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Expert System for Retaining Wall Selection PHASE I

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16. Abstract

The Bridge Branch of the Colorado Department of Transportation (CDOT) has organized a formal decision process for retaining wall selection (CDOT 1991a; CDOT 1991b). The selection process facilitates implementation of new technologies by encouraging Bridge Branch designers and consultants to consider a range of options when selecting retaining wall alternatives. The formalized retaining wall selection process puts the CDOT into a national leadership role. What was needed was a computerized implementation of the decision process that would reduce the time required to perform the retaining wall selection process; enforce consistency in decisions made by designers and consultants; and provide a mechanism for the CDOT to encode standard practices and minimum performance criteria within the decision process. The CDOT retaining wall selection process falls into a general pattern of organization that can be automated using currently available expert system technology.

Seed money (PHASE 1) was provided by the Colorado Department of Transportation to develop a conceptual system and design description that implements the CDOT selection process. This investigation has served to evaluate the feasibility and level of difficulty for full system development. The study included considerations for dissemination and program maintenance for a system that runs on IBM-compatible micro-computers. The cost of disseminating run-time versions of the full system were to be minimized. This report comprises the results of the pilot study.

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Expert System for Retaining Wall Selection
PHASE I

FINAL PROJECT REPORT

Submitted to the

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PROJECT SUMMARY

The Bridge Branch of the Colorado Department of Transportation (CDOT) has organized a formal decision process for retaining wall selection (CDOT 1991a; CDOT 1991b). The selection process facilitates implementation of new technologies by encouraging Bridge Branch designers and consultants to consider a range of options when selecting retaining wall alternatives. The formalized retaining wall selection process puts the CDOT into a national leadership role. What is needed is a computerized implementation of the decision process that will reduce the time required to perform the retaining wall selection process; enforce consistency in decisions made by designers and consultants; and provide a mechanism for the CDOT to encode standard practices and minimum performance criteria within the decision process. The CDOT retaining wall selection process falls into a general pattern of organization that can be automated using currently available expert system technology.

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RESEARCH OBJECTIVES

This report describes the results of the first phase of a multi-phase project for for developing a comprehensive system for retaining wall selection, design and cost estimation. This phase (PHASE I) focused on the conceptual model, knowledge base organization and inferencing for coding a system that allows designers and consultants to interactively assemble retaining wall project data for evaluating the **measurement indicator** values of the **spatial, behavior,** and **economic factors** shown on the *CDOT Work Sheets for Earth Retaining Wall Type Selection* (CDOT 1991b). The system will eliminate wall types that are infeasible due to spatial, behavior and economic factors. Weighted scores for the feasible wall types will be computed and the wall types will be rank ordered. The objectives of the system are:

1. To implement a representational framework for computerized retaining wall selection that is compatible with the CDOT decision process.

2. To enable designers and consultants to interactively assemble retaining wall selection decision criteria.

3. To codify of CDOT retaining wall selection process in Memos 5-4 and 5-5.

The system described in this report can be used to develop a retaining wall selection system that encodes the CDOT retaining wall selection process. The resulting system is expected to assist rather than replace a knowledgable, experienced retaining wall design engineer. This report can be used as the basis for developing the initial framework of a full system that can subsequently be expanded and maintained by CDOT Bridge Branch engineers. The full system will:

- Assist the engineer to eliminate infeasible, unsuitable, and undesirable walls based on spatial, behavioral and economic constraints.
- Assist in computing the evaluation score for each feasible wall alternative.
- Provide an output report of the selection process that can be included with other project design documents.

HISTORICAL PERSPECTIVE AND INTRINSIC MERIT

The last decade has seen enormous interest in the application of expert systems to geotechnical engineering and highway design problems. Table 1 contains a listing of a number of prototype systems that have been described in the literature.

Researchers have shown that expert systems can be applied to retaining wall problems. Retaining wall selection has been the subject of previous expert system prototypes (Arockiasamy et al 1991; Hutchinson 1985). In addition expert system technology has been applied to retaining wall management (Chahine 1986), failure diagnosis (Adams et al 1989; Adams et al 1988), and rehabilitation design (Adams et al 1991; Adams et al 1990; Ciarico et al 1989). In each case, researchers cite the potential for retaining wall construction cost savings.

