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A decision support system for geotechnical applications

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Abstract

A knowledge-based system shell called ‘Confound’ has been developed for the production of decision support systems. It was initially used for developing a system for conceptual foundation design but has subsequently been used for retaining wall, expansive soil and ground investigation applications. It uses a hierarchical object-oriented knowledge base where each object represents a decision in the decision making process. A simple rule-based approach is used to provide advice on the suitability of each potential choice, based on project specific information that is provided by the user. Confound has the ability to work with incomplete information and uses a system of confidence levels so that the user is aware of the confidence with which each piece of advice is given. Conflicting information in areas where knowledge is poorly defined can also be handled. Confound is designed to leave the user in full control. It simply provides comments on suitability (with an indication of confidence) and leaves the final decision to the user. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

This paper describes ‘Confound’, a knowledge-based system shell that was developed for a geotechnical application. It was designed for the purpose of developing a decision support system for the conceptual design of foundations (i.e. the preliminary qualitative aspects of foundation design when various options are considered prior to the start of detailed quantitative design). The name Confound comes from this application (CONceptual FOUNDation design) rather than any

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desire to confound the user! Although it was designed for a foundation engineering application it has the potential to be used in any decision support area. Knowledge from any domain can be entered into the shell to provide a decision support system for that domain. It has subsequently been used by other researchers for developing different geotechnical decision support systems [1–3].

Confound is a hierarchical decision support system. It consists of a hierarchical knowledge base (containing frames) and a database (containing factors). A frame is an option available to the user at a certain point in the decision process. Factors are facts (with values supplied by the user) that are relevant to the decision making process. Rules provide the linkages between the factors and the frames, so that the suitability (or otherwise) of any option can be determined from the factors supplied. The frames knowledge base uses an object-oriented approach where all information about each frame (including the rules relevant to that frame) is stored within the frame object.

Confound is not designed to give the user a definitive solution to any problem, but rather to highlight points that should be considered and provide direction and advice.

It has the ability to work with incomplete information and uses a system of confidence levels so that the user is aware of the confidence with which each piece of advice is being given. Confound can also handle conflicting information in areas where knowledge is poorly defined. In all cases, the final decision is made by the user based on the assistance provided by the software.

Confound was developed using Borland C++ for use within Microsoft Windows™. It also makes use of links to Windows™ help files.

This paper describes the structure of Confound, using the conceptual foundation design application as an example. The way in which the software would be used is explained, and the user interface is illustrated. In addition, the paper describes how a decision support system can be created using the software. The knowledge acquisition aspects of the system are outlined, showing how knowledge (frames, factors, rules etc.) is entered into the system. A short overview is also provided of other systems that have been developed with the software.

2. The structure of Confound

Since Confound is a decision support system, each frame represents an option available to the user at a certain point in the decision process. The knowledge base, therefore, takes the form of an explicit hierarchy representing the various paths open to the user during the decision making process. Each object in the hierarchy is a frame that contains detailed information and rules describing the circumstances that would make that object a suitable or unsuitable choice. An example frame hierarchy for the conceptual foundation design application is shown in Fig. 1.

Confound requires project specific information (i.e. facts about the project under consideration) in order to give specific advice. These facts are called factors within Confound. Factors are things that might influence the suitability of any of the

objects in the frames knowledge base. One factor may have an influence on several objects in the knowledge base. An example factor hierarchy for the foundation engineering application is shown in Fig. 2.

The particular form of representation used within the factors database has to be decided by the knowledge engineer designing the system. For example there are many ways to represent the ground in knowledge based systems [4,5]. For the

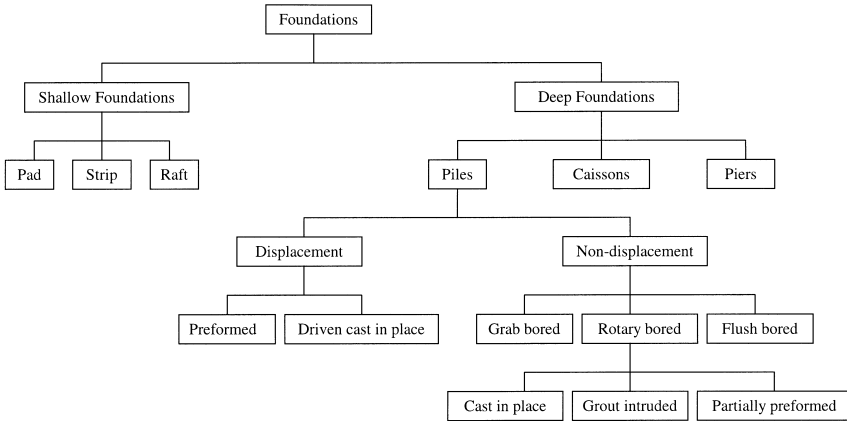


Fig. 1. The structure of the frames knowledge base for the conceptual foundation design example.

