 4D geo-information systems and related visualization techniques.

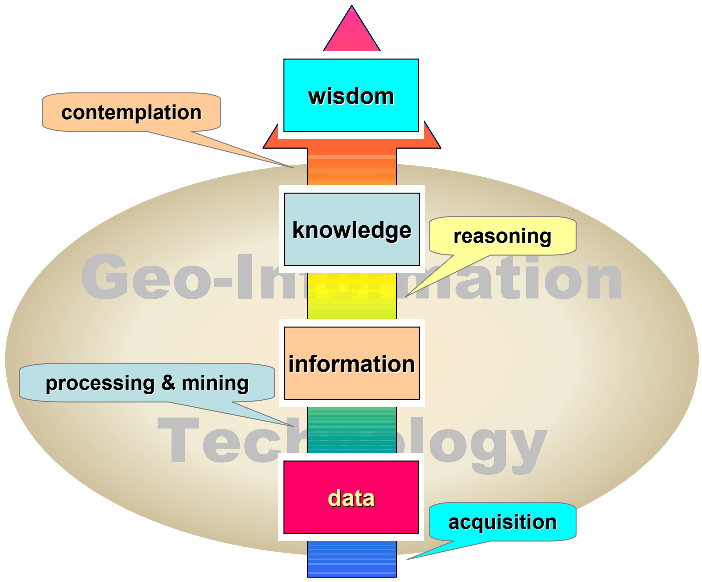

Figure 1. Relation between data, information and knowledge (Kainz, 2002)

Working with IT does not only mean the transformation of data and information into a digital format and manipulating those data and information in enormous amounts in ever more complicated algorithms. The "digital revolution" has allowed for important steps forward using ways of thinking that existed in the analogue era, but if we want to use the potentials of IT for the full extent in Engineering Geology we will also have to adapt our "way of thinking". In fact this means changing the methodological approaches that we were using to solve a problem. Traditionally we start with a vague idea on how to solve a problem. During the process of thinking we enlarge and couple this vague idea to the knowledge available in our brains, and to knowledge from external sources, and link the data and processes (we) think to be important to the 'idea'. We do generally not know how we select data and processes from our brains and how and based on what we link data and processes. To be able to use IT to the full extent we will have to set out the methodology for the analysis of our problems in advance and in detail. We cannot use the same methodology as we use in our brains because we do not know how that works. Hence, we have to re-define the methodology for the 'IT- thinking process'.

In the context of this keynote lecture it is not possible to describe the stage of development of IT applications in Engineering Geology worldwide. For this reason this paper is restricted to a general discussion on the developments in a number of the most important fields and is illustrated with examples of work done in those application fields in research institutes, universities and industry in The Netherlands. This choice is not based on the assumption that in this country the developments are ahead of those in other countries, but it is meant to illustrate that even in a small country many developments are taking place and that IT has been used extensively in various aspects of engineering geology. We are convinced that it would equally well be possible to present examples of developments of equal or greater interest in many other countries in the world.

The following aspects will be treated in this keynote:

Standardisation of engineering geological input data for use in IT
The (2D-, 3D-, 4D-) spatial model describing the engineering geological environment
Databases for large engineering geological data sets
Geotechnical (numerical) modelling
Spatial data integration and 2D modelling with GIS
Visualisation techniques
Public data exchange, data quality assurance and data accessibility
Access to newly developed knowledge

STANDARDISATION OF ENGINEERING GEOLOGICAL INPUT DATA FOR USE IN IT

The digital handling of engineering geological data leads to the great advantage that vast amounts of such data can be combined and analysed, as well as imported into and exported from databases and/or large (virtual) spatial models in fractions of seconds. In the pre-digital era this was not possible at all due to the time consuming character of such operations.

The biggest potential of IT is the possibility to process and analyse large amounts of primary data, such as in geophysical surveying, remote sensing and in cone penetration testing. Processes such as anti-aliasing, improvement of signal to noise ratios and, generally, processing of large data sets would not have been possible without the data handling capacity of IT.

Digital data handling, however, forces us also to adopt strict rules on the uniformity of data formats and to an appropriate choice of parameters to be described. The uniformity of the data formats is essential for the "interoperability" of data on different parameters and from different data sources. However, the use of large databases and the importation of datasets into programs for numerical analysis also require uniformity in the way to structure the description of the engineering geological parameters.

There exists a strong tendency for specialists, even within one organization, to work independently with newly emerging technologies as IT, selecting their own computing tools and their own structure and format for storing data. If there is no effort for standardisation then this may lead to users spending more time on transforming data than on solving geotechnical problems. Sharing data between organizations will add further complexity.

International associations as IAEG, ISRM, and ISSMGE have a responsibility to contribute to worldwide standardisation of data formats, description- and classification procedures. Only the implementation of such standards will allow better links with software packages and through data-networks such as the Internet.

A cross-section of oil companies addressed this issue by creating the (non-profit) Petrotechnical Open Software Corporation (POSC). "The standards and open systems environment to be facilitated by POSC represent a maturing of the industry that frees companies from worrying about the integration of their computer systems and lets them concentrate on areas of added value" (POSC, 1993).

This section will not focus on the aspect of data formats for the use of engineering geological data, but on the role that IT can play, because of its strong data handling capacity, in the process of the collection and processing of primary data:

- Digital analysis of SCPT data
- Digital description of borehole logs
- Digital field book for the collection of (engineering) geological data
- Digital outcrop mapping

Earth observation with Remote Sensing (RS) delivers large amounts of data on the earth surface. Automatic production of high resolution Digital Elevation Models (DEM) and monitoring of the changes in time of landform (pattern) and spectral reflection characteristics (related with vegetation and lithology) can only be achieved through digital image processing with computers. This aspect of primary data collection, although potentially very important for engineering geological applications, will not be treated here. For references to specialized literature on these aspects of remote sensing and image processing please refer to the ITC textbook on this topic (ITC, 2001).

Digital analysis of SCPT data

Cone penetration testing is very frequently used in The Netherlands to determine the vertical succession of different layers of soft soil and to give data on a number of the parameters of these layers. Huijzer (1992) worked first on the automatic interpretation of cone penetration tests, but a good automatic recognition of layers based exclusively on cone resistance turned out to be impossible. In many cases non-existing layers appeared, where an experienced engineer would have drawn a gradual transition between two really different layers.

A later study by Coerts (1996) started the interpretation from a pre-defined number of geotechnical units. This number was established from boreholes, or it was based on profiles published with the geological maps.

This method of working made it possible to follow fairly accurately the boundaries between the different layers at locations between the boreholes.

Digital description of borehole logs

For input in databases and GIS digital data of boreholes are needed. The Netherlands Research Center for Civil Engineering (CUR) Committee E18 has produced the GEF-BORE-Report in 2002 (CUR, 2002). The standard digital borehole description is designed to be connectable to existing software in a large variety of organisations via a simple interface. The data that are included are of course layer depth, and a detailed soil classification, according to NEN 5104, the standard for geotechnical soil description used in The Netherlands.

Figure 2. Automated field data acquisition

Additional information will be stored, like the method of execution of the borehole, contamination data, information about piezometers that were placed, details about the method of backfilling, (weather)-conditions during the execution, the name of the drillmaster and/or the laboratory technician who did the soil classification, the moisture condition during the classification.

The system is structured according to the Parent/Child principle. The Child files contain the secondary data, which are not important for all users. The design is such is that in the future also the data collected at the borehole later during the execution stage of the work can be stored in GEF-format. This can be the case for early measurements of settlements which can be valuable for the planning of maintenance work in the future of embankments, or housing areas on very soft soil, where the ground level has to be raised by filling.

Digital field book for the collection of (engineering) geological data

In many engineering geological investigations an important part of the data on the earth's surface are collected during field visits. Traditionally the data acquired during such field visits are noted down in field books and sometimes photographs are made to support the observations. While only a fraction of all field observations is actually captured as data in field books, it is usually very difficult to reconstruct where exactly the observations where made. Thus real data that are fit to be entered into a database are very often lost forever after a project is finished.

At the ITC since 1974 concepts of field data capture methodologies have been developed and implemented in geological field mapping exercises with students. These exercises started with the application of the Field log, developed at the Ontario Geological Survey in Canada (Brodaric and Fyon, 1989) on laptop computers. In 2001 personal digital assistants (PDA's) were introduced (Woldai and Schetselaar, 2002), for which palmtop computers were equipped with RDBMS (Relational Database Management Systems) software for direct data acquisition in the field. Incorporation of a Global Positioning System (GPS) enables automatic reception of the field coordinates and stores this information in the digital field book as well.

The acquired data are daily synchronized to laptop GIS systems at the base camp (Figure 2). As the database is populated at the source, and intimately used during the field mapping, the digital data represents the most accurate data repository of the field survey and thus is ideal for integration into larger corporate GIS databases, without requiring duplicate data entry or error-prone data transcription sessions in the office.

Obviously, if applied to engineering geological field studies, the database for the data to be acquired in the field has to be specially designed for this purpose. An example of a specific engineering geological database is given in part section 4.2.

Three-dimensional digital outcrop mapping

Traditionally samples as well as outcrops of soil and rock have been photographed to give a visual impression of the site conditions in engineering geological reports and archives. Terrestrial stereo-photography has been used to record the exact form of outcrops in a visual 3D model. Measurements of location coordinates of points in the outcrops, but also of orientations of planes can be extracted from the stereo-photo model using photogrammetrical methods.

The latest method in this field, that has become available through the increased data handling capacity of computers, is the use of lidar. This is a laser-based remote sensing technique that is applied in air-borne as well as in ground-based surveys. With ground-based laser scanning, the geometry of virtually any object can be measured in great detail and accuracy. The location of each point on the surface of the object in 3D space is calculated by determining the "time of flight" of the reflected laser beam, which is proportional to the distance from the scanner. Combined with the directional parameters of the scanner (azimuth and angle) this will give the location relative to the scanner's position.

