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# Excavatability evaluation and classification with a knowledge based GIS

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ABSTRACT: The development of a Knowledge Based Geographic Information System (KBGIS) for the production of a special purpose engineering geological map is presented. The implemented system prototype, ExpertMapper, uses available engineering geological data, produces the excavatability map of an area, and serves as a geotechnical consultant by giving assistance about the likely excavatability conditions at a certain location and the equipment suitable for excavation works. The development of ExpertMapper includes: the construction of the knowledge base for excavatability classification and mapping purposes, the optimization of the knowledge base rules, and the loose integration of geographic information system, database management system and output module with expert system shell. The output module produces excavatability maps which delineate the detailed excavatability classes within each geologic unit. The interactive consultancy module provides excavation profile, excavation classes and the proposed excavation method with explanatory text.

## 1 INTRODUCTION

Mathematical modelling in GIS, which deal with the numerical analysis of spatial data, lack the capability of incorporating heuristics or the expert's qualitative knowledge into the problem solution. Geographic Information Systems (GIS) can not handle imprecision because of their Boolean logic which is in fact a rigid two-valued mathematical system. Especially the analysis and query functions of the present GIS systems need enhancement through Artificial Intelligence (AI) techniques. Although the spatial data are very accurately stored in a GIS, merging and analysis of this data hardly involves the use of knowledge. Therefore, the results are less reliable and less useful for many geotechnical and engineering geological applications.

From the user point of view, spatial analysis in GIS is a black-box process. Correct application of spatial analysis techniques in special purpose evaluation and mapping of engineering geological conditions demand for a trained user in spatial statistics, interpretation, and map making and drafting techniques.

The weaknesses of GIS can partly be overcome by the employment of the expert knowledge and the integration of human reasoning into the spatial data analysis and map production processes. The goal of this paper is to discuss the integration of Knowledge Based Systems (KBS) with GIS for special purpose engineering geological applications. The integrated KBGIS (Knowledge Based Geographic Information System) approach is expected to answer the demand on knowledge based spatial data analysis, and ease the map production process by assisting user, and providing a friendly interface to the system. In the following sections, both the introduction to the conceptual model of a KBGIS integration is given and an implementation of the model on excavatability classification and mapping is presented.

The Commission on Engineering Geological Mapping of the International Association of Engineering Geology defines a special purpose engineering geology map in the UNESCO (1976) guidebook as: *"a type of map which depicts information about a specific aspect of engineering geology, or for one specific purpose or use".* The engineering geology map should provide a generalised representation of all those components of a geological environment of significance in land-use planning, and in design, construction and maintenance as applied to civil engineering. Good examples of engineering geological mapping practices were given in Varnes (1984), Dearman (1991), and Matula (1979). The engineering geological mapping process was simplified after the introduction of personal computers, Database Management Systems (DBMS) and GIS (Bonham-Carter 1994). The computerised mapping has brought about considerable benefits like; flexibility, productivity, centralisation, decision making, updating, and analysis (McCrary et al. 1993).

Using knowledge based systems in mapping and GIS applications was realised only recently. The first remarkable introduction of expert systems in earth sciences was marked by the PROSPECTOR system which was designed to assist the geologist in mineral explorations (Duda 1980). In geotechnology, expert systems have found a wider application domain. A review of 33 artificial intelligence (AI) and expert system applications in geoscience is given in Yatabe & Fabri (1988). Expert systems can be considered as the AI technology products. The modest definition of an expert system is given in Bichteler (1986) as: *"An expert system is an intelligent computer program which uses knowledge and inference procedures to model human expert reasoning in a narrow, specialised field"*. These systems, by using knowledge and inference procedures, replicate the human's heuristics or rule-of-thumb knowledge and allow reasoning with uncertainty. Both of these characteristics are also present in human problem solving. In literature *"knowledge system"*, *"knowledge based system"* and *"expert system"* are used interchangeably.

The basic integration of a GIS with a KBS is termed as Knowledge Based Geographical Information System (KBGIS). One of the basic components of a knowledge based information system is a spatial database management system which organises spatial object properties by their locations. The second component is a knowledge-base which organises domain knowledge and expertise (Robinson & Frank 1987, Smith et al. 1987, Egenhofer & Frank 1990). Two notable examples of KBGIS development for geotechnical mapping are the KBGIS of Usery et al. (1988), and that of Cress & Deister (1990). These rule based systems support the production of geological engineering maps. The rules are displayed in a decision tree format, which allows the optimisation of rules and incorporation of the needed parameters in evaluation processes and obtain unique classes. The facts of the knowledge base are represented in frame-based structures.

