Colorado's Knowledge System for Retaining Wall Selection

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The Bridge Branch of the Colorado Department of Transportation (CDOT) has organized a formal decision process for selecting retaining walls. The selection process facilitates implementation of new retaining wall technologies by requiring that a range of options be considered when selecting retaining wall alternatives. The CDOT retaining wall selection process falls into a general pattern of organization that can be automated using knowledge-based system technology. The computerized implementation of the decision process is described; it 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 CDOT to encode standard designs, practices, and minimum performance criteria within the decision process.

For various reasons, some departments of transportation (DOTs) resist new retaining wall technology and avoid integrating emerging retaining wall design and construction expertise into their internal hierarchies. Instead they opt for vendor designs, alternative bids, and after-the-bid value engineering. There is an apparent need to facilitate implementation of new retaining wall technologies and to foster a paradigm change on how retaining walls are selected. For example, district offices statewide of the Colorado DOT (CDOT) were asked to review existing plans and to consider substituting the CDOT geosystem wall where other types of walls were designed. Results indicated that more than $1 million in construction costs were saved in only a few CDOT projects (*1*). Geosystem walls are projected to save Colorado from $5 million to $10 million annually. Furthermore, hundreds of millions of dollars can be saved nationwide by using new retaining wall technologies.

Many factors are involved in an office's reluctance to leave the old paradigm where retaining walls are built from concrete and steel. Many who have traditionally been responsible for wall selection and design continue to limit their expertise (*2*). The failure to develop internal expertise for retaining wall selection and design results in a major technology gap that can result in unnecessary expenditures. Under current fiscal constraints, it is imperative that DOT engineers and consultants be capable of designing not only traditional walls but also mechanically stabilized embankment (MSE) walls, modular walls, and the variety of new ground improvement techniques.

The past decade has seen enormous interest in the application of expert systems in all areas of highway design. Researchers have shown that expert systems can be applied for retaining wall selection (*3*), failure diagnosis (*4,5*), and rehabilitation design (*6–8*). In each case, the potential for retaining wall construction cost savings is apparent.

This paper describes a formal retaining wall selection process as cast into a pattern of organization that can be automated using knowledge-based system technology. System development was initiated by the Bridge Branch, CDOT. This paper provides a complete overview of the system design and implementation. This paper emphasizes the conceptual framework, including the knowledge- and symbol-level representations. The techniques for encoding and processing knowledge are described and illustrated.

OBJECTIVES

The CDOT retaining wall selection system aims to assist rather than replace a knowledgeable, experienced retaining wall design engineer. Besides significantly reducing retaining wall construction costs by improving wall selection, the system can reduce an engineer's retaining wall selection and design time by 30 percent. The objectives of the system are to

1. Enable consistency and consideration of multiple retaining wall alternatives in decisions made by designers and consultants;
2. Provide a mechanism for encoding standard designs, practices, and minimum performance criteria within the decision process; and
3. Foster a paradigm change on how retaining walls are selected and to facilitate implementation of new retaining wall technologies.

KNOWLEDGE LEVEL

Before knowledge can be organized as a symbol system and encoded in a programming language, the knowledge level must be identified. The knowledge level describes the concepts, goals, actions, behavioral laws, and knowledge components of the system (*9*). The retaining wall selection system follows a problem-solving strategy described in Section 5 of the CDOT *Bridge Design Manual* (*10*) and contains knowledge from other sources (*11–14*).

The system acts as a sieve for eliminating infeasible walls using the constraints presented in Table 1. Functional constraints are related to the purpose of the retaining structure. Spatial constraints are related to site accessibility and space

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TABLE 1 Constraints That Influence Selection of Retaining Structures

Type	Constraint
Functional	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
Spatial	Material and Equipment Access
	Material Storage
	Proposed Profile (Cut/Fill)
	Working Space in Front of Wall
	Traffic Maintenance
	Excavation Space Behind Wall
Behavioral	Quality of Fill Material
	Ground Water Table
	Bearing Capacity
	Differential Settlement
	Backfill Settlement
	Construction Loads
Economic	Available Skilled Labor
	Noise/Vibration Control
	Construction Time

limitations. Behavioral constraints are related to structural performance of the system. Economic considerations are related to direct and indirect construction costs. Each constraint is related to one or more wall types and directly influences the selection of retaining structures.