Through the scanning of rock surfaces this technique generates high-resolution 3D geometrical information of natural outcrops or excavations in rock. Depending on the distance from the scanner to the object, scanning resolutions can be reached in the order of centimetres to millimetres. The subject of the research currently being undertaken by ITC (Slob et. al. 2002), is to obtain discontinuity information (joints, bedding planes, fractures) from the point cloud data set, and to determine statistically the orientation of joint sets. For this purpose, a laser scan data set of a rock outcrop is used where the discontinuity sets are clearly recognisable (Figure 3).

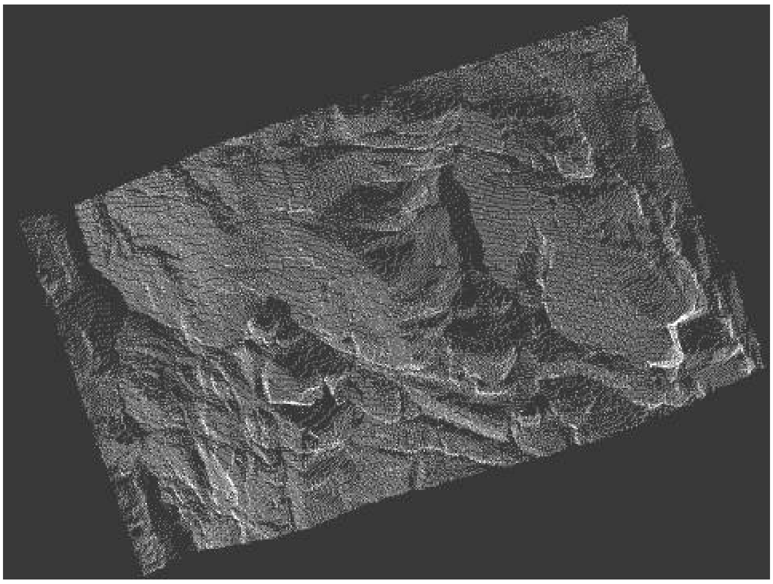

Figure 3. Point cloud data set of a rock surface, generated with a laser scanner

As a 3D triangulated surface, the scanned rock face is represented by a large number of triangles. The orientation and surface area of each triangle is computed using simple geometrical rules. Subsequently, the orientations of all triangles are plotted in a stereo net, and contoured in terms of density. From the density plot the orientation of the different discontinuity sets can be identified without difficulty. If this approach can be further developed and fully automated, this would give the site engineer or geologist, in real-time, evidence on the internal structure of a discontinuous rock mass. Particularly in areas where there is difficult access to rock exposures, where visibility is poor and/or measurements have to be done rapidly, application of this technique is very promising. Fields of application may include tunnelling, quarrying and mining.

3. THE (2D-, 3D-, 4D-) SPATIAL MODEL DESCRIBING THE ENGINEERING GEOLOGICAL ENVIRONMENT

What started already decades ago in the mining industry is now becoming everyday practice in larger civil engineering projects. All information on the spatial model and on the geotechnical characteristics of the ground layers below and around civil engineering works such as tunnels and deep excavations for foundations is introduced into a 3D digital ground model (3DGM).

Recently developed digital ground models allow for a number of special data handling facilities such as automatic definition of (sharp or fuzzy) boundaries, interactive input of true and simulated (virtual) data to work out a variety of scenarios, and most importantly powerful visualization tools and possibilities to export layer configurations and their geotechnical parameters into a geomechanical model.

However, it is good to be aware that the virtual model starts to play an important role by itself, and one of the major questions now is "how likely or how reliable" the model is. In the past with a "hand-drawn" model nobody asked that question because it was clear that it was unanswerable. However, in a digital model an answer is expected. To be able to answer the question we touch various very basic aspects. It starts with what is data, why do we have the data, and why have they been acquired. All these aspects influence the accuracy of the data itself, their reliability, but will also influence how the data are to be linked and modelled. Such problems are far from being solved and will need much attention.

North-South tunnel project Amsterdam

A large urban infrastructure project such as the construction of a new metro line below the city of Amsterdam, generates large amounts of data. Proper information management is one of the key elements for the success of such a project. Witteveen+Bos Consulting Engineers has developed for this project a 3DGM in a GIS (ArcInfo). The main engineering geological content of this 3D ground model is the three-dimensional layer model, and the geotechnical parameters of each individual layer.

All the site investigation data can be easily stored and extracted through user-friendly interfaces. One of the most important site investigation tools in the Dutch soft ground is the Dutch Cone Penetration Test. These DCPT records are ideal to store in a digital data system (see above in section 2). The 3DGM automatically creates a three-dimensional layer model of the subsurface. Automatically, a geotechnical profile can be drawn from this 3D layer model, along any given section. Apart from the visualisation of layers in the underground, 3DGM is used for a number of other GIS-based analyses, calculations, and data handling operations:

- Contour maps of the thickness, top or base of layers
- Volume calculations, quantifying the amount of excavated ground, subdivided per soil type and excavation phase
- Vertical stability calculations of the deep excavation floor
- Analyses of the sensitivity of the available site investigation data or the necessity for additional site investigation
- Export of automatically generated geotechnical profiles to geotechnical numerical model calculations

An important example where this three-dimensional character of the information is important is the design of station Rokin, because the model shows that at this site there is a large variation in the subsurface. Consequently, it was decided to model the whole station in a Finite element Model and not just half of the station as is common in this type of calculations (Figure 4).

A special feature of the described ground model is that it is connected with the Integrated Boring Control System, a system that assists the Tunnel Boring Machine pilot in causing a minimum of disturbance to the surroundings. It can be understood as a simplified form of an automatic pilot for the TBM (Netzel and Kaalberg, 1999). Using this type of information technology, the input geotechnical data will maintain their accessibility and their value throughout the entire project.

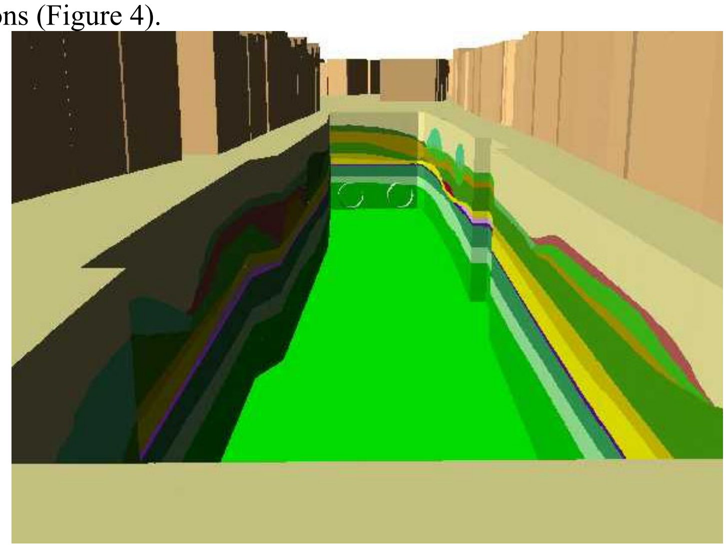

Figure 4. Station Rokin on Amsterdam Metro N-S line

Øresund Tunnel Link project

In the context of the Øresund tunnel and bridge project to link Denmark and Sweden a subsurface model for excavatability and dredging spill has been made consisting of a 3D GIS and a Decision Support System (DSS) (Brugman et al. 1999, Ozmutlu and Hack, 2001). Figure 5 shows the potential spill values in the area to be dredged.

Heinenoord tunnel

In the scope of a research program a comparison was made of the modelling of a bored tunnel in three different (true-) three-dimensional Geographic Information Systems (Hack et al., 2000, Veldkamp et al., 2001). The three programs used were: Lynx GMS, GoCAD and Intergraph. The modelling incorporated all available subsurface data and the geometrical dimensions of the tunnel. The data were three-dimensionally interpolated and these interpolated data were subsequently exported to a two- and three-dimensional numerical program. The calculated deformations of the tunnel and the subsequent settlement of the surface were returned to- and visualized in the 3D GIS. The research program showed that the various programs had all particular advantages and disadvantages, but that in general the Lynx GMS system worked out to be very suitable and easy to handle for engineering geological models.

Various data types were used and incorporated in the GIS. Zero-Dimensional sample data (sample descriptions or laboratory test results) were simply attached to a three-dimensional coordinate. Borehole and other line data such as CPT and SPT were introduced as One-Dimensional data. Two-Dimensional data such as maps and geophysical sections were introduced as planes with the correct orientation in space. Figure 6 shows the available topographic data in a geotechnical database that was imported in the 3D GIS. A Three-dimensional grid data model had to be created to export the data to an external numerical program.

The final subsurface volume model of the geotechnical units is shown in figure 7. The detail of the volume models is related to the size of the modelled area and the available data. Over a large area only scarce data was available, hence the model is less detailed there; near to location of the planned tunnel site investigation has been done which resulted in a more detailed volume model.

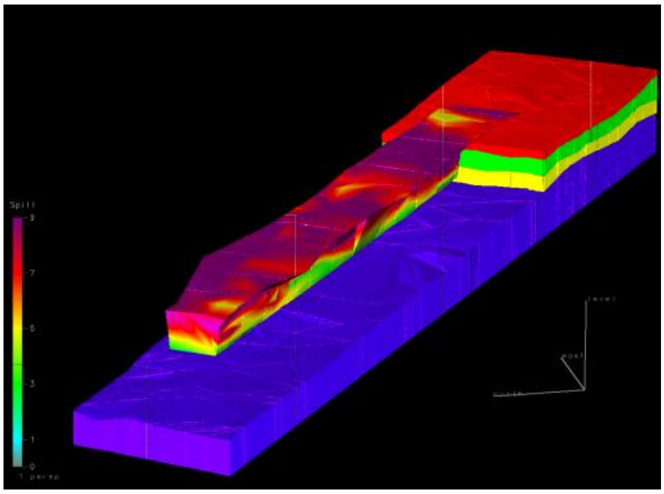

Figure 5. Volume model of the subsurface of Øresund Tunnel Link showing the potential spill due to the materials in the subsurface. The ground surrounding the channel to be dredged has been removed and the potential spill values are shown.