The barrier to full completion of previous retaining wall expert systems has been the need for additional knowledge sources and high-level commitment for system completion. The CDOT has compiled retaining wall selection knowledge from in-house sources. In addition, there is high-level commitment from the Bridge Branch to support the development of a computerized framework. It is expected that the experience gained from previous projects will benefit the CDOT. Thus, the proposed project will begin where similar projects have ended.

Table 1: Geotechnical Expert Systems

Year	System Name	Description	Development Environment
1991	ESPGIS	Selection of ground improvement methods (Motamed et al 1991)	VP Expert
1991		Geological site characterization (Halim et al 1991)	KEE
1991		Selection of geosynthetic ground improvement (Maher and Williams 1991)	Rulemaster
1991		Selection of retaining walls (Arockiasamy et al 1991)	M.1 Rulemaster
1991		Selection of earth retaining structures (Oliphant and Blockley 1991)	FRIL, Prolog
1991	CASS	Estimation of soil strength parameters (Gillette 1991)	PC +
1991	EDxES	Geotextile edge drain design and specification (Dimmick et al 1991)	PC +
1989	Improve	Selection of soil improvement methods (Chameau and Santamarina 1989)	
1989	RETAIN	Failure diagnosis and rehabilitation synthesis for retaining structures (Adams et al 1990)	OPS83, Informix
1989	USMS	Selection and scheduling of slopes stabilization strategies (Ho et al 1989)	CLIPS
1989	SITECLASS	Site classification (Wong et al 1989)	SUCAM
1989	SOIL	Soil classification (Madhavan et al 1989)	CBC X-pert
1988	FOOTER	Design synthesis for building foundation (Adams et al 1989)	EDESYN
1988	EXSEL	Diagnosis of seepage in dams (Asgian et al 1988)	ARITY PROLOG
1988	GEOTOX	Hazardous waste management (Mikroudis and Fang 1988)	Ada-Prolog
1988	GUESS	Site characterization (Righetti and Cremonini 1988)	Daisy
1987	LOGS	Boring log data interpretation and subsurface profile determination (Adams et al 1989)	Knowledgecraft
1986	WADI	Failure diagnosis of gravity and cantilever retaining walls (Chahine 1986)	
1985	RETWALL	Selection of earth retaining walls (Hutchinson 1985)	BUILD
1985	SITECHAR	Site characterization (Rehak 1985)	
1985	CONE	Interpretation of cone penetrometer test data results (Mullarkey et al 1985)	Lisp