## 2 AVAILABLE DATA AND EXCAVATABILITY EVALUATION

The excavatability evaluation and classification in this research cover surface excavations, quarries, trenches etc. The term excavatability defines the ease of excavating rock or soil masses by any mechanical means like ripping, digging, bucket hoeing, dozing or by blasting.

The excavatability classification system of Kirsten (1988) was employed in this research. This classification system is based on the adaption of the Norwegian Q system (Barton 1974). The classification system covers the excavatability characterization of geotechnical materials from soft soil to hard rock on a continuous basis. The class intervals are based on a logarithmic division from 1(hand spade) to 8(blasting).

The excavatability classification system (Kirsten 1988) considers six variables, namely: *mass strength number (Ms), rock quality designation (RQD), joint set number (Jn), relative ground structure number (Js), joint roughness rating (Jr), and joint alteration rating (Ja)*. Each of these variables is derived from the measured parameters of rock mass and rock material characteristics, such as; discontinuity properties, material strength, geometric properties, weathering, material type, grain size, etc. The descriptions and excavatability class rating values for each variable can be found in Kirsten (1988).

The classification of rock masses plays a key role in the determination of an excavation method which in turn will settle the resulting payment or cost of the civil engineering work. In practice, disputes are often arising from the erroneous forecasting of excavation method, tools and reimbursing costs.

The approach in the production of excavatability map and the development of KBGIS in this research is: 1) to include the engineering geologist's knowledge in spatial analysis and interpretation, 2) to implement the excavatability classification system as production rules, 3) to minimize the number of required map overlays for geotechnical evaluation. Especially intermediate products of GIS map analysis and calculations should be omitted. These are the most cumbersome operations for an untrained user, 4) to make full use of available data, to organize the information base effectively and to reduce the search path, 5) to provide user interactive consultancy and map production options. The resulting system should be applicable for surface excavations made for road cuts, pipeline trenches, foundation works, quarries for construction materials, etc.

The developed system was implemented on a pilot study area. The available data layers for that area are: an engineering geological map of the region, base maps, areal photos, remote sensing images, digital terrain model, database of rock and soil masses, database of laboratory test results on rock and soil samples, rock and soil mass classifications (Hack 1996), and hydrogeological data. A fieldwork of ten days was carried out in the pilot study area. During this fieldwork, the geotechnical characteristics and behaviour of rock and soil units at exposures were observed, the zones of faulting and geodynamic phenomena were identified, the weathering profile and terrain units were investigated, and some information on surface hydrology and groundwater were collected. The fieldwork practice was extremely useful to acquire the qualitative engineering geological knowledge that is important for knowledge base development.

## 3 DESIGN OF KBGIS - ExpertMapper

Two basic considerations of KBGIS design in this research are: 1) a comprehensive characterization of the area for the selected purpose, in this case for excavatability, and, 2) to satisfy the needs of potential users of the knowledge based system by providing an explanatory front-end and by displaying, printing or plotting the results.

The first objective can be partly accomplished by an efficient use of existing engineering geological data stored in GIS, and by a correct application of this data into the excavatability classification system. The excavatability evaluation should benefit from all the relevant engineering geological data stored in the attribute database. The assignment of excavatability class value to the field observation points should primarily be based on measured properties/quantities.

### *3.1 Excavatability evaluation at observation points*

The excavatability evaluation and classification at observation points can be accomplished by translating the excavatability classification system into production rules in its original form (first knowledge base) and in turn inferring on that knowledge base. While constructing the production rules in the knowledge base, a hierarchical value assignment to the variables should be obeyed. In other words, those rules which make ample use of all required parameters should have precedence over other rules which assign values on the basis of minimum number of measured parameters.

### *3.2 Excavatability evaluation of areas*

The interpolation of excavatability from points to areas is carried out in the following fashion:

A) After the information base and the knowledge base are prepared, the system assigns excavatability class values to the observation points and puts them in a database file (Table 1).

B) The value assignment to the rest of the study area involves the spatial data handling with GIS functions. The point information on the excavatability classes can be mapped as a raster overlay by using one of the existing raster map files (eg. geology) for georeferencing. The other map overlays; geology, geomorphology, structural geology, geodynamics, soils, and geotechnical sub-units can be displayed together with the point-raster map of excavatability classes. Then, the attribute values can be extracted from these map layers for the observation points on the point-raster map of excavatability (Table 2).