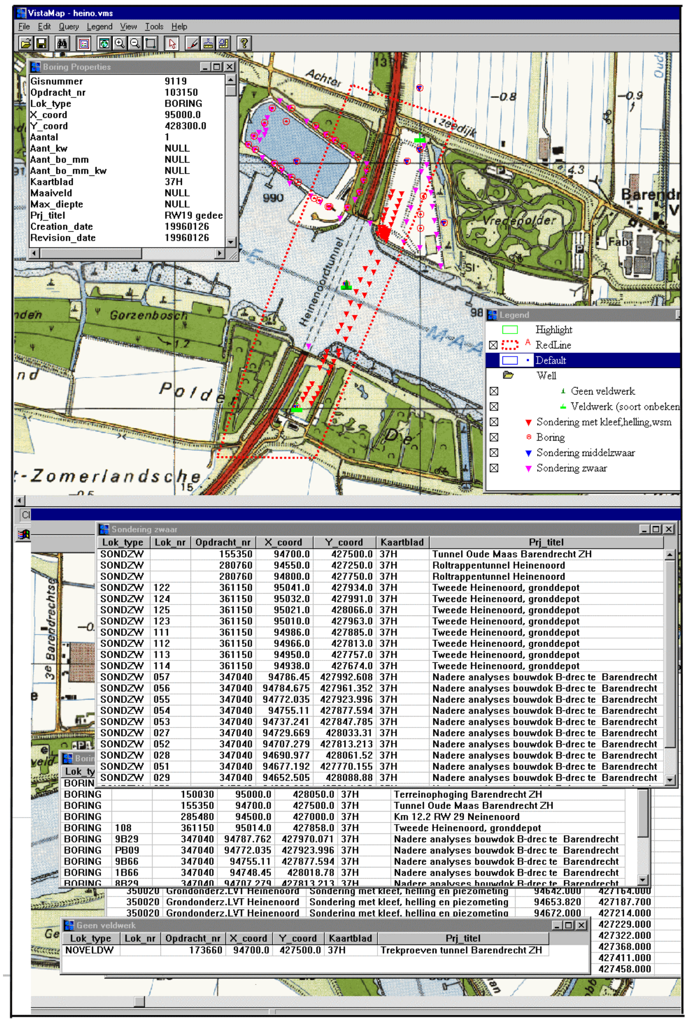

Figure 6. Example of GeoGis database for geotechnical data

Figure 8 shows how the volume model at each location in space is linked to the database with as well the original data as well as the interpreted data.

Figure 9 shows how the displacements (the results of numerical calculations on the deformations around the tunnel based on the data from the 3D GIS) are re-imported into the 3D GIS and projected onto the tunnel tube and thus visualised.

DATABASES FOR LARGE ENGINEERING GEOLOGICAL DATA SETS

One of the great new challenges for national geological survey organisations is the collection and storage as well as the organisation of the accessibility of all geological and geotechnical data and information that is available on the territory of a country. These organisations have changed their role from publishing geological maps in a systematic coverage of the territory to being a main provider of access to the geological and geotechnical basic data that are available. The form in which these data are available is progressively changing from analogue to digital. All new information is being added in a digital form and procedures of access to external users are developed (Culshaw, 2001, Groot, 2001). For more information on these aspects see chapter 8 of this keynote. Here two practical examples of large databases developed in The Netherlands are mentioned.

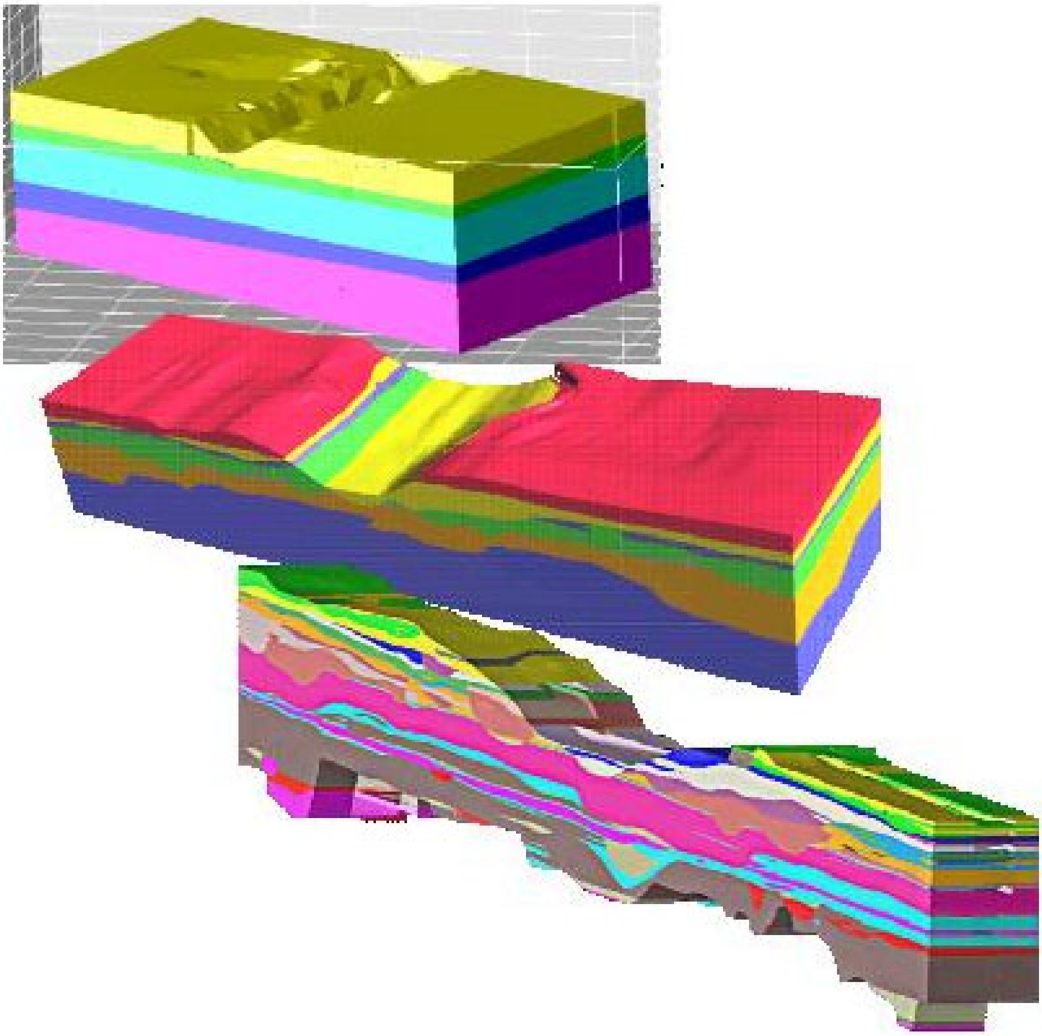

Figure 7. Volume model: from top to bottom smaller areas, but with more detail

Database on the Underground of The Netherlands Geological Survey (DINO)

TNO-NITG (The Netherlands Institute of Applied Geosciences TNO – *Dutch Geological Survey*) has been assigned as a main task to act as national custodian of all geo-scientific data and information of the subsurface of The Netherlands. This assignment prompted to the development of DINO (Data and Information on The Netherlands Underground). The DINO design challenge was to provide uniform access to data and information. An unequivocal interface implies, however, an even more unequivocal approach to the data: as to how the various tables are interlinked in a database and how the data are presented. The main aspects of DINO are the following:

The data acquired and the data collected from third parties are entered into the database

A quality control process is applied to the newly entered data

DINO the data can be selected and subsequently exported to an analysis and interpretation environment. Results of analysis can be entered again in DINO