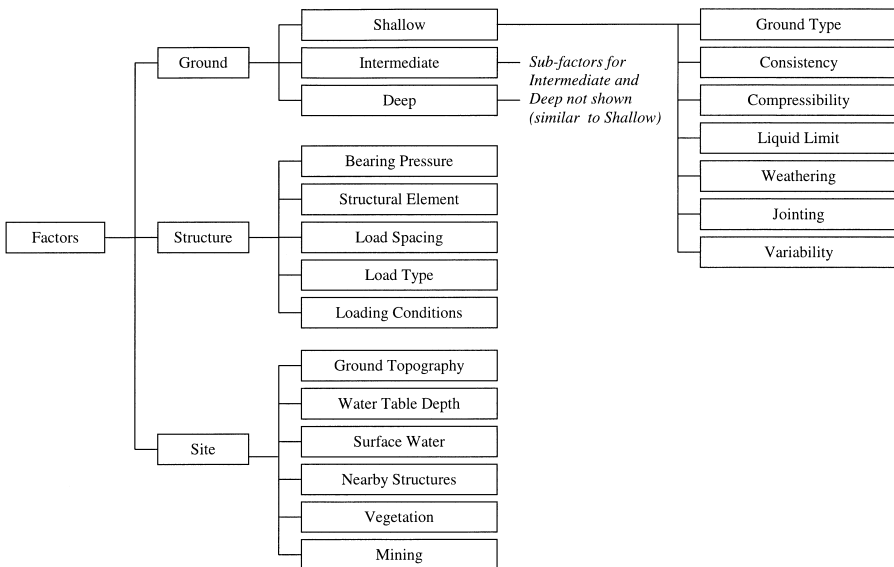


Fig. 2. The structure of the factors database for the conceptual foundation design example.

conceptual foundation design example a very simple representation was found to be appropriate. This involved dividing the ground into three conceptual zones (shallow, intermediate and deep) as shown in Fig. 2. These zones were defined as.

2.1. Shallow zone

This represents the top 3–4 m within which shallow foundations would be constructed.

2.2. Intermediate zone

This represents a zone below 3–4 m through which deep foundations would be installed. The properties of this zone will affect the frictional resistance of piled foundations but not the end resistance. This might typically extend to 10–20 m below ground surface, depending on the depth to a good bearing stratum.

2.3. Deep zone

This represents a zone below the intermediate zone in which deep foundations would be terminated. Normally this would represent a good bearing stratum, possibly bedrock.

Similarly, other classification systems had to be adopted for qualitative factors. For example, the qualitative factor ‘loading conditions’ was defined as light, medium, heavy and very heavy. Some guidelines on selection were then provided to the user:

Light	< 100 kPa	Typically domestic housing, or light warehousing units weighing in the order of 1–2 MN.
Medium	100–300 kPa	Normal civil engineering structures.
Heavy	300–600 kPa	Structures weighing of the order of 400 MN e.g. silos, blast furnaces etc.
Very heavy	> 600 kPa	Structures weighing in the order of 700 MN e.g. nuclear reactors etc.

The way in which frames and factors are represented within the Confound software will now be described in detail.

3. Frames

Each frame is assigned a frame name, a full name and a description. Each frame owns its own set of rules that dictate the suitability of that frame object under various conditions i.e. the suitability depends on the values entered for the factors relevant to that frame. For example the frame ‘Displacement’ has the following attributes:

Frame name: *displacement*
 Full name: *displacement piled foundations*
 Description: *insertion methods that results in soil being moved both vertically and radially as the pile shaft is driven or jacked into the ground (driven piles).*

3.1. Rules

In addition to the rule conditions, each rule is assigned a confidence level, a suitability value, a text description (or comment), a link to further information (in the form of a link to a Windows™ help file and the help file context number) and a reference to the source of the knowledge. Rules are grouped initially by topic (for the benefit of the knowledge engineer compiling the knowledge base) and then by confidence level. To give an indication of the numbers of rules involved in a system, the displacement piled foundation frame in the conceptual foundation design example has a total of 57 rules. For this frame the rules are grouped under the topics: general suitability, end bearing, skin friction, settlement, pore pressures, loose soils, loading, lateral loading, uplift, vibratory loads, groundwater, surface water, sloping ground, buckling, driving into rock, punch through, driving difficulties, noise and vibration, headroom, effects of ground heave. Other frame objects might have a similar number of rules, but might be grouped into different topics.