The relationship between the distribution of excavatability class values (Table 1), and spatial

Table 1. Excavatability class boundary values for each geological unit as calculated from the engineering geology database

| Geological unit | Class boundary values (VAL) |
|---|---|
| Carboniferous granites (H) | 3 ≥ VAL ≥ 7 |
| Carboniferous slates (Hs) | 3 ≥ VAL ≥ 5 |
| Lias1 calcisiltite / calcilutite (Jd11-12) | 5 ≥ VAL ≥ 8 |
| Buntsandstein sandstone (Tg1) | 5 ≥ VAL ≥ 8 |
| Lower Muschelkalk dolomitic calcilutite | 4 ≥ VAL ≥ 8 |
| Middle Muschelkalk sst-cls-gyp | 4 ≥ VAL ≥ 5 |
| Upper Muschelkalk dolomitic calcilutite | 3 ≥ VAL ≥ 7 |
| Keuper marl (/sst/cls/lmst) (Tg3) | 2 ≥ VAL ≥ 7 |

information on geology, geomorphology, faults/folds, soil, geodynamics etc. (Table 2) were taken as the basis of spatial analysis in this research. Spatial analysis is based on evaluation matrices of relevant variables with different weights assigned by the user (Table 3). More specifically, spatial analysis operations in this model are not left to analytical analysis of GIS, but rather being tackled in the knowledge base of the system. This approach makes full use of the available data, supports the analysis with uncertain, imprecise and incomplete information, and allows the inclusion of know-how and rule of thumb knowledge (Table 4).

C) The conversion of raster map overlays into database tables completes the required information (fact) base of the model. The second knowledge base analyses this spatial information base and evaluates the total area for excavatability purpose. It is important that all possible rule instances are treated in the knowledge base, otherwise the model will fail to assign an excavatability value under certain premises.

### *3.3 User interface design*

Two main user interfaces are included in the system design.

The first interface is the map output module for automatic map production. The knowledge base of this module was developed on the basis of a default value for ripping direction (from west towards east). The soil information and excavation depth variables were excluded from the knowledge base. The main reason for that is; on a 2D map only the excavatability class values of one depth level can be represented.

The second interface is the interactive consultancy service. In this case, the rules in the knowledge base include depth, soil layers and ripping direction variables. A graphical presentation of the conceptual model development is given in Figure 1.

Table 2. Class ratings for the spatial elements of excavatability knowledge base

| Numerical designation | Variable | Levels | Explanation |
|---|---|---|---|
| *1* | *GEOLOGY* | 10 | Carboniferous granites (H) |
| | | 30 | Carboniferous slates (Hs) |
| | | 50 | Lias I calcisiltite/calcilutite (Jd11-12) |
| | | 70 | Buntsandstein sandstone (Tg1) |
| | | 90 | Lower Muschelkalk dolomitic calcilutite (Tg21) |
| | | 110 | Middle Muschelkalk sst-cls-gyp complex (Tg22) |
| | | 130 | Upper Muschelkalk dolomitic calcilutite (Tg23) |
| | | 150 | Keuper marl (/sst/cls/lmst) (Tg3) |
| *2* | *TERRAIN UNITS* | 10 | concave, gentle undulating flat |
| | | 40 | convex, elongated-rounded hill |
| | | 70 | convex, gentle undulating flat |
| | | 100 | dissected-sharp-ridge |
| | | 130 | gentle slopes |
| | | 160 | rounded hill |
| | | 190 | steep dissected slope |
| | | 210 | steep knoll hill |
| | | 240 | steep slopes |
| *3* | *FAULTED* | 1 | not faulted zone |
| | | 11 | faulted zone |
| *4* | *GEODY/SLIDES* | 1 | geodynamically inactive area |
| | | 101 | geodynamically active area |
| *5* | *GEOT.SUB UNIT* | 1 | no geotechnical sub unit is mapped separately |
| | | 21 | geotechnical sub units are mapped separately |
| *6* | *SOIL UNITS* | 1 | there is no soil unit at pixel location |
| | | 6 | there are soil units at pixel location |

