

DECISION SUPPORT FOR SLOPE CONSTRUCTION AND REPAIR ACTIVITIES:
AN ASSET MANAGEMENT BUILDING BLOCK

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by
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**DECISION SUPPORT FOR SLOPE CONSTRUCTION AND REPAIR
ACTIVITIES:
AN ASSET MANAGEMENT BUILDING BLOCK**

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To my family ...

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ABSTRACT

The objective of this research was to develop a support system to facilitate appropriate decision making for construction, maintenance, and repair of earth slopes along transportation rights of way. The system was to be based on asset management principles to minimize life-cycle costs and maximize the life-cycle performance of geotechnical assets.

In the area of geotechnical transportation infrastructure, there are few decision support systems and little data available to facilitate effective decision-making for maintenance and rehabilitation of highway embankments and slopes. Because of ongoing efforts to improve the required data collection and maintenance, this research focused on the development of appropriate analysis techniques. Through the use of decision tree modeling, two basic forms of analysis were developed to predict the outcomes of alternative stabilization methods. The first form is referred to as the “Single Point in Time” (SPIT) model that models only a single application of a repair method. In its current form, it does not model the potential costs of alternative stabilization methods over a consistent life-cycle.

The second form of model is referred to as the Specific Time Horizon (STH) model. This model was developed to account for the possibility of having to apply a specific repair technique multiple times over a specific time horizon. Both models allowed developing preliminary tools, referred as “break-even” diagrams, to illustrate one potential application of the techniques.

CHAPTER 1 – INTRODUCTION

1.1 Background

It is known that for any asset, the total life-cycle cost takes into account the cost of the asset and the cost of the maintenance throughout its life-cycle. In the same way, the life-cycle cost of an engineering infrastructure such as a building, bridge or road takes into account the construction cost and its maintenance cost. In the case of roads or highways, while the construction cost is established with an acceptable degree of accuracy during the design stage, the total maintenance cost throughout its life-cycle is uncertain. According to Jha (2003), maintenance and operation costs constitute a major portion of expenditures over a highway's life and ought to be given due consideration.

Small routine maintenance costs of roads may include items such as re-painting, cleaning drainage channels and sign replacement. However, Departments of Transportation (DOTs) are additionally dealing with the repair of numerous erosional features and surficial slope failures that present significant hazards, including damage to or loss of pavement sections, loss or reduced effectiveness of guardrails and other safety measures, blocking of drainage channels, and potential damage to bridges and other structures due to loss of ground support or additional loads imposed by sliding soil and rock (Sanford Bernhardt and Loehr, 2001). According to the Transportation Research Board (TRB), the repair cost of these surficial slope failures exceeds the repair cost of major landslides with an annual estimate of over \$100 million dollars (TRB, 1996).

Unfortunately, slope repair methods are often chosen based on tradition rather than on technical or economic reasons (Sanford Bernhardt and Loehr, 2001). There are

several methods available to repair and stabilize slopes. These methods or techniques may vary from simple replacement of the unstable material with a more “selected” material to the construction of an earth retaining structure. The initial cost and effectiveness of these methods may vary significantly as well as their life-cycle cost. Because of a limited budget, it is not rare for a decision maker to choose the apparent most economic alternative (lowest initial cost), despite the fact that it may be less reliable. The problem is that inexpensive solutions such as regrading the unstable slope material, tend to be recurrent activities that may also increase the life-cycle cost in the long term (Sanford Bernhardt et al. 2003). Therefore, infrastructure engineers and managers have to be aware of the economic consequences (on a life-cycle basis) of selecting a particular rehabilitation and construction alternative (Salem, 2003). The problem is that there are few decision support systems available. Little research has been performed to assist decision makers in deciding whether, when or how a slope failure should be repaired so that limited funds would be applied where the most benefits, on the life-cycle basis, will be gained (Sanford Bernhardt et al. 2003).

1.2 Objective

The objective of this research was to develop a support system to facilitate appropriate decision making for the construction, maintenance, and repair of earth slopes along transportation rights of way. The system was to be based on asset management principles to minimize life-cycle costs and maximize its life-cycle performance.

1.3 Scope

The scope of this thesis includes identifying through literature review, the state of knowledge in the areas of decision support and slope stabilization repair. Based on this information, formal decision making was researched by modeling stabilization decisions through graphical and mathematical models known as decision trees. Numerous models were developed and evaluated. Description of the models and the results of various analyses are discussed in this thesis.

1.4 Thesis Outline

The thesis is organized in six chapters including the introduction. The literature review presented in Chapter 2 describes three well known geotechnical decision support systems developed by departments of transportation. The description of decision tree modeling is presented in Chapter 3. In Chapter 4 various decision tree models are described and evaluated. This chapter also includes a preliminary decision user spreadsheet for the input of model values. Breakeven-line concepts are described in Chapter 5. Two basic forms of decision tree models referred as the “Single Point in Time” (SPIT) model and the “Specific Time Horizon” (STH) model are introduced. Applications, advantages and limitations of both models are discussed in the chapter. Finally, Chapter 6 includes a summary of the thesis along with conclusions and recommendations for future study.

CHAPTER 2 – LITERATURE REVIEW

2.1 Introduction

As part of the study, a literature review was performed to find existing systems or methods that would address the problem of making effective decisions for managing geotechnical problems. The most well known support systems are briefly described and compared in this chapter.

2.2 Existing Slope Decision Support Systems

In the area of geotechnical transportation infrastructure, there are few decision support systems and little data available to facilitate effective decision-making for maintenance and rehabilitation of highway embankments and slopes. Among others, probably the three best developed or most widely known systems are the (1) the *ODOT Landslide & Rockfall Pilot Study-Final Report* developed in May 2001 by the Oregon Department of Transportation (ODOT), (2) the *Development of an Unstable Slope Management System* developed by the Washington Department of Transportation (WSDOT) and (3) the *Blue Ridge Parkway Landslide Rating System* developed by the Eastern Federal Lands Highway Division (EFLHD) of the Federal Highway Administration (FHWA). Each of these systems is described in the following sections.

2.2.1 Oregon Department of Transportation System

Between late 1999 and early 2001, the Oregon Department of Transportation (ODOT) developed a system to identify, inventory and rate all active landslides and rockfalls according to their level of hazard, along three major state highways in Oregon (Region 3). Among others, the main objective of the study was to develop a hazard

scoring system that would allow development of a process for prioritizing and selecting landslides and rockfall projects for the Statewide Transportation Improvement Plan (STIP). The prioritizing process was to take into account both safety hazards (risk) and economic impacts to be applied to the landslide and rockfall sites in the studied area.

To make the prioritized landslide and rockfall list, the study considered, quantified, and combined several factors into a final scoring system. Hazard and economic impacts were included in the final selection process. Hazard rating was quantified taking into account physical and historical information. Five categories were considered for the hazard rating of each site. Each of the five categories would top 100 points for a maximum of 500 points per site. It is important to mention that according to the study criteria, sites with higher hazard scores were not predicted to fail sooner, they were considered to pose a higher level of hazard or risk. The five categories considered for the hazard rating were the following:

- Failure type/hazard (speed of failure)
- Roadway impact (for landslides or rockfalls)
- Annual maintenance frequency
- Average daily traffic
- Accident history

After scoring the relative hazard of each site, the scores would then be multiplied by factors related to the annual maintenance costs (economic impacts) and highway importance to arrive at the Final STIP Score. The annual maintenance costs included the two economic impacts that were (1) the cost impact to ODOT maintenance forces and (2) the cost impact due to traffic delays. The cost impact to ODOT maintenance forces is

evaluated in Table 2-1 and a factor is determined based on a benefit/cost ratio. The second economic impact (potential traffic delays), was difficult to quantify and therefore was considered as a supplemental factor to be considered in the final selection process.

The maintenance Benefit-Cost ratio is a 20-year maintenance cost divided by the repair cost (assumed as permanent repair). According to Table 2-1, factors ranged between 1.5 and 0.5. The highest factor 1.5 is applied when the cost of maintenance over a 20-year was twice the cost of fixing the failure. And the lowest factor 0.5 was applied when the 20-year maintenance cost was very small with respect to the repair cost.

Table 2-1. Maintenance Benefit/Cost Factor

<u>20-Yr Maintenance Cost</u> Repair Cost	Maintenance Benefit-Cost Factor (MB/C)
> 0.0 – 0.2	0.5
≥ 0.2 – 0.4	0.75
≥ 0.4 – 0.6	1
≥ 0.6 – 0.8	1.06
≥ 0.8 – 1.0	1.12
≥ 1.0 – 1.2	1.18
≥ 1.2 – 1.4	1.24
≥ 1.4 – 1.6	1.3
≥ 1.6 – 1.8	1.36
≥ 1.8 – 2.0	1.42
≥ 2.0	1.5

The highway classification factor was the second multiplier to the Hazard score, taking into account the route importance. As shown in Table 2-2, the factors ranged between 1.0 and 1.2.

Table 2-2. Highway Importance Factor

Highway Type	Highway Factor
District Highway	1.0
Regional Highway	1.05
Statewide Highway	1.1
Interstate Highway	1.2

The Final STIP Score was obtained by multiplying the hazard score by the two factors described above. The equation that summarizes this step of the process is as follows:

$$(\text{Hazard Score}) \times (\text{MC20}_{\text{factor}}) \times (\text{Highway}_{\text{factor}}) = \text{Final STIP Score} \quad (2-1)$$

Sites were then sorted by their Final STIP Score to produce the prioritized list. Project selection was made from this final list, taking into account the estimated repair costs and other non-scoring factors. The other non-scoring impacts that were taken into consideration in the final selection are the following:

- Potential traffic delay costs
- Emergency lifeline priority ranking
- Existing culvert damage (possibly contributing to slope instability)
- Environment impacts (fisheries, wetlands)
- Impact to adjacent structures or private properties, and
- Interagency funding opportunities.

Although the ODOT pilot study was successfully completed, the scoring system and selection process developed was applied to only three state highways and only 100 sites in Region 3. Several issues such as average daily traffic scoring, repair cost

uniformity and traffic delay cost, needed to be solved as this system expanded before it would be applied to the entire statewide highway system.

2.2.2 Washington Department of Transportation

The Washington Department of Transportation (WDOT) developed a landslides and slopes management system that was published in December of 1991 through a final report titled *Development of an Unstable Slope Management System (USMS)*. The technical report is composed of two parts: a database and priority programs. The intent of the system was to provide the user with a systematic approach to manage the maintenance and repair of unstable slopes.

The USMS was developed through questionnaires and conversations with WSDOT personnel concerning unstable slope maintenance. Throughout the questionnaires, personnel were asked to rate an item from 1 to 10. The value 10 represented the most important, severe, or extreme case. For example, if the personnel considered that landslides, rockfall, and flows were all extremely important in a particular site, then they would assign each item a value of 10 or whichever value they felt appropriate.

The data for this system was divided into two different categories: Temporary and Permanent. The permanent data was considered site information that would not, for practical purposes, change over time. Temporary data was considered information that may have varied each time the site failed.

The priority programs were known as CLIPS programs. From the questionnaire information, CLIPS programs assigned various priority ratings to each site so that they could be compared in a methodical manner.

After the CLIPS programs were executed and the priorities were determined, weighted priorities and total priority were determined. The weighted priorities were calculated by a program known as the WEIGHT.PRG program that would multiply the temporary priority ratings and permanent priority ratings with appropriate weights. The weighting values for temporary and permanent factors are shown in Table 2-3.

Table 2-3. Weights for temporary and permanent factors used in the WSDOT site rating system.

Temporary Weighted Factors:

<u>Factor</u>	<u>Weights</u>
1. Problem type	6
2. Traffic impedance	5
3. Lawsuit potential	1
4. Pavement damage	3
5. Structure type and damage	5
6. Temp. Static & dynamic load	3
7. Failure frequency	8
8. Repair cost	15
9. Failure size	2
10. Failure water level	10
11. Failure data	1

Weight Total	59

Permanent Weighted Factors:

<u>Factor</u>	<u>Weights</u>
1. ADT	12
2. Road type	10
3. Seismic	3
4. Soil type and layers	4
5. Rock joint-layers & loose & intact	4
6. Economic	3
7. Perm. Static & dynamic load	3
8. Geographical hazard	2

Permanent Weight Total	41

Finally, the total priority rating for each site was calculated by adding the weighted priority ratings divided by 19 which was the total number of factors. The total priority rating was a number that theoretically ranged from 0 to 100, with 100 being the highest priority. The total priority of a failure site was considered independent of all other failure sites.

2.2.3 Blue Ridge Parkway Landslide Rating System

Similar to the two systems described before, the Blue Ridge Parkway Landslide Rating System was developed to assist in the evaluation and prioritization of the landslides encountered along the Blue Ridge Parkway (unpublished FHWA - Eastern Federal Lands Highway Division documents). This evaluation and rating system is based on technical considerations without accounting for estimated landslide repair costs. According to the system's description, the future programming will be assisted by a master spreadsheet that will summarize all landslide data including preliminary cost estimates.

The system is comprised of two phases. In the first phase, Parkway district personnel (maintenance supervisors) compile an inventory list of all known areas of instability (including spur roads, interchange ramps or other facilities for which the Parkway is responsible). The information includes location, type of slope (cut or fill), slope material, climatic conditions, slide type (shallow failure, settlement, earth/rock flow, rockfall, etc.), history of instability and an estimate of the annual maintenance cost of each identified site. In the second phase, geotechnical personnel conduct a detailed inspection, a preliminary evaluation and a numerical rating of the known landslides listed on the inventory. The Parkway's rating system is a matrix evaluation system which

assigns numerical values to several criteria in order to objectively evaluate the landslides. After assigning numerical values and compiling the totals, the slides are prioritized according to the numerical rating. Rating system criteria are tabulated in Table 2-4. A weighting factor ranging between 1.0 and 1.5 was assigned to each rating criteria to assign a relative degree of importance.

Table 2-4. Blue Ridge Parkway landslide rating system matrix

Category	Points = 2	Points = 4	Points = 8	Points = 16	Weighting Factor
Soil Slide	Surface slough (<3' deep)	Settlement or slow moving slide (years)	Moderately moving slide (months)	Rapidly moving slide (days)	1.0
Rock Slide – Volume of Rock	Minimal (<1 cy)	Minor (1-10 cy)	Moderate (10-50 cy)	Major (>50 cy)	1.25
Rock Slide – Width of Catchment Area	> 25'	25'-10'	10'-5'	< 5'	1.5
Average Daily Traffic	< 250'	250 to 1000	1000 to 2500	> 2500	1.0
Minimum Sight Distance	> 500'	500'-250'	250'-100'	< 100'	1.5
Length of Parkway Impacted	< 50'	50' to 100'	100' to 250'	> 250'	1.0
Width of Parkway Impacted	None	Shoulder	One lane	Both lanes	1.25
Average Vehicle Risk	<10% of the time	10% to 30% of the time	30% to 50% of the time	> 50% of the time	1.5
Pavement Damage	None to minor–not noticeable	Moderate driver must slow	Severe driver must stop	Extreme–not transversible	1.25
Annual Maintenance Costs	< \$2500	\$2500 to \$10,000	\$10,000 to \$25,000	> \$25,000	1.0

2.2.4 Summary

The life-cycle cost of engineering infrastructures (buildings, roads, bridges) takes into account the cost of construction and maintenance. In the case of roads, although the construction cost is established with an acceptable degree of accuracy during the design stage, the total maintenance cost throughout its life-cycle is uncertain. Departments of transportation (DOTs) are dealing with the repair of numerous erosional features and surficial slope failures that according to the Transportation Research Board (TRB) exceed the repair cost of major landslides with an annual estimate of over \$100 million dollars.

Unfortunately, slope repair methods are often chosen based on tradition rather than on technical or economic reasons (Sanford Bernhardt and Loehr, 2001). Little research has been performed to assist decision makers in deciding whether, when or how a slope failure should be repaired. Furthermore, there are few decision support systems and little data available to facilitate the effective decision making for highway maintenance and rehabilitation. A summary of the three best developed or most widely known systems (*ODOT Landslide & Rockfall Pilot Study-Final Report, Development of an Unstable Slope Management System*, and *Blue Ridge Parkway Landslide Rating System*) was discussed in this chapter.

CHAPTER 3 – DECISION ANALYSIS METHOD

3.1 Introduction

The inherent uncertainty of situations or complexity of some problems can make decisions difficult to make. A decision analysis approach can help identify and handle important sources of uncertainty and provide effective methods to organize a complex problem through a structure that can be analyzed. According to Clemen (2001), the purpose of decision analysis is to help a decision maker think systematically about complex problems and to improve the quality of the resulting decisions. This chapter will focus on the general process of structuring and analyzing decisions.

3.2 Structuring Decisions

Decisions making is a key function of engineering and management that should account for technical and economic effects (Buck 1989). Some decisions are so simple to make that they do not require thinking of them in the process. Other decisions that are more complicated may require taking considerable time and effort within the process (Buck 1989). The criteria of complicated decisions are usually economic in character and they may normally involve several variables. Decision makers may resolve these complex economic problems by performing decision analysis.

One common way to solve complex problems through a systematic approach is by the use of influence diagrams or decision trees. Fortunately, innovations in computers and software offer friendly graphical interfaces that simplify the structuring process of these models. Influence diagrams and decision trees are graphical modeling tools for representing the basic structure of a decision (Clemen 2001). Influence diagrams allow

many aspects of a problem to be displayed in a compact and intuitive form while a decision tree provides an alternative image of a decision in which more details can be displayed (Clemen 2001). Decision trees, also known as event trees, allow representing complex networks of conditional probability problems (USACE, 1999). In general, decision trees are precise mathematical models that provide a visual representation of a decision situation.

According to Clemen (2001), a good decision is one that gives us the best outcome. In order to create alternatives and make a good decision, it is necessary to first identify and understand well the problem. The next step to approach the problem systematically would be to develop a model. Modeling is critical in decision analysis (Clemen 2001). Regardless of the model used, a decision analysis will not provide a solution but rather the information to make a good decision.

Decision trees and not influence diagrams were used to model unstable slope solutions in the thesis. A description of the decision tree modeling used in the thesis is described below.

3.3 Structuring a Decision Tree

The decision tree modeling used in the thesis was heavily based on Clemen's (2001) drawings which represented the alternatives as branches. These branches emanate from nodes flowing from left to right. It can be useful to think of the nodes as occurring in a time sequence. In this sense, beginning from the left side of the tree, the first thing to happen would be typically a decision followed maybe by another decision or a chance event in a chronological order.

In relation with the construction of the trees, square nodes represent the decisions to be made, circle nodes represent chance events and end nodes are represented by triangles. The branches that emanated from the square nodes corresponded to the available alternatives (choices) and the branches that emanated from circle nodes represented the possible outcomes of the uncertain events. A decision maker has no control of the chance events. The possible things that can happen in the resolution of an uncertain event are called outcomes (Clemen 2001). The numerical values of the outcomes are displayed at the end of the branches. These values were obtained through the decision analysis. They allowed identifying the optimum path through the tree that included the preferred alternative.

The tree models also display information near their branches and nodes. The computer software used for the thesis displays the name of the node near each node and the value of the tree at that node. The possible outcome branches that emanated from circle or chance nodes display the value (cost) of the outcome and the probability of the outcome to occur. Decision branches that emanate from the decision node display the label *True* or *False* identifying the preferred alternative. Finally at end nodes, the probability of the path and the value of the path are displayed.

Recalling from the previous chapter, slope repair decisions may involve both technical and economical aspects. The objective of the thesis modeling was measured only in monetary terms (minimize costs). The analysis therefore required to calculate each decision's expected monetary value (EMV), which was displayed near the chance nodes. The EMV of each decision (alternative) was obtained by weight averaging the

outcome costs with respect to their probabilities of occurrence. If costs were modeled as negative values, the preferred alternative was identified as the least negative.

The example shown in Figure 3-1 depicts the terminology described above. The example was obtained from Palisade software which accompanies Clemen’s 2001 book: *Making Hard Decisions*. The name of the example is “Lottery”. The tree was developed to have one decision node from which two alternative branches emanate for whether to buy or not to buy a lottery ticket for the price of 2 (two) dollars. If the decision maker decides to buy the ticket, he must pay 2 dollars. There is no cost associated with the alternative to not buying a ticket. The cost value of 2 dollars is displayed in the tree model as negative 2 dollars because gains are normally expressed as positive values and losses or costs are expressed as negative values. If there is no gain or loss, then the value is zero (Clemen, 2001).

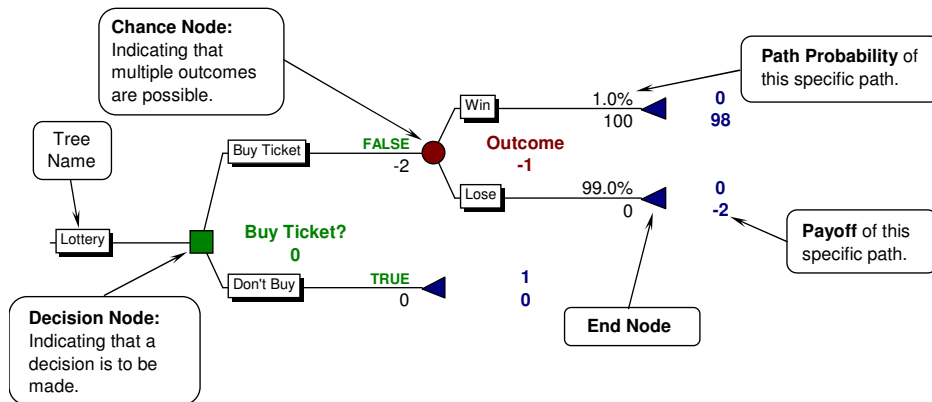


Figure 3-1. Decision tree example: “Lottery” (PrecisionTree–Palisade, 2000).

If the decision maker decides to buy the ticket and the game is played, there are two possible outcomes that are shown emanating from the chance node: “Win” or “Lose”. As displayed in Figure 3-1 and Figure 3-2, each outcome branch displays the

probability of occurrence and the value of its cost. The probability value shown on the branch “Win” indicates that there is a 1 percent chance of winning a prize of 100 dollars. And the value displayed on the outcome branch “Lose” indicates that there is a 99 percent chance of not winning anything.

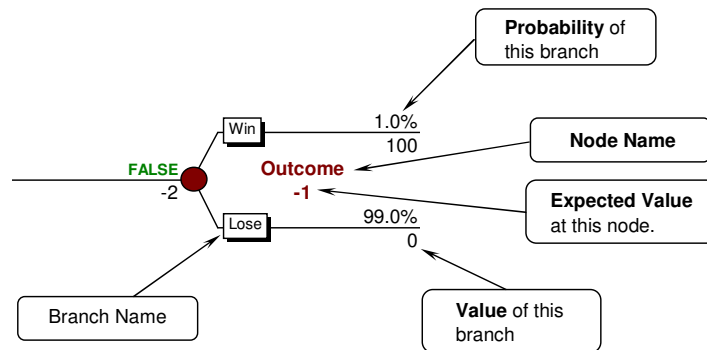


Figure 3-2. Parts of outcomes branches.