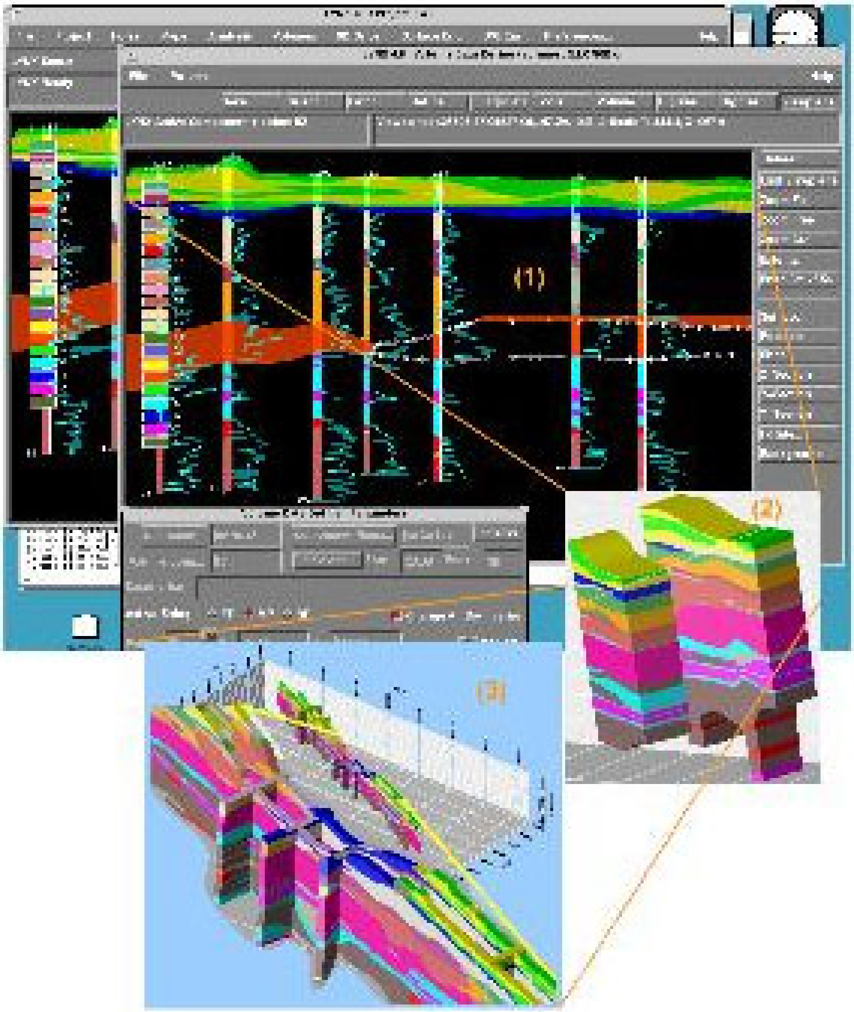

Figure 8. Interactive modelling process

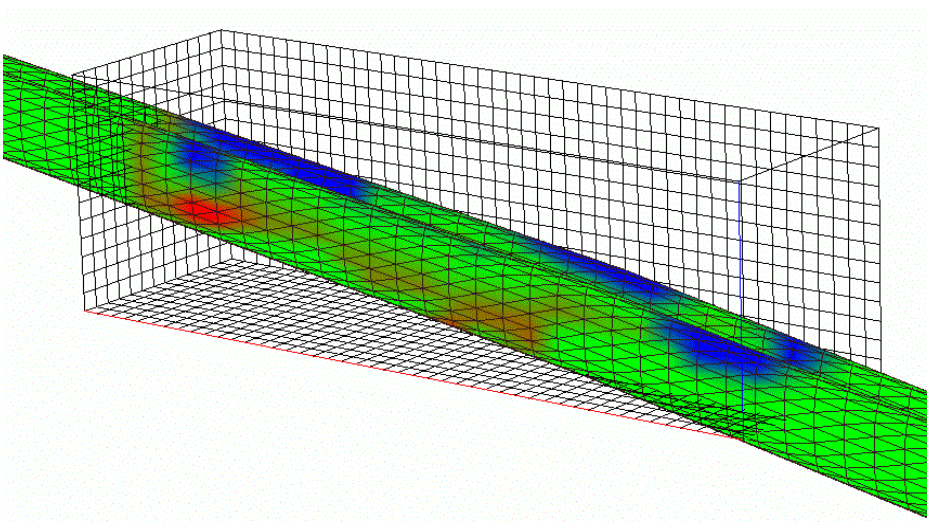

Figure 9. Vertical displacements at the location of the tunnel tube projected onto the tunnel tube, blue small displacements, red large displacements

Apart from lithological descriptions of boreholes (400,000 entries) also the introduction of data on groundwater data and Dutch Cone Penetration Tests (DCPT) as well as the data on deep borings (generally deeper than 1000m) and offshore borings will be completed in the course of 2002. For more information please contact: dinoloket@nitg.tno.nl

Database for an engineering geological mapping program

At the ITC a large digital database was designed to store engineering geological data and information collected in a program of engineering geological field mapping near Falset (province of Tarragona, Spain) with large numbers of students from the ITC and Delft University of Technology over a period of almost 11 years.

The main purpose of this database is to facilitate the input process of engineering geological rock and soil data that is collected during each annual four-week fieldwork period. In addition, this database will be the core data source for monitoring the temporal and spatial variation of rock and soil properties for different geotechnical units. Since the database contains thousands of records of very detailed standardised rock and soil outcrops description over a relatively small area, the database will be a very important source of information for all kinds of research topics.

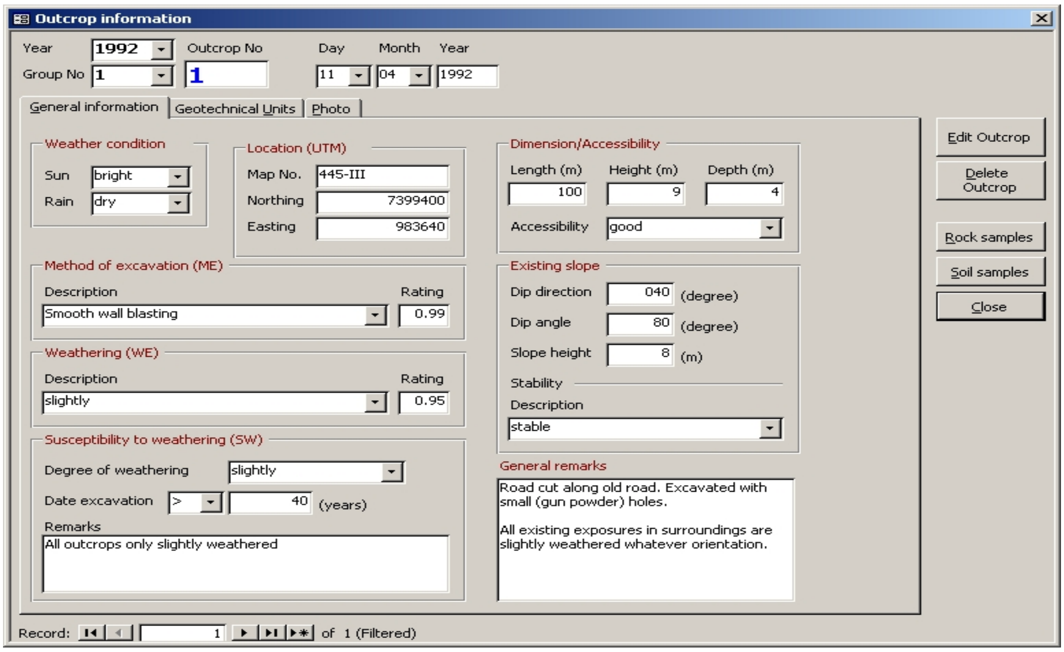

Figure 10. General outcrop information form

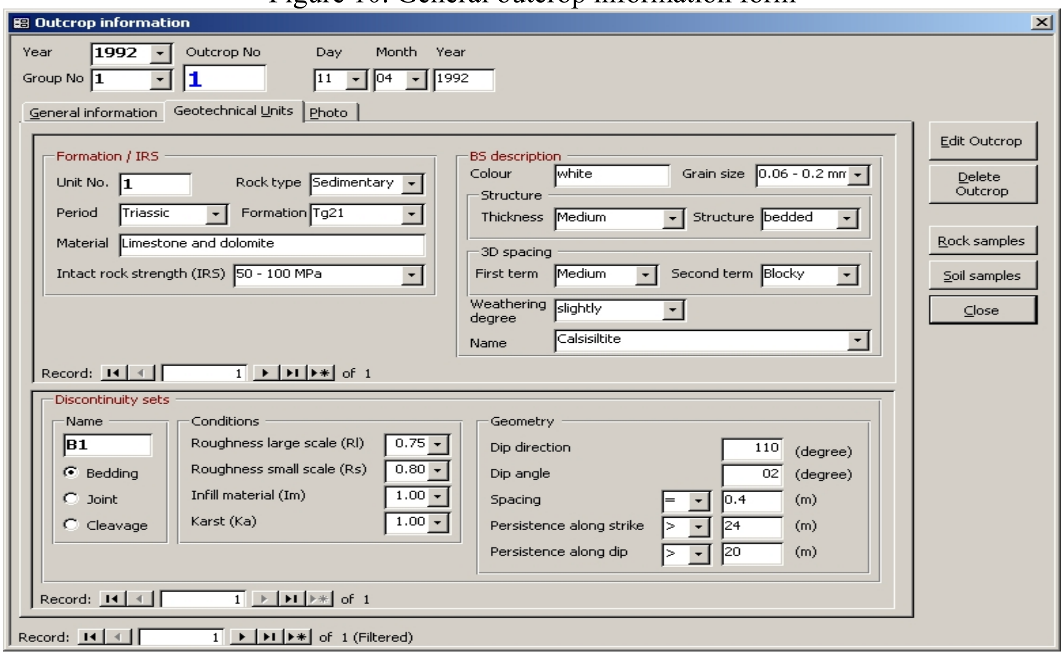

Figure 11. Geotechnical unit description form

The Falset database is implemented in Microsoft Access application. Several input forms and queries are designed to support the data input and retrieval processes (Figures 10 to 12).

The Falset database provides the following utilities for the end-users:

Graphical user interface (GUI) forms

Drop-down lists for most of predefined values in order to reduce the typing errors during the data input process.

Calculation of the slope stability of each rock outcrop based on the SSPC system (Hack, 1998)

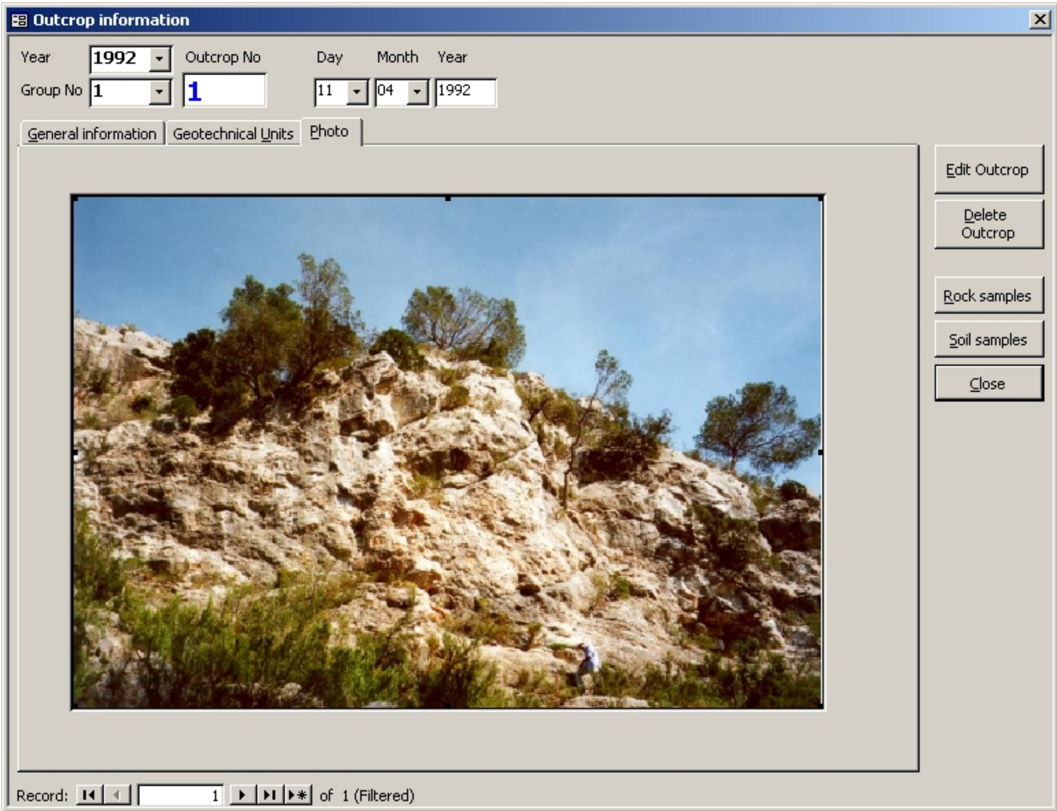

Figure 12. The database also allows for inclusion of digital photographs

Ability to import or export data for further data processing, such as integration with engineering geological maps or different thematic maps stored as digital information in a GIS.