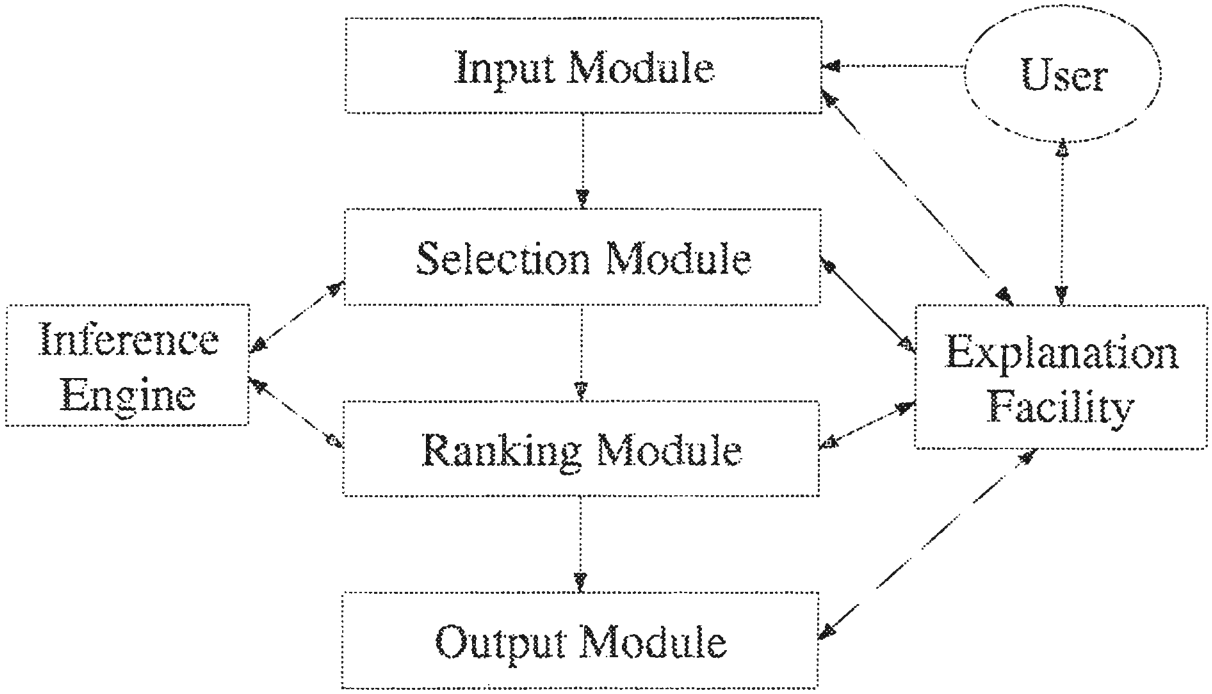

Figure 1: Architecture of the CDOT Wall Selection System

FRAMEWORK FOR AN EXPERT SYSTEM FOR RETAINING WALL SELECTION

The conceptual framework for an expert system for selecting retaining wall alternatives is shown in Figure 1. The conceptual framework for the CDOT retaining wall selection system including consideration of the user interface, explanation facilities, and reasoning with uncertainty. The system is comprised of four main modules: **Input, Selection, Ranking** and **Output**. The system selects feasible wall types by process of elimination then scores and ranks feasible retaining alternatives. The functional description of each module comprise the following paragraphs.

Input Module

In the Input Module, the user inputs problem-specific constraints as per Memo 5-4 of the CDOT Bridge Branch. In this module, the user will also input general information such as wall height and length. Constraints are organized into five categories:

1. Functional Constraints are related to the purpose of the retaining structure.
    - Roadway (Front/Back-top)
    - Grade separation
    - Landscaping

- Noise control
- Ramp or Underpass
- Temporary Shoring of Excavation
- Stability of Steep Side Slope
- Flood Control
- Bridge Abutment

2. Spatial Constraints are related to site accessibility and space limitations.
    - Material and Equipment Access
    - Material and Equipment Storage
    - Maintaining Existing Traffic
    - Proposed Profile (Cut/Fill)
    - Working Space in Front of Wall
    - Excavation Space Behind Wall
3. Behavioral Constraints are related to the structural and geotechnical performance of the system.
    - Quality of Fill Material
    - Ground Water Table
    - Bearing Capacity
4. Economic Considerations are related to the cost of wall construction.
    - Noise/Vibration Control
    - Construction Time
5. Other Constraints include additional spatial, behavioral, environmental, and economic constraints that are listed in Memo 5-4. These constraints are reported at the end of the consultation.
    - Other Spatial Constraints: Right of Way; Geological Boundaries; Temporary and Permanent Easement; Minimal Site Disturbance; Underground easement.
    - Other Behavioral Constraints: Wall Design Life.
    - Environmental Constraints: Ecological Impacts on Wetlands; Stream Encroachment; Fish/Wildlife Habitation or Migration Routes; Aesthetic Constraints; Urban Versus Rural; Design Policy of Scenic Routes; Anti-graffiti Wall Facing; Avoiding Valley Effect of Long/High Wall.

- Other Economic Factors: "Buy Colorado" Impact; Temporary Versus Permanent Wall and Future Widening; Negotiated Bidding and Design/Build on Non-Standard Projects; Complexity of Project; Experience and Equipment of Local Contractors; Proprietary Product and Quality Assurance.

Input constraint data can be stored as "facts" in working memory of the system. The user can access the explanation facility to learn WHY a particular constraint is requested; that is how the constraint will be used to eliminate wall types.

Selection Module

The purpose of the Selection Module is to eliminate infeasible wall type. Wall types are eliminated using the Function, Spatial, Behavioral, and Economic Constraints gathered in the Input Module. This module has three phases.