As shown in Figure 3-3, the preferred alternative, “Don’t buy” a lottery ticket, is identified by the label “True” displayed on the outcome branch.

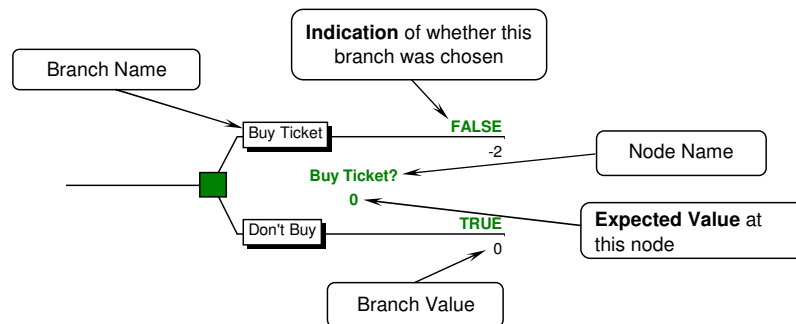


Figure 3-3. Parts of the alternative branches

Calculations to establish the monetary value that justifies the solution of the example is shown in the next section.

3.4 Solving a Decision Tree

The purpose of structuring a problem is to simplify finding a preferred alternative. An easy way of picking an alternative when the alternatives are risky, is choosing the highest expected value (EV) or the (EMV), when the consequences involve money. When using decision trees, the backward procedure to find the (EMV), is often called the “averaging out and folding back” procedure (Park and Sharp-Bette, 1990). The procedure consists of calculating all EV encountered at chance nodes starting from the right side of the tree and proceeding to the left side of the tree. As the tree is being folded back, and decision nodes are encountered, the preferred alternative is identified as the branch with the highest EV.

A double-risk dilemma example was taken from Clemen’s (2001) book to illustrate the averaging out and the folding back procedure. The situation is one in which a decision maker needs to choose between two risky alternatives. The decision maker has a lottery ticket that will let him participate in a game of chance with a 45 percent chance of winning 10 dollars and 55 percent chance of getting nothing. His friend has a ticket of a different lottery that has a 20 percent chance of winning 25 dollars and an 80 percent chance of getting nothing. The friend has offered to trade the tickets if the decision maker gives him one dollar. The question is: should the decision maker trade the tickets and play to win 25 dollars or should he keep his ticket with a better chance of winning only 10 dollars?

Figure 3-4 shows the decision tree. Notice that the cost of the decision “Trade Ticket” is negative 1 dollar. At the end of each alternative branch path (at the end nodes) there are two values. The upper value, which represents the probability of the path, is

calculated by multiplying all the chance probabilities along the path. The lower value is obtained by adding all the values (costs) of the branches along the path. In the case of the path “Trade Ticket–Win \$25” the value 24 is the summation of the cost of the decision “Trade Ticket” (negative 1 dollar) and the payoff (positive 25 dollars) of the chance branch “Win \$25”.

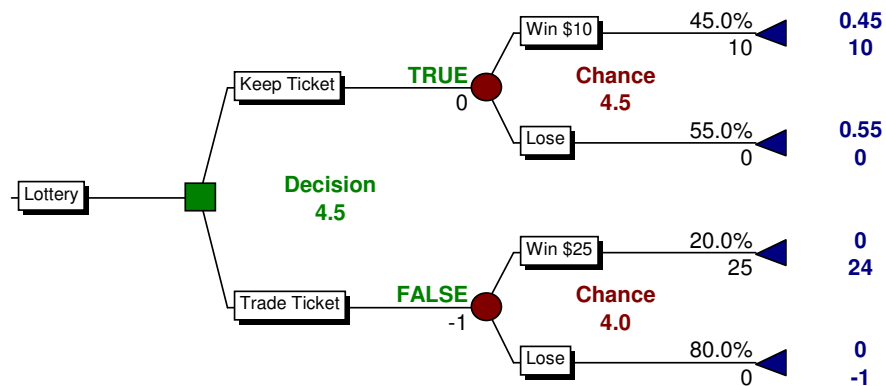


Figure 3-4. Double-risk dilemma (Clemen, 2001)

In this example, the first step to solve the decision tree is to calculate the expected value of the alternative “Keep Ticket” and playing for 10 dollars. The expected value is obtained by calculating the weighted average of the possible outcomes of keeping the ticket.

$$\begin{aligned}
 EMV(\text{Keep Ticket}) &= 0.45(10) + 0.55(0) \\
 &= \$4.5
 \end{aligned}$$

This value can be interpreted as the average value obtained by playing the lottery many times. The value 4.5 dollars is displayed next to the chance node of the preferred

alternative. The next step is to calculate the expected value for the possible outcomes of the alternative “Trading Tickets”.

$$EMV(Trade\ Ticket) = 0.20(24) + 0.80(-1)$$

$$= \$4.0$$

Once the expected values are calculated, they will replace the chance nodes in the decision tree as shown in Figure 3-5.

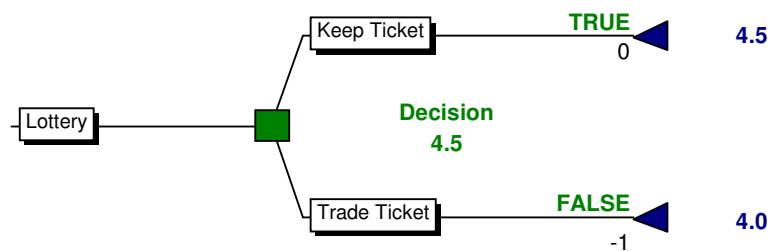


Figure 3-5. Replacing chance nodes with the EMVs

Finally the decision maker will choose between the two alternatives depending of the highest expected value. In this case the preferred alternative is “Keep Ticket” and is labeled as “True” as shown in Figure 3-5.

3.5 Summary

In this chapter the importance of performing decision analysis to improve the quality of resulting decisions was discussed emphasizing the importance of structuring complex problems so that they can be analyzed systematically.

Two graphical and mathematical approaches have been described in this chapter; influence diagrams and decision trees. Considering that decision trees were used in the thesis, only this method was described in detail. Finally, a couple of examples were shown for better explanation of the structuring and algorithm aspect of the tree. The examples also showed how to calculate the expected monetary value, (EMV) that allows identifying the preferred decision.

CHAPTER 4 – DEVELOPMENT OF DECISION SUPPORT MODEL

4.1 Introduction

In the previous chapter it was mentioned that complex problems may be better approached through the analysis of decision models. In the area of engineering and management, the complexity of most problems is often related to the optimization of technical and economical aspects. The objective of this thesis was to develop a decision support framework to facilitate the effective programming of slope maintenance and repair decision. Therefore, economical and technical aspects were considered in the tree modeling. Since decision trees are supposed to mimic the problem as truthfully as possible, it was necessary to compare several tree models to confirm their accuracy with respect to the objective of the thesis.

4.2 Initial Decision Models

The basic structure of a decision tree that is related to a geotechnical transportation infrastructure problem may begin with an unstable slope issue. Two or more alternatives to stabilize the slope may emanate from an initial decision node as shown in Figure 4-1. In the tree models developed in this thesis, the costs associated with the alternatives were assumed to be the costs of stabilizing the slope by using a certain repair technique. These alternative costs were referred to in the thesis as the “initial cost” of the stabilization method. At the right end of the alternatives, as displayed in Figure 4-1, there are two chance nodes each of which has two outcomes. These outcomes are either “No Failure” or “Failure” representing all possible occurrences of a stabilized slope. Conceptually, a partial slope failure was considered as a failure although the consequence cost could have

varied. In Figure 4-1 tree values are displayed as variables. Tables showing the values and descriptions of the variables will be presented in a later section.

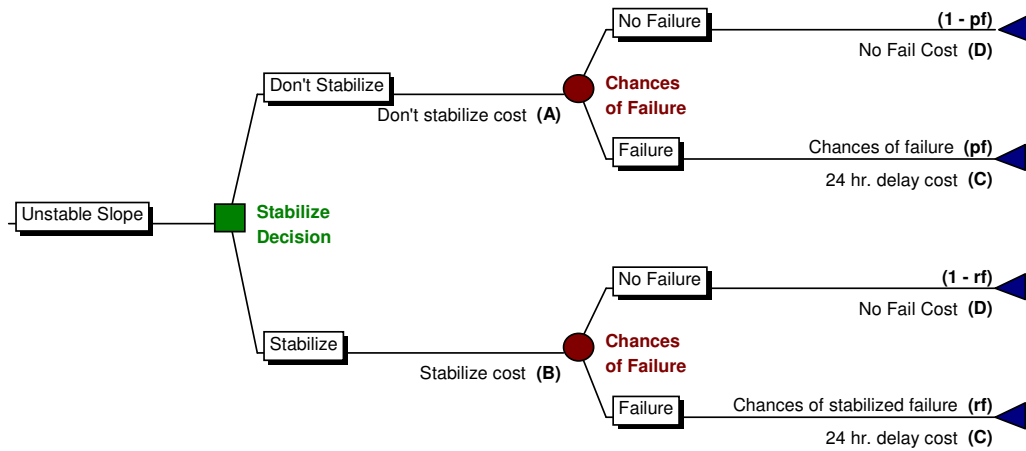


Figure 4-1. A two branch unstable slope tree model

The outcomes were associated with costs and probabilities of occurrence expressed in percentages. The probability of occurrence of each outcome was assumed to depend on the reliability of the stabilizing method. Finally, the costs of the methods were assumed to be related to their reliabilities (although not always true in the practice). Therefore in the tree models, a more expensive stabilizing method was assumed to be more reliable and therefore less likely to fail.

In the first tree models, the values of cost considered were estimated or assumed for easy analysis, to understand the behavior of the results and to make adjustments to the model itself. For example, the cost associated with the outcome of “Failure”, was assumed to be the average cost suggested in ODOT’s report for a 24 hour traffic delay (ODOT, 2001). The cost associated with the outcome “No Failure” was assumed to be zero. The initial cost for the stabilization method was obtained from ODOT’s suggested average cost for slope failure repair. And for the alternative “Don’t Stabilize” shown in Figure 4-1, the cost was assumed to be zero (or very little if considered that the slope can be only instrumented for monitoring).

In the decision trees, decision branches were ordered according to their initial costs. In the case of having three or more alternatives, the alternative with the lowest initial cost would be located above. The bottom alternative would always have the most expensive initial cost. Following this order, Figure 4-2 shows an example of a tree in which the upper method has the less expensive initial cost (zero).

An intuitive estimate would show that in a tree model like the one shown in Figure 4-2 in which the cost of failing of all methods were to be the same (same outcome

cost and same probability of occurrence), then the alternative with the lowest initial cost would be the preferred alternative.

According to the tree examples shown in Figure 4-2, the costs of no failure were considered zero, which may be unrealistic considering that many slope stability methods require maintenance cost or monitoring cost. In the case of failure, it was assumed that the alternative with the less expensive initial cost would have a more expensive maintenance cost.

Complexity in the identification of the preferred alternative was based on the tradeoff that occurs between initial costs, the outcome cost and their probability of occurrence. The more expensive alternatives were assumed to have a less expensive outcome and a lower probability of occurrence.

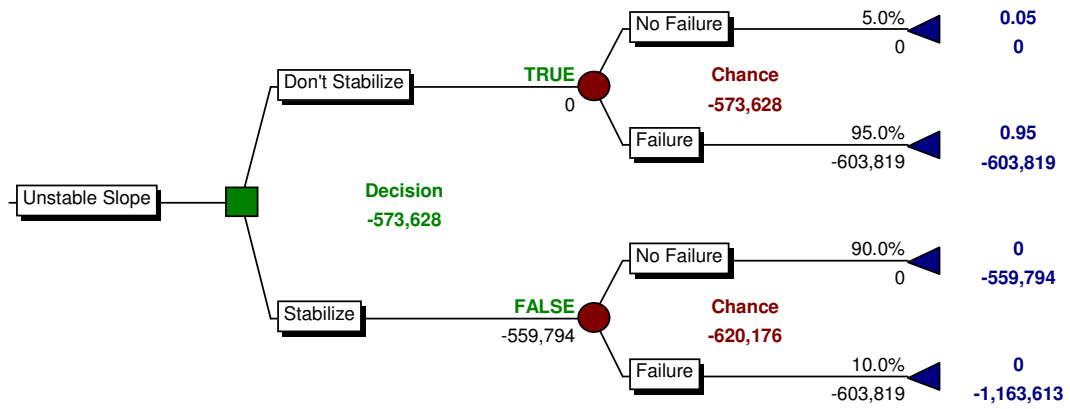


Figure 4-2. Less expensive alternative is preferred when outcomes are similar.

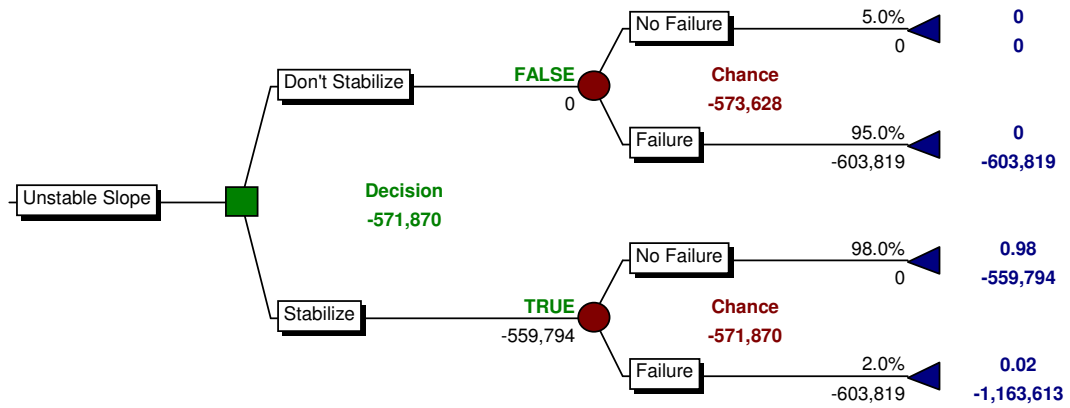


Figure 4-3. Expensive alternative is preferred when probability of failure is very low.

For early tree models (Figure 4-2 and Figure 4-3), the outcome costs of failure were considered to be the same for all stability methods (\$603,819). The balance in the preference of the alternatives was obtained by increasing or decreasing the probabilities of failure. Figure 4-3 shows the results of a model in which the preference of the tree shown in Figure 4-2 is changed by increasing the probability of failure of the less expensive method and decreasing the probability of the most expensive method. The preferred and not preferred alternatives are identified in both Figure 4-2 and Figure 4-3 with the labels “True” or “False” respectively. These preference labels are switched in both trees. It is noticed in the figures that at the end nodes (triangles), the values of the probabilities of failure are only displayed for the preferred alternative. This was a characteristic of the specific software.

By comparing Figure 4-2 and Figure 4-3 in more detail, it can be noticed that the probability of failure of the most expensive alternative “Stabilize” decreased from 10% to 2% allowing this alternative to be preferred. The summaries of the final alternative cost were displayed next to their chance nodes of the models. These values show that by decreasing the probability of failure of the alternative “Stabilize” from 10% to 2%, the cost of the alternative decreased from \$620,176 to \$571,870 allowing this value to be slightly preferred over the value of the first alternative which was set constant at \$573,628.

Varying the outcomes’ probabilities of failure would not always result in switching the model preference. In the case of a decision tree like the one shown in Figure 4-4 in which the outcome cost of the less expensive alternative is smaller than the

initial cost of the most expensive alternative, a balance would never be achieved nor would the preference switch regardless of the probabilities assumed for both alternatives.

The values assigned to the probabilities of failure were observed to significantly influence in the identification of the preferred alternative. It was therefore important to establish true probability values at some stage.

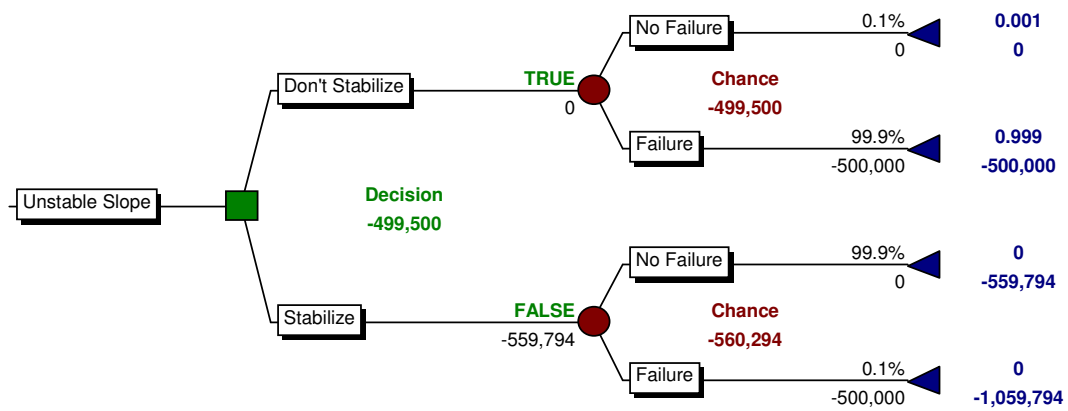


Figure 4-4. Tree model with cost values in which the alternatives can not be balanced

4.3 Decision Tree Variables

4.3.1 Definition of Variables

The structure of the tree model and the values assigned to the branches were changed several times during the study. In early models, the values that were assigned to the trees depended in part on the structure of the tree and mostly on the desired results. Their influence on a preferred alternative was very important; therefore, in the models they were considered as variables.

In a simple tree model such as the one shown in Figure 4-1, each alternative had the following five variables: the initial cost, the probabilities of failure and no failure and the costs of failure and no failure. The model had two alternatives and ten variables. The number of variables in a simple two-alternative tree model was sometimes simplified by assuming that the cost of no failure (variable C) for both alternatives was the same. The same way the cost of failure (variable D) was also assumed to be the same for both alternatives. Using the same value for two variables allowed decreasing the number of variables in the model from ten to eight.

The variables used in the model are listed in Table 4-1 which includes a description of the base values and the lower and upper bound value of each variable. Many of the values that appear in the table were obtained from ODOT's database (ODOT, 2001). They were used as economic factors to score and prioritize the hazard sites. The notation assigned for each variable was changed and standardized in later tree models. Both early and later notations are shown in Table 4-2.

Table 4-1. Variable values

Variables	Description	Base value	Lower Bound	Upper Bound
pf	Probability of failure	20%	0%	100%
rf	Probability of failure	10%	0%	100%
A	Don't stabilize initial cost	0	0	0
B	Stabilize initial cost	589,794	1,600	6,000,000
C	No failure cost	0	0	0
D	Failure cost	603,819	0	3,901,349
(1-pf)	Probability of not failing	80%	0%	100%
(1-rf)	Probability of not failing	90%	0%	100%

Table 4-2. Comparison between new and old variable names

Description	Before	After
Initial cost Method A (Don't Stabilize)	A	A
Initial cost Method B	B	B
Initial cost Method C	E	C
Cost of Not Failure A	D	T
Cost of Not Failure B	D	U
Cost of Not Failure C	D	V
Cost of Failure A	C	X
Cost of Cost of	C	Y
Cost of Failure C	C	Z
Chance failure A	pf	P
Chance failure B	qf	Q
Chance failure C	rf	R
Chance no failure A	(1-pf)	(1-P)
Chance no failure B	(1-qf)	(1-Q)
Chance no failure C	(1-rf)	(1-R)

4.3.1.1 Variable Values

The values of the variable to be assigned for probabilities were difficult to obtain from the literature. The difficulty was associated with the understanding of what is considered failure in engineering. According to the United States Army Corps of Engineers (USACE), failure may be a catastrophic or non catastrophic event. While a non catastrophic event may only require repair or maintenance to assure the usability of structure, a catastrophic event may be a total loss. Both concepts were used to assign the values of failures in later models.

One approach to obtain values for the probability variables is the use a statistical analysis in which risk and uncertainty (reliability) theory are included. However this approach was avoided because it was considered beyond the objective of the modeling. According to soil behavior theory, the probability of failure of a slope is not a constant value; rather it varies with time (short or long term stability). Time factor was not included in the early models but was emulated to some extent in later models as will be discussed later. To simplify the work in the thesis, the probability values were always assumed.

In general the variables' lower and upper bounds shown in Table 4-1 defined a range in which the values were allowed to vary. In the case of the cost of stabilizing the slope (variable B), these bound values were obtained from ODOT's smallest and largest value for "repair cost" (ODOT, 2001). The base value considered for this variable was the calculated arithmetic average of ODOT's repair costs. The same considerations were applied to obtain the bounds and base value of the no failure cost (variable C); although

these values were obtained from the “24-hour delay” costs used for the site scoring in ODOT’s report.

The variable’s ranges were used to perform sensitivity analyses on the model to observe their influence in the identification of the preferred alternative. For example the “24-hour delay” from ODOT’s data was observed to fit a log-normal distribution rather than a normal distribution. Although similar in magnitude, values obtained from a log-normal distribution were also used to analyze the model.

4.3.1.2 Three-Branch Decision Tree Variables

Decision analysis showed that a two-branched decision tree was capable of modeling many scenarios in which two alternatives were applicable. However, considering that a decision maker would have more than two alternatives available, later tree models included a third alternative branch as shown in Figure 4-5. This third alternative branch with its two outcomes (sub-branches) justified incorporating new variables and justified renaming the variables of the two-branch tree shown in Table 4-1. The new alternatives variables along with the renamed variables are shown in Table 4-2. Alphabetic representation (notation) of the initial costs lettered A, B and C used for a better tracking of the variables. The methods’ names were also generalized as methods A, B and C. The variables used for the failure of the methods were X, Y and Z. These variables replaced the variable C used in the decision tree shown in Figure 4-1.

