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An Overview of Semi-Quantitative, Qualitative and Knowledge-Based System Methodologies Relevant to Solid Waste Disposal Site Design in Arid and Semiarid Environments

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This paper provides an overview of the methodologies and techniques currently being employed in geotechnical engineering and engineering geology fields and examines their relevance to waste disposal site design in arid and semi-arid environments. The methodologies covered are: semi-quantitative, qualitative and knowledge-based systems. Various fundamentals and limitations associated with each of the techniques are discussed. The combination of semi-quantitative and qualitative techniques in developing Knowledge-Based System Model Methodologies for evaluating the performance and design of waste disposal sites in arid and semiarid environments can provide relevant and sufficient data, and reduce uncertainty in the final results. However, such systems should be aimed at giving advice rather than attempting to replace human expertise.

Introduction

This paper deals with semi-quantitative and qualitative techniques as well as knowledge-based system methodologies relevant to waste disposal site design in arid and semi-arid environments. The design of municipal solid waste disposal sites in these environments requires the use of various data sets such as the following:

- Climatic data sets, which include precipitation, evaporation, transpiration as well as wind speed and direction
- Environmental data sets which include ecological data, social settings, type of industries, type of waste and likely contaminants
- Ground data sets, which include geological, geomorphological, hydrological as well as geotechnical data.

The capturing of all the various data sets requires the use of semi-quantitative and qualitative as well as quantitative techniques. In the process of evaluating the significance of each of these data sets to waste disposal site design, semi-quantitative techniques can be employed for specific parameters governing the interactions of various data sets, such as discontinuity influences on rock mass characteristics. Semi-quantitative and qualitative techniques have been developed and used in various fields, particularly in contaminated land investigation and risk assessment related aspects (Myers *et al.*, 1994; Cairney, 1995; Petts *et al.*, 1997; Nathanail *et al.*, 2002). These techniques are also used in various engineering projects during the desk study, preliminary and detailed investigation, as well as in risk assessment and risk management. Semi-quantitative techniques provide 'scores', rather than an estimate of probability and are designed primarily for decision-making with respect to priorities, whereas qualitative techniques use the methodologies that are based on standard descriptive approach.

On the other hand, knowledge-based systems or expert systems (KBS) are interactive computer programmes that incorporate judgement, experience, rule of thumb and other expertise in providing knowledgeable advice about a variety of tasks associated with engineering project activities, such as site investigation, interpretation of soils and rocks, risk assessment and parameter design evaluations (Toll, 1996). Knowledge-based system technology is an area of research within Artificial Intelligence, which is a branch of computer science concerned with simulating human intelligence in a computing machine (Oliver, 1994). Various KBS have been developed over the years integrating both semi-quantitative and qualitative techniques in problem-solving processes.

Semi-quantitative techniques

The term semi-quantitative does not necessarily signify a greater degree of understanding of the problem, compared with the qualitative approach. Model methodologies that use semi-quantitative techniques are designed for use by non-experts in order to allow decisions to be made as an expert would in a robust and consistent manner (Shook and Grantham, 1993; Droppo *et al.*, 1993). The system described by Shook and Grantham (1993) and Droppo *et al.* (1993) is a decision-making tool developed for prioritising groundwater pollution sources, and it is similar to the DRASTIC described by Aller *et al.* (1987), Canter, (1991), Close 1993 and Windhoek Municipality (2000), as well as the Hydrological Assessment Framework (HAF) described by Freeze *et al.* (1990). The majority of these systems were developed for authorities to exercise regulatory responsibilities particularly with regard to contaminated land and risk evaluation and assessment aspects (United States Environmental Protection Agency, 1990a, b; Council of Canadian Ministers of the Environment, 1992; McFarland, 1992, Parker *et al.*, 1993, Jenni *et al.*, 1995 and Goldsborough and Smit, 1995). Semi-quantitative tools have few computational requirements compared with quantitative techniques (Mwiya, 2003). However, semi-quantitative techniques incorporate less potential uncertainty compared with qualitative techniques, because of the 'scoring methodologies', which are often used. Together with knowledge and experience, the scores are means to express the results of an assessment. However, even in situations where standard terms are used, uncertainty due to observation and interpretation still exists.