1. In the first phase, obviously infeasible wall types are eliminated without further consultation. A knowledge base of the infeasible relationship between constraints and wall types will be prepared for this phase. The knowledge base can be visualized in tabular form. A meta rule can operate to eliminate infeasible wall types by matching input constraints with the relationship in the knowledge base table. Elimination of obviously infeasible wall types based on a combination of constraints is also possible (Adams 1992).

2. In the second phase, the number of the feasible wall types can be further reduced through consultation according to problem-specific constraints. The knowledge base for this phase should contain zero, one, or more rules for each combination of constraint and wall type. Based on the user's response, each rule can potentially eliminate a wall type. For example, a rule to eliminate modular walls due to inadequate storage space for materials may be as follows.

```
(defrule STORAGE-SPACE
?ptr<- (WALL (wall_type modular) (prospect feasible))
       (SITE (constraint_type spatial)
             (constraints $? storage $? ))
=>
(printout t crlf "Is storage space inadequate for a modular wall[y/n]: ")
(bind ?ans (read))
(if (eq ?ans y|Y|yes|YES)
    then (modify ?ptr (prospect infeasible)))
```

3. In the third phase, site-specific (or allowable) conditions are logically compared to wall-specific (or required) conditions to eliminate infeasible wall types (see Worksheet Memo 5-5). The value of site-specific and wall-specific conditions are represented in terms of the measurement factors used in Memo 5-5. Table 2 contains the hierarchy of the value of measurement factors. In this module, the user inputs all site-specific conditions once. Wall-specific conditions are input as the comparison process progresses. A wall type is found infeasible and eliminated when a single wall-specific (required) condition cannot be satisfied by a site-specific (allowable) condition. For example, below is a rule for eliminating a wall type by logically comparing the measurement factor for the required working space of the wall with the allowable working space at the site.

```
(defrule ALLOWABLE_SPACE
?ptr <- (WALL (space ?required) (prospect feasible))
        (SITE (space ?allowable))
        (test ( < ?allowable ?required))
=>
(modify ?ptr (prospect infeasible)))
```

The Selection Module should include WHAT-IF explanation to allow the user to revise wall-specific conditions. At the end of this module, a set of feasible wall types are passed to the Ranking Module.

Ranking Module

Feasible retaining wall alternatives are scored and ranked according to the Evaluation Factors in Memo 5-5 and listed in Table 3. The steps of the ranking process are listed below. In the ranking process, weight values are assigned by the user. It is envisioned that some rating values may be generated by the expert system from the measurement indicators in the Worksheet of Memo 5-5.

1. Weight value, W_i, is assigned by the user to each evaluation factor.
   - W_i represents the importance of the i^{th} evaluation factor in the overall project decision.
   - Each W_i is independent of any wall alternative.

$$\sum_{i=1}^{8} W_i = 100$$

2. A set of rating values, R_{ik} is generated for each k^{th} wall alternative.

Table 2: Hierarchy of Measurement Factor Values

Factor	Hierarchy
Spatial Factors	
Excavation Behind Wall	L M S
Working Space of Wall	L M S
Front Face Battering	N ? Y
Behavioral Factors	
Sensitivity of Differential Settlement	L M S
Quality of Backfill Material	L M H
Water Table Presence	Y ? N
Active Earth Pressure Condition	N ? Y
Construction Dependent Loads	N ? Y
Economic Factors	
Noise/Water Pollution	Y ? N
Quantity of Backfill Material	L M S
Fill Compaction and Control	H M L
Relative Construction Time	H M L
Cost of Maintenance	H M L
Availability of Standard Design	N ? Y
Labor Usage	H M L
Facing as an Extra Cost	Y ? N
System Durability Problem	Y ? N

Table 3: Evaluation Factors and Subscripts Used to Rank Feasible Retaining Walls.

i	Evaluation Factor
1	Constructibility
2	Maintenance
3	Schedule
4	Aesthetics
5	Environment
6	Durability
7	Standard Designs
8	Cost

- Each R_{ik} indicates how well wall type k satisfies evaluation factor i.
- Ratings can range from 1 to 5.