GEOTECHNICAL (NUMERICAL AND STATISTICAL) MODELLING

In the Seventies and Eighties there was strong growth in calculation speed and in the handling capacity of large data volumes (as well as the increased accessibility of calculation power in the form of PC's). This enabled the development of new methods of geotechnical analysis (finite element, finite difference, distinct element, and particle flow methods), allowing for models of irregular forms with the third dimension, consisting of materials with more complicated stress-strain relationships. The fourth dimension could be introduced where progressive stages of excavation and/or loading, and or time dependent deformation processes introduce time as an important factor into the analysis. Departing from numerical methods developed for applications in the aeroplane design industry, ITASCA (ITASCA, 2002) developed software packages like FLAC and UDEC (www.itascacg.com) that are at present standard packages and still state-of-the-art. A new development are the programs PFC2D and PFC3D (Particle Flow Code in two- and three dimensions - ITASCA, 2002) which model rock blocks as bounded clusters of balls, which is particularly suitable for situation where many blocks of rock are splitting up in smaller blocks that fall and roll, for example, in a draw point of a mine. These packages also allow for 2D and 3D continuous and discontinuous numerical analysis of geotechnical models.

The bottleneck in numerical modelling has shifted from limitations in the hardware (restricting the quantity of data sets and model elements), towards issues dealing with the quality of the input data. This new bottleneck concerns the detail with which the engineering geological environment can de defined. There are still too many uncertainties as to what amount of detail the subsurface should be modelled. Particularly, a proper quantification of the spatial variation in geotechnical properties is very difficult to achieve. This leads to a paradox in the use of modern IT technologies: "by knowing more, we actually learn that we do not understand a great deal at all". This may subsequently result in a more conservative instead of less conservative design of major engineering projects, in order to be certain that all uncertainties and risks are excluded.

In order to properly quantify those uncertainties and deal with them accordingly, rather than using an overly conservative design, an appropriate statistical analysis is called for. A promising development in this respect is the "bootstrap method": a data-based simulation method for statistical inference, representing in the words of Efron and Tibshirani (1998): "the mathematical equivalent to pulling oneself up by one's bootstrap". Starting from a limited amount of true data, a larger set of hypothetical but still realistic data is generated using simulation techniques such as the Monte Carlo or Latin Hypercube methods (Hammersley and Hanscombe, 1964). Based on the distribution of the simulated data, bootstrap analysis enables us to quantify statistical parameters that can only be determined with difficulty, or not at all, from the original samples (Efron and Tibshirani, 1998 and Hack, 1998). It should be noted that the validity of the results largely depends on the assumptions that are made in the data simulation, and these should be made with care. If done properly, bootstrap analysis can be applied to sparse data sets, which are typical in the geosciences. Its use to date seems however to be restricted mainly to bootstrap percentiles, which are an accepted and effective method to determine reliability intervals (e.g. Chernick, 1999).

An approach used to reduce the need of infinite detail of input data is to determine with the help of "sensitivity analysis", the amount of influence of each of the input parameters on the final outcome of the numerical calculation. Where the traditional calculations only resulted in an average, or a pessimistic value, now more information is found about the possible variation in the results.

The trend in IT is to make the software packages more and more user-friendly. However, the negative effect is that they develop more in the direction of black box models, in which a large number of assumptions have been introduced, that are not anymore apparent to the user. The basic assumptions are usually well described in the manuals, but users often do not read the manuals from A to Z, or just miss the appropriate education to understand it. A larger problem is that for more elaborate calculations values of parameters are needed which are not directly available from traditional field or laboratory tests. Their value may therefore be based on a rule of thumb of which it is not always clear whether it is valid for the specific site that is investigated.

Much can be gained from a proper integration of monitoring data, during and after construction, into a back-analysis of the numerical model. The experience obtained in this way is very valuable for the development of knowledge on numerical geotechnical modelling. Unfortunately, this is not systematically done for the simple reason that all parties involved are satisfied when monitoring shows less deformation than predicted. The money that has been spent for the (probably too conservative) design, cannot be recovered and nobody wants to be reminded of it.

Numerical packages developed in The Netherlands

In the Seventies geotechnical software packages were developed jointly by Rijkswaterstaat (Ministry of Traffic, Public Works and Water Management) and the Laboratorium voor Grondmechanica (LGM) in Delft (presently known as GeoDelft or Delft Geotechnics).

These computer programs were concerned with slope stability using the method of Bishop, settlements using the method of Koppejan, and sheet-piled walls and diaphragm walls as well as road pavement design based on an elastic girder supported by linear elastic - fully plastic springs. The most important improvements in the slope stability programs involved a number of different methods to achieve the best possible condition of the pore water pressures. This plays a role during execution, when high excess pore water pressures occur in the soft soil layers, but is also of vital importance during the design stage where a dike body has to withstand a water level that occurs with a frequency of for example 1:2500 per year.

The research and consulting institute TNO-Bouw developed the finite element program DIANA for the design of concrete structures. (DIANA, 1998). The user-friendliness of the program was gradually improved. In the course of the years this program was extended to a soil-mechanical component which is suitable to study the interaction between foundation structures and soil, but also for continuous rock models. With DIANA also dynamic effects can be studied. Leenders (2000) used this software package to model the highly complex influence of terrain surface morphology on the ground motion characteristics for the Quindío earthquake of 1999, in Colombia.

An important numerical modelling package developed at Delft University of Technology (Brinkgreve, 1999) is the finite element program called PLAXIS. The earliest version of PLAXIS was based on linear elastic-fully plastic stress-strain behaviour of the soil layers. In later years more elaborate models for soil behaviour were incorporated. With the introduction of interfaces, also sheet-piled walls and diaphragm walls could be added to the soil models. The latest development is the modelling of the 3D stress/strain condition around a tunnel-boring machine.

An embankment of 8 m. height for the new High Speed Railway Line Amsterdam-Brussels will be built as an embankment immediately alongside the existing railway. The deformations of the existing railway due to the new embankment are very important for the design of the project. The soil below the existing embankment is made up of approximately 5 m of soft clay and peat. For the calculation of the deformation of these layers the Soft Soil-model and the Soft Soil Creep-model of PLAXIS were used (Figure 13).

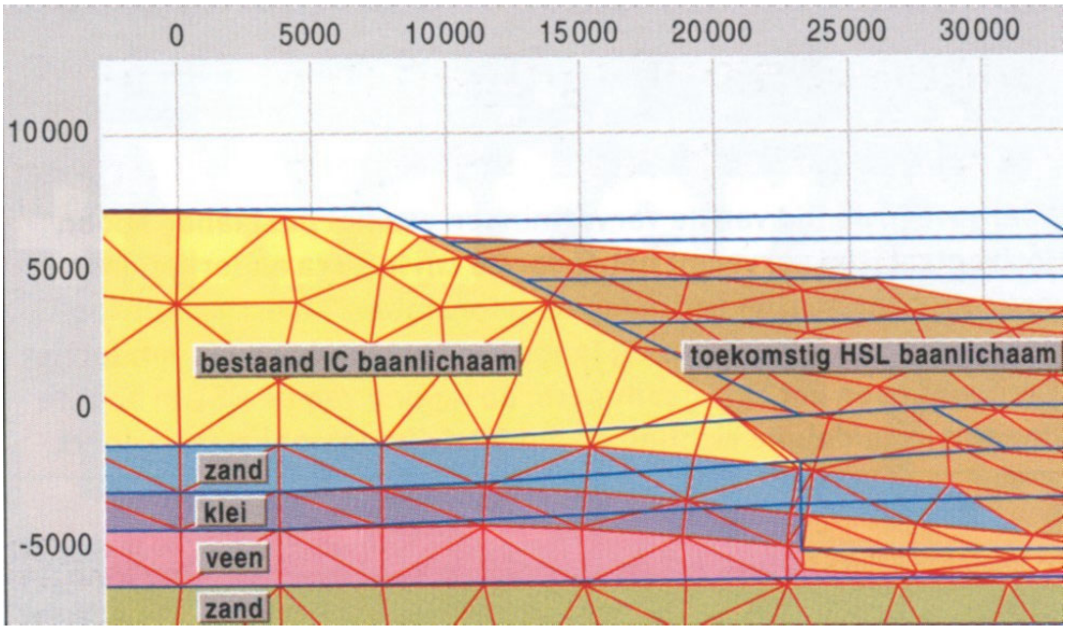

Figure 13. Due to the construction of the future HS-Railway embankment (on the right) are deformations occurring of the existing railway embankment (on the left). With the finite element program Plaxis the deformations of the two embankments in the final situation have been calculated. (from: Spierenburg and van der Velden, 2002).

The calculations indicated that the new embankment will settle approximately 1.8 m., and that the deformations of the existing tracks would be 0.26 m. in horizontal direction, and 0.28 m. in vertical direction. These values are sufficiently small, so that they can be corrected by extra maintenance work on the existing railroad. In particular in situations where horizontal as well as vertical deformations are important finite element programs are superior to any other, more traditional, calculation method.