Qualitative techniques

The philosophy of qualitative techniques is based on descriptive approaches that are to a certain degree subjective. The subjective element can be minimised by systematic examination using relevant standard terminologies. The aim of using a standardised scheme of description is to convey accurate and relevant information in an identical format by considering all factors in a logical sequence without omissions. Differently ranked methodologies, which incorporate standard terms such as low, medium or high, have been developed particularly for contaminated land studies (Cairney, 1995; Petts *et al.*, 1997; Nathanail *et al.*, 2002). Cairney (1995) and Petts *et al.* (1997) reveal some of the problems associated with the descriptive approach without any scores (qualitative techniques), particularly in contaminated land risk assessment. Their conclusions were:

- Lack of a consistent approach that enables the replication of results
- Lack of standard protocol resulting in personal bias during the evaluation process
- Lack of transparency of data and assumptions made
- Inability to explore all plausible scenarios
- Lack of ability to identify information deficiency
- Not cost effective

Fundamentals of Knowledge-Based Systems

The knowledge base is a component of a KBS that contains all the information associated with the data requirements to which the system is applied (Figs. 1a and b). The information may be documented in definitions, facts, rules and heuristics. The working memory is the component of a KBS that contains all the information about the problem to be solved (Fig. 1). This memory changes dynamically and includes information that defines the parameters of the specific problem as well as information derived by the system at any stage of the solution process (Toll and Giolas, 1995; Winter *et al.*, 1996). KBS generally consists of the knowledge base, working memory and the inference mechanisms (Fig. 1a). However, some of the systems have internal or external database facilities (Fig. 1b).

The inference mechanism controls the reasoning process of the systems (Fig. 1). It uses the knowledge base to modify and expand the working memory in or-der to solve a specific problem. A database is a computer-based record keeping system, whose overall purpose is to record and maintain information in a specific standard. However, the term database relates to the physically stored data and the software required to allow that data to be stored (Bamford and Curran, 1987). The Database Management System (DBMS) provides the user with a framework of communication (interface) to the physical data stored in the database.

The methodologies that are used in the representation of knowledge within the framework of a KBS include rule, frame and logic or predictive calculus (Oliver, 1994). The rule-based representation schemes utilise a set of rules to store the knowledge, and the rules take the form of IF (situation, condition, pattern) THEN action. The inference mechanism controls the manner, in which the rules are executed. The IF clause, or precondition, is matched against a series of facts held in the working memory, and the rules that meet the pre-conditions statement are executed and used to produce new sets of facts. The new facts are then matched against other rule preconditions in order to achieve the solution of the problem to which the rules are designed to apply.

The frame-based knowledge representation uses a concept similar to the rule-based methodology. The term 'frame' covers a variety of knowledge representation schemes, which include networks. The frame-based KBS utilises either slots on objects or frames, or nodes and their interconnections in a network. Alteration of data in certain slots results in action in others and knowledge is inherited from frames precedent in the network. KBS that utilise predictive calculus of logic-based methodologies use languages that allow quantified statements and well-defined formulas as assertions.

Knowledge-based systems use two main inference mechanisms, namely: forward and backward solution-driven. Forward-solution-driven mechanisms assume an initial state of known facts and progresses through the problem, utilising the data or facts (knowledge) in the system to reach a final solution. Backward-solution-driven mechanism assume a possible final solution or hypothesis and from there reason back through the problem utilising available knowledge in assessing the assumed hypothesis. A mixture of forward and backward inference mechanisms (hybrid approach) has also been used in some KBS and examples of such systems can be found in Toll (1996; 1998).