Starting with a set of all wall types, the process of eliminating infeasible wall types can be conceptualized as through two sieves that filter out infeasible wall types. The first sieve eliminates obviously infeasible wall types on the basis of required functions of the wall. The second sieve further reduces the number of feasible wall types according to spatial, behavioral, and economic constraints. The knowledge for elimination is both qualitative and quantitative. Five types of knowledge are used to eliminate infeasible walls.

First, unique circumstances of feasibility under certain constraints are difficult to evaluate in terms of exact data. For example, storage, workspace, and access constraints involve consideration for construction materials and equipment. In such cases, construction expertise is required to judge the sufficiency of storage or workspace and the access for a particular wall type.

Second, combinations of constraints preclude some wall types. Certain constraints, such as durability and fill quantity, work in combination with other constraints. In such situations, the relationship between interdependent constraints is inherent.

Third, the potential advantages or disadvantages of a wall type incorporate local practices and trends of construction that can result in overall economy. For example, certain wall types are a particularly good solution under some constraints and a bad solution under other constraints.

Fourth, quantitative evaluation of site-available measures can be used to determine whether wall-specific requirements are satisfied. For example, given the approximate dimension of available excavation space and the predefined approximate backspace required (in terms of percentage of wall height), then if the available space is less than required, the wall is infeasible. Also, a range of economical wall heights can be used to decide whether to eliminate a wall type that is not economical.

Fifth, qualitative evaluation of site-available measures can be used to determine whether wall-specific requirements are satisfied. Site-specific (allowable) spatial, behavior, and economic factors are logically compared with wall-specific (required) factors to eliminate infeasible wall types.

SYSTEM DESCRIPTION

Colorado's retaining wall selection system eliminates infeasible alternatives then scores and ranks feasible alternatives. The system aims to assist an experienced retaining wall design engineer with construction knowledge of 24 gravity, semigravity, nongravity, and hybrid earth retaining wall types. The architecture of the system is shown in Figure 1. The system is composed of four main modules: input, elimination, ranking, and output. A discussion of the knowledge-based techniques used for elimination and ranking follows.

Elimination

The objective of elimination is to use given constraints to reduce the set of all walls to a subset of feasible walls. The implementation is based on Bayesian decision theory, assuming that each constraint is conditionally independent. The method requires two components of knowledge: the prior probability of each wall type and the conditional likelihood ratios for each constraint. Then, on the basis of a sequence of independent constraints, the likelihood ratios are used to revise the prior estimate of the probability of each wall type.

Bayesian decision theory is used for diagnosis, identification, and selection problems and in rule-based systems (*15*). The method was established in the context of the Prospector system (*16*) for identifying ore deposits. It was also used for the diagnosis of retaining wall failures (*5*). A version of the method is described and illustrated herein for retaining wall selection. The approach differs from the plausible relations in Prospector because plausible relations are most useful for identification and diagnosis problems when both the existence and lack of evidence are needed to make a decision. For the

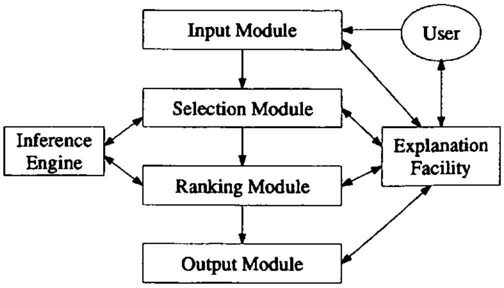

FIGURE 1 Architecture of CDOT wall selection system.

retaining wall selection problem, only existence of evidence (in the form of constraints) is needed. A secondary difference occurs because the selected paradigm of the Colorado system is to eliminate infeasible solutions rather than to search for the best solution.