A general problem with finite element programs in soils is that they require input parameters that are not directly available from traditional field and laboratory tests. When input data have to be based on correlations and estimations, the accuracy of the output may obviously decrease. Many soil parameters are in fact stress-level dependent. In finite element programs for each soil layer, a Poisson's ratio is often needed. This parameter is usually not available as an immediate test result. One can run the calculation with high and with low estimated Poisson's ratio values, and judge by the different results how important the parameter is for the problem that is studied. There remains a risk that for complicated calculations only poorly known parameter values are used as input. There is still much work to be done in the field of development of appropriate site investigation and laboratory techniques.

The Slope Stability Probability Classification (SSPC)

Computers allow us to use large amounts and data to optimise very complicated and non-linear relations. An example is the development of the Slope Stability Probability Classification (SSPC) system (Hack, 1998, Hack et al., 2002). The SSPC system is based on a three-step approach and on the probabilistic assessment of independently different failure mechanisms in a slope. First, the scheme classifies rock mass parameters in one or more exposures. In the second step, these are compensated for weathering and excavation disturbance in the exposures. This gives values to the parameters of importance to the mechanical behaviour of a slope in an imaginary unweathered and undisturbed 'reference' rock mass. The third step is the assessment of the stability of the existing or any new slope in the reference rock mass, with allowance for the influence of excavation method and future weathering.

A large quantity of data obtained in the field has allowed the development of a classification system based on the probabilities of different failure mechanisms. This has resulted in a classification system based on a probability approach: the "Slope Stability Probability Classification" (SSPC). The SSPC-system has been developed during four years of research in Falset, Tarragona province, Spain. Recently the system has been used with good results in Austria, South Africa, New Zealand, and The Netherlands Antilles.

In order to develop the system, data on stability, geometry and physical properties of the rock masses in which the slopes were made, have been assembled from some 184 slopes and stored in a digital database (see also section 4.2). Subsequently, various relations were defined between the stability of the slopes and the physical and geometry properties measured in the field. The relations are non-linear (example Equation 1). An optimisation routine was used to find the 6 unknown factors in Equation 1 such that the stability of the slopes was rightly forecasted for the maximum number of slopes. This optimisation has only been possible because of the number-crunching capabilities of modern computers. By hand such optimisation would have been virtually impossible.

Equation 1. The various non-linear relations between the stability of the slopes and the physical and geometry properties measured in the field, used for determining the SSPC system.

$$dip_{slope} \geq \varphi_{mass} \rightarrow H_{\max} = 4 * \frac{coh_{mass}}{UW} * \frac{\sin(dip_{slope}) * \cos(\varphi_{mass})}{1 - \cos(dip_{slope} - \varphi_{mass})}$$

$$dip_{slope} < \varphi_{mass} \rightarrow H_{\max} = \text{unlimited}$$

$$coh_{mass} = a0 * \frac{IRS}{100} + a1 * SPA + a2 * CD$$

$$\varphi_{mass} = \left(\frac{a3 * \frac{IRS}{100} + a4 * SPA + a5 * CD}{a3 * a6 + a4 + a5 * 1.10165} \right) * \frac{\pi}{2}$$

$$\text{if } \frac{IRS}{100} \leq a6 \rightarrow IRS = \text{intact rock strength (in MPa)}$$

$$\text{if } \frac{IRS}{100} > a6 \rightarrow IRS = a6 * 100$$

$a0$ through $a6$ = unknown factors

dip_{slope} = dip of slope

H_{max} = maximum possible slope height

UW = Unit Weight of the rock mass

For each slope j:

$$\text{visually estimated stability} = \text{class 1} \quad \begin{cases} \frac{\varphi_{mass}}{dip_{slope}} \geq 1 \quad (stable) \rightarrow er = 1 \\ \frac{\varphi_{mass}}{dip_{slope}} < 1 \begin{cases} \frac{H_{max}}{H_{slope}} \geq 1 \quad (stable) \rightarrow er = 1 \\ \frac{H_{max}}{H_{slope}} < 1 \quad (unstable) \rightarrow er = \frac{H_{slope}}{H_{max}} \end{cases} \end{cases}$$

$$\text{visaually estimated stability} = \text{class 2 or 3} \quad \begin{cases} \frac{\varphi_{mass}}{dip_{slope}} \geq 1 \quad (stable) \rightarrow er = \frac{\varphi_{mass}}{dip_{slope}} \\ \frac{\varphi_{mass}}{dip_{slope}} < 1 \begin{cases} \frac{H_{max}}{H_{slope}} \leq 1 \quad (unstable) \rightarrow er = 1 \\ \frac{H_{max}}{H_{slope}} > 1 \quad (stable) \rightarrow er = \frac{H_{max}}{H_{slope}} \end{cases} \end{cases}$$

$$ER = \sum_j er_j$$

A secondary computer-aided feature in the SSPC system is that the results are presented in the form of probabilities, rather than the point ratings that is the standard in most classification systems. To determine the probabilities also enormous numbers of calculations had to be done using Monte Carlo techniques for simulating data out of the distributions of the data used for developing the SSPC system.

The bootstrap method (see in the introduction of this chapter) has proven to be useful in the SSPC method of slope stability analysis. An example of the application of such bootstrap percentiles is presented in Figure 14, which shows the slope stability probability against orientation independent failure (i.e. not related to discontinuity and slope orientation), according to the SSPC system (Hack, 1998).

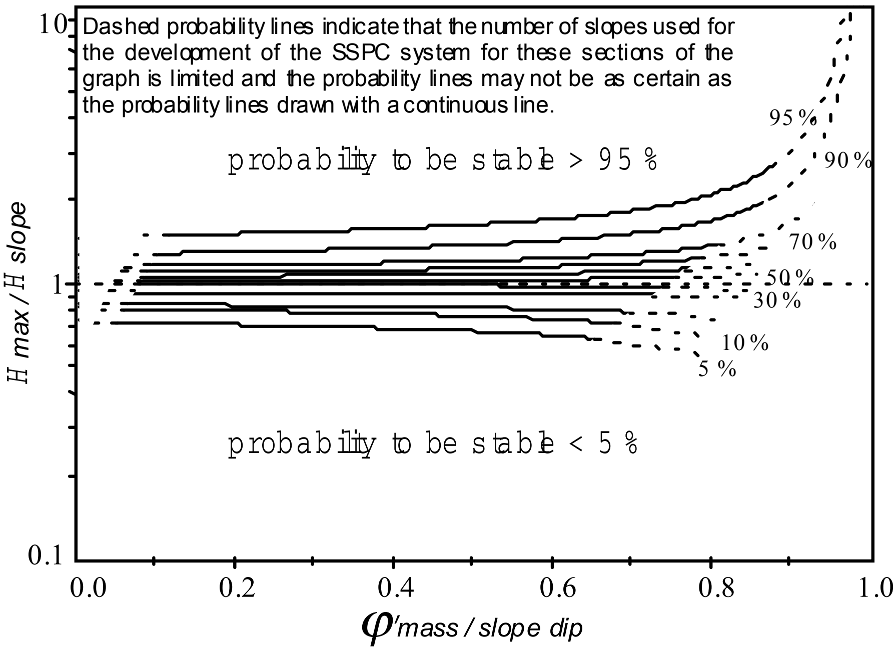

Figure 14. Bootstrap method applied to SSPC method of slope stability analysis

Using Monte Carlo simulation, bootstrap percentiles were calculated relating the height of the slope (as a ratio of a maximum slope height calculated in the SSPC to the actual slope height) to the ratio of the rock mass friction angle to the slope dip. This approach gives the slope stability not as a deterministic but estimated value (such as Factor of Safety), but as a probability of being stable or unstable. By calculating the height ratio and the friction angle to slope dip ratio, the probability to be stable can be found; the example shown in the graph falls on the 5% percentile, meaning that out of every 100 slopes constructed with the same height and dip angle in the same rock mass, only 5 would be stable and 95 would fail.

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SPATIAL DATA INTEGRATION AND 2D MODELLING WITH GIS

Geographic Information Systems are computer-based systems for handling map information in a digital way (Bonham-Carter, 1994, Burrough and McDonnell, 1998). GIS enables the introduction, processing, storage, and retrieval, of geo-referenced data sets (digital maps, digitised analogue maps as well as point and line information), and offers procedures to achieve the interoperability of such data sets by modification of projection systems and data formats. The integration of different data sets by overlaying and map calculations is possible in GIS for spatial modelling processes in which various factors play a role. At ITC the Integrated Land and Water Information System (ILWIS) GIS has been developed in the Eighties and Nineties (ILWIS, 1997) The ILWIS package has also well developed Remote Sensing digital image processing functionalities.

In fact, 2D GIS has already achieved a solid position as a standard IT tool in many businesses and industries and is therefore not a real novel development. The general public are making use of GIS data almost every day, whether they are driving in their car (with a GPS navigation system), or whether they are looking up a street address on the Internet. Obviously, in Engineering Geology, 2D GIS has an established position as a very useful tool for storing, manipulating and visualising geo-referenced geotechnical data. However, like many other standard IT packages, such as word processors or spreadsheets, novice users are often not aware of the advanced functionalities GIS packages have. If an organisation merely uses a GIS for making "nice maps", it does not recognise the true value of the system. The real added value of using a GIS lies the fact that the GIS functionalities allow the user to create new information by combining and manipulating existing information. Through the recent advances in 3D visualising techniques, the GIS user can also look at his/her data from a wide variety of perspectives, shedding a different light on the data, thus creating also different types of information. Presently, the main development in the field of 2D GIS remains with the end-user, whose only limitation is its own imagination.

Figures 15 to 17 illustrate various GIS thematic information shown in 3D perspective view, using a Digital Terrain Model. These examples are created from actual data gathered by ITC and Delft University students for an Engineering Geological field mapping exercise in the Baix-Camp area in Spain.