An example of a rule attached to the displacement piled foundation frame is given below:

Topic: *general suitability*
 Confidence level: *2*
 Suitability: *highly suitable*
 Comment: *low-displacement piles are suitable in most cases in dense materials*
 Help file: *foundat.hlp*
 Help file context: *310*
 Source: *Poulos in Bell p52/5*
 Conditions: *intermediate ground type = any of {fill, sand, gravel}*
intermediate ground consistency = any of {dense, medium dense}.

This rule indicates that if the intermediate ground type is fill, sand or gravel and the intermediate ground consistency is dense or medium dense then a displacement piled foundation would be ‘highly suitable’ with a confidence level of 2. The definitions of confidence level and suitability are discussed below. The help file and context number provide a means to link to a Windows™ help file with a help page relating to displacement piles (defined by the context number). The source information is for the benefit of the knowledge engineer as a reminder of the source of the knowledge and is not presented to the user. In this case the reference is to a book by Bell [6].

‘Intermediate ground type’ and ‘intermediate ground consistency’ within the rule conditions refer to the factors for ground type and consistency for the intermediate ground zone (Fig. 2). This rule will only fire if values have been entered for these two factors and the values match the conditions specified. All rules fire independently and it was not found necessary to introduce rule chaining within the system.

3.2. Confidence levels

The use of confidence levels means that the system can operate with an incomplete set of data about a project. The more information the user enters about a project, the more confidence the system has in its assessment of the suitability of different frames. The confidence levels in Confound range between 0 and 5. A value of zero represents no confidence (i.e. no specific factor information is available that is relevant to the rule). Therefore, rules with a confidence level of zero indicate general knowledge about each frame object. The system always ranks its advice according to confidence level so that information with the highest confidence is given at the top of the list of advice.

We can take an example from the conceptual foundation design application. Rules relating to the bearing capacity of a particular foundation type might have different confidence levels based on the type or amount of information the user has entered about the project:

- Level 0 — (no values entered)
- Level 1 — soil type only
- Level 2 — soil type and soil consistency
- Level 2 — structural load only
- Level 2 — soil strength only
- Level 3 — soil type and structural load
- Level 4 — soil type, soil consistency and structural load
- Level 5 — soil strength and structural load.

3.3. Suitability

Each frame object can contain rules with different suitability values to cover all possible scenarios. The suitability value represents the suitability of the frame, should the scenario described by the rule conditions arise. The suitability value represents one of the following:

- Highly suitable
- Suitable
- Neutral
- Unsuitable
- Highly unsuitable.

Rules with neutral suitability (i.e. neither suitable nor unsuitable) are used to present general knowledge about each frame object in the event that no relevant factor information has been provided.

3.4. Comments and link to further information

Comments are text descriptions explaining why the frame should be suitable (or not) given the conditions appropriate to the rule. This explanation can then be reported to the user. The link to a Windows™ help file allows the user to access more information about the issue relevant to that specific rule.

3.5. Conditions

Each rule is made up of a set of conditions. It is at this level that there is a link to the factors database, as each condition refers to a single factor. For example, a rule may be based on the factor called ‘bearing pressure’. An example of a condition might be:

bearing pressure < 100 kPa.

This condition could be true or false depending on the value of bearing pressure entered by the user. Conditions can take different forms depending on the type of the factor considered. However, whatever form the factors take, the outcome of each condition will always be either true or false. If all the conditions within a rule are true then the rule will fire and will be displayed to the user.

4. Factors

The factors database contains all the factors that might influence the suitability of any of the objects in the frames knowledge base. One factor is likely to have an influence on several frames. The structure of the factors database is defined by the knowledge engineer. However, values for the factors are entered by the user to define the context (referred to as project specific information in Confound) of the decision making process.

Confound makes provision for four different types of factor:

- Numeric
- Boolean (true/false)
- Character strings (text)
- Selectable list.

A factor could be represented by more than one type. For example, if the angle of friction was an influencing factor, this could be stored as a numeric factor i.e. 30° or as predefined ranges that could be selected from a list i.e. “below 10°”, “10–25°” etc.