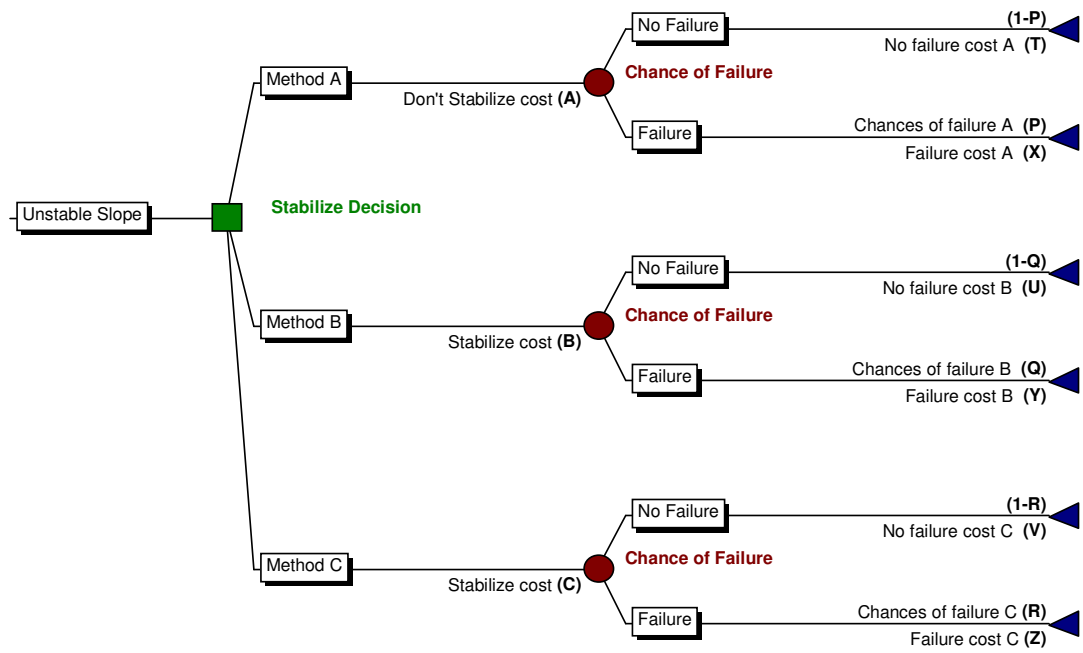


Figure 4-5. Three branch decision tree structure with revised variable names

Incorporating three alternatives for the cost of failure allowed assigning three different values of failure for each alternative. The alphabetic representation of no failure was T, U and V. Similar to X, Y and Z, these variables replaced the variable D. Finally the new representation for the probabilities of failure were P, Q and R. It was assumed in the thesis that the possibility of failure and the possibility of no failure would always add to unity. The increase in the number of variables available in the model did not restrict the decision maker to consider the same value among homologous variables.

The advantages of incorporating a third alternative (with the most expensive initial cost) are discussed later. However towards the third alternative was dropped to keep the model simple. Two alternatives allowed understanding the behavior of the decision tree model and development of charts or “rules-of-thumbs” to facilitate decision making by personnel in the field.

4.3.2 Decision Maker Input Spreadsheet

Variable values are different for every unstable slope site. For example, the cost of a stability method and/or the cost of failure (which include damages to the road structure, third party properties, etc.) will be different even between two slopes in the same area but located on opposite sides of a road. Furthermore, two slopes that have been stabilized with the same method may have a different probability of failure if exposed to different conditions such as loads and water content.

The large variability in variable values and costs suggest using a spreadsheet to assist decision tree users in establishing these values. During the thesis work, a spreadsheet form was developed to be used with Microsoft Excel®. The use of the spreadsheet requires a certain degree of project cost experience to input adequate values

for each alternative. For example, the items considered would be for example maintenance costs per year, slope reconstruction and damage costs of the road pavement and private property.

The user's spreadsheet was a tool made to assist users to establish decision tree variable values. The example spreadsheet displayed in Figure 4-6 shows tables with input and output values. The input values are mostly costs that are estimated by the users' experience and judgment. The output values are either calculated with the spreadsheet or are established from a database. The database values were obtained from the decision support systems described Chapter 2.

An example of the database value is shown in Table 4-3 in which the number of cars and trucks are pre-established according to the type of highway. These values were linked to the spreadsheet and could be updated by the user before using the spreadsheet.

Table 4-3. Average daily traffic values

	Highway type	Cars	Trucks
ADT	District	300	60
	Regional	800	160
	Statewide	8,000	1,600
	Interstate	15,000	3,000

Date: _____
 Location: _____
 Slope ID : _____

Highway type:

District	0
Regional	0
Statewide	0
Interstate	1

Assumed:

	Amount	(Delay cost)/hr	Passengers
ADT _{Cars}	15,000	15.46	1.35
ADT _{Trucks}	3,000	20.94	1.00

Stabilization Costs:

	Initial Cost	Chances of Failure %
Method A	100,000	50%
Method B	1,500,000	10%
Method C	3,000,000	5%

Maintenance:

	Maintenance
Method A	90,000
Method B	40,000
Method C	20,000

Outcomes (consequences):

	Reconstruction	Pavement	Properties	Structural	Total
Method A	500,000	250,000	150,000	150,000	1,050,000
Method B	200,000	150,000	70,000	70,000	490,000
Method C	100,000	100,000	50,000	50,000	300,000

Delay Costs:

	Delay days	% Roadway Closed	Delay Cost
Method A	7	25%	15,787,170
Method B	3	10%	2,706,372
Method C	1	5%	451,062

Figure 4-6. User's input and output spreadsheet

Towards the bottom of the spreadsheet, the user must input the remaining values needed to calculate the delay costs according to ODOT’s formula. These estimated values are associated with the number of days and the percentage of roadway interruption caused by a failure outcome.

The spreadsheet has two sets of outputs (tables) displayed towards the bottom. The first set totals the outcome costs and the second set totals the delay costs. These values and the user’s estimated values for initial costs and maintenance costs for each method are connected to the variable values of the decision tree model.

Table 4-4. Relationship between spreadsheet outputs and tree variables.

Tree Variables	Spreadsheet output	Comment
A B C	Stabilization initial cost	Estimated by user
T U V	Maintenance	Estimated by user
X Y Z	Outcomes + Delay costs	Calculated
P Q R	Chances of failure	Estimated by user

Some problems were observed when linking the spreadsheet to the tree model in accord to Table 4-4. For example delay cost values calculated with ODOT’s formula were too large even for reasonable input values. So, some changes were made. More realistic values for outcomes X, Y and Z were calculated by adding the outcome output of the spreadsheet (first set of outputs) plus the 10% of the delay cost output (second set of outputs). This change in the spreadsheet was justified by considering that the traffic delay

costs are not possible to be paid through a slope stability budget. In other words, there is no realistic link between the economic impact produced by a slope failure and the cost of the repair method.

Another problem observed was the availability of software for all users. The spreadsheet was prepared in Excel[®] and therefore accessible to most users, but the decision tree model software was not. The spreadsheet form had the potential of being improved by linking it to another budget type spreadsheet in which construction or repair costs could be estimated by items more accurately. Unfortunately tree modeling was considered less feasible. To operate and/or customize a tree model it was required to use particular software such as Palisade. This limitation suggested developing another decision model (in a spreadsheet) so that it could be more accessible to all users. The development of this model will be mentioned later in the thesis.

Finally, the most important assumption in the spreadsheet was that costs such as maintenance, stability methods, chances of failure, and outcome costs in general, were compared in an annual cycle. In other words, the tree model compared the costs between the alternatives considering that stability method was expected to fail in one year. This important assumption will be handled in a different tree model later in the thesis.

4.3.3 Time Value of Money Applied to Stability Costs

A decision maker could consider the costs of a stability alternative as an investment. One of the fundamental principles of investing is the time value of money. In general time value of money is an important concept in financial management where investment alternatives are to be compared in a time frame.

In the activity of programming projects, engineers apply the concept of time value of money to compare alternative projects. The value of the future dollar (i.e. promised benefits) is converted to an equivalent value today by decreasing its numerical representation by an annual interest. Present value of money can also be compared in the future by compensating the market depreciation of money with an annual interest. In the study the use of the concept time value of money was evaluated before being incorporated in the decision tree model, and is described in the following section.

If a decision tree would model future outcomes (maintenance, failure cost, etc.) for many years, these future costs would probably need to be numerically larger than present outcome values. For example, observing Table 4-5, if an annual maintenance cost of a thousand dollars (\$1,000) in present time is compounded at an annual interest rate of 4% during twenty years, the future cost would be \$2,191. However the intrinsic value of a “maintenance cost” today will be the same as the value of a “maintenance cost” in the future; it will not be more expensive to maintain a slope in the future although the numerical representation of this cost would increase from 1,000 to 2,191. In the same manner, a “slope failure” today will have the same value cost of a “slope failure” in the future although the numerical representation will increase.

Table 4-5. Example of the time value of money.

Input Data :

i = 0.04 (Interest/period)
 PV = 1,000 (Present value)

Output :

FVA = **30,969** (Future value / total cost)
 Years = 20

	<u>PV</u>	<u>FV</u>	<u>Time Lapse</u>
Period 1	1,000	1,040	1
Period 2	1,000	1,082	1
Period 3	1,000	1,125	1
Period 4	1,000	1,170	1
Period 5	1,000	1,217	1
Period 6	1,000	1,265	1
Period 7	1,000	1,316	1
Period 8	1,000	1,369	1
Period 9	1,000	1,423	1
Period 10	1,000	1,480	1
Period 11	1,000	1,539	1
Period 12	1,000	1,601	1
Period 13	1,000	1,665	1
Period 14	1,000	1,732	1
Period 15	1,000	1,801	1
Period 16	1,000	1,873	1
Period 17	1,000	1,948	1
Period 18	1,000	2,026	1
Period 19	1,000	2,107	1
Period 20	1,000	2,191	1
	20,000	30,969	20

The time value of money is a useful concept to evaluate alternative projects. In order to evaluate the use of the time value of money concept in the model it seemed appropriate to establish similarities and differences between choosing a stability method and choosing a project. Projects (investments) are chosen by comparing their net benefits (the accumulated benefits of many years minus the initial costs and minus maintenance costs). Considering that interest is an economical fact, the numerical benefit values and the initial cost must be compared somewhere in time (future or present) with the assistance of the time value of money concept. In the case of choosing a stability method, there are no monetary benefits involved. However, the maintenance cost could be considered as a negative benefit. In this case, its numerical representation would be increased or decreased (future or present value) by an interest rate and then added to the initial cost forming numerically increased total cost for each alternative. These total costs would be used to compare the stability alternatives as the net benefits are used to compare projects. Given the mentioned reasoning, the time value of money concept would seem to be necessary to compare stability decisions. However the following example shows that in some cases, the use of the time value of money concept is not necessary to choose a stability method.

An important assumption made to model time was to consider the occurrence of one slope event (outcome) per year. As before, the outcome events were either failure or no failure. In the case of the no failure outcome, the end node was replaced by a new chance node from which two possible outcomes could occur; to fail or to not fail. These new outcomes were assumed to occur in the second year. Further extensions from no failure outcomes could be added each representing a different year event.

A different extension was considered to emanate from a failure outcome branch. Considering that after a failure event there is a slope stability problem again, the end node was replaced by a new decision node from which the same two alternatives (stability methods) considered in the first year were available again. By connecting the outcome branches through chance or decision nodes with either fresh outcomes or decision alternatives respectively, the decision tree could increase the number of branches to conform a large tree representing several years.

A graphical display of the one and two year trees are shown in Figure 4-7 and Figure 4-8 respectively.

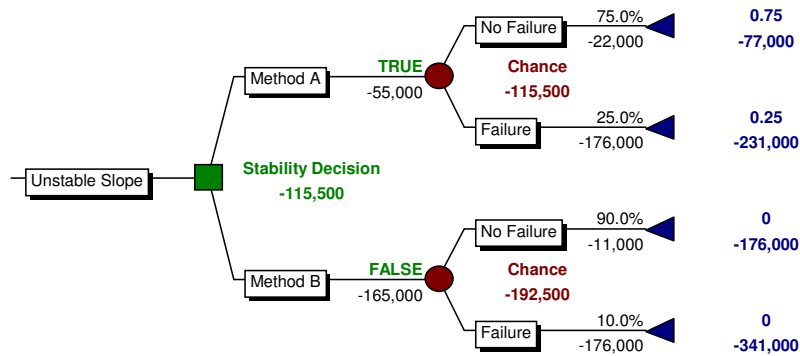


Figure 4-7. One year decision tree

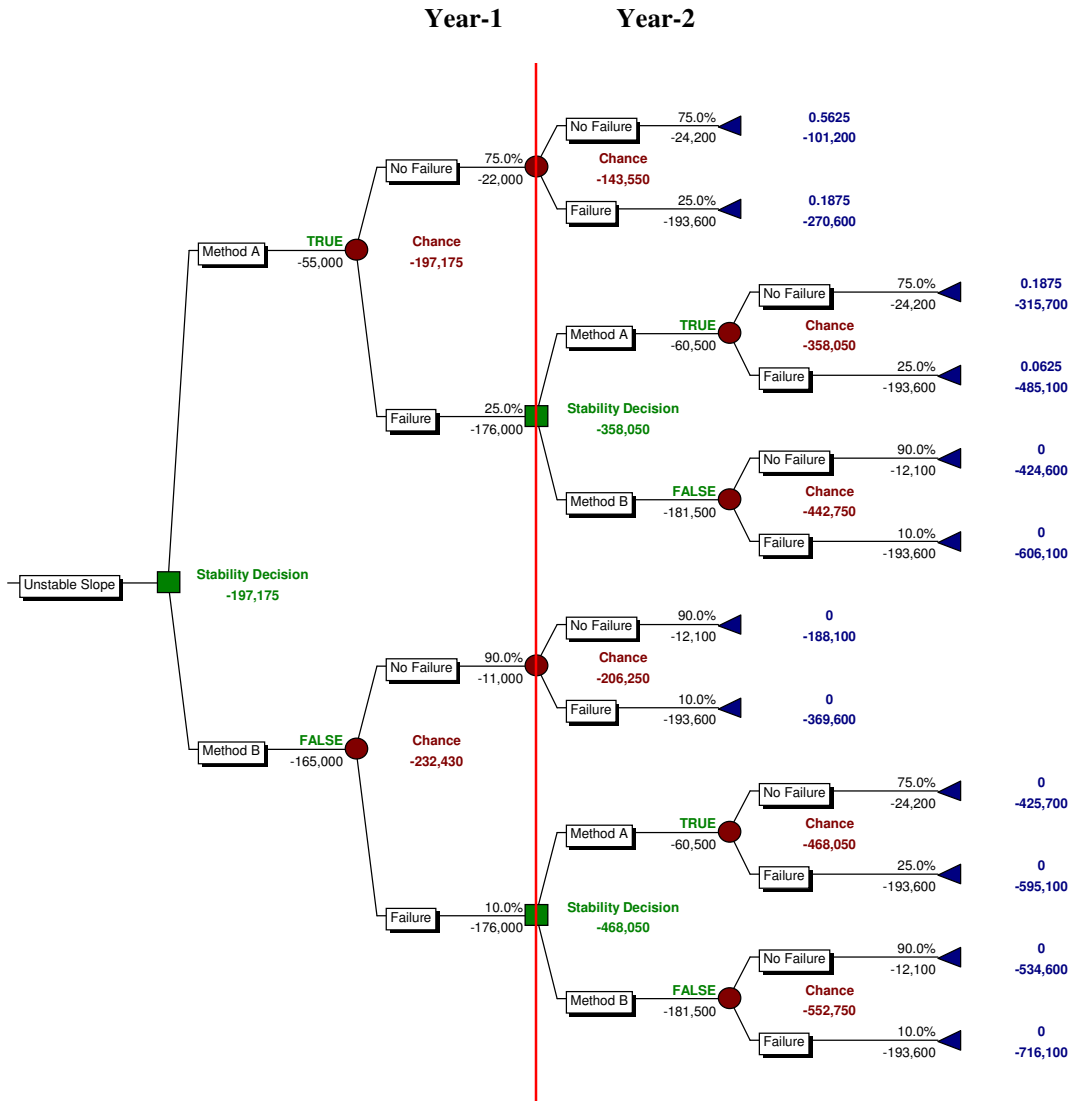


Figure 4-8. Two year decision tree model

Year-1 Year-2 Year-3

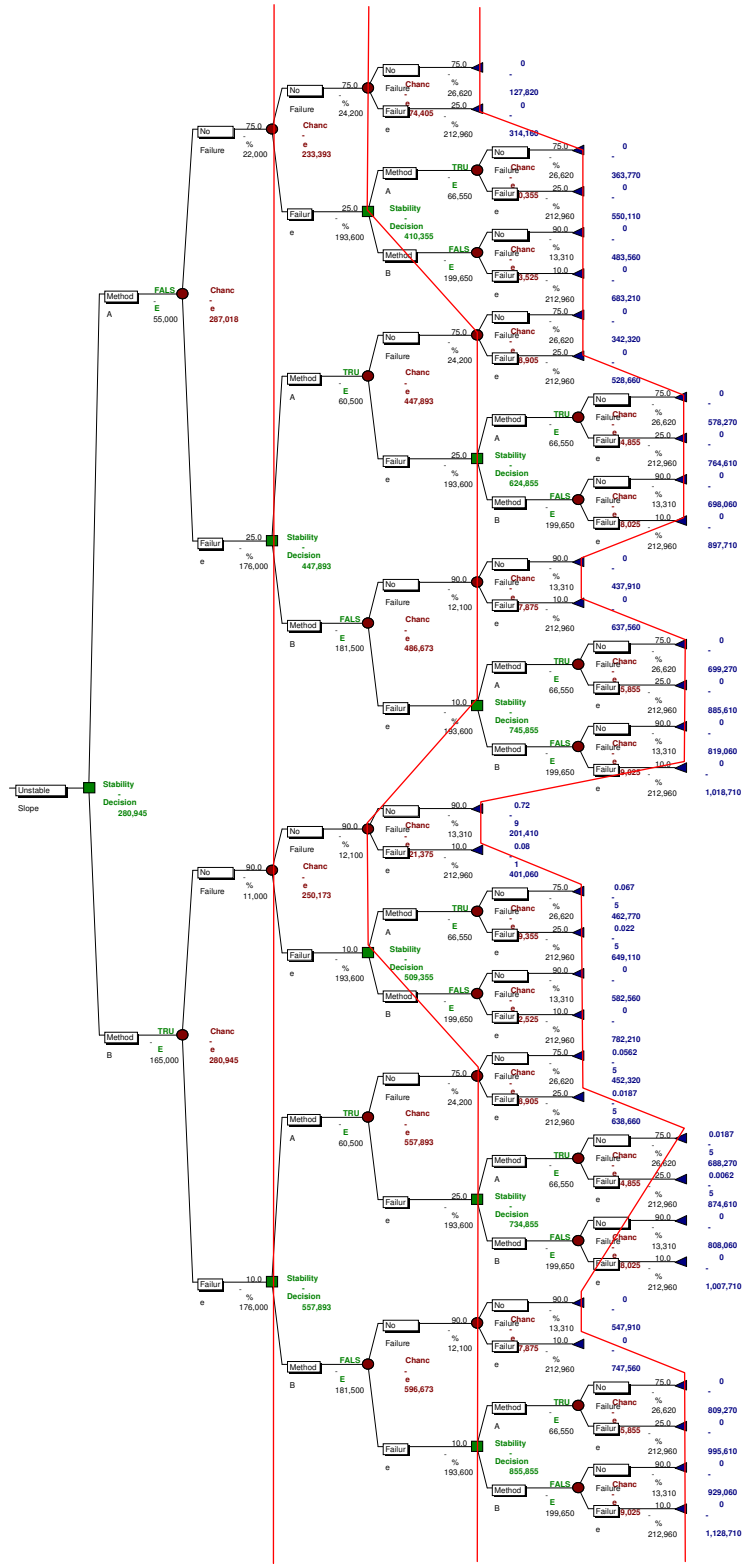


Figure 4-9. Three year decision tree model with two alternatives.

Extensions of the tree from the end nodes can be added on and on. Unfortunately, the decision tree grows bushy very fast. The decision tree model shown in Figure 4-9 shows a three year decision tree model with only two alternatives. In the thesis, five-year tree models were developed for 3 alternatives. In Figure 4-8 and in Figure 4-9, vertical lines were drawn for better observance of the year breaks.

Once the tree models were extended to include time, they were considered different trees. Although the one-year, two-year a three-year trees of the examples have the same alternatives and maybe the same variable values, they are different trees. Therefore the preferred alternative of a two-year tree may not be the preferred alternative of a three-year tree.

Considering the assumption of having one slope event per year, the years in a multiple year tree model were identified as the branches flowing from left to right between outcome events. Year zero or present time was considered as the moment when the initial cost decision was made. Table 4-6 shows the costs of alternatives A and B for one-year, two-year and three-year tree models. The zero-year column shows the value of the initial costs at a preset time. The values of the alternatives were calculated by using method and outcome costs that did not vary with time (constant costs).

Table 4-6. Cost of alternatives for different years (constant variable values).

	0	1	2	3
Method A	-50,000	-105,000	-172,500	-240,000
Method B	-150,000	-175,000	-208,000	-244,450

Table 4-7. Alternative costs for each year considering the time value of money concept.

	0	1	2	3
Method A (TMV)	-50,000	-115,500	-197,175	-287,018
Method B (TMV)	-150,000	-192,500	-232,430	-280,945

Similar to Table 4-6, Table 4-7 shows the costs of alternatives A and B for one-year, two-year and three-year tree models. However costs considered for the method and outcomes were not constant. They increased numerically 10% each year according to the time value of money approach. A summary of these numerical values are displayed in Table 4-8.

Table 4-8. Tree input variable values for the zero, one, two and three year models.

Variables	Description	0 yr	1st	2nd	3rd
A	Method A (Don't Stabilize)	50,000	55,000	60,500	66,550
B	Method B	150,000	165,000	181,500	199,650
X	Failure A	160,000	176,000	193,600	212,960
Y	Failure B	160,000	176,000	193,600	212,960
T	Not Failure A	20,000	22,000	24,200	26,620
U	Not Failure B	10,000	11,000	12,100	13,310
P	Failure chance A	25%	25%	25%	25%
Q	Failure chance B	10%	10%	10%	10%
(1-P)	Chance no failure A	75%	75%	75%	75%
(1-Q)	Chance no failure B	90%	90%	90%	90%

The values displayed in Table 4-6 and Table 4-7 are plotted in Figure 4-10 as continued and discontinued lines respectively. The continuous lines are associated with the results of applying the constant variable values in the time assumption in the tree models while the discontinuous lines are associated with the results of increasing the variable values with the time value of money concept. The lines represent the cost of each alternative (method) in time. Both sets start at the same value cost for zero years. As time

increases in the plot, the cost values of alternatives (Methods A and B) are more alike in both assumptions. At approximately three years the costs of Methods A and B are equal for both assumptions. If the plotted lines were to be extended beyond three years, the alternative Method B would be preferred for both assumptions.