The combination of KBS and databases illustrated in Figure 1b can enhance the capabilities for modelling real world systems, and has the advantage of having a form of centralised data store (databases) that can be accessed by other users. The essential basic element of a database is the data items or fields, which are grouped together for representing similar objects. The main advantages of using a database are that it provides centralised control of its operational data, high speed processing, consistence and standardised record keeping; it also provides a platform for data sharing (Date, 1986). There are three types of recognised data models, which are the structural and fully oriented data model (relational), the hierarchical and the network models (Benyon-Davies, 1991). The structural and fully oriented data model is

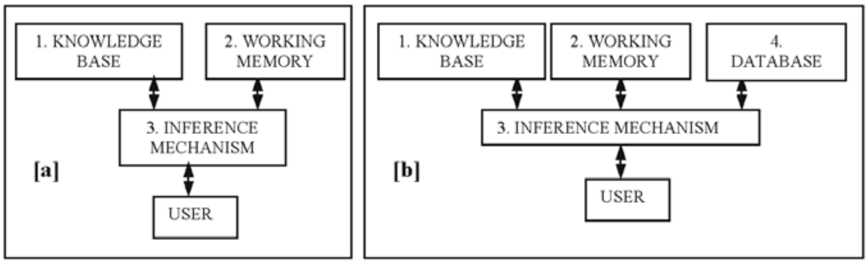

Figure 1: Typical KBS (a) and enhanced KBS (b) (modified after Oliver, 1994).

increasingly used nowadays due to adequate representation of the real world, such as a Digital Terrain Model (DTM).

The hierarchical data model consists of several separate files, where each file represents a separate data group and the data is organised hierarchically in relation of ownership. The network data model extends the hierarchical model by introducing the network concept, where each record within a system is joined to other relevant entities by a system of markers. The relational data model is the most frequently used data model, where the data is represented and organised in the form of two-dimensional tables related to each other by common attributes (Allen *et al.*, 2002). Relational databases are accessed and shared using a pool of shared resources called the Relational Database Management System (RDBMS) (Oliver, 1994). The RDBMS provides a framework of communication between the end-user, application programmes and the database itself, allocating storage, providing security and handling all file and data processing.

However, KBS are also expected to deal with uncertainty in various data sets used, as well as in the inference process. Various models for handling uncertainty due to incomplete information in the database have been proposed, and some are discussed in Mullarkey (1987). Miles and Moor (1994) describe uncertainty as an area, which in itself is uncertain and prone to subjectivity, with respect to the person assigning uncertainty to an event or set of facts or knowledge, who must be in full possession of all the facts that can affect this event. However, gaining knowledge from experts or reference material is a relatively simple task when compared to assigning a certain rating for that particular piece of knowledge (Oliver, 1994). Nonetheless, uncertainty assessment methodologies are included in most KBS (Toll, 1996; 1998).

The methodologies that are used in various KBS cover qualitative, semi-quantitative and quantitative techniques. Compared with standards and guidelines that have been developed, the advantages of KBS techniques are that they are (1) based on a standard protocol, (2) are consistent, (3) information deficiencies can be identified at various stages of the processing, (4) various scenarios can be evaluated and (5) assumptions are also highlighted. However, there are not very many cost-effective KBS that deal with specific project developmental and design processes, such as waste disposal design, from investigation to aftercare, in specific environments.

Knowledge-Based Systems and Waste Disposal Design

The development of waste disposal sites follows standard site investigation procedures, which start with the desk study and proceed to preliminary investigation, detailed investigation, design, construction and monitoring. This is similar to the standard site investigation procedure described by Clayton *et al.* (1995) and Anon (1999). Various knowledge-based systems (KBS) have been developed for solving specific aspects associated with site investigation, analyses and mitigation assessments. There has been no true KBS developed for evaluating the design and performance of waste disposal sites in general, or in arid and semiarid environments in particular.

Nevertheless, a number of knowledge-based "expert systems" (KBS) directly and indirectly relevant to waste disposal have been developed for different aspects of geotechnical engineering (Adams *et al.*, 1989). Toll (1996; 1998) reviewed some of the knowledge-based systems applicable to geotechnical engineering problems associated with site characterisation, classification of rocks and soils, foundation design, earth retaining structures, slopes, underground openings, liquefaction, ground improvement, groundwater, dams, roads and earthworks. He concluded that all these systems are valid for solving many engineering problems, but they should be developed to provide support and advice to users rather than attempting to replace human expertise.