Confound provides the ability for the factors to be grouped into a hierarchical structure for presentation to the user, in order to facilitate data entry, (Fig. 2). However, the factors database is not object-oriented and two factors cannot be given the same name. Therefore, factors have to be named appropriately e.g. the factor ‘ground

type' has to be given different names (such as 'Shallow ground type', 'Intermediate ground type' and 'Deep ground type') when referring to shallow, intermediate and deep zones.

5. Using Confound

The opening screen of Confound provides the user with the option of defining 'project specific information' (i.e. values for the factors specific to the project under consideration) or consulting the knowledge base. If no project specific information is provided the knowledge base will provide only general knowledge about the different options.

Project specific information is entered through the dialogue box shown in Fig. 3. This shows the hierarchy of factor groups on the left-hand side (ground, structure and site, with the subgroups of ground: shallow, intermediate and deep). The tree structure displaying this hierarchy can be expanded and reduced in the same manner as other Windows™ software (e.g. Microsoft Explorer in Windows 95 or File Manager in Windows 3.x).

If the user clicks on the appropriate factor group then the factor instances at the lowest level of the hierarchy are displayed. Appropriate controls for entering information are provided. Fig. 3 shows list boxes for ground type, consistency and compressibility, allowing selection from a predefined list. For liquid limit an entry box is provided to allow the user to type in a numeric value. If Boolean factors were used then a tick box would be provided.

The tick boxes to the left of each factor are used to indicate whether values are known or unknown. If the box is not ticked then that factor is treated as unknown. If the factor is unknown then it is greyed out in the dialogue box, as is the case for weathering in Fig. 3.

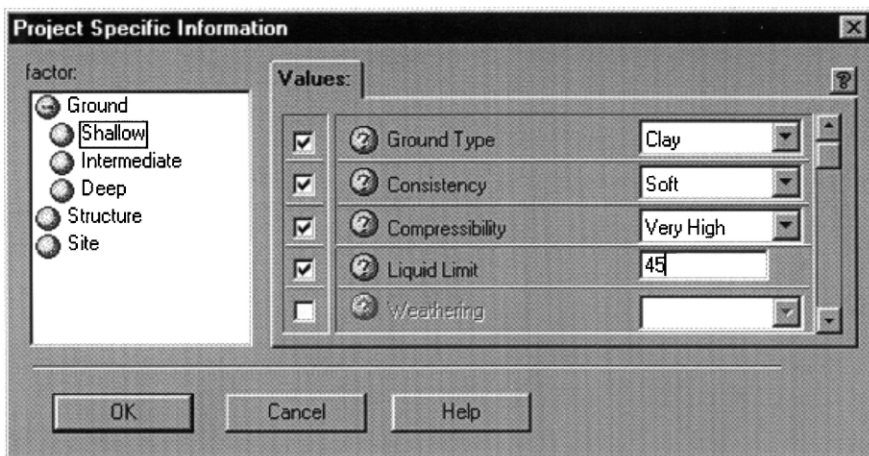


Fig. 3. Dialogue box for entering project specific information.

Once the user has entered values for the project specific information they can then consult the knowledge base. Information is displayed in the form shown in Fig. 4. This shows the decision options (frames) within a tree structure in the left-hand pane of the window. This reflects the hierarchical structure of the knowledge base. As before, the tree structure can be expanded and reduced by the user. The user can jump to any point in the hierarchy by clicking on the appropriate frame object.

The top right-hand pane of the window in Fig. 4 displays the full name of the frame object selected and the description. The bottom right-hand pane shows the output from the rules. For each rule the suitability, confidence level and the comment is displayed. Suitability is shown as two ticks for highly suitable, one tick for suitable, a horizontal bar for neutral, a single cross for unsuitable and two crosses for highly unsuitable. These symbols are also colour coded as green for suitable and highly suitable, red for unsuitable and highly unsuitable and yellow for neutral.

The confidence level is displayed graphically as a series of dots on a 5 point scale. The number of dots reflects the confidence level. The rule output is sorted according to confidence level, with the highest confidence values at the top. The top rule shown in Fig. 4 shows *Highly suitable* with a confidence level of 2 and with the comment: “*Low-displacement piles are suitable in most cases in dense materials*”. This indicates how the rule example given above would be displayed within the software.