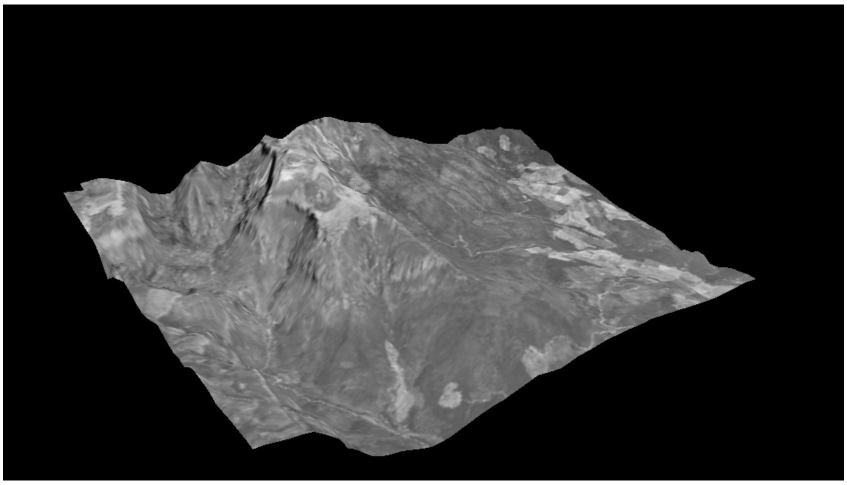

Figure 15. Digital ortho-airphoto draped on top of a Digital Terrain Model

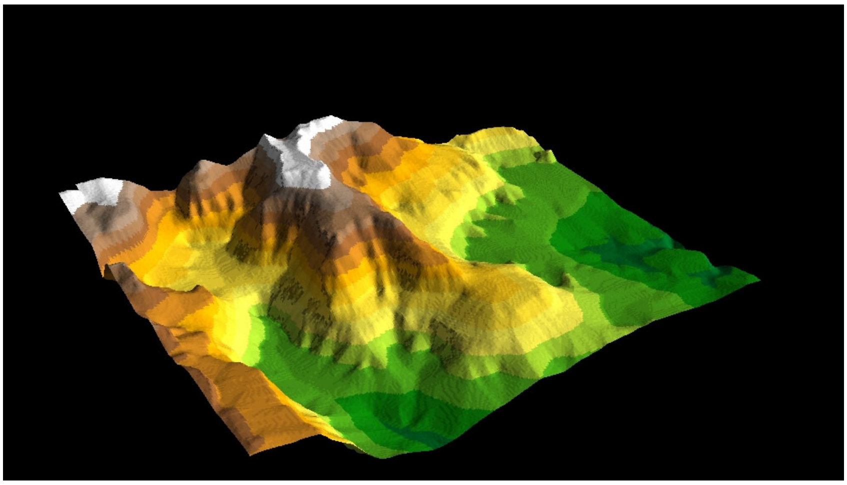

Figure 16. Digital Terrain Model showed in perspective view as a “hillshaded relief model”

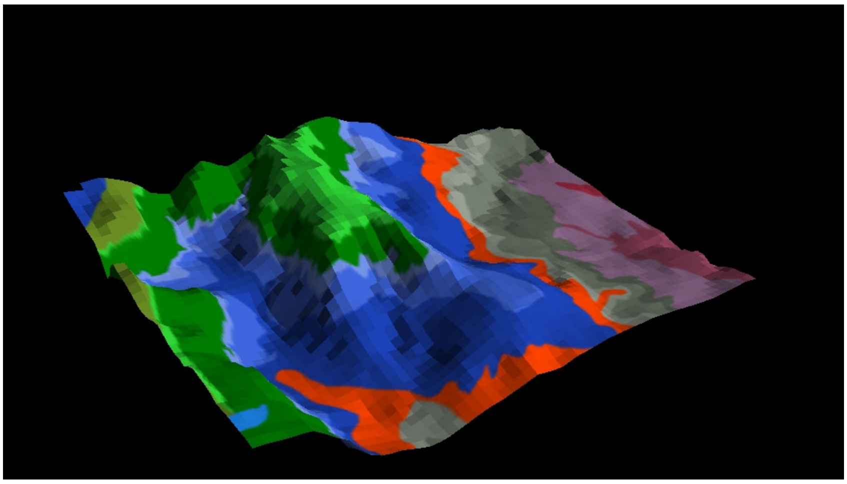

Figure 17. Engineering Geological rock units mapped out and displayed with different colours

A special training package Geographic Information Systems in Slope Instability Zonation (GISSIZ) has been developed for educational purposes (GISSIZ, 2002). Slope instability hazard zonation aims at mapping of areas with an equal probability of occurrence of landslides within a specified period of time. For the analysis of the influence and interaction of causative factors such as terrain steepness, lithology, land use, vegetation, etc., GIS is indispensable for the large data handling capacity needed. The Figures 18 and 19 show the principle of spatial data analysis developed in the GISSIZ package.

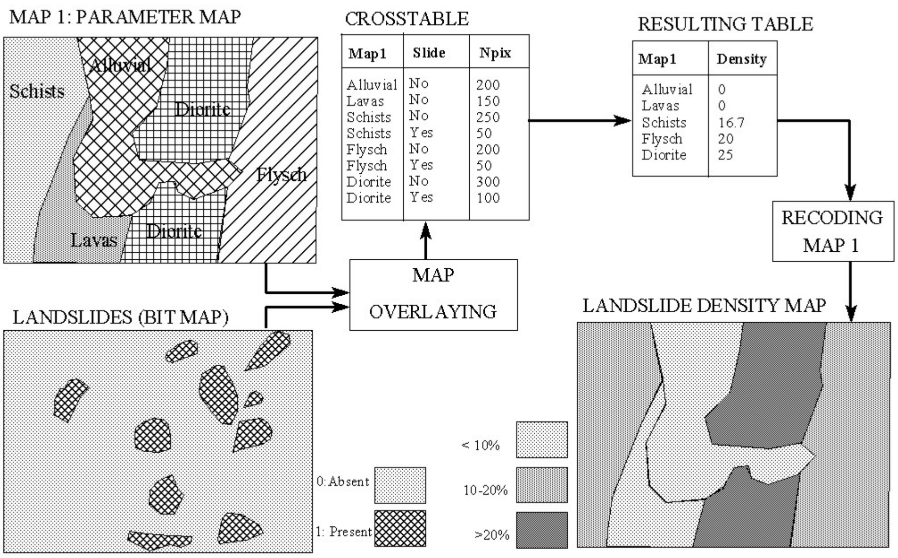

Figure 18. Principle of preparation of a landslide density map for different lithological units from a landslide occurrence map

An example of the use of spatial modelling in GIS for flood management is described by Scholten et al. (1998): GIS showed its great value for flood control measures to be taken by decision makers at the provincial level during the 1995 floods in the rivers Meuse and Waal. Superimposing different data layers, GIS experts could detect the weak parts in the dikes and generate an evacuation plan. Shortcomings within the organization were experienced as well: important data could not be retrieved, and the coordination of efforts by the different governmental departments and institutions was not optimal. To overcome these shortcomings and to optimise the modelling process, Scholten et al. (1998) proposed the development of a spatial decision support system (SDSS), aggregating several models, heuristic and procedural, into integrated software tools. The system proposed was developed by Simonovic (1993). It combines the use of optimisation techniques and other numerical methods with GIS, an expert system (ES) assisting in the input of data into the models to be used in flood damage analysis, engineering expertise and database management software. The architectural design of the Decision Support System (DSS) for flood control management basically follows the architecture for a Spatial Decision Support System (SDSS) as proposed by Armstrong et al. (1986) (Figure 20).

The experience with two cases of floods has shown that a new Spatial Information Infrastructure (SII) needs to be developed. This requires both technical and organizational solutions and standards. Proper documentation of the data will allow the GIS experts to more quickly find, store, update, and re-use the data.

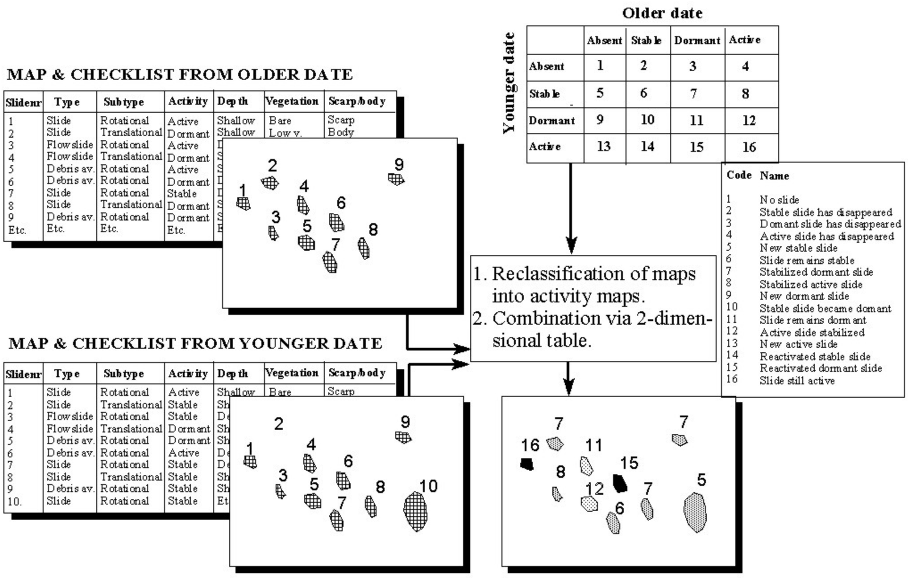

Figure 19. Principle of the preparation of a landslide activity map from landslide occurrence maps at different data

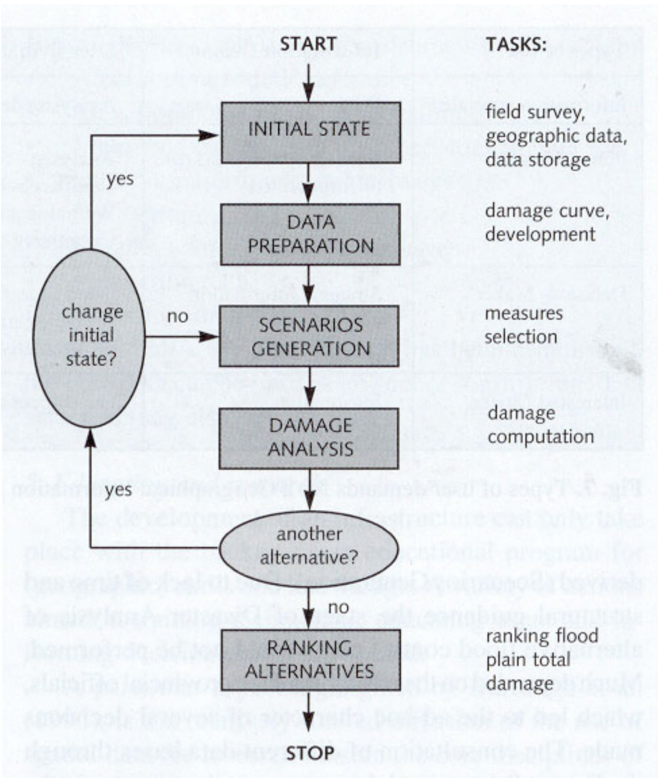

Figure 20. Diagram showing the architectural design for a flood management Decision Support System (Simonovic, 1993)

VISUALISATION TECHNIQUES

Traditionally the visualization of engineering geological information was done in the form of maps, schematic block diagrams and in the form of cross sections, construction site plans, etc. (Dearman, 1991).