The conditional probability of wall type W_k is expressed in terms of the likelihood ratio LR_k. To compute LR_k, the initial likelihood ratio LR_{k0} is updated by the appropriate conditional likelihood, CLR_j, for each constraint C_j (Equation 1). In this formulation, the subscript k denotes a particular wall type, and j denotes a particular constraint. LR_k depends on the number of constraint observations, not on the order in which they occur. CLR_{kj} and LR_{k0} are defined in Equations 2 and 3. LR implicitly defines probability such that P can be computed from Equation 4.

$$LR_k = LR_{k0} \prod (CLR_{jk}) \tag{1}$$

$$CLR_{kj} = \frac{P(C_j/W_k)}{P(C_j/\text{non}W_k)} \tag{2}$$

$$LR_{k0} = \frac{P(W_k)}{1 - P(W_k)} \tag{3}$$

$$P = \frac{LR}{(1 + LR)} \tag{4}$$

The likelihood ratio is derived from Bayes' theorem. It provides a rapid means to revise the prior estimate of probability. The advantage of using the likelihood ratios rather than Bayes' theorem is that the prior probability of each constraint $P(C_j)$ does not have to be explicitly known or updated (*17*). The conditional likelihood ratios can be determined in advance regardless of the number of constraints, and they do not depend on $P(W_k)$.

To implement the method, for each wall type k, prior probability $P(W_k)$ and a set of CLR_{kj} must be collected from experts familiar with retaining wall selection. Values of CLR can range from 0.000001 to 1,000,000. Numerical likelihood ratios are described in Table 2. The interpretation of the magnitude of CLR for supporting or refuting the feasibility of a particular wall type is related to the existence of a constraint.

$$CLR \begin{cases} > 1 & \text{degree of support} \\ = 1 & \text{indifferent} \\ < 1 & \text{degree of refutation} \end{cases}$$

TABLE 2 Verbal Description of Numerical Likelihood Ratios

Verbal Description	Likelihood Ratio
completely supports	1000000
extremely supports	10000
very supportive	100
moderately supportive	10
mildly supportive	5
weakly supportive	2
indifferent	1
weakly refutative	0.5
mildly refutative	0.2
moderately refutative	0.1
very refutative	0.01
extremely refutes	0.0001
completely refutes	0.000001

TABLE 3 Sample Prior Probabilities of Gravity Wall Types

k	Wall Type	$P(W_k)$
1	MSE	0.3
2	soil-nailed	0.05
3	modular	0.2
4	generic	0.2
5	mass-concrete-spread	0.15
6	mass-concrete-deep	0.05

To illustrate the approach, Table 3 provides prior probabilities of gravity walls, and Table 4 provides conditional likelihood ratios for the gravity walls. The reader should note that the values of $P(W_k)$ and CLR are for illustrative purposes only. (Actual values are being collected and analyzed.) If the wall functions are landscape and ramp, denoted by subscripts "ls" and "ramp," respectively, then the likelihood ratio of each gravity wall type can be computed from Equations 1 and 3.

$$LR_1 = \frac{P(W_1)}{1 - P(W_1)} CLR_{1,\text{ls}} CLR_{1,\text{ramp}} = \frac{0.3}{1 - 0.3}(1)(10) = 4.28$$

$$LR_2 = \frac{P(W_2)}{1 - P(W_2)} CLR_{2,\text{ls}} CLR_{2,\text{ramp}} = \frac{0.05}{1 - 0.05}(0.1)(0.1) = 0.00$$

$$LR_3 = \frac{P(W_3)}{1 - P(W_3)} CLR_{3,\text{ls}} CLR_{3,\text{ramp}} = \frac{0.2}{1 - 0.2}(25)(0.03) = 0.19$$

$$LR_4 = \frac{P(W_4)}{1 - P(W_4)} CLR_{4,\text{ls}} CLR_{4,\text{ramp}} = \frac{0.2}{1 - 0.2}(25)(0.05) = 0.31$$

$$LR_5 = \frac{P(W_5)}{1 - P(W_5)} CLR_{5,\text{ls}} CLR_{5,\text{ramp}} = \frac{0.15}{1 - 0.15}(1)(20) = 3.53$$

$$LR_6 = \frac{P(W_6)}{1 - P(W_6)} CLR_{6,\text{ls}} CLR_{6,\text{ramp}} = \frac{0.05}{0.05}(0.01)(20) = 0.01$$