Table 3. An example of the evaluation matrices used to construct the rules for spatial analysis in the knowledge base

| Variables designation | 1 | 2 | 3 | 4 | 5 | 6 | Resulting class |
|---|---|---|---|---|---|---|---|
| 1 | 10 | 10 | 11 | 1 | 1 | 1 | 3 |
| 2 | 10 | 40 | 11 | 1 | 1 | 1 | 3 |
| 3 | 10 | 40 | 1 | 1 | 1 | 1 | 4 |
| 4 | 10 | 70 | 11 | 1 | 1 | 1 | 4 |
| 5 | 10 | 70 | 1 | 1 | 1 | 1 | 5 |
| 6 | 10 | 130 | 11 | 1 | 1 | 1 | 5 |

Table 4. An example rule in the knowledge base of Expert Mapper for spatial analysis and interpolation

| | |
|---|---|
| *RULE MAPPING46*<br><br>*IF excav_class = UNKNOWN AND*<br>*geo_unit = 90 !(Tg21) AND*<br>*terrain_class = 100 !(D. S ridge) OR*<br>*terrain_class = 210 !(S. knoll hill) AND*<br>*faulted_zone = 11 !(faulted area) OR*<br>*geodynamic_pheno. = 101 !(active area)* | *THEN excavatability_ mapping = 8 CLS* |

### *3.4 Implementation strategy*

The developed KBGIS was aimed to perform the following tasks: 1) to automate the special purpose map production (excavatability map in this case), 2) to increase the accuracy and reliability of map products by including the knowledge into the processes of map making, 3) to provide a consultancy service for the prediction of likely excavatability conditions at selected location, 4) to embrace the flexibility within a single system in order to use the same system architecture for other special purposes (like site suitability for solid waste disposal, suitability for urban development, load admissibility etc.) with modifying its knowledge base.

### *3.5 Components of the system*

The architecture of the developed system, ExpertMapper, is characterized by a loose integration of heterogenous software components (Ilwis, DbaseIV, Geosoft) with an expert system shell (VP-Expert) (Figure 2).

VP-Expert (1989) is a simple rule-based expert system development tool with backward and forward chaining mechanism with simple uncertainty handling as confidence factors. It supports data and file exchange with database, spreadsheet, and text files. However, it has limitations in handling the large knowledge base files and can not handle spatial data directly from GIS.

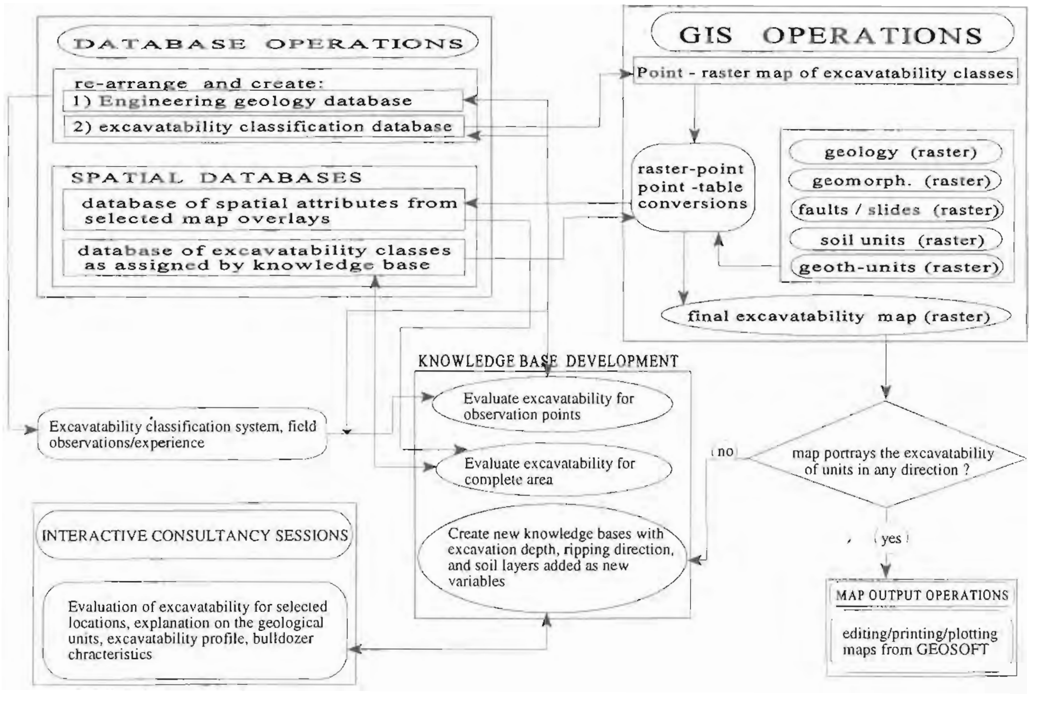


Figure 1. Procedure for development of knowledge based GIS for special purpose engineering geological applications