It can be seen in Fig. 4 that, for the specific example, the top two rules indicate that the foundation choice is highly suitable and the third rule indicates it to be unsuitable. These three rules have the same confidence level of 2. The user has to read the comments associated with each rule and balance up the various considerations involved

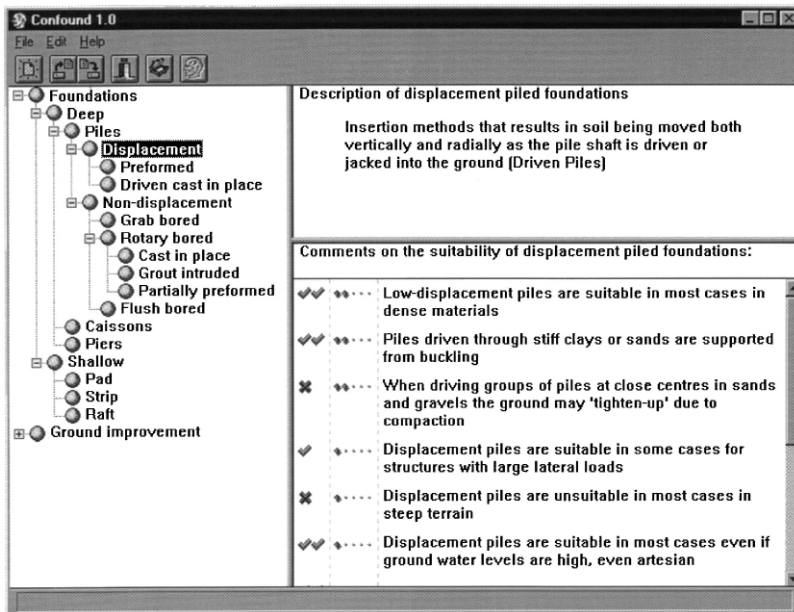


Fig. 4. Consulting the knowledge base for displacement piled foundations.

in order to come to an overall conclusion. It is possible that the ‘unsuitable’ factor can be overcome. For instance, in this case the third rule refers to driving piles at close centres. The user might decide to go ahead with this choice, but to ensure the pile spacing is sufficient to avoid this potential problem.

Of course, the other rules with lower confidence levels must also be considered in the overall decision. In some cases the rule with lower confidence may dominate if the problem it describes is of more significance than rules with higher confidence.

If the user requires more information than is given in the brief comment then they can double click on the comment to follow the link to a help page. The specified Windows™ help file is then opened at the appropriate page defined by the context number [7]. The user can then follow hypertext links within the help file if they need further information than is provided on the specific page.

6. Creating a decision support system

The task of creating a decision support system, using Confound, should be tackled in the following order:

- Identify and organize those objects from the domain that will form the frames knowledge base
- Develop a list of the factors that may influence the suitability of each frame within this knowledge base
- Cross reference all the influencing factors for each frame and organize them into a suitable hierarchy that will become the factors database
- Within the frames knowledge base produce a comprehensive set of rules for each frame using the factors database in order to define the rule conditions.

The knowledge within Confound can be accessed by running the software in ‘Supervisor’ mode. This is done by adding ‘-s’ to the command line when starting the software. A new knowledge base can be created or an existing knowledge base can be opened for editing. Fig. 5 shows Confound in supervisor mode.

All the frames within the knowledge base must come from a single base object. This base object appears as the top frame in any hierarchy and is always present (even when the hierarchy is empty). It has no rules associated with it and is not shown during the normal running of the system, only in supervisor mode. It enables a domain to have more than one top level frame. For example, Fig. 5 shows ‘foundations’ and ‘ground improvement’ as child objects of the base object. In normal mode these will be seen as alternative options at the top level (see Fig. 4).

In supervisor mode, frame objects can be created, deleted or edited. When a frame object is selected, the rules for that frame are shown in the lower right-hand pane (Fig. 5). Rules are shown grouped according to topics (e.g. settlement, punch through, mining, shrinkable clays etc). If the topic is expanded (by clicking on it) then the rules within that topic are displayed, grouped according to confidence level and factors. For instance, under the Settlement topic, Fig. 5 shows rule groups for con-