Some of the knowledge-based systems that have been developed and could be relevant to waste disposal development and site characterisation are described by Wharry and Ashley (1986), Siller (1987), Smith and Oliphant (1991), Halim, *et al.* (1991), Thomas *et al.* (1992), Oliver (1994), Winter, *et al.* (1996), Jia (2000), Al-Yaqout and Townsend (2001) and Allen, *et al.* (2002). The earliest knowledge-based system to address the level of site investigation required for specific engineering projects has been described by Wharry and Ashley (1986).

The system of Wharry and Ashley (1986) matches the user input requirements of a proposed structure with the level of information known about a site and the amount of information required to reduce the risk involved. The system starts by asking the user for preliminary site data. Based partly on the responses to the preliminary questions, the user is then asked to provide more advanced site information. The level of site investigation required is calculated, based on the information accumulated in the knowledge-base. The system contains information about 24 investigation techniques, ranging from very preliminary, such as topographic data, to more advanced methods which involve drilling and other intrusive techniques. It uses the backward-solution-driven inference mechanism and a rule-based knowledge representation scheme. The major shortcoming of the system is its inability to handle qualitative geometrical descriptions (Oliver, 1994). The size of the project is defined as small, medium or large, while the foundation geometry is given as shallow, or deep. Nonetheless, the system is a good example of a KBS, with rule-based reasoning applied to site investigation.

Halim, *et al.* (1991) described a knowledge-based system that incorporates probabilistic analysis in the selection of an appropriate site investigation programme. The system first uses the combination of rule-based reasoning and the information provided by the user to infer the prior estimates of the lateral and vertical soil variations (Toll, 1996). The prior estimates are then updated using the probability techniques in the selection of the most effective exploration programme. The user can select and input various exploration techniques together with the associated costs. Finally, the system evaluates the associated design variables as well as the data reliability, using the information available in the knowledge-base. This system employs a combination of rule-based and frame-based reasoning with a forward-solution-driven inference mechanism in the evaluation of an appropriate site investigation programme.

Smith and Oliphant (1991) describe a knowledge-based system that assists the user in the planning stage of a site investigation by providing suggestions for the next stage of the investigation. This system uses a systematic data input facility that minimises omissions of the most relevant data. The data obtained from the planning stages of different site investigations are of similar format, which makes it possible for the system to use a multiple menu system to get the data from the user. The data obtained is utilised to provide suggestions on the possible locations of boreholes, as well as the types of soils suitable for testing. This information is presented in the form of a two-dimensional visual representation of the subsurface. However, in most cases ground conditions vary considerably and a two dimensional representation of site investigation data will still require human experience, knowledge and understanding to synthesise the data and evaluate appropriate design variables. Nonetheless, the system also provides recommendations regarding the type of foundation suitable, with respect to specific soils conditions. It uses rule-based reasoning and backward solution driven inference mechanisms.

Knowledge-based systems, which can provide qualitative advice regarding the type of investigation and testing methods required have also been developed (Winter *et al.*, 1996). The system described by these authors is designed to advise and guide the user in collecting sufficient relevant data for developing a sound conceptual ground model with respect to trunk road projects. The system contains knowledge about the different phases and stages of an investigation from desk study and detailed investigation to design and construction. The desk study phase is the initial stage for collecting existing relevant information regarding the project. This information is then used in the preliminary and detailed site investigation stages. The system uses the data provided by the user in generating an activity log of the proposed investigation. The activity log is then compared with a list of mandatory and advisory procedures contained in the knowledge-base. The cross checking ability enables the system to highlight omissions in the way that an investigation has been carried out. It uses a rule-based reasoning mechanism with a hierarchical menu structure.

The primary objectives for using the phasing process described by Winter *et al.* (1996) are to obtain high quality reliable design parameters from a variety of techniques, which include in situ and laboratory tests. The detailed structures of the systems of Thomas *et al.* (1992) and Winter, *et al.* (1996) offer systematic guidance on data collection and evaluation using mandatory and advisory cross-checking procedures. The degree of reliability of the field data, with respect to selecting appropriate techniques during site investigation, has been addressed by the knowledge-based systems described by Moula and Toll (1993) and Moula, *et al.*, (1995). These systems offer advice on the type of tests, with respect to specific ground conditions. The evaluation of various aspects associated with site investigation data involves the use of different techniques and the results have to be accessible with a KBS.