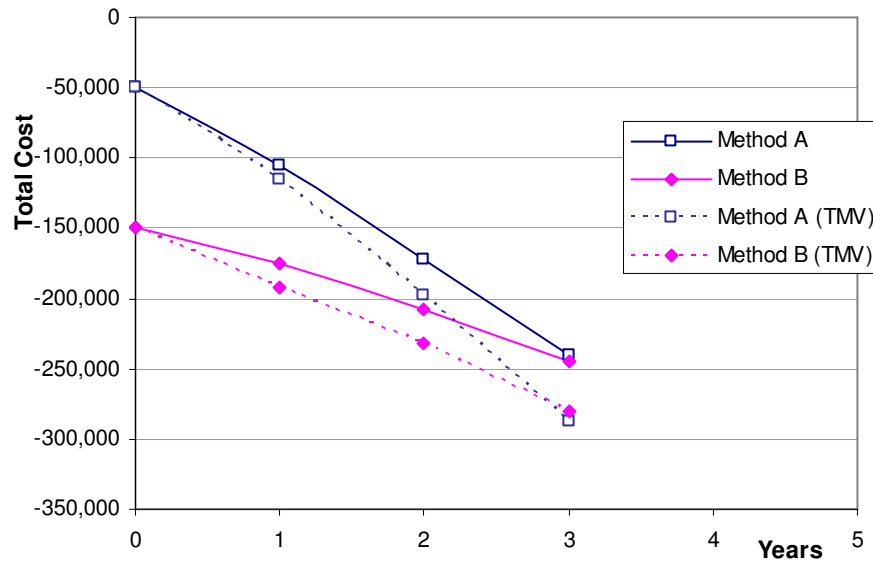


Figure 4-10. Comparison of alternative costs with and without the use of the Time Value of Money concept.

Table 4-8 shows that the cost of failure (variables X and Y) are the same for both methods (160,000). They were assumed to be the same considering that the cost of failure (structure, property, road damages and possible traffic delay costs) did not depend on the stability method. On the other hand, the costs of no failure (variables T and U) were not considered the same (20,000 and 10,000) because it was assumed that a more expensive stability method (larger initial cost) would require less maintenance cost.

Observing Figure 4-10, if the costs of failure would be assumed to be compensating the initial costs, then the interception of the alternative costs when considering the time value of money, would occur before the three year point. This information may distort the identification of the preferred alternative if the time interception is considered an important criterion in the identification of the preferred alternative.

It was assumed that the intrinsic cost of maintenance or the intrinsic cost of failure would not change with time. Therefore the intrinsic values used for these costs should not vary with time. In this sense, the time value of money concept may be omitted to identify the preferred alternative.

A difference between choosing a stability method and choosing a project is that when choosing a project, the money is available at the initial moment. The money needs to be invested in the project that may produce the largest benefits. In the case of the choosing of a stability method, the money for the entire investment is not totally available at the initial cost stage. According to annual budgets, the necessary amount of money for maintenance will be available later and will be the same in value regardless of its numerical representation in time. This may be another reason to not consider the time value of money as an important factor in choosing the preferred alternative. Furthermore, the time value of money concept was not used in the study for being considered as a refine factor that could be incorporated in the model after understanding its behavior. Furthermore, the time value of money concept was not used in the study for being considered as a refine factor that could be incorporated in the model after understanding its behavior.

4.4 Parametric Analysis Using Initial Models

According to Clemen (2001) decision analysis not only provides a structured way to think about decisions, but also more fundamentally provides a structure within which a decision maker can develop beliefs and feelings. Structuring and refining a decision model is an iterative process done in the decision-analysis cycle. A fundamental tool for the model development is the *sensitivity analysis*.

A sensitivity analysis illustrates how dependent the outcome of a model is to changes in one or more aspects of the model (i.e. model structure or variable values). If the sensitivity of a model to a variable is large enough to change the preference of a decision, then analysis helps to identify what matters and what does not matter. If a model is sensitive to a degree in which the preferred alternative will not continue being preferred, then the decision maker may want to reconsider more carefully those aspects in which the model is sensitive (Clemen 2001).

Once a model is developed, it is analyzed sensitively to identify its sensitive aspects. The identified aspects may be altered producing a new refined model. This model may again be analyzed sensitively producing another new model. This cycle, which could be repeated several times, is known as the *decision-analysis cycle*. According to Clemen, the ultimate objective of this cycle of modeling and analyzing is to arrive eventually a required decision model and to analyze it just enough to understand clearly which alternative should be chosen.

There are many sensitivity analysis procedures for decision analysis. In the following sections a few tools for performing sensitivity analysis will be presented.

4.4.1 One-Way Sensitivity Analysis

A one-way sensitivity analysis can be defined as an analysis performed to a decision model in which the impact of changing the value of one variable is observed. The objective of performing this analysis is to identify which variables are the ones that matters in a model. It is important to mention that the sensitivity of a model to a variable will also depend on the range of values of this variable. If the range of values of a variable to which the model is sensitive changes, then the model may no longer be sensitive to that variable. Identifying the variables and values to which the model is sensitive, may suggest to the decision maker to think more carefully about the uncertainty associated with the values of these variables.

The one-way sensitivity analysis procedure is simple and associated with the range of values (values between the lower and upper bounds) given to each variable. In the thesis, the analysis was done by keeping all the variable values of a model constant (base values), while the values of one variable varied throughout its given range. The tree output or expected value was recorded for each assumed input variable value during the analysis. This procedure was repeated for each variable. The variables that produced the largest changes in the model's expected value were identified as the sensitive or critical variables.

In the thesis, several one-way sensitivity analyses were performed to the early decision models. Using ODOT's report data to provide a range for the variables, the following are examples of a one-way sensitivity analysis performed to a three year decision tree model.

The three decision tree shown in Figure 4-11 was developed considering the variables and variable ranges shown in Table 4-9. The one-way sensitivity analysis was performed using the software DecisionTools from Palisade Corporation which is an Add-In for Microsoft[®] Excel[®]. For the base values considered in the example, the preferred alternative was Method A with an expected value of 1'205,487. The expected value of Method B was slightly larger than Method A's and the expected value of Method C was more than twice the expected value of Method A. In order to make Method C preferred, its variables values (cost values and chances of failure) had to be smaller. When performing the sensitivity analysis, the value of only one variable can be changed at a time. The other variables remain at their base values.

For example a sensitivity analysis was performed the variable probability of failure ($R=0.5$) of Method C. When the values of this variable was changed allowing it to vary only within the range shown in Table 4-9, ($R \in [0,1]$), the tree's preferred alternative did not change. Method A continues being the preferred alternative. Therefore the tree was not sensitive or not sensitive enough to the probability of failure of Method C.

The result of the one-way sensitivity analysis performed to the chance of failure of Method C (variable R) is illustrated in Figure 4-12. The horizontal line is interpreted as a constant output. While the variable R varies along its range in the abscissa axis, the expected value shown in the ordinate axis remains constant. The constant expected value of the tree (negative 1'205,487) continues being the expected value of the preferred alternative, Method A.

Table 4-9. Variable values considered in the one-way sensitivity analysis performed to a three branch decision tree. The variable values and ranges are based on ODOT's report

Variables	Description	Base Value	Lower Bound	Higher Bound
A	Method A (Don't Stabilize)	100,000	50,000	400,000
B	Method B	1,500,000	750,000	6,000,000
C	Method C	3,000,000	1,500,000	12,000,000
X	Failure A	2,628,717	1,314,359	10,514,868
Y	Failure B	760,637	380,319	3,042,549
Z	Failure C	345,106	172,553	1,380,425
T	Not Failure A	90,000	0	180,000
U	Not Failure B	40,000	0	80,000
V	Not Failure C	20,000	0	40,000
P	Chance failure A	40%	0%	100%
Q	Chance failure B	10%	0%	100%
R	Chance failure C	5%	0%	100%
(1-P)	Chance no failure A	60%	0%	100%
(1-Q)	Chance no failure B	90%	0%	100%
(1-R)	Chance no failure C	95%	0%	100%

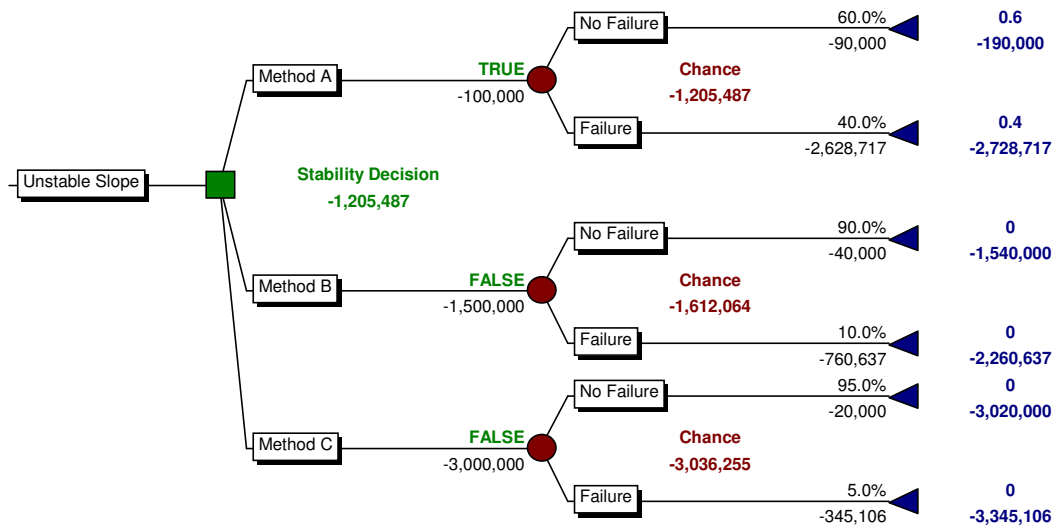


Figure 4-11. A three branch decision tree to which a one-way sensitivity analysis was performed.

The results of the one-way sensitivity analysis performed to the variable chance of failure of Method A (variable P) was found to be different than to Method C. Considering that Method A was the preferred alternative, the expected value of the tree was the same as the expected value of the alternative. Therefore changing the value of any variable of this alternative may change the expected value of the alternative and the expected value of the tree.

Figure 4-11 shows the base value of Method A's chance of failure (P) was set at 40% and that the range of the variable was $P \in [0, 1]$. Figure 4-13 shows a linear relation between the input variable chance of failure and the output variable tree expected value for chance values below 60% (approximately). For chance values above 60% the expected value was constant and equal to 1'612,064.

The shift of the linear function to a constant function showed that the tree expected value did not depend on Method A's chance of failure when its values were above 60%. For chances of failure larger than 60% Method A's expected value exceeded Method B's expected value (1'612,064). For this range, Method B was the preferred alternative.

As shown in Figure 4-13, the number of segments (10) that was considered to perform the sensitivity analysis did not allow precision to determine the exact probability of failure that switched the tree preference. Unfortunately there was a tradeoff between computing time and accuracy. As will be shown in a further section, the exact value can also be determined mathematically and not only graphically.

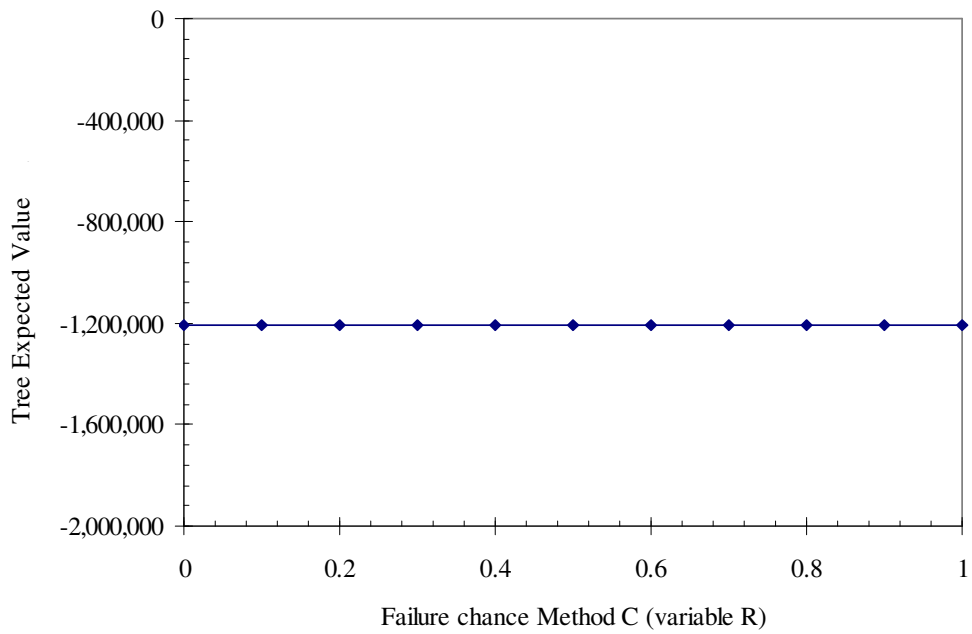


Figure 4-12. One-way sensitivity analysis on Method C's chances of failure.

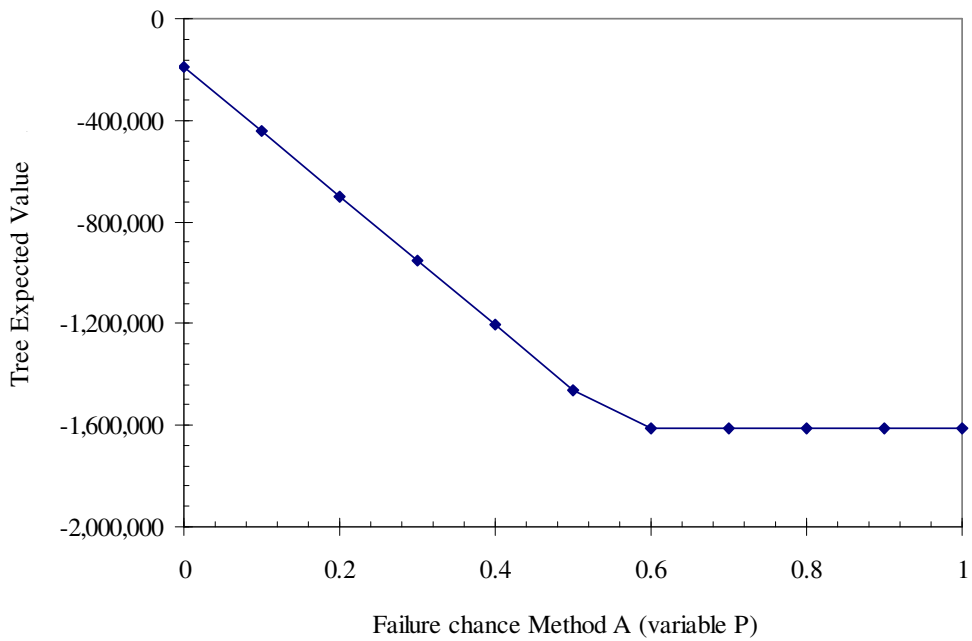


Figure 4-13. One-way sensitivity analysis on Method's A chances of failure.

Another one-way sensitivity analysis plot for the same decision tree example but for a different alternative is shown in Figure 4-14. The alternative analyzed was Method B and the variable was the initial cost or variable B. In the example, the base value of Method B's initial cost (variable B) was 1'500,000 and the lower and upper bound of the range were 750,000 and 6'000,000 respectively.

As mentioned, Method B was not the preferred alternative but its expected value (1'612,064) was not far from Method A's expected value (1'205,487). For Method B to be the preferred alternative, its partial costs (initial and failure) needed to be smaller or its probability of failure needed to be smaller. The variation of Method B's initial cost is plotted and shown in the abscissa-axis of the graph shown in Figure 4-14. These values were plotted negative because costs are considered negative values in the model. It was observed in Figure 4-14, that the tree's expected value was constant at 1'205,487 for values of initial cost B greater than 1'275,000 (B value was rounded considering the tolerance when setting the software). For initial cost values B smaller than 1'275,000 the tree's expected value decreases linearly with the initial cost of B. The switch from constant to linear was understood to be similar to the previous analysis. For initial costs B greater than 1'275,000, the expected value was 1'205,487 established by Method A's expected value. For initial costs B less than 1'275,000, the tree expected value decreased with Method B's expected value for being this alternative now the preferred alternative.

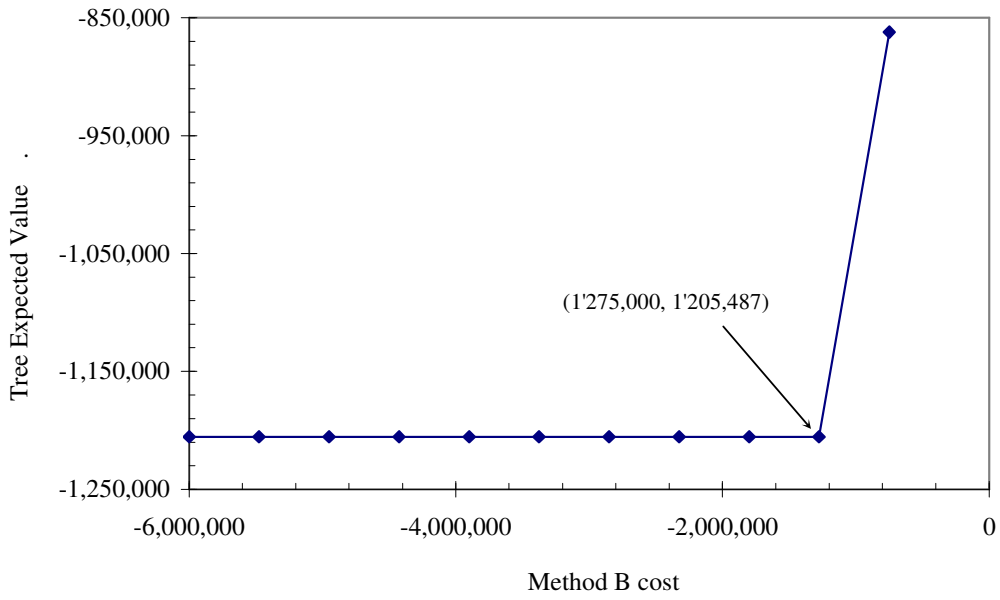


Figure 4-14. One-way sensitivity analysis on Method B's initial cost.

4.4.1.1 Tornado Diagrams

There is a variety of graphical sensitivity analysis techniques. One technique is known as the *tornado diagram*. According to Clemen (2001) tornado diagrams were presented and named by Howard (1988). Tornado diagrams allow comparison the impact of several different variables on the tree expected value simultaneously.

Figure 4-15 shows a tornado diagram that corresponds to the decision tree example shown in Figure 4-11. The lengths of the bars represent the degree of the model's sensitivity to the variables. Normally the graph layout locates the longest bar (most sensitive variable) at the top. However considering that the decision analysis is optimizing negative values, the plot layout shown in Figure 4-15 is inverted.

Tornado diagrams were used extensively in this thesis. The plots were used to confirm the one-way sensitivity analysis results and to visually observe and compare the degree of sensitivity of the model to all variables.

In tornado diagrams, the degree of sensitivity of a model to a variable is displayed in percentage. The bar values are the tree expected values for the upper and lower bounds of the variable range. For example, according to the plot shown in Figure 4-15, the bar that represented the Chance of Failure A extends between -84% and 33% which were the tree expected values when the value of the Chance of Failure A was assumed to be zero and unity respectively.

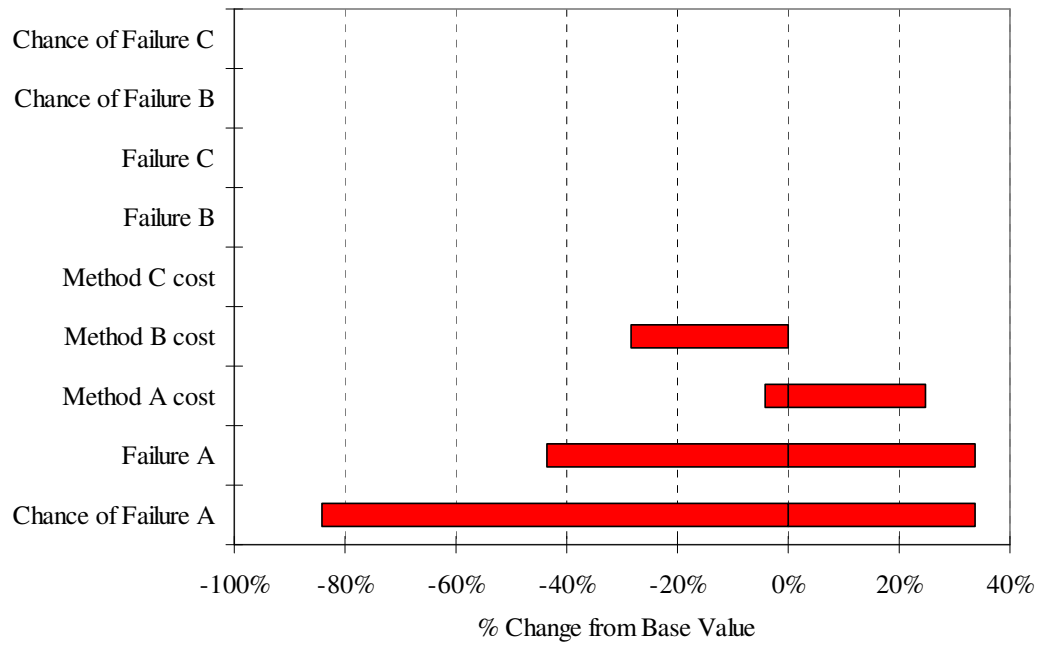


Figure 4-15. One-way sensitivity analysis tornado diagram.

The graphical results of the most sensitive variables were always confirmed analytically in the study. The expression to calculate the extreme values of a sensitive variable is displayed in Equation 4-1. In this equation, the term “*expected value at base*” is the original tree expected value or the tree expected value obtained when the variable analyzed is at its base value. The term “*expected value at new input*” is the tree’s expected value for the analyzed variable value which is different than its base value.

$$\text{Extreme value} = \frac{100 \times (\text{expected value at new input} - \text{expected value at base})}{\text{expected value at base}}$$

Equation 4-1

Figure 4-16 and Figure 4-17 show the tree’s expected value for chances of failure A different than its base value 40%. For a chance of failure of zero, Figure 4-16 shows a tree expected value of -190,000 and for a chance of failure of unity, Figure 4-17 shows a tree expected value of -1’612,064.