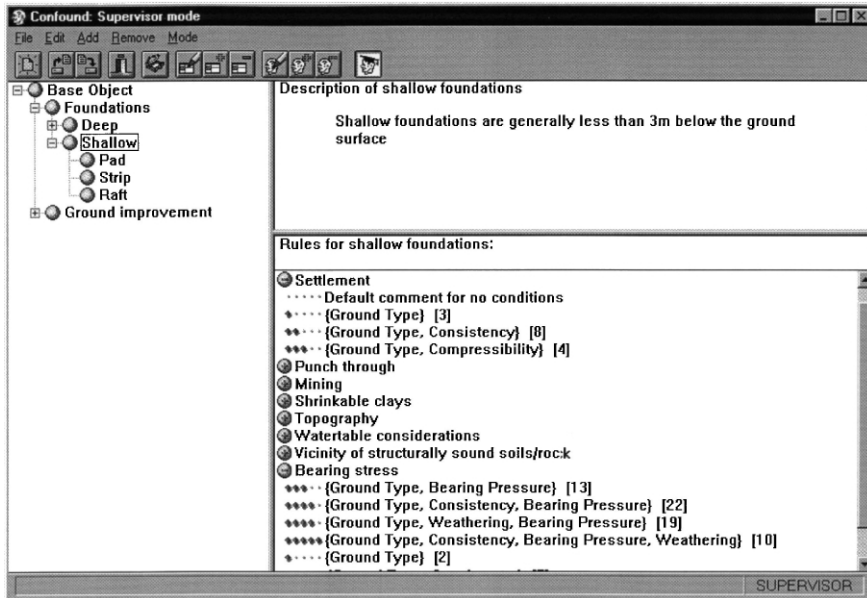


Fig. 5. The Confound software being run in supervisor mode.

confidence levels of 0, 1, 2 and 3. Since there can be multiple rule groups with the same confidence level, information on the factors that define each rule group is listed.

Confidence levels are defined according to the amount and type of information used within that rule group. The topic settlement in Fig. 5 shows a single rule with zero confidence (a default comment that will be displayed if no factors have been identified relevant to settlement). It also shows rules with confidence level 1 based on ground type only; confidence level 2 based on ground type and consistency; confidence level 3 based on ground type and compressibility. The latter rules with confidence level 3 have a higher confidence level, even though they are based on the same number of factors as confidence level 2, since the factor compressibility is directly related to settlement. Consistency, on the other hand is only an indirect measure of compressibility and therefore has a lower confidence level.

There may be rules leading to different suitability within each confidence level/factor group. The number in brackets shown after each rule group (Fig. 5) indicates the number of rules in that group. The rules within each group can be edited through the dialogue box shown in Fig. 6. New rules with different suitability can easily be added, or existing rules deleted.

Fig. 6 shows a rule for bearing stress (with confidence level 5). This rule group has ten rules and the suitability can be viewed by scrolling through the rules. An 'unsuitable' rule (indicated by the cross: ×) is shown. This rule is based on four factors (Consistency, ground type and weathering for the shallow zone and structural bearing pressure). These factors were identified when creating the rule group and cannot be varied within the group. In Fig. 6 the condition for structural bearing pressure is

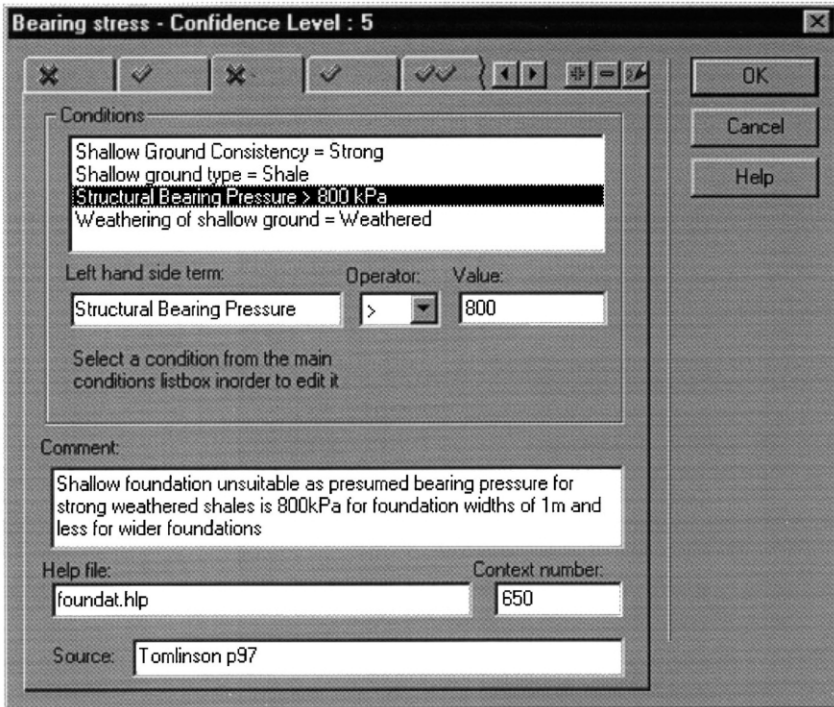


Fig. 6. Rule dialogue box for bearing stress.

selected (a numeric factor) which uses the ' $>$ ' operator. The conditions for each rule can be changed (by changing the operator and the values of the factors) to be appropriate to each suitability level.