IT has opened a whole new spectrum of computer assisted visualization possibilities that surpass the possibilities of before IT. Efforts here should not be directed towards producing the best possible imitation of the conventional map product but to develop a better product. In this case "better" products are maps that are more tailored to the need of the customer. What (engineering) geologists show on a map is an inextricable mixture of hard fact and interpretation. With computer support, the aspects of the geometry could be sampled more rigorously in the field and the three-dimensional structure could be recorded and tested for consistency. The same is valid for computer-assisted processes of interpolation and other aspects of spatial variation of parameters in the engineering geological model, which cannot be reached when working in a conventional way. The selection of features and data to be shown in a map, a 3D model or a vertical, horizontal or inclined cross section (number of contour lines, details of existing infrastructure, drainage lines, but also the detail or the generalization of the spatial and/or thematic (engineering/geological) information can vary for the different users.

We generally know more than we are able to express and share with others. The visualization of (engineering geological) information is subject to cartographic constraints. Scale is the most obvious factor that influences the detail with which the information in the form of a conceptual model in the mind of the engineering geologist must be simplified before it can be shown on a screen or printed on paper. The complexity of nature must be reduced to a few significant and characteristic mapping units.

Furthermore there is obviously a large variation in the information density on the ground and even more below the surface. This is not only due to the variation in accessibility and exposure of the ground materials in the terrain and the density of subsurface information sources as boreholes and soundings, but the information density is also influenced by the relevance of different parts of the terrain or of the stratigraphic sequence for the specific geotechnical problem that has to be solved.

The process of moving from observation in the field to visualisation involves generalization, showing only the most important forms and removing unnecessary details. (Buttenfield and Master, 1991). This process of generalization leads to choices of which type of information will be reduced, a question that would be answered differently by different types of end users, but must receive an unequivocal answer when the map is printed in the conventional way. This printed product is a permanent snapshot of the author's ideas at a particular time. Revision is costly and therefore infrequent, and in the case of engineering geological mapping practically never occurring. This means that very often at the time of printing the information is already out of date. A solution to this problem is to print on demand extracts of the existing information selected from a Geographic Information System (GIS), using the scale, and the instructions for generalization as appropriate as possible for the requirement of the user involved.

GIS offers perspectives for a type of approach that frees the users from the constraints of scale, dimensionality, and cartographic representation of the engineering geological (spatial) model imposed by the paper map. This creates more freedom to develop multiple conceptual models and scenarios and to express these more freely in a record that can be shared. Thus modern IT can extend the means of expression and communication (Kraak, 1999).

This keynote does not cover in detail the aspect of 3D visualisation techniques, which has become a very specialised industry by itself. 3D visualising has undergone tremendous progress. The multi-billion dollar movie- and gaming industry have been the driving forces in this. The widespread development, application, acceptance and distribution of 3D visualising programs (often browser-based, such as VRML) via the Internet creates also a very positive spin-off in this respect that the end-user is at the moment presented with affordable, often freely available and advanced 3D visualising programs. Commercial (geo-scientific) software that caters mostly to a relatively small and specialised group of end-users can obviously gain from these developments. This in turn, will benefit the geotechnical end-user, which is presented with advanced visualising techniques at affordable prices.

PUBLIC DATA EXCHANGE, DATA QUALITY ASSURANCE AND DATA ACCESSIBILITY

The development of IT has had an enormous impact on the availability, access, and interchange of engineering geological data and information between data providers, the general public, and engineering geological experts. Two aspects will be treated briefly in this chapter:

The changing role of the traditional survey organizations,

The improved possibilities of data and information exchange between team members within one organisation or in different organisations.

The changing role of the traditional survey organizations

National Surveys, including Geological Surveys, have been subject to a lot of pressure to redefine their role in government and adapt their mandates to an ICT-dominated world. They had to respond to serious budgetary pressures, implement new technologies and associated staff capacity, establish new and often very different relationships with their client communities and redesign their organizations to meet the demands for products and service diversity. Groot (2001) describes an economic model for efficiency in the pricing and distribution of national geological survey products and services.

The data repositories should provide safe and long term custody of information with ready access to comprehensive, appropriate, current, coherent and testable records (Loudon, 2000). This means that well structured metadata and a network of links and cross references must be provided. Furthermore the integrity of the repository is of greatest importance, coping with past, present and future knowledge and possibilities to freeze versions as necessary for historical reasons, preferably with linkages to show their relationships with the metadata of the time.

The client community is no longer solely the professional engineering geologist. Today everybody can be a user because now we are far more concerned with the consequences of our actions on our environment and vice-versa. We are concerned about the influence of contamination on our health, about whether ground conditions and/or future earthquake occurrence will affect the stability of our homes, and the cost of insuring it and about whether climate change will increase the risk from geo-hazards (Culshaw, 2001). Traditional geological maps and academic publications do not meet these new needs. However, the increasing availability of information in digital form and the improving access to it have revolutionized what can be provided to a wide range of users.

Who will be the users of engineering geological surface and subsurface data and information, and what are their user demands? We must provide a family of distinctive delivery products, each targeted to a distinct class of users. We should distinguish between the needs and abilities of sophisticated users, most "researchers" for example, and those of less sophisticated users (Turner, 2001). While some users can re-analyse or reprocess original data, the general public usually want an answer to their questions and not the original data, which they probably cannot process and may not understand. How can we help users understand data limitations and data quality? Experience suggests that the design of the user interface is critical. The expert wants to enter his/her request rapidly and precisely; she/he wants shortcuts. In contrast the novice user needs assistance in understanding the options, perhaps by on-line help or tutorials. The novice user would be mystified by the expert interface; while the expert will become exasperated with the novice interface.

IT as support for interaction in teams

Communication between participants in a project can be improved by IT, and the closer coordination improves productivity. Where it is impossible or undesirable for all participants to be accommodated at the same location, IT can offer good links for an increased mobility of data and information within and between organizations (Loudon, 2000). IT offers a variety of communications methods, from telephone, fax, email, voicemail, teleconferencing, file transfer, data sharing/exchanging/networking, to project management. The interoperability of data provided by the different participants is in this case an issue of the highest importance.

ACCESS TO NEWLY DEVELOPED KNOWLEDGE

The heart of science is the efficient exchange of ideas and the formal dialogue between producers and consumers of research. For over half a millennium, the printed page has mediated this dialogue. The advent of electronic publications can improve this dialogue and improve the efficiency of research and transfer of scientific results. The role of traditional publication as the primary method of communication is rapidly changing. Electronic publications and network technology are radically altering the relationship between interpretative results and the underlying data. On the other hand the importance of journals in scientific communication is rapidly declining, amongst other things, because of the numerous inadequacies of the traditional editorial and peer review system.

Research institutions can concentrate on assuring broad access to research and data while questions about the physical location of the primary research materials and final research products becomes secondary. Information technology makes it also possible to improve the quality and accessibility to what might be called "non-traditional" research products (such as digital geographic information, unpublished archival material etc.).

Electronic publication provides the means to create dynamic forms of communication, that can only be displayed in an electronic environment - forms of communication that use hypertext and relational database functions to provides text and graphics with which the reader can interact. Many institutes are experimenting with new forms of on-line publication that assure broad access to research and data and improve application of research results to societal problems.

Electronic publication permits reproducibility of the research and permits continued manipulation and enhancement of the research product to better address transfer of scientific results in a form usable to society or as unforeseen applications of technology. Access to new knowledge as available in scientific literature is more rapidly and easily by using IT, which allows for quick inventories of contents through keyword approaches, text scanning; downloading only when suitable for the user.

The scientific publishing industry will probably very soon make a drastic change in the way they provide information to the end user. Loudon: "Computer mediated communication is likely to replace much print publication because of the lower publication and library cost (storing and managing books is likely up to 50% of library costs), and because of the improved representation of scientific findings, increased flexibility and ease of use. IT promises quicker access to more appropriate and up-to-date information at lower cost. Use of hyperlinks and of forward links through references in future publications.

CONCLUSIONS

The digital revolution and the development of widely different applications of digital techniques has been enhanced strongly by the ever increasing calculation power of PC's and mainframe computers in the last decades of the 20th century. The developments in this field are by far not completed yet and it is likely that the IT revolution will have a comparably important effect on all aspects of society as the industrial revolution achieved by making available machine produced power for industrial activities.

In engineering geology the IT applications are partly improving the work with existing methodologies, but also some completely new ways of working have been developed that were not possible in then pre-IT era. To be able to use IT to the full extent we will have to rethink our approaches to define and solve the problems we are facing.

An important conclusion as well is the fact that for most numerical geotechnical modelling the most important bottleneck for further improvements is not the calculation power of computers but the detail with which the input parameters can be determined in the field and underground.

ACKNOWLEDGEMENTS

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