If the values -84.24% and 33.73% were to be confirmed, then the expected values at the new input and at the base value are to be inserted in **Error! Reference source not found.** as follows.

$$-0.8424 = \frac{100 \times (-190,000 + 1'205,487)}{-1'205,487}$$

and

$$-0.3373 = \frac{100 \times (-1'612,064 + 1'205,487)}{-1'205,487}$$

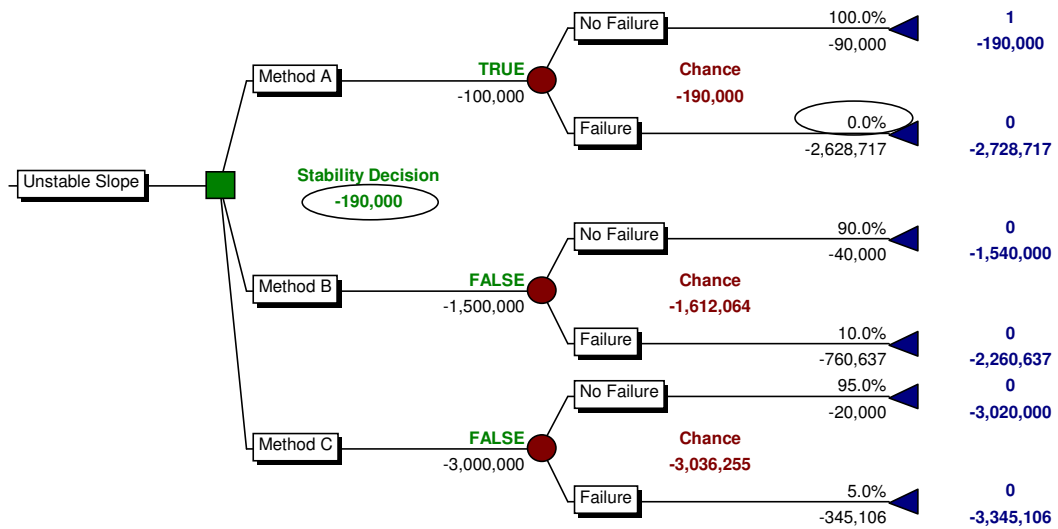


Figure 4-16. Decision analysis considering a 0.0% chance of failure of Method A.

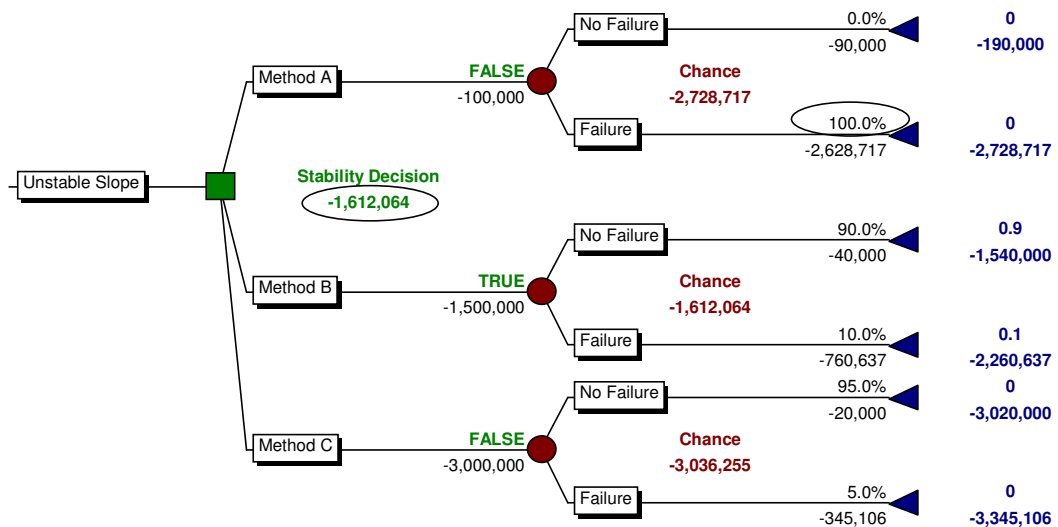


Figure 4-17. Decision analysis considering 100% chance of failure of Method A.

4.4.2 Two-Way Sensitivity Analysis

One-way sensitivity analysis layouts in general, provided considerable information about the influence of variable values in the model. Although tornado diagrams allow comparing the impact of several variables at once, they are limited to analyze the impact of the change in value of one variable at a time.

A *two-way sensitivity analysis* is a graphical technique that allows exploring the impact of more than one variable at a time. For example, it could allow analyzing the joint impact of the two most critical variables of the model as determined by the tornado diagram.

4.4.2.1 Volumetric or 3-D Graphs

The two-way sensitivity layouts are plots that show surface functions defined by three variables in a 3-D space (octant). By default, DecisionTools[®] software displays the tree expected value on the vertical axis leaving the other two horizontal axes to define the bottom plane of the octant.

All the two-way sensitivity analyses results that were performed in the study showed agreement with the one-way sensitivity analysis results. For example, the projection of the horizontal surface shown in Figure 4-18 to the wall of the octant or to the plane defined by the variables failure C and the expected value is a horizontal line. This line is similar to the line shown in Figure 4-12 between axes failure C and the expected value. Notice that in Figure 4-18, the surface function crosses the expected value at a constant value equal to 1'205,487 which is the same value in which the constant line of Figure 4-12 crosses this variable.

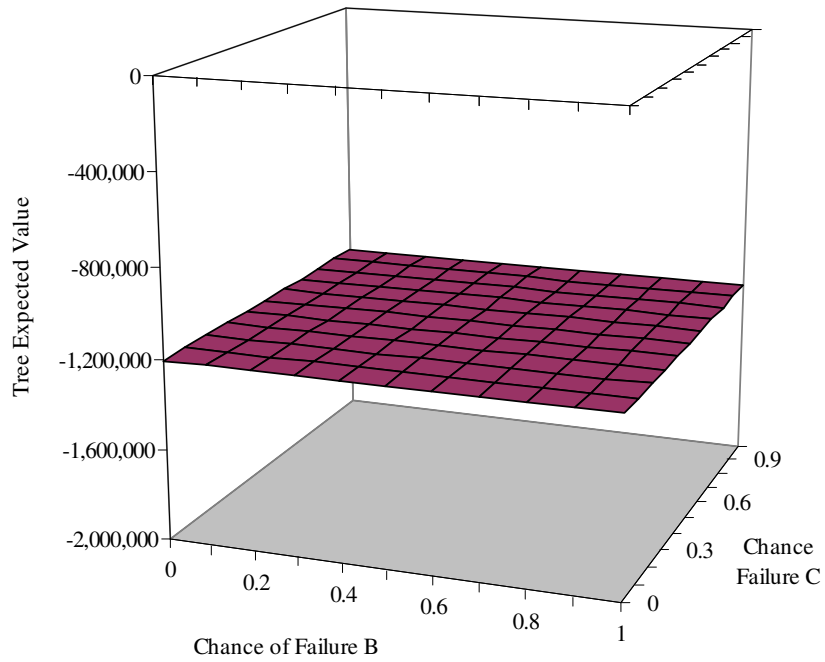


Figure 4-18. A two-way sensitivity analysis result. This is plot shows the 3-D image of the one-way sensitivity analysis result shown in Figure 4-12.

The one-way sensitivity analysis results displayed in Figure 4-13 shows a linear function adjacent to a constant function between variables failure A and the expected value. As mentioned before the inaccuracy to define an exact point of intersection between the two functions is due to the tolerance of the software settings. The corresponding results in a two-way sensitivity analysis are shown in Figure 4-19. In this figure, when failure A is equal to zero, the intersection of the surface function with the plane defined by failure C and the expected value is a horizontal line. In Figure 4-13, this horizontal line is projected as a point in the quadrant failure A versus expected value. In both quadrant and octant, the magnitude of the expected value is -190,000. Additionally, the horizontal surface of Figure 4-19 is projected in Figure 4-13 as a horizontal line. In both figures, the magnitude of the expected value is 1'612,064.

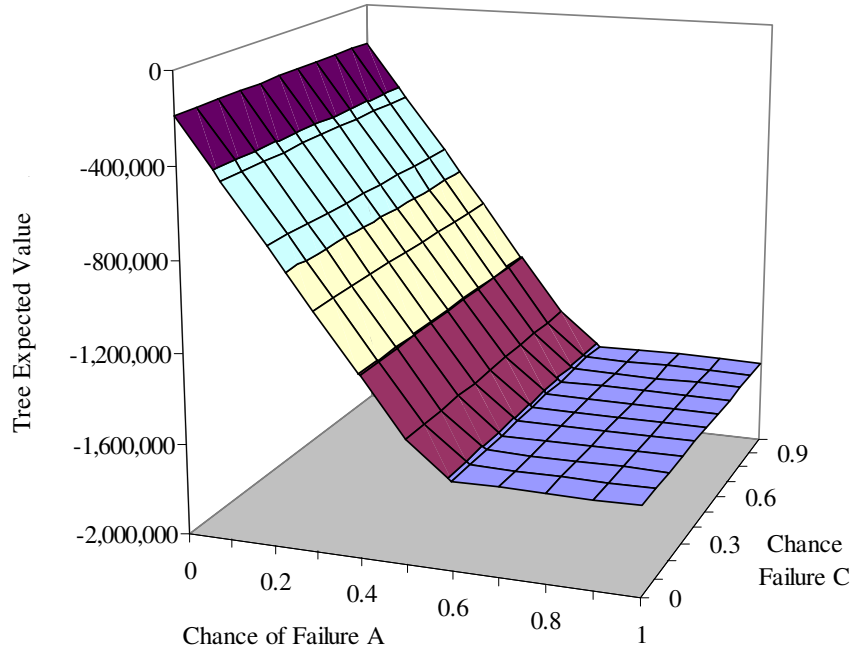


Figure 4-19. This is a two-way sensitivity analysis results related to the one-way sensitivity analysis result shown in Figure 4-13.

The understanding of how the 3-D plots were projected to 2-D planes was considered important in the thesis. For example, Figure 4-20 shows a 3-D space (octant) in which two surfaces P and Q intersect forming a line $m-n$. The three spatial axis of this particular octant could be defined by any three variables such as failure B, the expected value and any third variable from the model. According to Figure 4-20, depending on the variable chosen for the third axis and the sensitivity of the model to this variable, the intersection line $m-n$ may dip as the third variable increases its value.

If a vertical plane R parallel to the plane defined by axis failure B and axis expected value were to cut planes P and Q , it would define an intersection line (lines a-b and b-c) with each surface P and Q . The projection of these lines to the plane defined by axis failure B and axis expected value would be lines shown in the one-way sensitivity analysis results.

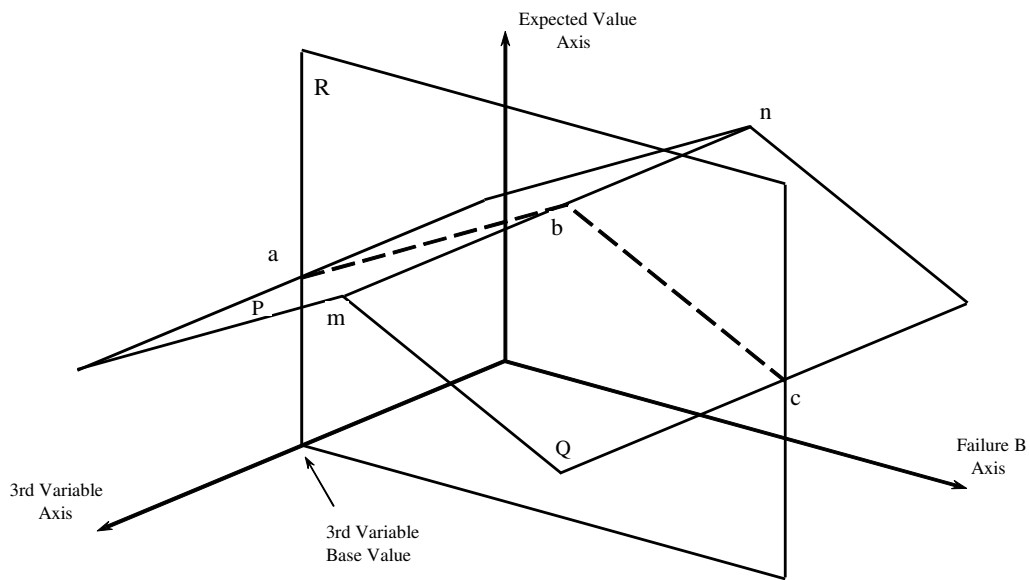


Figure 4-20. Plot that assist to conceptualize the two-way sensitivity analysis layouts.

Assuming that line $m-n$ may be dipping depending on the third variable value, the larger the value of the third variable in which plane R may cross, the smaller the magnitude of the projection of point b to the expected value axis. In a one-way sensitivity analysis, it is assumed that plane R crossed the third variable axis at its base value. When plane R crosses a third variable at any value different than its base value, the projection of lines a-b, b-c will shift in the Failure B versus Expected Value plane.

As an example, Figure 4-21 shows the two-way sensitivity analysis results between variables Method A, Method B and the tree expected value. If a plane parallel to Method B and expected value were to cut Method A's axis at its base value the projection of the intersection lines would be the same as the lines shown in Figure 4-14. However if the intersection plane cuts Method A's axis at a value different than the base value, the intersection lines would be shifted vertically.

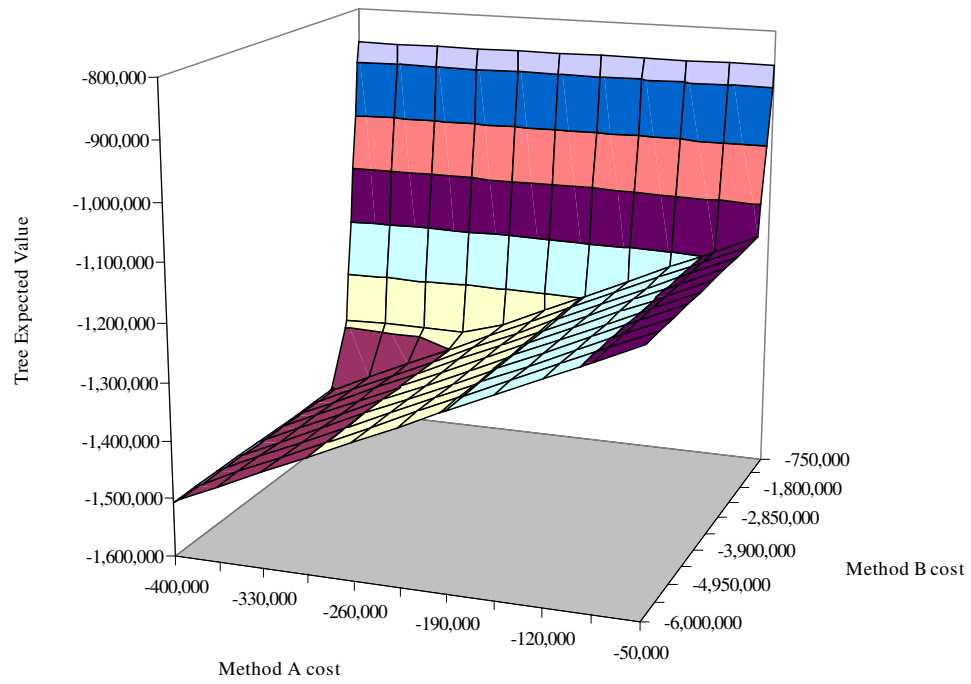


Figure 4-21. A two-way sensitivity analysis result showing the variation of functions defined by the expected value and Method B for different values of Method A costs.

4.4.2.2 Break-even Line Concepts

Two-way sensitivity analysis can also be used to develop the so-called *break-even* relations plots. Break-even plots show graphically the values required by two variables to make two decisions equal when fixing the values of the other variables to their base values.

Although break-even plots are developed applying two-way sensitivity analysis concepts, their layouts are 2-D plots. The most important components of the plots are the *break-even lines* which are lines that separate the 2-D space into regions in which a certain method is preferred over the others. As shown in Figure 4-22, depending on the values of the two variables that are chosen as axes, there will be regions of points in which a certain method is preferred.

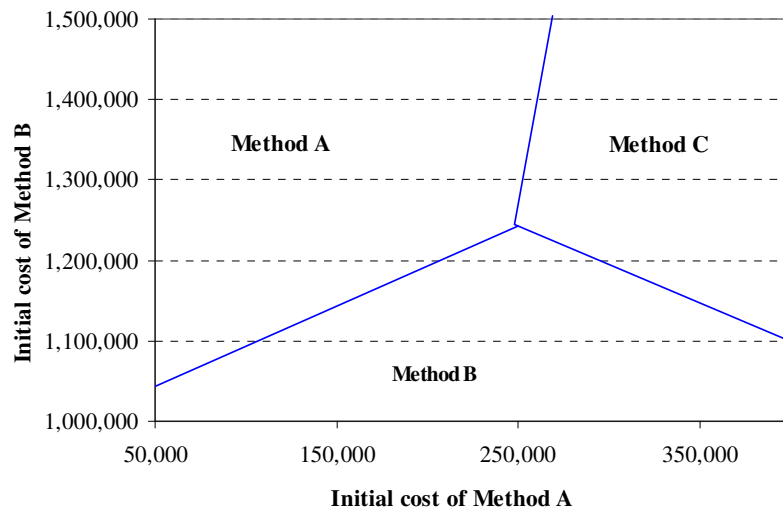


Figure 4-22. An example of a break-even line plot with three regions.

One of the applications of the break-even lines in the thesis was to identify the value range of a variable (such as initial cost) that made a method preferred. An example of an analysis performed in the study is shown in Figure 4-23. The plot shows a break-even line that separated all possible combinations of Method A and B initial costs (variable A and B) into two regions. In the plot, all point values above the break-even line made Method A preferred over Method B and all point values under the break-even line made Method B preferred.

In Figure 4-23, the three decision trees shown below the plot are the same tree shown in Figure 4-11. These trees were analyzed to identify the preferred method when considering initial costs values above and under the break-even line. As before, the preferred decision in each tree is identified with the label “True”. In this example, the initial cost of Method C was chosen to assure that this method was not preferred. However, if Method C’s initial cost were smaller or if the initial cost range of Method A and B would be extended in the plot, there would be a third region in which Method C would be the preferred decision as shown in Figure 4-22.

Points that fall on a break-even line or close to it make the methods’ expected values equal or very similar. In these cases, from a financial point of view, there is not much difference between choosing one decision or another. This is where a decision maker must apply subjective judgment to make the decision. The decision maker must consider for example that there is uncertainty involved with the values of some variables such as the possibility of failure, where there is a risk issue related to the chance of failure with time and there is a financial issue related to the money available at the moment and the accumulated maintenance cost.

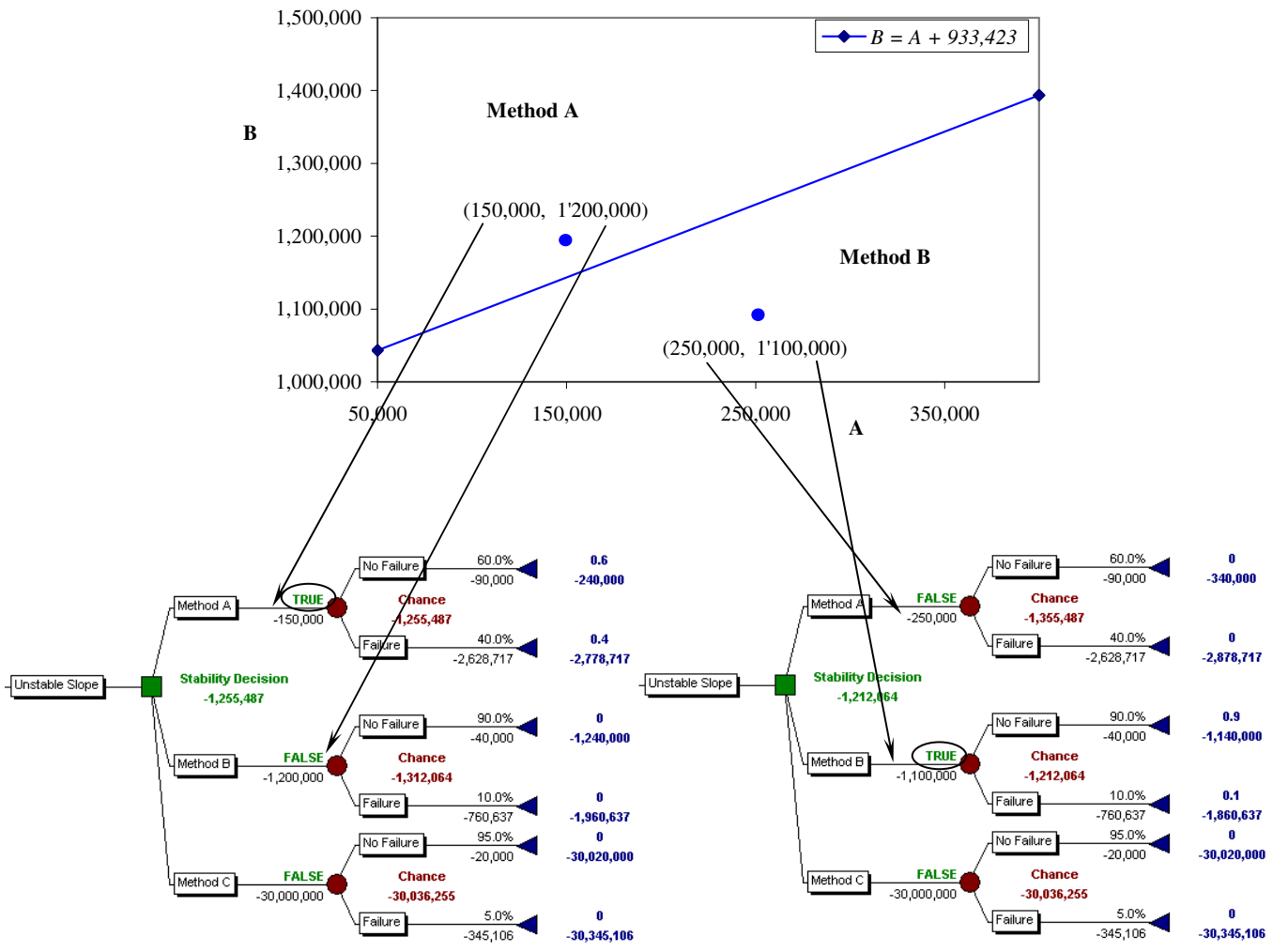


Figure 4-23. Coordinate pair's values of a break-even plot that makes one method preferred over the other.

4.5 Summary

Decision tree models used in the thesis and the analysis performed on them were described in this chapter. Geotechnical transportation infrastructure problems were modeled by trees that had two and three alternatives. Several examples were described in the chapter showing that the values of variables, such as the probability of failure, were recognized to be important in the identification of the preferred alternative. Considering that not all the variable values were available from the literature, a way of estimating them was described through the use of a spreadsheet form. However it was mentioned that the use of the spreadsheet still required a certain degree of project cost experience for adequate input values.