The operators available within Confound are:

- Numeric factors:
 - Equal to ($=$)
 - Greater than ($>$)
 - Less than ($<$)
 - Between ($<..<$) this requires the definition of a lower and an upper value for the permissible range
- Boolean factors — a simple selection between true and false is available
- List factors — all the items available in that list appear in a list box on the right hand side (the values in the list are defined by the knowledge engineer when defining each factor). More than one item in the list may be selected.

Testing of the system can be carried out while the knowledge base is being defined. The supervisor button on the tool bar provides the opportunity to toggle between test mode and supervisor mode. Test mode shows how the knowledge base would look during normal user operation.

The development of Confound was evaluated as a computer-aided learning tool by other tutors and also by students. The evaluation process was described by Thompson and Toll [8].

7. Other applications of Confound

Although the Confound shell was originally designed for a specific application (foundation design) it has subsequently been used to develop applications for retaining walls [1], expansive soils [2] and ground investigation [3].

The retaining wall application (WallAid) described by Smith et al. [1] is very similar to the conceptual foundation design problem. It deals with selection of appropriate types of retaining walls: gravity walls; embedded walls; reinforced soil walls and hybrid systems. It uses the same form of ground representation as Confound by dividing the ground into conceptual zones (shallow, intermediate and deep). However, it also provides rules based on data about the nature and size of the project, environmental and aesthetic consideration and construction requirements.

The flexibility of Confound is clearly demonstrated by the way in which it has been used by Hamadto [2]. In this application Confound has been used for the process of selecting a suitable foundation type on expansive soils. However, the process has been divided into three main parts, 'classification' 'heave prediction' and 'evaluation of design alternatives' (Fig. 7). While the 'design alternatives' part of Hamadto's application is similar to the original intention of Confound, the other parts have made use of Confound in a different way. In the 'classification' part, Hamadto has used the rule-based approach of Confound to identify the potential expansiveness of a clay deposit based on three different classification systems as shown in Fig. 7. The three schemes use different input data (plasticity index and clay fraction for one, liquid limit for the second and a 'shrinkage index' and clay fraction for the third) and are accorded different confidence limits. Therefore, depending on the type of data entered in the project specific data, the system will give an indication of the potential expansiveness of the soil and the attendant level of confidence. If sufficient data are provided for all three classifications, then a comparison of the three systems would be achieved.

Another system developed using Confound [3] is also an application where decision support is needed. In this case it involves the selection of appropriate testing methods (choosing between types of in situ and laboratory tests for carrying out a ground investigation). Moreau's system can give advice based on the type of measurement required, the type of ground to be tested, type of technical support available, cost, time etc. (Fig. 8).

These other applications that have been developed using Confound clearly illustrate the generic nature of the software, and its potential for use in developing other systems. It is ideally suited to applications where choices have to be made between different solutions (whether it be foundations, retaining walls or geotechnical tests). However, it can also be used for other rule-based applications such as classification systems.

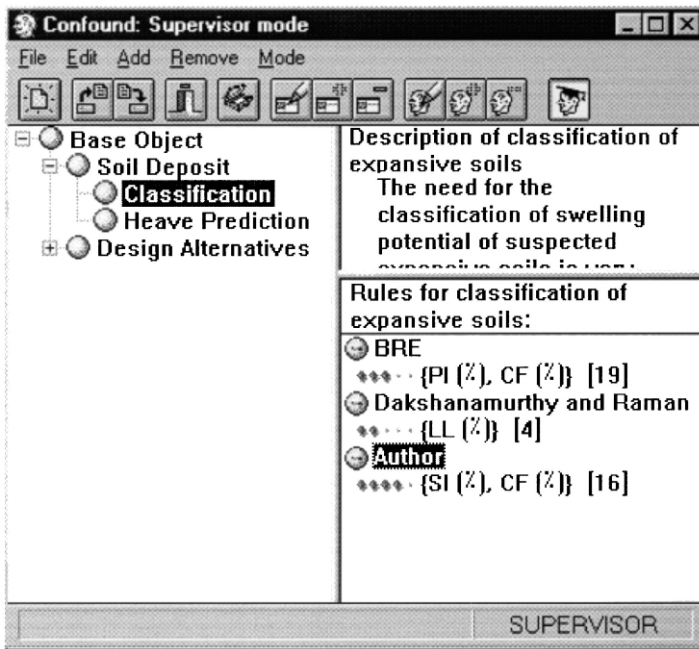


Fig. 7. Using Confound for classifying expansive soil [2].