From LR_k, the conditional probability of each wall type, given the functional constraints, can be computed from Equation 4. For this example, results indicate that Wall Types 1, 3, 4, and 5 are feasible and should be considered further.

$$P(W_1/C_{\text{ls}}, C_{\text{ramp}}) = \frac{LR_1}{1 + LR_1} = \frac{4.28}{1 + 4.28} = 0.81$$

$$P(W_2/C_{\text{ls}}, C_{\text{ramp}}) = \frac{LR_2}{1 + LR_2} = \frac{0.00}{1 + 0.00} = 0.00$$

$$P(W_3/C_{\text{ls}}, C_{\text{ramp}}) = \frac{LR_3}{1 + LR_3} = \frac{0.19}{1 + 0.19} = 0.16$$

$$P(W_4/C_{\text{ls}}, C_{\text{ramp}}) = \frac{LR_4}{1 + LR_4} = \frac{0.31}{1 + 0.31} = 0.24$$

$$P(W_5/C_{\text{ls}}, C_{\text{ramp}}) = \frac{LR_5}{1 + LR_5} = \frac{3.53}{1 + 3.53} = 0.78$$

$$P(W_6/C_{\text{ls}}, C_{\text{ramp}}) = \frac{LR_6}{1 + LR_6} = \frac{0.01}{1 + 0.01} = 0.01$$

The method just described is computationally simple and works well for constraints that can be measured as booleans.

TABLE 4 Sample Conditional Likelihood Ratios for Gravity Walls

				Construction Time			Bearing Capacity		
k	Wall Type	Landscape	Ramp	Min	Avg	Max	Min	Avg	Max
1	MSE	1	10	1	4	10	1	5	15
2	soil-nailed	0.1	0.1	0.1	0.5	1	1	1	1
3	modular	25	0.03	1	4	6	1	6	9
4	generic	25	0.05	2	4.5	6	1	6.5	12
5	mass-concrete-spread	1	20	0.1	0.4	1	0.4	0.5	1
6	mass-concrete-deep	0.01	20	0.05	0.2	1	1	8	20

If the constraint exists, then the appropriate *CLR* is included in Equation 1. If the constraint does not exist, then no action is necessary. Thus, with no input about the planned functions of the wall, the method returns the prior probability of each wall type. However, uncertainty about each constraint or knowledge of the user for measuring the importance or severity of each constraint is not included. Furthermore, uncertainty in the values of the conditional likelihood ratios is not included.

To include uncertainty, a severity index, S_j, is input for each constraint. The severity index, which ranges from -1 to 1, applies for all constraints and can be interpreted from Equation 5.

$$S_j = \begin{cases} 1 & \text{constraint } j \text{ is critical in the selection decision} \\ 0 & \text{constraint } j \text{ is typical} \\ -1 & \text{constraint } j \text{ does not exist} \end{cases} \tag{5}$$

Then, effective conditional likelihood, *CLR*′, can be mapped as a piecewise linear function of severity normalized with respect to conditional likelihood. As shown in Figure 2, a separate mapping function is required when *CLR* supports or refutes. For $CLR \geq 1$, such that the presence of a constraint is supportive for selecting a particular wall type, the mapping function in Equation 6 should be used.

$$CLR' = \begin{cases} CLR_{\max} - (CLR_{\max} - CLR_{\text{avg}})(1 - S) & S \geq 0 \\ CLR_{\min} + (CLR_{\text{avg}} - CLR_{\min})(1 + S) & S \leq 0 \end{cases} \tag{6}$$

For $CLR \leq 1$, such that the presence of a constraint refutes selecting a particular wall type, the mapping function in Equation 7 should be used. In all cases, if $S_j = 0$, then $CLR = 1$ and has no effect on the decision.

$$CLR' = \begin{cases} CLR_{\min} + (CLR_{\text{avg}} - CLR_{\min})(1 - S) & S \geq 0 \\ CLR_{\max} - (CLR_{\max} - CLR_{\text{avg}})(1 + S) & S \leq 0 \end{cases} \tag{7}$$