It was assumed that the intrinsic cost of maintenance or the intrinsic cost of failure would not change with time. In this sense, the time value of money concept was omitted to identify the preferred alternative. To model time, it was assumed that an outcome event would occur each year so by connecting the outcome branches to new outcomes or decision alternatives, the decision tree could represent several years.

Sensitivity analyses that allowed identifying the important variables were performed on several tree models. These analyses were described to help decision makers to think more carefully about the values assumed for sensitive variables. The chapter included description and examples of one and two-way sensitivity analyses. Sensitivity analysis allowed developing the so-called *break-even* relations plots which showed graphically the possible variation of the variable values within a preferred alternative.

CHAPTER 5 – APPLICATION OF DECISION TREES

5.1 Introduction

According to Clemen (2001), decision models are mathematical and graphical in nature. The mathematical representation of a model can be subjected to analysis to identify the preferred alternative and to identify the range of variable values that make a decision preferred over another.

In the present chapter, the mathematical representation of decisions will be shown. In this study, these representations allowed to develop break-even lines that graphically identified the variables' ranges that made decisions preferred. The variation of break-even lines and its behavior for different combinations of variables will be discussed in this chapter.

5.2 Break-even Line Equations

The break-even line between two variables can be defined as the geometrical locus of the points that make two decisions equal. The equation of a decision is that which defines its expected value. As mentioned in Chapter 2, the expected value of a stability decision is calculated by adding the initial cost to the outcome costs which are previously averaged according to their probabilities of occurrence.

The expected value expression shown in Equation 5-1 was developed considering the three branch decision tree structure shown in Figure 5-2 and the variable definitions shown in Table 5-1.

$$EV_A = A + (1 - P) \cdot T + P \cdot X$$

Equation 5-1

or

$$EV_A = (1 - P) \cdot (A + T) + P \cdot (A + X)$$

Equation 5-2

Although mathematically, the two alternative expressions for Equation 5-1 and Equation 5-2 are the same, the first option is straight forward in terms of the definition of expected values. The second alternative can be derived mathematically from the first alternative or can be obtained with the path values shown at the end nodes of the tree in Figure 5-2. As mentioned before the path values are the sum of the variables through the path. Therefore the expected value of a decision for a brief decision tree (one year) can also be calculated by weighting the path values of the decision according to the possibility of the path.

In a two-way sensitivity analysis, the points that define a break-even line are calculated by equating two expected value equations. In a one-way sensitivity analysis, equating two expected values equations allows obtaining graphically the break-point in which the preferred alternative ceases to be preferred. An example of a one-way sensitivity analysis breakeven point is shown in Figure 5-1. The limitation of software accuracy locates the break-even point between 55 and 60 percent chance of failure (the exact possibility of failure can be calculated with the expected value equation).

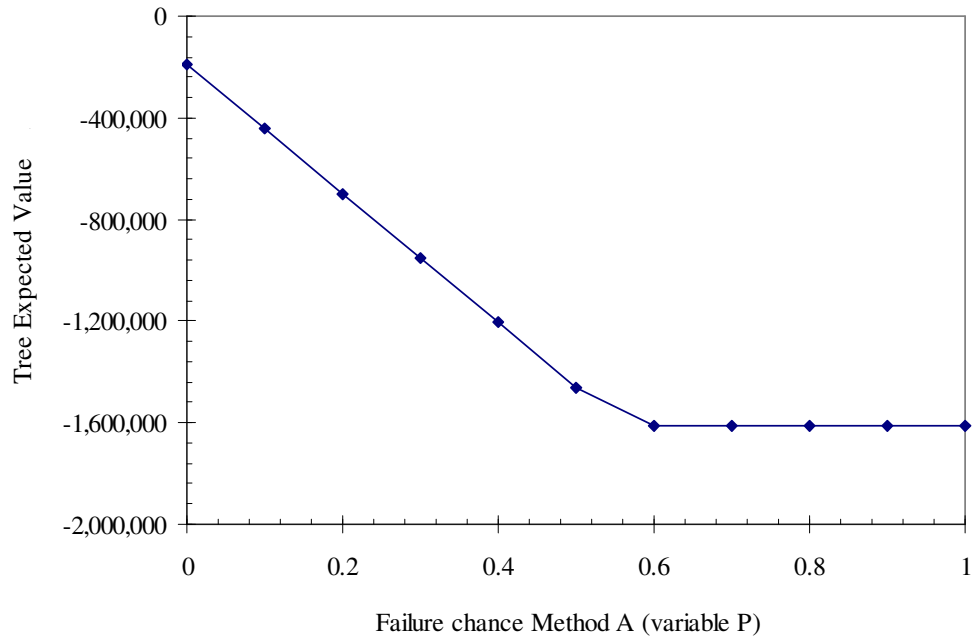


Figure 5-1. One-way sensitivity analysis on Method's A chance of failure.

As mentioned in the previous chapter, the tree's expected value is always the preferred alternative expected value. In the example shown in Figure 5-1, for probabilities of failure P below the break-even point, the expected value of the tree is dictated by the expected value of Method A. For large probabilities of failure P (pass the break-even point), the expected value of tree is dictated by the expected value of Method B which remains as a constant in the plot. In the study, the task was therefore to find the value of the possibility P that equaled the expected value of Method A with the expected value of Method B. Considering that the expected value of Method B is \$1'612,064, the calculations to find possibility P in the study were as follows.

$$EV_A = A + (1 - P) \cdot T + P \cdot X$$

$$1'612,064 = 100,000 + (1 - P) \cdot 90,000 + P \cdot 2'628,717$$

$$\therefore P = 0.56$$

Where according to Table 4-9, the base value of the other variables of Method A are:

$$A = \$100,000$$

$$T = \$90,000$$

$$X = \$2'628,717$$

Break-even points are dependent on one variable while break-even lines are dependent on two variables at a time. In both cases the values of the other variables normally remain fixed at their base values.

Although two-way sensitivity analysis, through break-even lines, revealed more information than the one-way sensitivity analysis, it was still limited to the variation of

only two variables and to the assumption of the values of the remaining variables. In this study, an option to avoid this limitation was to develop a family of break-even lines. This property of the break-even lines was possible due to the linear characteristic of the expected value equations.

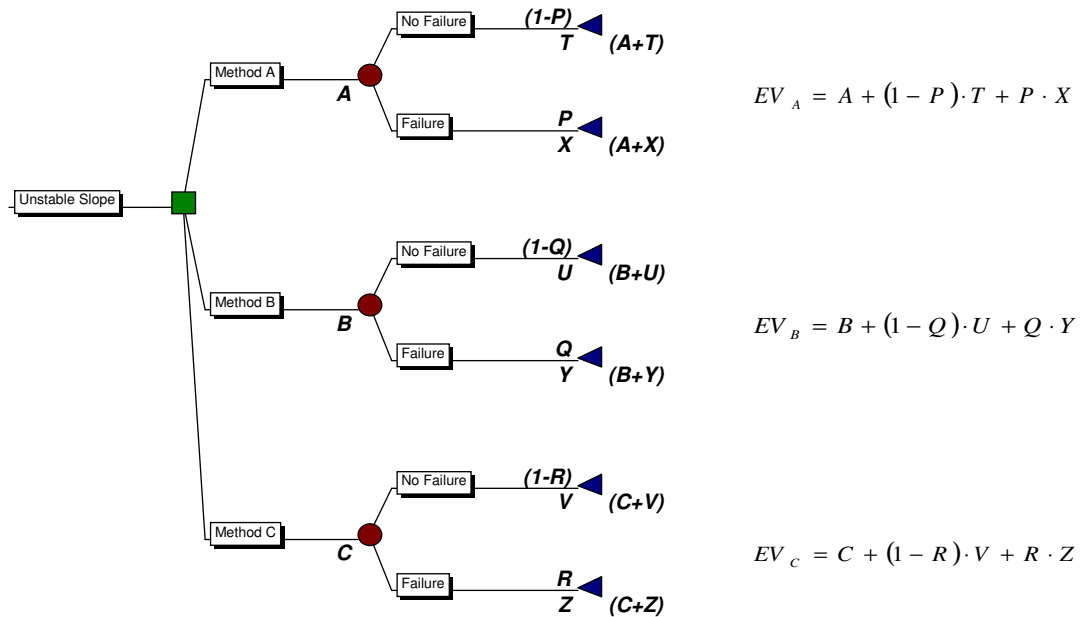


Figure 5-2. The path values and the expected values of a three-branch decision tree.

Table 5-1. Description of the variables of a three-branch decision tree.

Variables	Description
A	Method A (Don't Stabilize)
B	Method B
C	Method C
X	Failure A
Y	Failure B
Z	Failure C
T	Not Failure A
U	Not Failure B
V	Not Failure C
P	Failure chance A
Q	Failure chance B
R	Failure chance C
(1-P)	Chance no failure A
(1-Q)	Chance no failure B
(1-R)	Chance no failure C

An example of a break-even family could be developed from the basic slope repair decision tree shown in Figure 5-3. If the values of variables of failure (C), not failure (D) and probabilities of failure (p_f) were assumed to be \$75,000, \$0 and 20% respectively, then the break-even line found by equating both decisions' expected values would be:

$$B = A + (1 - p_f) \cdot D + p_f \cdot C$$

$$B = A + (0.80) \cdot 0 + 0.20 \cdot \$75,000$$

$$\therefore B = A + \$15,000$$

Equation 5-3

As shown in Equation 5-2, the relation between variables A and B is linear; therefore its graphical representation will be a straight line in a A versus B plot as shown in Figure 5-4. Two examples of break-even line family plots are shown in Figure 5-5 and

in Figure 5-6. While Figure 5-5 shows the shifting of the break-even line when varying the value of failure C, Figure 5-6 shows the shifting when varying the value of the possibility of failure p_f .

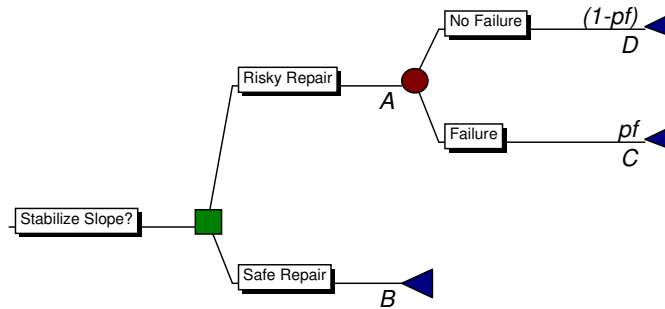


Figure 5-3. Example of a simple decision tree modeling the slope repair problem.

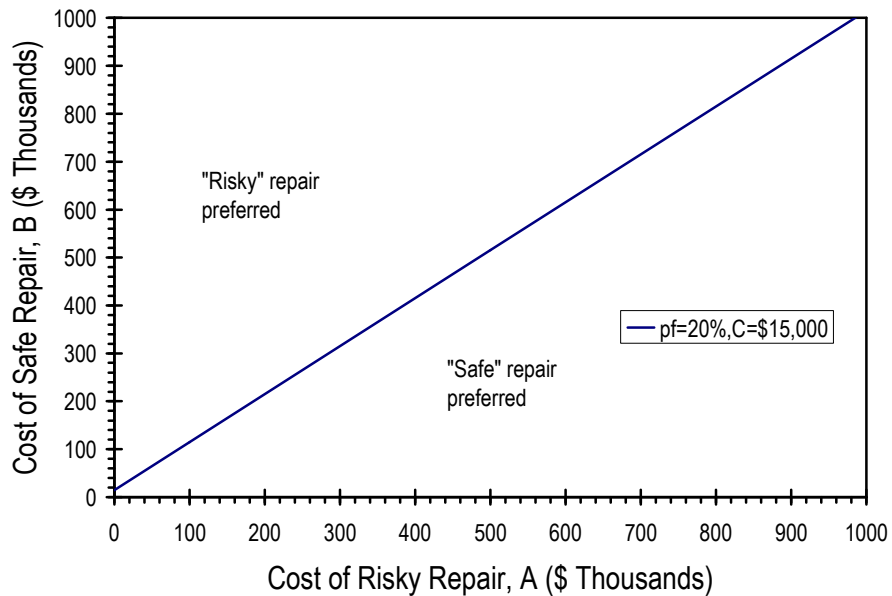


Figure 5-4. Break-even relation for simple decision tree of Figure 5-3 for $C=\$75,000$, $D=\$0$, and

$$p_f=20\%$$

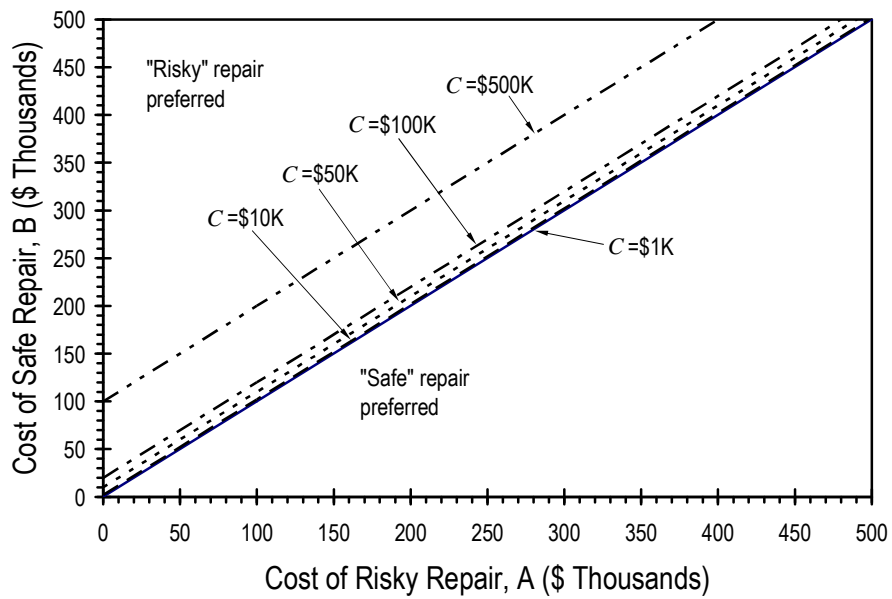


Figure 5-5. Family of break-even lines for different assumed values of C .

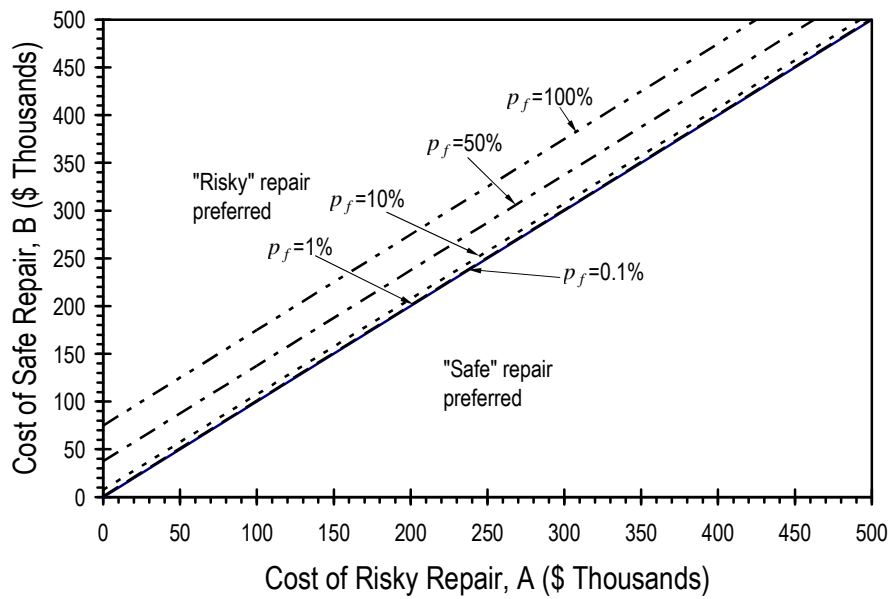


Figure 5-6. Family of break-even lines for different assumed values of p_f .

5.3 Decision Models for Slope Repair Problem

Several different decision tree models were developed and evaluated during the study. Differences among them were related with the number of decisions available, variable values and their representation (e.g. variable C was used to represent the cost of failure in the early models and was also used to represent the initial cost of Method C in later models), and the number of sub-branches. Of these models, two types were found to be best suited to model the slope repair problem. The first model referred in the study as “Single Point in Time” or SPIT model was used to represent alternative decisions without taking into account time. The second model referred as “Specific Time Horizon” or STH allowed modeling the possible change in decision preference with time. The specifics of both model types are described in more detail in the following sections.

5.3.1 Basic “Single Point in Time” Model

An example of a “Single Point in Time” or SPIT model is shown in Figure 5-7. In this model, the possibility of failure of Method A is denoted p_f and the possibility of failure of Method B is denoted r_f . The costs of no failure are denoted C and D respectively and they are assumed to be the same for both alternatives.

Although simple in aspect, the decision model shown in Figure 5-7 allows covering many stability situations by assigning the appropriate values to the decision variables. The model allows more than two alternatives to be analyzed by comparing two decisions at a time. In this sense, adding complexity to the model does not warrant more accurate results. In fact keeping the model simple may allow deriving expressions to develop break-even lines and to develop broad generalization (e.g. rules-of-thumb) as

shown in Figure 5-5 and Figure 5-6 that would assist field personnel in making effective decisions.

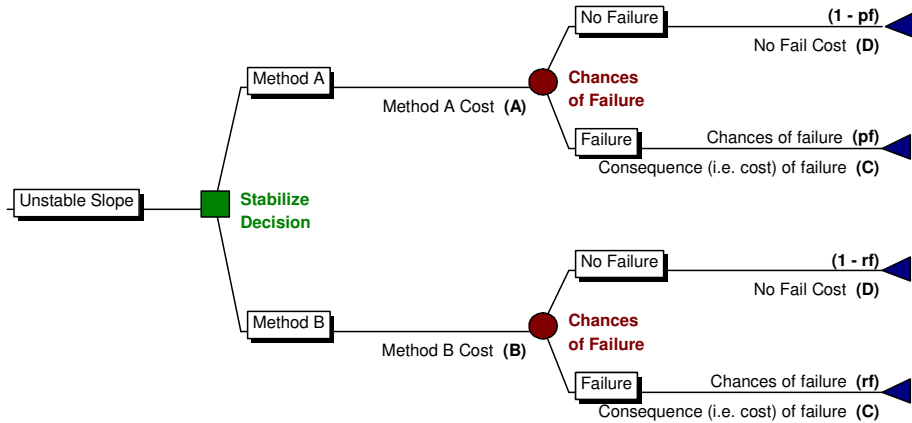


Figure 5-7. Basic “Single Point in Time” model representing the slope repair problem.

The break-even line equation for the tree shown in Figure 5-7 can be developed by equating the decisions’ expected values expressions.

$$EV_A = A + (1 - p_f) \cdot D + p_f \cdot C = (1 - p_f) \cdot (A + D) + p_f \cdot (A + C)$$

Equation 5-4

$$EV_B = B + (1 - r_f) \cdot D + r_f \cdot C = (1 - r_f) \cdot (B + D) + r_f \cdot (B + C)$$

Equation 5-5

Break-even lines for the decision tree shown in Figure 5-7 can be developed between any pair of variables by simply equating their expected values expressions. In

$$A + p_f C = B + r_f C$$

Equation 5-6

Rearranging and isolating variable p_f in terms of r_f leads to the following expression:

$$p_f = \frac{(B - A)}{C} + r_f$$

Equation 5-7

which allows calculating the probabilities of failure required to make the decision's expected values equal. According to this expression, the probabilities p_f and r_f are related through a linear function. This linear function has the form:

$$y = b + m \cdot x$$

where

$$y = p_f$$

$$b = (B - A) / C, \text{ which is the y-intercept of the function}$$

$$m = \text{slope of the linear function which is equal to unity, and}$$

$$x = r_f$$

As shown in Figure 5-8, the break-even lines develop with Equation 5-6 will divide an r_f versus p_f plot in an upper and bottom region. The value of the pair coordinates above the line will make Method B preferred, while values of the pair coordinates below the line will make Method A preferred.

Considering that the y-intercept of Equation 5-6 is related to the dimensionless ratio of the relative initial costs $(B-A)$ to the cost of failure C , several parallel lines can be developed when assuming different costs. Parallel lines, also known in the study as family lines are presented in Figure 5-8 for values of $(B-A)/C$ between 0 and 1 and probabilities of failure between 0 and 100%.

When the initial costs A and B of both alternative methods are the same, the y-intercept term $(B-A)/C=0.0$. In this case, Equation 5-6 is reduced to $p_f = r_f$ defining a 1:1 break-even line and simplifying the identification of the preferred alternative to the one with the smallest probability of failure (as intuitively obvious). When $(B-A)/C=1.0$, the initial cost of Method B is larger than Method A by a value equal to the cost of failure C . In this case Method A will be preferred regardless of the probabilities of failure p_f and r_f . This condition is represented by a point located at $p_f=1, r_f=0$ as shown in Figure 5-8. The convenience of Equation 5-7 is that between these two extremes, the preferred alternative will depend on the values of the probabilities of failure and the relative initial cost to failure cost ratio $(B-A)/C$.

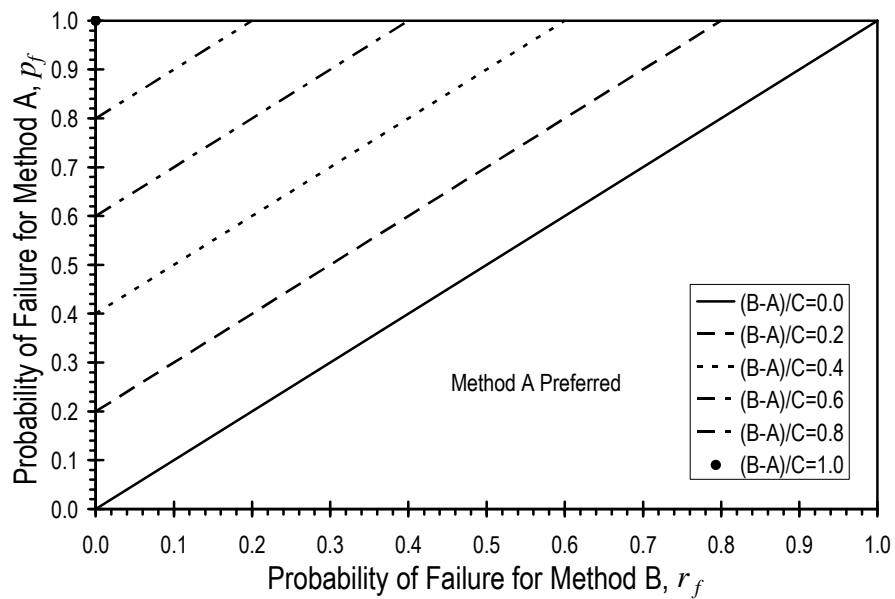


Figure 5-8. Break-even lines for Basic SPIT Model in terms of p_f and r_f .