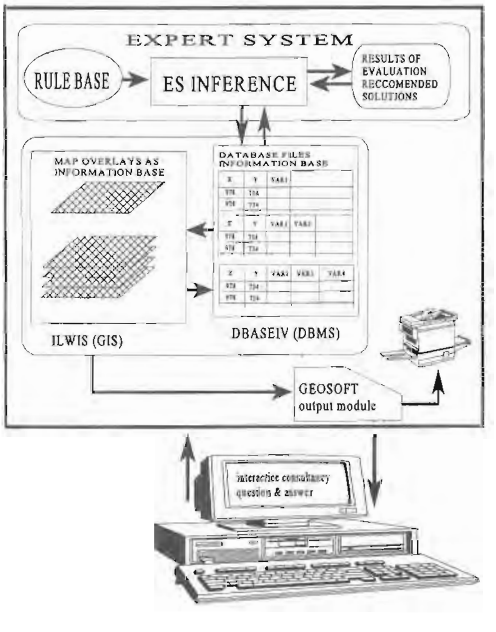


Figure 2. System architecture

The tasks of the expert system shell within the ExpertMapper are: 1) to assign values to the variables required for the excavatability classification by using the data from the engineering geology database, 2) to calculate the excavatability values for observation points, and to store the results in a database file, 3) to evaluate the excavatability of entire area by using the facts in spatial database, 4) to provide a user interface for consultancy and for invoking the components of the knowledge based system (VP-Expert, Ilwis, DbaseIV, Geosoft).

Ilwis (1993) is a geographic information system which was developed by ITC. It integrates image processing and spatial analysis capabilities with tabular database and other conventional GIS functionality. The main functions of Ilwis in ExpertMapper are: 1) to display map overlays, 2) to convert tabular, vector, and raster data for input and output purposes.

DbaseIV (1990) is a data management system with standard query language (SQL) capability, full query-by-example, application generator etc. It uses a relational data model. The roles of DbaseIV in this system are: 1) to store, retrieve, and query data into/from engineering geology database, 2) to serve as an information base of expert system, 3) to store converted spatial database files of GIS for further use by VP-Expert as spatial information base.

Geosoft (1994) is a map processing and modelling software. In this system, Geosoft is used as the output module.

### 3.6 *Knowledge acquisition and knowledge base optimization*

The knowledge acquisition for the excavatability evaluation of point observations in the engineering geological database is based almost entirely on quantitative data. The classification system and accompanying tables for the ratings of engineering geological variables are well structured to acquire knowledge in the form of rules. Therefore, in some instances, rule induction mechanism was employed. At some field observation points, the measured parameters do not include all the required values for the variables of excavatability classification system. The reasons behind this are numerous. During the general purpose engineering geological mapping campaign the outcrops are analysed either for mapping purpose, or for detailed slope analysis, they may or not be sampled for laboratory testing, or the outcrop is difficult for taking any useful measurement other than dip and strike reading. When the measured engineering geological parameters are scarce then the production rules in the knowledge base infer for the worst condition within that particular engineering geological unit. In other words the highest excavatability value is assigned to the observation point. For example, the value assignment to the variable mass_strength_number in the following rule is based on the highest UCS (Unconfined Compressive Strength) value of the unit Tg1 in the database, because, all the premises of the rule are unknown. If any of the premises in the rule is known, then some other rule will pass and assign a value for the goal variable before this rule is checked.

*RULE 11C*
*IF geo_formation = Tg1 AND ucs = UNKNOWN AND point_load_strength = UNKNOWN AND rock_material_strength = UNKNOWN AND average_strength = UNKNOWN*
*THEN MASS_STRENGTH_NUMBER_[Ms] = 35*

The knowledge acquisition for the areal interpolation of the excavatability is based both on the point excavatability class values and the distribution of these class values within each engineering geological unit. The distribution of excavatability class values is related to the geology, terrain units, sub-units, faults, and geomorphology of this engineering geological unit (Tables 1-4). There is a direct relation between the excavatability class values and the underlying rock or soil mass, terrain class, disturbance of the rock mass by faulting, and existence of sub-units with differing geotechnical characteristics. The excavatability class range within some engineering geological units is quite wide. The wider range in excavatability class values is an indication of nonuniformity of rock mass characteristics within the same unit. This property is a valuable qualitative knowledge and should be fully represented rather than being averaged or generalized as in GIS interpolations. The production rules in a knowledge based system is a very suitable method of representing this knowledge. This approach increases the reliability of excavatability evaluation by delineating small areas with different excavatability class values within each unit, and also simplifies the spatial analysis operations by omitting the need of producing intermediate map products(by products) until the final map is produced in GIS.