Databases have been incorporated in some KBS in order to provide data management capabilities. SIGMA described by Oliver (1994) is a decision-support system designed for the interpretation of site investigation data, using a relational database to store data on all aspects associated with a site investigation. It assists the user in making decisions by using the mandatory cross-checking, database management and parameter assessment methodologies. The system contains a number of knowledge-bases that hold information about the ground, geotechnical tests and correlations between geotechnical parameters. This system uses two types of interpretation: interpretation of design parameters from laboratory and field test results and interpretation of ground conditions from borehole records. In addition, parameters can also be derived from qualitative information, such as engineering descriptions of ground con-ditions, if quantitative data is not available.

The database contained in SIGMA has an important data management role, which includes storage, checking and manipulation of large quantities of data produced during site investigation. The data is stored in the form of tables where each table represents a data group, the data group being a function, property or parameter of the site investigation (Oliver, 1994). The table structure ensures efficient data retrieval and handling, which is necessary for the potential volume of data to be stored. However, the combination of Geographical Information Systems (GIS), such as ARC/INFO, and the application of a graphical interface would allow more efficient data access and exchange amongst various us-ers.

Nonetheless, Geographical Information Systems have also been integrated into the development of some knowledge-based systems (Thomaz and Altschaeffl, 1994; Adams and Bosscher, 1995; Jia, 2000; Faghri *et al.*, 2002; Allen *et al.*, 2002). Jia (2000) describes the IntelliGIS system developed for representing and reasoning of spatial knowledge. The system uses the transmission control protocol or Internet technologies, which have increasingly been applied in many different fields (Allen *et al.*, 2002). Using the GIS-based systems, solutions are derived from spatial knowledge and represented graphically (Jia, 2000). However, the ability to identify potential risks associated with specific projects is based on human experience. The system described by Allen *et al.* (2002) uses a GIS database to delineate areas suitable for waste disposal development. The data synthesis for risk evaluation within the system is not well defined, because different data sets are produced in separate layers. However, this system is still being developed.

Other GIS knowledge-based systems incorporating generic modelling and qualitative site-specific information models for assessing and managing risks during the construction phase of a project have also been developed (Tah and Carr, 2001). The system described by Tah and Carr (*op. cit.*), evaluates the risk associated with the project by creating a qualitative knowledge representation model for supporting the quantitative risk analysis. The overall model uncertainties are reduced by the qualitative knowledge model, which establishes the parameter interdependencies in the quantitative risk analysis model. However, uncertainty can be modelled using Monte Carlo simulation, which has become popular particularly in risk assessment related studies (Guyonnet *et al.*, 1999; Whitman, 2000; Sohn *et al.*, 2000; Wong and Yeh, 2002).

Discussion

The problems associated with qualitative techniques described by Cairney (1995) and Petts *et al.* (1997), are largely due to lack of protocol. However, even in semi-qualitative techniques for which scoring protocols have been developed, significant problems can arise due to lack of understanding of the factors associated with specific scores (Pett *et al.*, *op. cit.*). The problems associated with the scoring approach used in semi-quantitative techniques can be resolved by design methodologies that incorporate the assessment and mitigation process schemes. The assessment scheme should provide background knowledge on the nature and characteristics of the factor/s scored. The background knowledge should form part of the system methodology by providing an indication of the level of influence associated with each score. The indicator should show a level of influence with respect to mitigation measures required.

Standards and guidelines on various aspects of engineering projects, including waste disposal development, monitoring and aftercare, have been developed and are used by regulators in different parts of the world (Department of Water Affairs, 1991; United States Environmental Protection Agency, 1992a, b, c; Department of Water Affairs and Forestry, 1994; Department of the Environment, 1986a, b, 1995a, b). These standards and guidelines can potentially be used as indicators with respect to site investigation and mitigation measures. The indicators and the required mitigation measures can be incorporated in a knowledge-based system model methodology, which utilises the know-ledge-based approach. However, a more effective approach is to incorporate semi-quantitative and qualitative techniques in specially designed computer-based decision tools, such as knowledge-based systems, for waste disposal in specific environments.