From Equation 5-7 and Figure 5-8, it can be noticed that as the relative initial cost to failure ratio $(B-A)/C$ increases, the region of pair coordinates that make Method A preferred increases. This suggests that methods with low initial costs are preferred when the cost of failure is relatively small with respect to the initial cost.

Intuitively, it is expected that a method with low initial cost may have a large probability of failure. If this method would be chosen recurrently after failure, the accumulated cost in time of this method may exceed the cost of a more expensive method. To perform analysis to observe this case is a notable limitation to the SPIT model and one that needs to be addressed before the model can be implemented. Possible methods for addressing this limitation were presented subsequently in this study.

5.3.1.1 Break-even Relations for Basic Spit Model in Terms of B-A and C

As mentioned before, break-even relations can be arranged between any two variables of the Equation 5-6 in the basic SPIT model. One of the useful break-even relations is to develop break-even lines in a relative initial costs $(B-A)$ versus failure cost C space. Rearranging Equation 6 produces the following expression

$$(B - A) = (p_f - r_f) \cdot C$$

or

$$C = \frac{1}{(p_f - r_f)} \cdot (B - A)$$

Equation 5-8

Where according to the linear form

$$y = C$$

$$m = \frac{1}{(p_f - r_f)} \text{ slope of the break-even lines.}$$

$b = 0$, which is the y-intercept for all break-even lines, and

$$x = (B - A)$$

The break-even lines developed using this relation for a range in possible relative initial costs (B-A) and failure costs C are presented in Figure 5-9. In this figure, pair coordinate that fall above the break-even lines indicate that Method B is preferable while pair coordinates that fall below the break-even lines indicate that Method A is preferable. The extremes of the break-even lines occur for $(p_f - r_f) = 0.0$ and $(p_f - r_f) = 1.0$. As the term $(p_f - r_f)$ approaches the value zero, the slope of the break-even lines increases and approaches infinity which defines a vertical line that runs along the y-axis as shown in Figure 5-9. For $(p_f - r_f) = 1.0$, it is necessary that $p_f = 1.0$ and $r_f = 0.0$. In this case the break-even line will be a 1:1 line indicating that Method A is only preferable if the costs of failure C are less than the additional cost of selecting Method B over Method A. Break-even lines for intermediate values of $(p_f - r_f)$ fall between these two extreme slopes.

For a given set of input variables (A, B, C, p_f and r_f , with D assumed negligible), the break-even lines presented in both Figure 5-8 and Figure 5-9 will produce identical results and therefore can be used interchangeable. However Figure 5-8 can have a more general application though it covers a complete range of possible input variables while Figure 5-9 may be graphically restricted to some range of relative initial costs (B-A) and failure costs C.

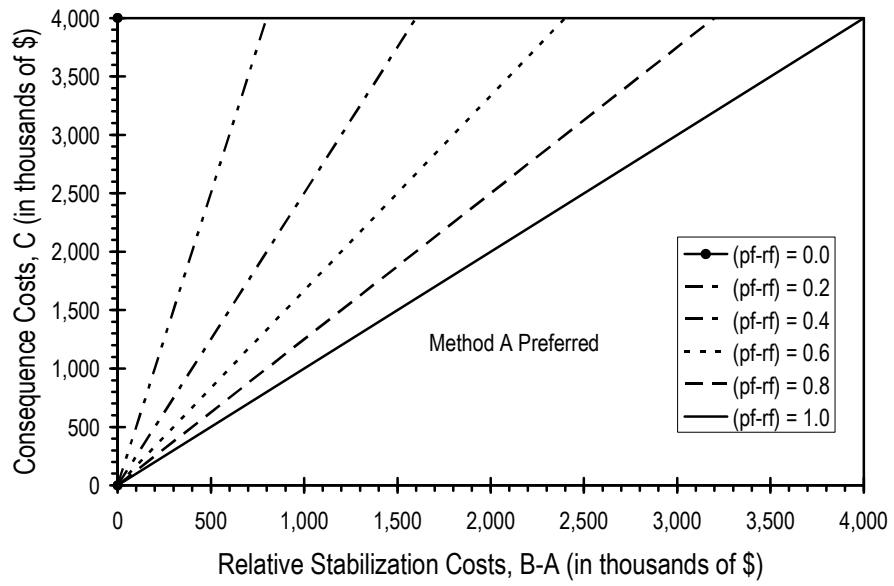


Figure 5-9. Break-even lines for Basic SPIT Model in terms of (B-A) and C.

5.3.1.2 Application of the Basic SPIT Model

For any value assumed for variables A, B, C, p_f and r_f , the application of the basic SPIT model is relatively straight forward. The preferred alternative is established by substituting the assumed values in Equation 5-6 or in Equation 5-7 to develop the break-even lines and compare graphically what values of the variables that configure Figure 5-8 and Figure 5-9 make one alternative preferred over the other. The following case study made with data from the Oregon Department of Transportation report shows the applicability of the basic model.

In this case study, the decision maker has to choose between stabilizing an unstable slope using a hypothetical risky stabilization technique assigned as Method A in the model or using a “tried and true” technique assigned as Method B. As considered before, the initial cost of Method A is assumed to be less expensive than Method B. In this case the initial cost of the risky Method A is assumed to be \$350,000, while the cost of the “tried and true” Method B is assumed to be the average cost of all stabilizations in ODOT database or \$589,794. While the probability of failure p_f of the risky method is assumed to be 30%, the probability of the tried and true method r_f is assumed to be zero to reflect the belief that the method is certain to stabilize the slope. According to the model, the cost of failure C is assumed to be the same for both methods and was taken to be the average of the 24-hour traffic delay costs for all cases in the ODOT database, or \$603.819.

Considering these variables, the ratio of the relative initial costs to the failure cost is found to be

$$\frac{(B - A)}{C} = \frac{(\$589,794 - \$350,000)}{\$603,819} = 0.4$$

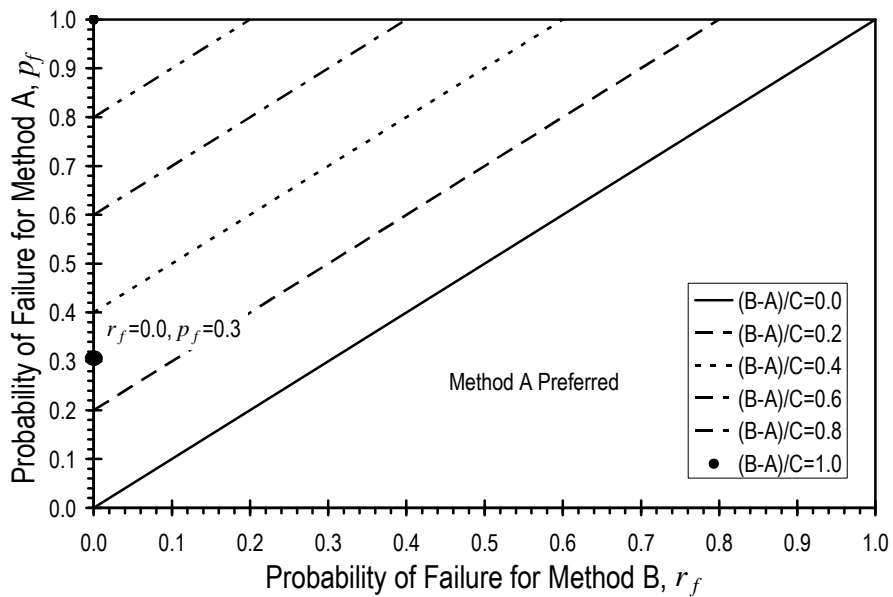


Figure 5-10. Application of basic SPIT model using input from ODOT database.

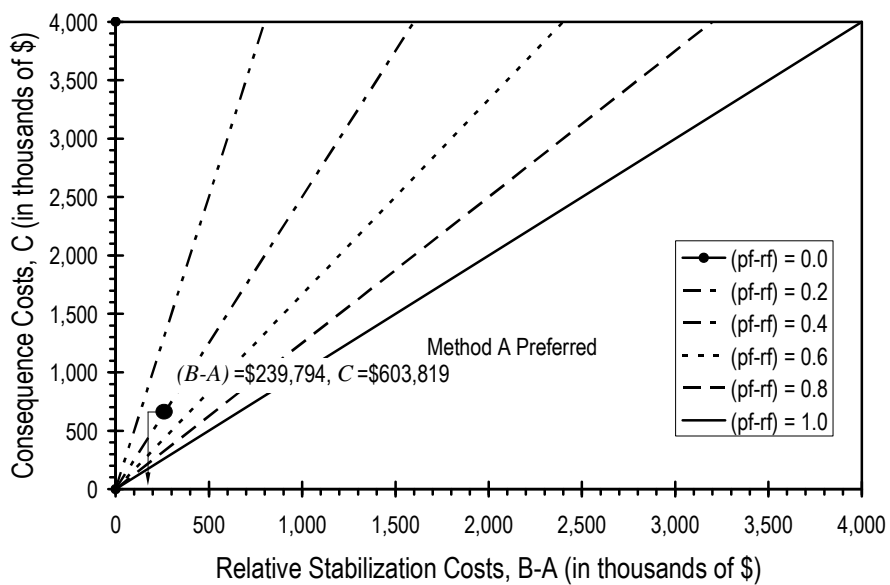


Figure 5-11. Application of basic SPIT model using input from ODOT database.

which is the y-intercept of one of the break-even lines plotted in Figure 5-8. Figure 5-10 shows that the probability point defined by the pair coordinates ($p_f = 0.3$ and $r_f = 0.0$) lies below the appropriate break-even line. This indicates that for these probabilities, the risky stabilization technique Method A is preferred.

According to Figure 5-10, the same decision would be preferred if the probability of failure of the risky Method A would be 40%. Considering that there is always a certain degree of uncertainty in the variable values, this information would give some comfort to the decision maker. If the values of the probabilities p_f and r_f would fall closer to the break-even line, the decision maker may consider a more rigorous evaluation of the parameters p_f and r_f instead of assuming values.

A similar calculation can be performed with the use of Figure 5-9 to establish the appropriate ranges of relative initial costs of stabilization. The results of this calculation would remain the same. In this case Figure 5-11 shows the appropriate pair coordinates point for $(B-A) = \$239,794$ and $C = \$603,819$. The break-even line for $(p_f - r_f) = 0.3$ lies between $(p_f - r_f) = 0.2$ and 0.4 . Notice in Figure 5-11 that the appropriate break-even line crosses the ordinate level $C = \$603,819$ at a point which abscissa $(B-A)$ is approximately $\$175,000$. This suggests that for $C = \$603,819$, Method A would continue being preferred for relative initial costs as low as $\$175,000$. Again this provides the decision maker important information regarding the need of additional refinement of the input variable values.

It is important to note that the identification of the preferred alternative with the SPIT model or any other model does not imply the success of the slope when played out in reality. The recommended decision is a merely a mathematical or statistical preference.

In this sense, after many applications, the costs of applying the recommended techniques will be less than the costs of applying alternative methods, which is beneficial from a broad, “organizational” perspective.

5.3.1.3 Limitation of the Basic SPIT Model

The SPIT model presented and analyzed in the examples had two primary assumptions. The first assumption was that the cost of no failure D was zero or negligible. This assumption made the calculations very easy, however considering that the cost of no failure may involve maintenance costs such as mowing, etc. its negligibility may not always be likely. In the case that this component may be significant, the basic SPIT model must be modified to incorporate such costs in addition to the initial costs and failure costs. These cases are believed to be relatively rare and therefore this limitation not believed to be significant.

The second and more significant limitation is associated with assumption of having both alternatives the same failure cost. This assumption limits the model to analyze the alternatives for a “one-time repair”. The model is not able to compare the costs of repeated repairs limiting the possibility of making decisions over some finite time horizon. The decision maker may not be able to compare the accumulated costs of frequent risky repairs with the accumulated costs of a more expensive but less frequent stability method. Therefore the SPIT model, as presented, needs to be modified to be able to consider the life-cycle costs of stability methods. The Specific Time Horizon, or STH model described in the next section presents an approach to compare life-cycle costs of stability methods. Although some modifications could have been incorporated to the SPIT model, they were not considered in this study.

5.3.2 Basic “Specific Time Horizon” Model

Although similar in logic to the SPIT model, the Specific Time Horizon, or STH decision tree model was developed to account for the possibility of having to apply a specific repair technique multiple times over a specific time horizon. The basic assumption, regardless of the stability method, is to consider year cycles in which a failure will occur and a stability decision is to be made each year. The justification of this assumption relies in considering that although it is possible for more than one failure to occur in a year, experience with nuisance slides suggests that having multiple failures per year at given site is rare. The assumption of having multiple failures per year can be incorporated in the model if considered important for the decision maker.

In this study, two variations of the STH model were developed and evaluated. Although both forms differ only slightly, their mathematical representation and their results were found to be different.

5.3.2.1 Three-method STH Model

The first form of the STH model is referred as the “Three Method STH” model, which can be used to simultaneously evaluate three alternatives of stability methods over a specified time horizon. Figure 5-12 shows a Three-Method STH decision tree model for a time horizon of two years. The root of the tree model is identical to the one-year tree model shown in Figure 5-2. The variables of the SPIT model were renamed or redefined to account for a third alternative. The definitions of these variables are shown in Table 5-1.

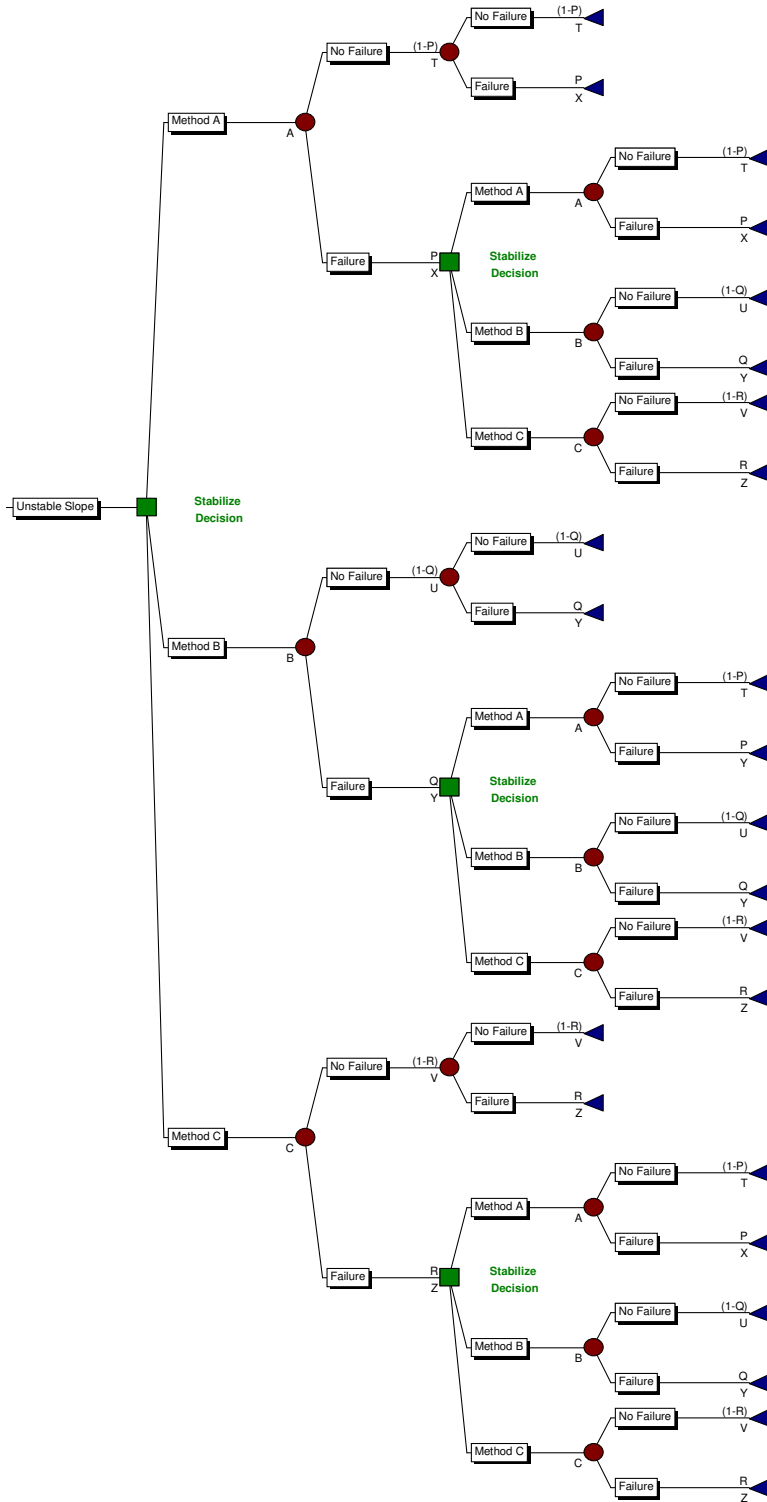


Figure 5-12. Three-method “Specific Time Horizon” model for two year time horizon.

Tree nodes flow from left to right, starting from the decision node “Unstable Slope” and continuing to the three alternatives Methods A, B and C. Each alternative is initially associated with a chance node from which two possible outcomes are presented as “No Failure” and “Failure”. At this level of the tree, the cycle of the first year is completed though, in a year, an unstable slope is assumed to either fail or not fail. In this model, the probability of failure for each method will now be an “annual” probability of failure since each chance node now represents the possibility of having a failure within the year.

The branches that emanate beyond the outcome end nodes of the first year will represent the events of the second year. In this second year level, depending on whether the outcome of the first year is a failure or not, additional decisions or/and chance nodes are added. In cases of no failure at the end of the first year, the model adds chance nodes and chance branches to model the possibility of failure or no failure in the second year. In cases where failure has occurred in the first year, the model adds a decision node from where the branches with the same alternatives available in the first year are again available in the second year. It is assumed that the decision maker will choose a stability decision that may or may not be the same chosen in the first year. The variable values are assumed to remain constant throughout the specified time horizon.

Additional levels can be added to the decision model to represent additional years within the time horizon of interest. However, as years are added to the tree, the number of branches grows geometrically fast. After five years the outcome branches are so numerous that they are difficult to keep track manually. The computational effort required to evaluate the model also increases as years are added. For a five-year event

tree, the computational time is on the order of 20 minutes when running Palisade's decision tree software. The dramatic increase in tree size limited the development of graphical modeling and analysis to time horizons of up to 5 years.

5.3.2.2 *Break-even Relations for Three-method STH Model in Terms of p_f and r_f*

The three-method STH model was developed to identify the lowest accumulated cost among three alternatives for an assumed time horizon. In the case of time horizons of many years, tree modeling was very laborious and calculations were long. One option to simplify these calculations during the study was to artificially increase the probability of failure of the third alternative so that in effect, the three-method model would become a "two-method" model. Doing this, break-even relations would be similar to those shown for the basic SPIT model shown in Figure 5-10 for time horizons of up to five years. Figure 5-13 shows the specific break even relations for a five year time horizon. The break-even lines of the figure were developed for relative initial costs to consequence ratios, $(B-A)/X$, of 0.1, 0.5 and 0.9 which were calculated considering $B = X = \$600,000$. During the study, the results obtained using different assumed values for B and X, evidenced that the break-even relations are not sensitive to the assumed values. However additional evaluation may be needed to confirm where these relations can be used for broad ranges in costs. In this case, it would be necessary to develop new sets of break-even relations that can be applied over different cost ranges.

The differences between the three-method STH model break-even lines and the basic SPIT model break-even lines are observed by comparing Figure 5-13 and Figure 5-10. The break-even lines for the three-method STH model are not parallel and do not increase proportionally with the increase of relative initial cost to consequence ratio.

Furthermore, the break-even lines determined for the three-method STH model are slightly non-linear. This non-linear behavior can be explained by observing the equation that defines the break-even lines of each model. Equation 5-3, Equation 5-4, Equation 5-5 and Equation 5-6 show that in the case of the basic SPIT model, its break-even lines are linear because they are developed by equating linear expressions. These linear expressions are the expected values of each alternative that is the summation of first order terms. By definition break-even lines are developed by equating the expected value of two alternatives therefore although the three-method STH model has three alternatives, the break-even line equations will be developed by equation only two alternatives at a time. Only the variables of the two alternatives will be involved in the break-even line equation and only the variables of the two alternatives will represent the plot axes. As years are added to the tree, probabilities of occurrence are added along each path. As observed in Equation 5-3 or Equation 5-4, when developing the expression of an expected value, the probabilities of occurrence (failure or not failure) are multiplying the values of the end nodes or the values of the paths. Doing this, the expected value is the weighted average, according to the probabilities of occurrence of each path, of the possible outcomes (failure or no failure). But when more years are added and therefore more probabilities are added along the paths, when folding back the branches to calculate the expected value, recent probabilities will multiply the later year probabilities. When this occurs, the equations to calculate the expected values will have terms in which the factor “probability of failure” will be in the same order as the number of years. Breakeven lines relations will therefore be exponential expressions and not linear as the SPIT models. The more years the tree has, the larger the order of the expression.

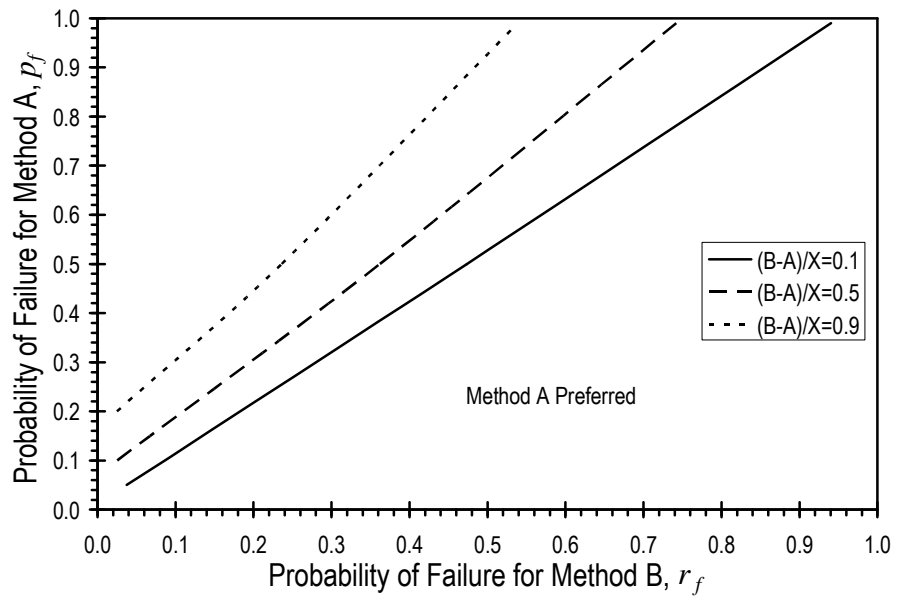


Figure 5-13. Break-even lines determined using the three-method STH model for a five year

time horizon with B-X=\$600,000

5.3.2.3 *Constant-method STH Model*

The constant-method STH model represents a simplification of the three-method STH model. The simplification of this model consists in assuming that the same alternative method will be adopted after every failure throughout the specified time horizon instead of permitting to choose a different method as modeled in the three-method STH models.