The most critical stage of the knowledge base development is the optimization of rules in the knowledge base. The size of each knowledge base and the number of facts in the information base have direct influence on the ease of the optimization process. The main considerations in the knowledge base optimization process are: 1) the correct and complete representation and evaluation of all possible combinations of facts in the information base, 2) the avoidance of repeating rules in different combinations, 3) inclusion of rules which may not be necessarily used with the existing information base but will be needed when another information base is incorporated into the system, and 4) optimal placement of rules in knowledge base for faster inferences.

In order to attain these goals the knowledge base has to be checked in slow execution mode while all the information bases attached to the system. The non-passing conditions should be found and the knowledge base must be modified. For large knowledge bases, evaluating multi variables, this process should be repeated so many times until the knowledge base handles every possible combination of facts.

### 3.7 *Operational modes*

In automatic map production mode, the expert system reads all the field values for the first record from the engineering geology database (first database), uses these field values to assign a value for each variable of the excavatability classification system in its knowledge base, and then puts (writes) these assigned values to the excavatability classification database (second database). This process continues in a loop fashion until no records are found. When this stage is reached, the expert system will ask user to enter a value for each variable in the knowledge base. If no value assignment is made then the consultation will be finalized and the control will be returned to the inference engine.

In interactive consultancy mode, the user tells the system for which location it should calculate the excavatability. The expert system returns the calculated excavatability conditions to the user. During an interactive consultancy session, the expert system asks the user to enter the coordinates and the depth of planned excavation, and the ripping direction for excavation works. Then, the system returns: 1) the likely excavation depth profile, including the soils, 2) excavatability class of each unit in the profile, 3) suggested method of excavation, and 4) additional explanatory text.

### *3.8 System testing and further development*

The system was tested on a continuous basis. The tests were started with the sub-knowledge base construction and reasoning checks. Then the implementation of these sub-knowledge bases on test files and information bases was carried out. At the last stage of the system testing, the absolute checking of final integrated system design with various information bases (attribute and graphical database files) was done. The system validation is best achieved with many sample applications preferably with large scale information bases. However, the testing routines in such large scale integrated knowledge based systems are usually slow and demand powerful hardware. Therefore a considerable amount of time was spent for the system tests.

The printed map reflects the excavatability of the mapped area quite in detail. However it can be criticized, as for any other 2D map, for its limitations in representing excavatability with reference to the vertical variations within each unit or between the units. The excavatability evaluation should be based on volume models of the subsurface.

Therefore, the research has been extended to the integration of three dimensional GIS (3D GIS) and artificial intelligence development tools. 3D volume model construction of the pilot study area was completed and the decision support modules are still under construction. The results of the new system development will be discussed in near future.

## 4 CONCLUSIONS

The production of special purpose engineering geological maps and the evaluation of engineering geological conditions can successfully be accomplished using expert system approach. In this research a Knowledge Based Geographic Information System (KBGIS) for production of excavatability maps, called ExpertMapper, was developed and implemented on a pilot study area.

The construction and optimization of knowledge bases are found to be the most important stages of the system development. The translation of the expert's knowledge, experience and reasoning process into the expert system rules is critical for the efficiency and reliability of the system. The knowledge base construction for special purpose engineering geological application should be done by collaborative work of an experienced engineering geologist and the knowledge engineer.

The spatial analysis and interpolation of engineering geological data with the knowledge based approach is found to be more reliable than analytical techniques. Because, the knowledge based approach makes the full use of both observations at sampling points and the relationships between excavatability values and geology, geomorphology, geodynamics etc., which are inferred by the engineering geologist.

Integration of expert systems with 3D GIS will increase the quality and reliability of special purpose engineering geological assessment and evaluation, and will allow various excavation scenarios with changing geometrical, geotechnical and economical constraints.

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