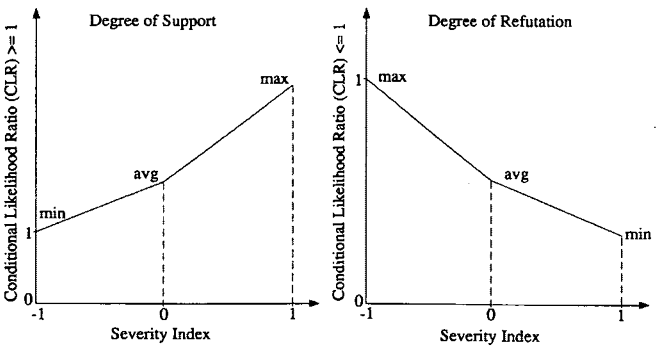

FIGURE 2 Effective conditional likelihood as piecewise linear function of severity index.

Then, to account for uncertainty using effective conditional likelihoods, Equation 1 could be rewritten as Equation 8.

$$LR'_k = LR_{0k} \prod (CLR'_{jk}) \tag{8}$$

To illustrate the use of the severity index, consider for construction time, $S_{\text{time}} = 0.6$, and for bearing capacity, $S_{bc} = -0.2$. *CLR*′ values for these constraints are computed from Equations 6 or 7, depending on the range of *CLR*. For example, using the *CLR* in Table 4, the effective conditional likelihood ratios that indicate support are computed from Equation 6.

$$\begin{aligned} CLR'_{1,\text{time}} &= CLR_{\max} - (CLR_{\max} - CLR_{\text{avg}})(1 - S) \\ &= 10 - (10 - 4)(1 - 0.6) = 7.6 \\ CLR'_{3,\text{time}} &= CLR_{\max} - (CLR_{\max} - CLR_{\text{avg}})(1 - S) \\ &= 6 - (6 - 4)(1 - 0.6) = 5.2 \\ CLR'_{4,\text{time}} &= CLR_{\max} - (CLR_{\max} - CLR_{\text{avg}})(1 - S) \\ &= 6 - (6 - 4.5)(1 - 0.6) = 5.4 \\ CLR'_{1,bc} &= CLR_{\min} + (CLR_{\text{avg}} - CLR_{\min})(1 + S) \\ &= 1 + (5 - 1)(1 - 0.2) = 4.2 \\ CLR'_{3,bc} &= CLR_{\min} + (CLR_{\text{avg}} - CLR_{\min})(1 + S) \\ &= 1 + (6 - 1)(1 - 0.2) = 5.0 \\ CLR'_{4,bc} &= CLR_{\min} + (CLR_{\text{avg}} - CLR_{\min})(1 + S) \\ &= 1 + (6.5 - 1)(1 - 0.2) = 5.4 \end{aligned}$$

The refutative effective conditional likelihood ratios are computed from Equation 7.

$$\begin{aligned} CLR'_{5,\text{time}} &= CLR_{\min} + (CLR_{\text{avg}} - CLR_{\min})(1 - S) \\ &= 0.1 + (0.4 - 0.1)(1 - 0.6) = 0.22 \\ CLR'_{5,bc} &= CLR_{\max} - (CLR_{\max} - CLR_{\text{avg}})(1 + S) \\ &= 1 - (1 - 0.5)(1 - 0.2) = 0.60 \end{aligned}$$

TABLE 5 Updated Likelihood Ratio and Conditional Probability of Gravity Walls

k	Wall Type	LR	$P(W_k/C_{ls}, C_{ramp}, C_{time}, C_{bc})$
1	MSE	136.8	0.99
3	modular	4.88	0.83
4	generic	9.11	0.98
5	mass-concrete-spread	0.47	0.32

From Equation 8, CLR' for construction time and bearing capacity are used to update the likelihoods ratios found previously for wall functions of landscape and ramp. The conditional probability of each wall, given the constraints landscape, ramp, time, and bearing capacity, is provided in Table 5. For this example, Wall Types 1, 3, and 4 with high conditional probability would be considered feasible alternatives.