8. Discussion

Knowledge-based systems (and other artificial intelligence techniques) are starting to make inroads into geotechnical engineering (see reviews by Moula et al. [9]; Toll [10]). However, there is still some reluctance to adopt such technologies [11]. It is important that systems are developed that provide assistance to engineers without attempting to usurp their professional role.

Confound uses a very simple knowledge-based system approach which is deliberately designed to leave the user in full control [7]. It is a decision *support* system rather than a decision *making* system. It is merely intended to act as a tool that professional engineers can use for checking during design, to ensure they have not overlooked anything, or to provide some advice in an area with which they might not be familiar. Confound does not impose any pathway that the user must follow through the decision process. Instead, the user can jump to any point in the decision hierarchy. Similarly Confound does not attempt to come to an overall decision; it simply provides comments on suitability (with some indication of confidence) and leaves the final decision to the user.

It is hoped that such software will be accepted by the geotechnical profession as something that is a useful tool. Its simplicity is its strength. However, for all its simplicity, Confound can contain a great deal of useful knowledge (for instance the conceptual foundation design application contains many hundreds of rules) in a

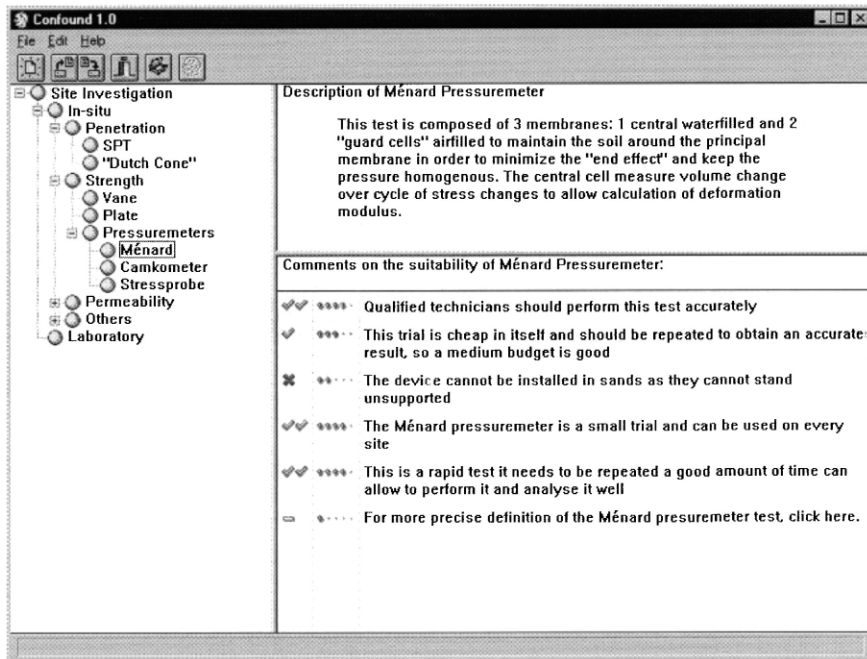


Fig. 8. Using Confound for ground investigation planning [3].

form that can be readily accessed. Therefore, its potential should not be underestimated.

9. Conclusions

Confound is a knowledge-based system shell that can be used for developing decision support systems. It was originally developed for the production of a system to assist with the conceptual design of foundations. However, Confound can (and has) been used with knowledge from other domains in order to develop other decision support systems. The different uses to which Confound has been put illustrates the generic nature of the software, and its potential for use in developing other systems.

Confound uses a hierarchical object-oriented knowledge base where each object represents a decision in the decision making process. It uses a simple rule-based approach to provide advice on the suitability of each potential choice, based on project specific information that is provided by the user. However, it is not designed to give the user a definitive solution to any problem but instead to highlight points that should be considered and provide direction and advice. It has the ability to work with incomplete information and uses a system of confidence levels so that the user is aware of the confidence with which each piece of advice is being given. Confound can also handle conflicting information in areas where knowledge is poorly defined.

Confound does not impose any pathway that the user must follow through the decision process but is designed to leave the user in full control. The user can jump to any point in the decision hierarchy. Similarly Confound does not attempt to come to an overall decision; it simply provides comments on suitability (with some indication of confidence) and leaves the final decision to the user. It is hoped that such software will be accepted by geotechnical practitioners as a useful tool that does not threaten their autonomy as professionals.

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