Knowledge-based systems are efficient tools. However, these systems should be regarded as assisting during the data capture process by providing guidance on progressive data collection stages, evaluation techniques and advice (Toll, 1996). This will ensure the collection of relevant and sufficient data, based on the appropriate conceptual models. KBS provide a solution to the problems associated with qualitative and semi-quantitative techniques, which include lack of protocol and inconsistencies (Cairney, 1995, Pettes *et al.*, 1997). KBS have the ability to utilise symbols that represent data in the various processing stages, which can provide flexibility range of application. In addition, these systems are able to apply heuristic reasoning to data or data ranges through repetitive or iterative processes (Oliver, 1994). However, KBS have been developed for specific aspects of various project activities, such as general laboratory and field data interpretation. The full benefit of KBS will only be realised, once systems are developed for specific engineering projects, such as the KBS described by Winter *et al.* (1996) and Allen *et al.* (2002).

Conclusions

The design of waste disposal sites in arid and semi-arid environments requires the use of climatic, environmental and ground data sets. These data sets can have qualitative format (descriptive approach) and include types of waste and geological and geomorphological data, as well as vegetation characteristics. Sound conceptual models for waste disposal in arid and semiarid environments have to be developed using such field and laboratory methodologies as described by Al-Yaqout and Townsend (2001) and Nathanail *et al.* (2002). However, some of these methodologies have been incorporated into KBS, as described by Thomas *et al.*, (1992) and Winter *et al.*, (1996). In addition, standard field and laboratory testing methodologies for both soils and rocks covering fundamental properties, testing methods and site characterisation are described by Bieniawski (1993a; b), Hudson (1993) and Anon (1990; 1995; 1999). Furthermore, current good practices in ground investigation are exemplified in Anon (1986), Hights (1986), BS Eurocode 7: (1995), Pusch (1995), Clayton *et al.*, (1995), Toll (1996), Association of Geotechnical and Geoenvironmental Specialists Guide (1998), Smith and Ellison (1999), Culshaw and Northmore (2002) and Culshaw and Ellison (2002).

Typical computer models in this area require extensive primary data (hard data), a database and complicated validation processes in order to obtain reliable re-sults (Khire *et al.*, 2000; Allen *et al.*, 2002). These complicated processes are necessary because of the various types of heterogeneity associated with the input data relevant to waste disposal development. Nonetheless, lack of knowledge and understanding of the interdependencies among the parameters used in a model can result in the inability to identify uncertainties associated with individual parameters and the model itself (Durgaprasad and Appa Rao, 1997; Shelley *et al.*, 2001). Estimation emission techniques are appropriate tools, which can contribute to effective design and operation of waste disposal sites particularly in developing countries with arid and semi-arid environments.

The combination of qualitative and semi-quantitative and quantitative techniques in developing Decision Support Tools (DSTs), such as the Knowledge-Based System Model Methodologies (KBSMM), for evaluating the performance and design of waste disposal sites in arid and semiarid environments, described by Mwiya (2003), can provide reliable data and reduce uncertainty in the final results. The DSTs have to incorporate the standard phasing stages involved in project development, which include desk study, preliminary investigation and mitigation (Clayton *et al.*, 1995, Anon, 1999; Nathanail *et al.*, 2002). These phasing stages should ensure that uncertainties associated with various data sets are quantified at each stage in order to avoid the effect of combined uncertainties in the final result. However, the role of any knowledge-based system should first be to provide consistent, formal, flexible, cost-effective and comprehensive data capturing and processing strategies, so that the user understands the problem and can build a sound conceptual model. The systems then have to guide the user in collecting relevant data for site characterisation and the development of appropriate mitigation and monitoring strategies for specific projects, such as waste disposal site design and performance in arid and semi-arid environments.

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