Ranking

After elimination, the set of feasible wall alternatives are rated according to the evaluation factors (sometimes called objectives or criteria) given in the following table:

i	*Evaluation Factor*
1	Constructability
2	Maintenance
3	Schedule
4	Aesthetics
5	Environment
6	Durability
7	Standard design
8	Cost

Using these ratings, a set of noninferior solutions is identified. A noninferior solution is one such that no other feasible solution is better on all objectives (*17*). The noninferior solutions are then scored and ranked according to the same evaluation factors given in the table.

Ranking is an application of a weighting method that transforms the multiobjective problem into a single objective problem. The weighting method starts with sets of ratings and weight values. A weight value (W_i) is assigned to each evaluation factor in the preceding table. A set of rating values (R_{ik}) is generated for each kth alternative. Each R_{ik} indicates how well wall type k satisfies evaluation factor i. A score (S_k) is computed for each kth wall type according to Equation 9.

$$S_k = \sum_{i=1}^{8} R_{ik} W_i \tag{9}$$

The alternative with the highest score is a noninferior solution. Systematic repetition of Equation 9 for different sets of weights defines most of the noninferior solutions. Thus the weights do not have to be given a meaningful interpretation.

The weights can also be interpreted as the relative values of each objective. This interpretation is valid if each unit of achievement of each ith evaluation factor is worth W_i. Then maximizing the weighted sum of the objectives maximizes the total value. In practice, one generally does not know the value of different objectives. It is also unlikely that the weights are constant over the entire range of achievement R_{ik}. At least two methods are used in practice for assigning weights to rank retaining wall alternatives; these methods are described in the CDOT *Bridge Design Manual* (*10*) and in the U.S. Department of Agriculture Forest Service Region 6 *Retaining Wall Design Guide* (*14*) used in Oregon. For both methods, the assignment of weight values is purely empirical.

According to CDOT, the range of values for R_{ik} is given by Equation 10. The summation of the weight values is defined by Equation 11. W_i represents the importance of the ith evaluation factor in the overall project decision. Each W_i is independent of any wall alternative. Another constraint (Equation 12) is that the sum of any two weights must not be greater than 70.

$$1 \leq R_{ik} \leq 5 \tag{10}$$

$$\sum_{i=1}^{8} W_i = 100 \tag{11}$$

$$W_m + W_n \leq 70 \tag{12}$$

The scores S_k are used to rank each feasible wall alternative. The alternative with the highest rank is then designated the "default wall" while the remaining feasible walls are designated "alternative walls." In special cases, such as on difficult soils or deep foundations, the default wall should be adopted for final design and detailed cost estimation. In other cases, the designer may provide full designs for the default wall and an alternative wall if the contractor wishes to bid and build one of the alternatives rather than the default.

Environment

The development tools for the system are CLIPS Version 5.1 (*18*), Microsoft Windows Version 3.1, Borland C++ Version 3.1, and Application Frameworks. A Microsoft Windows application using wall sketches, pull-down menus, sliders, and radio buttons is being prepared as the front-end and output user interfaces. The interface is being developed using Borland C++ and Application Frameworks.

CLIPS is a rule-based expert system development shell that includes an object-oriented language. CLIPS was developed by The National Aeronautics and Space Administration and is distributed through COSMIC at the University of Georgia. The system will run on an IBM-compatible microcomputer. After initial development, the system will be expanded and maintained by CDOT Bridge Branch engineers. Run-time (compiled) copies of the final system may be distributed without licensing restrictions.

CONCLUSION

The CDOT retaining wall selection system is a knowledge-based formulation of the problem-solving strategy described in the CDOT *Bridge Design Manual* (*10*). It is expected that successful implementation of the system will foster a paradigm change on how retaining walls are selected and facilitate implementation of new retaining wall technologies. The system is being designed and coded such that individual states can customize and enhance it. It is expected that the system will benefit not only CDOT but other state DOTs as well.

ACKNOWLEDGMENTS

Funding for the conceptual design of this system was provided by CDOT. Subsequently, this material is based on work supported by an award from FHWA and the National Science Foundation, Mehmet Tumay, cognizant program director.

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Publication of this paper sponsored by Committee on Applications of Emerging Technology.