3. Score, S_k, is computed for each k^{th} wall type.

$$S_k = \sum_{i=1}^{8} R_{ik} W_i$$

4. Alternative with the highest score is the "default design."

Output Module

All project-specific input is summarized in the Output Module. Eliminated wall types are summarized with the first unsatisfied constraint that eliminated the wall type. Scores and ranking of alternative wall types are reported. Other constraints that are collected in the Input Module but not considered by the system are summarized. These constraints may influence the final decision. WHAT-IF explanation will allow the user to change certain values of input and check the effect of those values on the system results.

EXPERT SYSTEM SHELL SELECTION

An expert system can be developed using an AI (Artificial Intelligence) language or an expert system shell. When selecting a shell or language, one must consider the trade-off of ease of use for power and flexibility. For an ill-structured problem, one may select an AI language or a low level shell. For a well-structured problem, one may find a shell that provides pre-programmed features and knowledge representation that are needed. Table 4 contains a comparison of AI languages and shells (Ferrada and Holmes 1990).

Features of expert system shells can be categorized into groups of built-in tools that aim to simplify the development process by providing for *knowledge acquisition, knowledge representation* and *user interface* (Simmons et al 1991). Knowledge Acquisition (KA) is an expensive, people intensive activity where knowledge is elicited by a domain expert. KA is typically the bottleneck in building an expert system. There have been efforts to build KA tools, but they have not evolved into commercial products.

Table 5 contains a comparison of the various features of commercial expert system shells. Most shells utilize facts and rules as primitives for constructing the knowledge base and knowledge representation. In some tools primitives may be combined, such as rules into modules or facts

Table 4: Differences Between AI Languages and Shells

AI Language	Shell
Considerable amount of code has to be written.	Provides substantial programming code including a tested, debugged and maintained INFERENCE ENGINE.
System can be programmed to approach the solution to a problem from different perspectives.	Applies the same rules of inference to a variety of problems (ie., PROGRAMMED HEURISTICS).
May require considerable amount of time to develop components of the application from 'scratch'.	Can shorten development time by providing pre-programmed components.
Used when certain features are not provided by a shell OR to reduce overhead when a shell has many features that are not utilized in a particular application.	
Often requires the participation of a computer programmer.	Can be used by technical personnel not having extensive programming capabilities.
Examples : LISP, PROLOG, SMALLTALK, C++, OBJECTIVE-C	Examples: CLIPS, VP-EXPERT, KEE, NEXPERT

into frames with inheritance. All shells include pattern matching and inference mechanisms, however, the flexibility of the pattern matching and the possibilities for inferencing vary among shells. Some shell features for knowledge representation include the following. Depending on the shell, input data or conclusions can be TRUE, FALSE, UNKNOWN, POSSIBLE, UNLIKELY, UNDECIDABLE etc. Flexibility of truth values are used for assessing the degree to which data is known to be correct. Reasoning with uncertainty allows the developer to represent plausibility by attaching certainty to the logic in the rules. Schemes have been developed for reasoning with uncertain and imprecise knowledge. They include Bayesian techniques, confidence factors, Dempster-Shafer evidential reasoning and fuzzy logic.

Flexibility in the inferencing allows the developer to modify the basic control of the system; that is the order in which rules are fired. Shells typically provide one or both or the two fundamental control strategies: Forward and Backward chaining. Message passing and Demons are the control mechanisms in object oriented programming.

Temporality is a feature that is necessary when elements of the problem must be associated with specific points in time or time intervals. Real-time systems make use of this property. In temporal system, data and conclusions possess distinct truth values at different times.

Procedural knowledge can be represented using conventional programming languages such as Fortran and C. Shells that only use non-procedural technique are considerably limited in their usefulness for engineering applications. Most shells provide some type of interface to conventional programming languages, although the efficiency and ease of use of these interfaces varies widely. Some shell provide a simple Pascal or BASIC-like language so that simple algorithms may be incorporated into rules without the need for external languages.

Shells vary widely in their user friendliness to the developer and to the end user. All shells provide some mechanisms for entering data about the problem. Input options include automatic menus, line input, multiple responses and uncertain responses. Explanation facilities are useful to the developer in debugging the systems as well as to the end user. Explanation falls into three basic types: HOW, WHY, and WHAT-IF. Most shells provide the HOW explanation of how the system arrived at a conclusion through rule tracing or audit trails of the line of reasoning. The WHY explanation indicates why certain input is needed in terms of how it will be used in certain rules. The WHAT-IF explanation allows the user to generate alternative problem solutions by changing input data.

All shells that provide external hooks to procedural languages can incorporate graphics into a final application. Some shells provide a feature for graphical representations of the knowledge base in the form of a tree or network. A shell may also include features for active images and simulation.

Some shells provide specialized links to databases, spreadsheets, CAD software, real-time data acquisition tools. Most shells provide links to external procedures and text files. Some shells are available on several hardware and operating system platforms.

RECOMMENDATIONS

This report describes the framework for an expert system for retaining wall selection that follows the problem solving methodology described in the CDOT Memos 5-4 and 5-5. Development and implementation of a system that follows this framework will:

- Reduce the time required to perform retaining wall selection;
- Enable consistency and consideration of multiple retaining wall alternatives in decision-making by designers and consultants; and
- Provide a mechanism for the CDOT to encode standard practices and minimum performance criteria.

The recommended criteria for selecting a development shell for the CDOT project are summarized below. The criteria were established as a result of meetings with Colorado Bridge Section Engineers and formulating the functional specification of the final system.

- Knowledge Representation–system is expected to be primarily rule-based
- Inference Mechanism–forward chaining
- Explanation–why, what-if, how
- Development Toolbox–Trade-of features for flexibility and power for ease of use. We want a shell that allows us to develop a system that is patterned after the CDOT memos.
- External Hooks–algebraic programming, database systems
- Cost for Dissemination–distribution cost of runtime copies of the system should be minimized.

The shell recommended for the Colorado project is CLIPS version 5.1 (Giarratano 1991). 'C' Language Integrated Production Systems (CLIPS) is a knowledge-based shell initially developed at Johnson Space Center in 1984. CLIPS accommodates storage of domain knowledge; provides an inference engine that fires on rule bases; and supports CLIPS Object-Oriented Language (COOL). Run time (compiled) copies of the final system may be distributed without licensing restrictions.

Table 5: Comparison of Commercial ES Shells (Simmons et al 1991)

Name	Knowledge Representation	Inference Mechanisms	Explanation Facilities	Uncertainty	Development Interface	External Hooks
VP Expert	rules; booleans (∨, ∧); modules	F, B, H	how, what-if, why		automatic menus; multiple responses	yes
GURU	rules; booleans (∨, ∧, ¬)	F, B, H	how, what-if, why	truth values–T/F; CF range–no limit	automatic menus; line; multiple responses	limited
CLIPS 5.1	rules; booleans (∨, ∧, ¬); modules, objects	F, B	how	truth values–T/F	line, CRSV, user-defined graphics	any language
ECLIPSE	rules	F	how	truth values–T/F		
KES	rules; demons; frames	F, B, H		CF (-1 to +1)		
Level5	rules	B		CF (0 to 1000)		
KEE	rules; booleans (∨, ∧, ¬); frames; inheritance; modules, messages, demons	F, B, H	how, what-if, why	truth values–T/F ?	automatic menus; line; active images; multiple responses; simulation; user-defined graphics	Lisp
Rule Master	rules; booleans (∨, ¬)	F, H	how	truth values–T/F; CF range–no limit	automatic menus; line; multiple responses; user-defined graphics	yes
PC+	rules; booleans (∨, ∧, ¬); demons	F, B, H	how, what-if	truth values–T/F ?; CF (0 to 100)	automatic menus; multiple responses; user-defined graphics	Lisp
Exsys	booleans (∨); inheritance; frames; rules; demons	F	how, why	truth values–T/F; CF (-100 to 100)	automatic menus; line; multiple responses	any language
NEXPERT	rules; booleans (∨, ∧, ¬); frames; inheritance; modules; messages; demons	F, B, H	how, what-if, why, graphics	truth values–T/F ?	automatic menus; line; multiple responses; user-defined graphics	any language

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