Results of evaluating several three-method STH models showed that the preferred path would have the tendency of considering the same stability alternative after each failure along the time horizon due to less accumulated cost. In this sense, it is believed that the constant-method STH model can serve as a reasonable approximation to the more rigorous three-method STH model. Unfortunately, in cases where the difference between the initial costs of two alternatives is small with respect to the accumulation of many years of consequence costs, this simplification may restrict somewhat the accuracy of the model.

Figure 5-14 shows one alternative of a constant-method STH model for a two year time horizon. Considering that all alternatives will have the same structure, the graph of this branch can be used to represent any alternative just by substituting the respective variables. In the case of the mathematical representation of this branch, the preferred alternative can be identified by comparing the expected value of the same equation structure with different variables and values. In fact the break-even relation can be established mathematically by identifying the values of the variables of interest that would make the difference between the equations of two alternatives equal to zero.

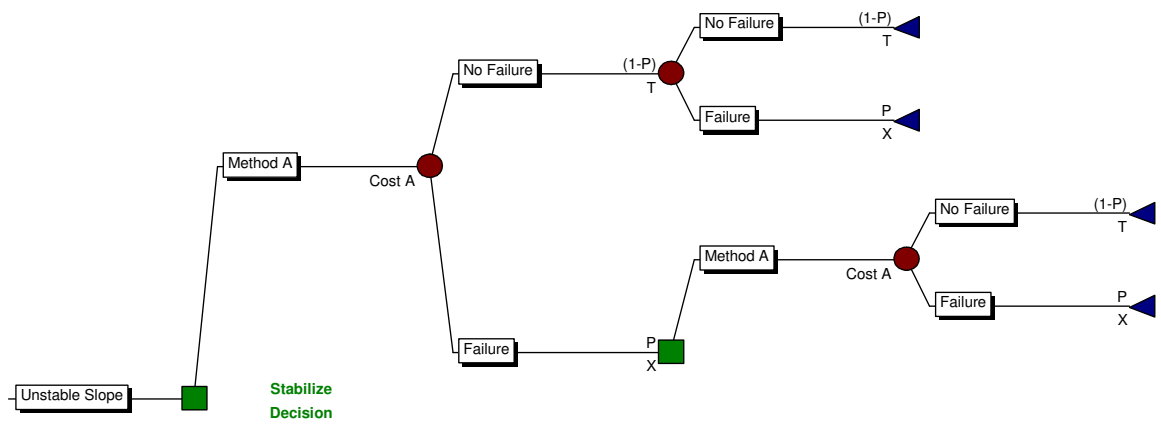


Figure 5-14. Method A branch of constant-method “Specific Time Horizon” model for two year time horizon.

An important advantage of the constant-method STH model is that adding additional year levels does not increase the size of the model as dramatically as the three-method STH model. This slower increase in model size reduces the computational effort required to analyze cases with large time horizons. But the most important advantage of the constant-method STH model is that this simplified form permits analytical algorithms that can be developed in Microsoft Excel® for time horizons over 20 years with little or reasonable effort. Algorithms for 20 years were developed and used during the study. For example the equation shown in Equation 5-9 for a five year tree to be prepared in a spreadsheet would be:

$$\sum_{j=0}^{j=1} P^{n-j} (1-P)^j [nA + jT + (n-j)X] + 4 \sum_{j=1}^{j=2} P^{n-j} (1-P)^j [(n-1)A + jT + (n-j)X] +$$

$$6 \sum_{j=2}^{j=3} P^{n-j} (P^{n-j} (1-P)^j [(n-2)A + jT + (n-j)X]) + 4 \sum_{j=2}^{j=3} P^{n-j} (1-P)^j [(n-3)A + jT + (n-j)X] +$$

$$\sum_{j=4}^{j=n} P^{n-j} (1-P)^j [(n-4)A + jT + (n-j)X]$$

Equation 5-9

where n is the number of years (in this case n=5), j is a counter and the remaining variables are described in Table 5-1. The mathematical model can be used to compare any number of possible stabilization models just by changing the branch variables.

5.3.2.4 Break-even Relations for Constant-method STH Model in Terms of P and R

Considering that the constant-method STH model is simple to express mathematically, break even relations were developed for time horizons of both 5 and 20 years. Figure 5-15 and Figure 5-16 show the break even relation for probability variables r_f and p_f and for 5 and 20 years, respectively. The computation of these relations were again made assuming that $B=X= \$600,000$ and therefore applicable to cases where costs are reasonably close to these values. However, according to preliminary evaluations performed to different values of B and X, break-even relations provide reasonable results over different input costs.

5.3.2.5 Comparison of Break-even Lines for Alternative STH Models

During this study, it was of interest to compare the break-even lines determined with STH models in order to observe the influence of the different assumptions. The graphical differences are shown in Figure 5-17 and in Figure 5-18. Break-even lines determined using the three-method and the constant-method STH models for a time horizon of 5 years are shown in Figure 5-17. Note that the break-even lines for the three-method STH model were determined assuming high costs for alternative Method C and therefore the model would in fact be representative of a “two-method” STH model. In the figure, the heavy lines are used to represent the break-even lines determined using the three-method STH model while the light lines are used to represent the break-even lines determined using the constant-method STH model. Dashed lines are used to differentiate the different relative cost to consequence ratios.

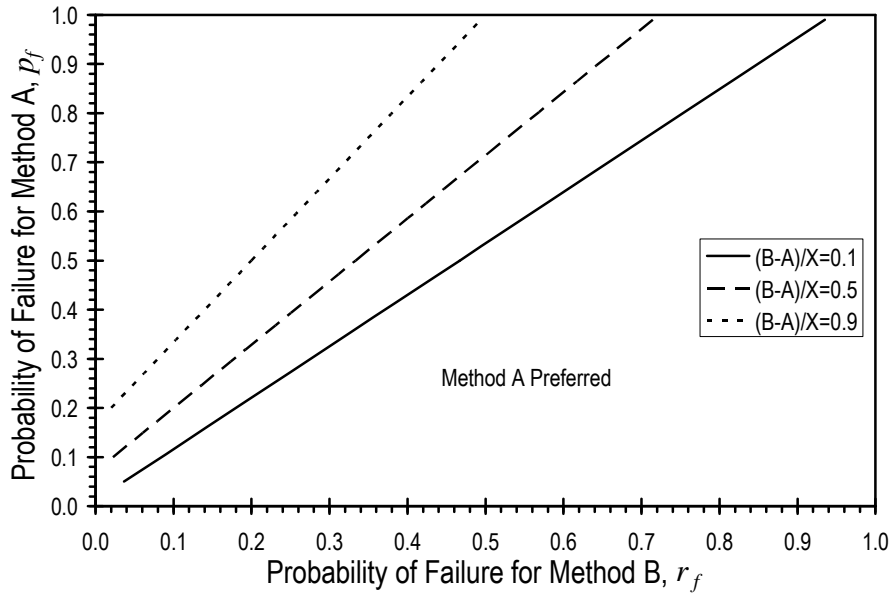


Figure 5-15. Break-even lines determined using the constant-method STH model for a five year time horizon with $B=X=\$600,00$.

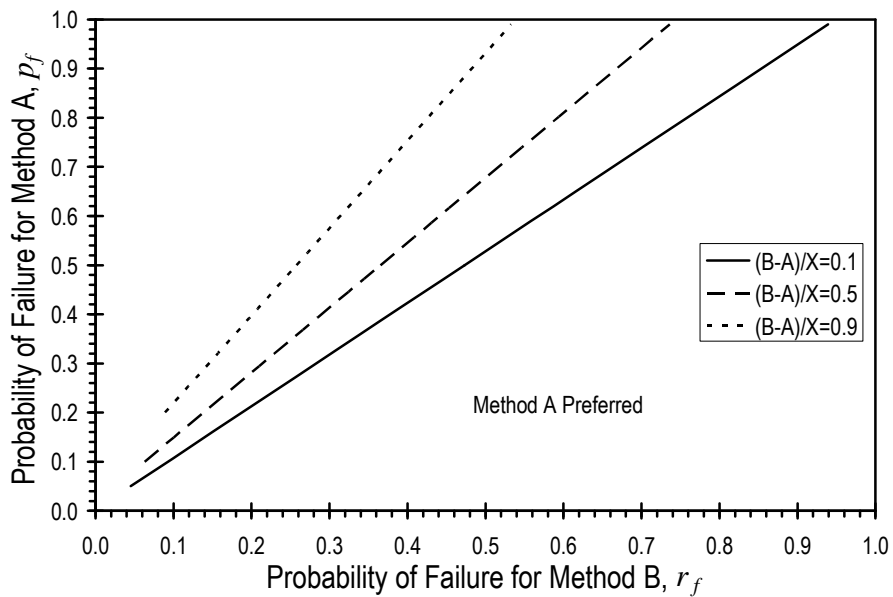


Figure 5-16. Break-even lines determined using the constant-method STH method for a twenty year time horizon with $B=X=\$600,000$.

According to Figure 5-17, the break-even lines determined with both models are very similar for low values of relative cost to consequence ratio. However as the ratio increases the difference between the break-even lines tend to increase. The break-even lines for the three-method STH model are consistently below those of the constant method probably indicating some preference towards Method A (smaller initial cost) for the constant-method model. This could also suggest that by switching alternatives during the specified time horizon, a lower total cost can be achieved. However considering the precision in input data, for practical purposes, the results determined using the three-method and constant method can be considered identical.

Figure 5-18 compares break-even lines determined using the constant-method STH model for time horizons of 5 and 20 years . The heavy lines in this figure are used to represent the 20 year time horizon while light lines are used to represent the time horizon of 5 years. The dashed lines are used to differentiate the relative cost to consequence ratios. For ratios values of 0.1, the break-even lines are similar. However as the ratio increases the break-even lines become less similar. Again as observed in Figure 5-17, when the consequence cost (X) is large with respect to the differences between the initial costs of the alternatives, the assumptions considered of each method seems to be less important. The slope of the line also seems to defer for the two time horizon. For low probabilities of failure, the break-even lines are relatively different. As the probability of failure increases for both methods, the break-even lines get closer. These differences in break-even line slopes increase as time horizon increases. It is also noted that the break-even lines for a 20 year time horizon are consistently lower than for

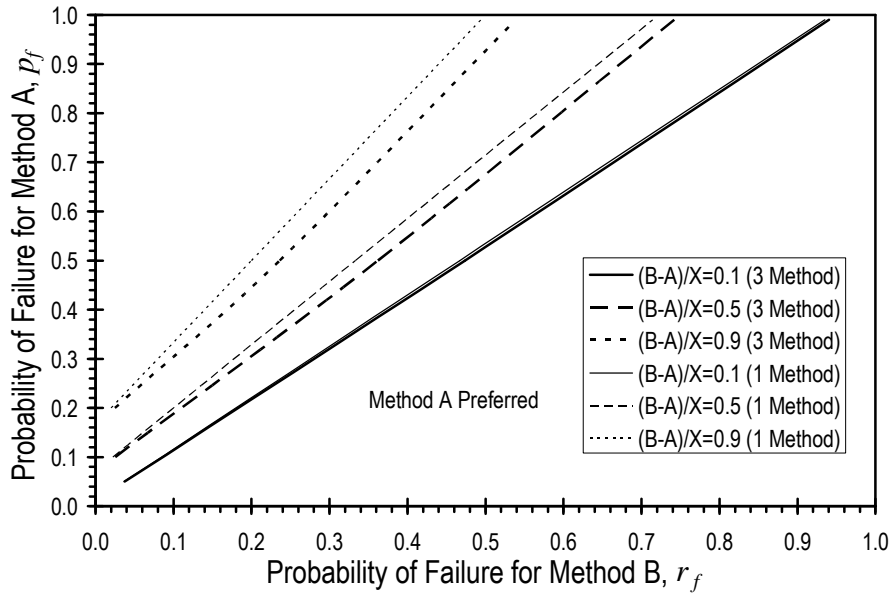


Figure 5-17. Comparison of break-even lines determined for a time horizon of 5 years using the three-method and constant-method STH models.

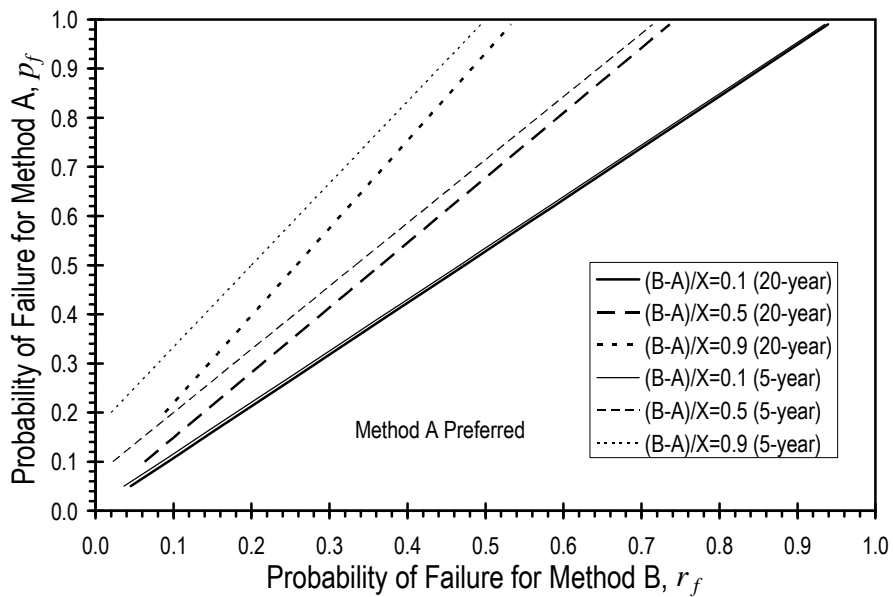


Figure 5-18. Comparison of break-even lines determined for time horizons of 5 and 20 years using the constant-method STH model.

those of 5 year time horizon. These observations suggest that the duration of the time horizon is important, particularly for small probabilities of failure. They also suggest that for short time horizon, there is some preference for alternative Method A (the less costly but more risky method), while for longer time horizons, more preference should be give for alternative Method B (more costly, less risky method).

5.3.2.6 Application of the STH Models

The application of the STH models is simple and relatively straightforward. Variable values are inputted to the numerical models which are implemented in Microsoft Excel[®] and commercially available “add ins”. Using these models give the decision maker the advantage of not needing to make further assumptions (other that those involved in the model) or interpolations. In this sense, the approaches require the availability of the numerical models and in some scenarios may require significant personal and computational effort. For cases where the decision is deemed critical involving significant cost the “direct application” approach and significant effort to determine the model variable values are recommended. For more common applications, the break-even graphs presented above or similar ones can be applied. The results (decisions) obtained using this approach are generally consistent (particularly with the precision that can be expected of the input parameters) with those obtained using the direct application. The advantage lies on the simplicity and quickness of the use of the graphs. To illustrate the application of the break-even graphs, two hypothetical examples are presented using the Oregon Department of Transportation database.

As an application of the SPIT model, the first example assumes the initial cost of the “risky” stabilization Method A to be \$350,000 while the initial cost of the “tired and true” stabilization Method B is again assumed to be the average cost of all stabilizations in the ODOT database, or \$589,794. The probability of failure for Method A (p_f) is assumed to be 30% while the probability of failure of Method B (r_f) is assumed to be zero since the method is considered to be a “certain” stabilization. The cost (consequence) of failure (X) is assumed to be equal for both alternatives and was taken from the average 24-hour traffic delay cost for all cases in the ODOT database, or \$603,819 (the SPIT model could have assumed the cost of failure to be different for both alternatives). Based on these values, the relative cost to consequence ratio $(B-A)/X$ is again equal to 0.4. To determine an appropriate decision, the break-even developed for $(B-A)/X$ equal to 0.5 would be a reasonable approximation.

Figure 5-19 shows the probability point $p_f=0.3$ and $r_f=0.0$ plotted in the constant-method STH model break-even graph previously shown as Figure 17. In Figure 5-19, the probability point is located above the break-even line that corresponds to $(B-A)/X=0.5$ for both 5 year and 20 year time horizons, indicating that for both time horizons, the “tired and true” Method B is preferred. This conclusion disagrees with the SPIT model example shown before where Method A was shown to be preferred. The difference lies on the more accurate accounting for the fact that multiple failures may occur if the risky stabilization method is implemented which in the long term increases the life-cycle cost of stabilization for the risky approach. Finally, the same conclusion would be drawn by considering a break-even line for $(B-A)/x=0.4$ or by using the break-even lines determined from the three-method STH model.

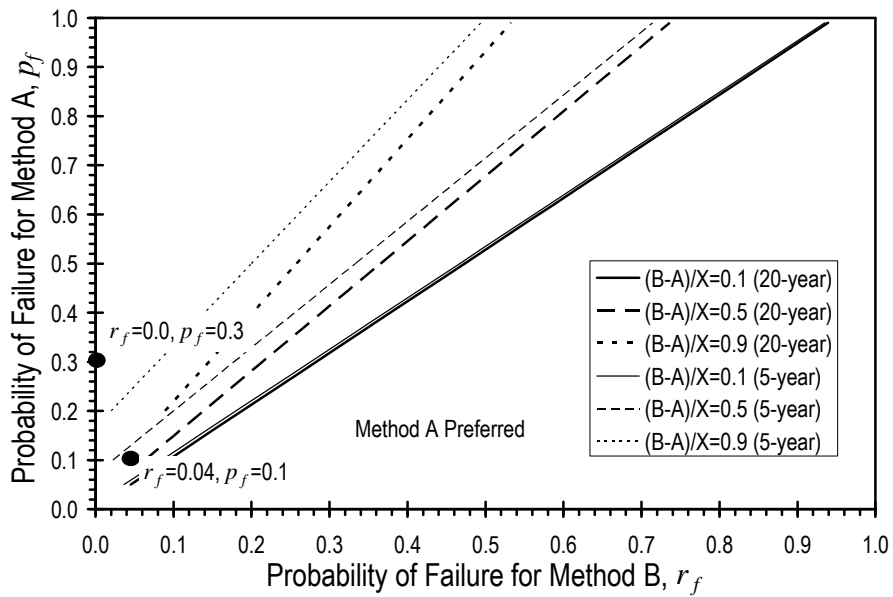


Figure 5-19. Application of constant-method STH model for two example problems based on input from ODOT database.

The second example is similar to the first with the variation of the probability of failure values. To assume that the probability of failure of Method A is 10% (i.e. $p_f=0.1$) and the probability of failure of Method B is 4% (i.e. $r_f=0.05$) might be more typical of what to expect for most common applied stability method. This probability point is also shown in Figure 5-19. It is to notice in the figure that the probability point lies above the appropriate break-even lines determined using the constant-method STH model for a 20 year time horizon meaning the Method B is preferred. However for a 5-year time horizon, the preferred alternative is Method A. In cases like this, judgment is required by the decision maker to select the appropriate decision. The decision maker must consider other issues such as budget availability for slope repair, political considerations, among others, that might make one of the methods preferred over the other. In general, the decision maker must keep in mind that in these cases the conditions are generally close to the break-even line, which implies that the overall outcome (from an average point of view) is likely to be similar regardless of the final judgment.

5.3.2.7 *Limitation of the STH Models*

The primary limitation of the SPIT model is that it does not quantify the potential life-cycle costs of alternative stabilizations methods over a specified time horizon. The STH model overcomes this limitation allowing more realistic decisions for the most common slope stabilization scenarios. The development and simplification of the STH model equation may require a little more effort than the SPIT model, however the tools they offer such as the break-even charts are essentially identical to use.

The most significant limitation of the STH is the assumption of constant variable values throughout the specified time horizon. Values such as probability of failure are expected to change over time (either increasing or decreasing depending on the type of soil or stabilization method). A less significant limitation of the STH model is the assumption of having a maximum of one failure per year. Changes in the model to include such considerations to the current model are suggested prior to the evaluation of their significance in the results.

5.4 Summary

The chapter describes in more detail breakeven-line concepts and equations that were previously mentioned in Chapter 4. Two basic forms of decision tree models that referred “Single Point in Time” (SPIT) model and the “Specific Time Horizon” (STH) model were introduced. For both models, breakeven-lines plots were presented and preference regions were described. Finally, the applications, advantages and limitations of both models were discussed in the chapter.

CHAPTER 6 – SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Proposed in this thesis is a decision support framework based on asset management principles to support slope maintenance from an economical point of view. During the study, very few decision support systems and little data were found available that could facilitate effective decision-making for maintenance and rehabilitation of highway embankments and slopes. Among the few systems available, the systems developed by the Federal Highway Administration, the Oregon DOT, and the Washington Department of Transportation were described and compared in the thesis.

The general process of structuring and analyzing decisions to solve complex problems was described in the thesis. Formal decision analysis was performed by using decision trees. This modeling allowed graphical comparison of the different stabilization alternatives by considering their costs, consequences and reliability.

Numerous trial models were developed, compared and evaluated. Analyses of tree models included performing sensitivity analysis and break-even line concepts. These analyses allowed developing charts to assist decision makers in selecting the preferred slope stability method. A spreadsheet was also developed to assist decision tree users in establishing the values of the tree variables.

Two basic forms of decision tree models referred as “Single Point in Time” (SPIT) model and the “Specific Time Horizon” (STH) model were introduced. For both models, breakeven-line plots were presented and preference regions were described. Finally, the applications, advantages and limitations of both models were discussed.

6.2 Conclusions

The following conclusions were drawn based on the literature review and the results of analyses performed on decision tree models:

1. In the area of geotechnical transportation infrastructure, there are few decision support systems and little data available to facilitate the effective decision-making for maintenance and rehabilitation of highway embankments and slopes.
2. Using decision tree modeling has proven to be an effective method to model slope repair problems.
3. Under certain conditions when applying time modeling models, the repeated selection of the less costly but more risky stability technique is more cost effective in the medium term (between 5 and 10 years) than the repeated election of most costly but less risky decision.
4. The models that were analyzed still have some limitations that impede their practical applicability. However they provide the foundation to create more effective and practical models.

6.3 Recommendations

Seeking to develop a geotechnical asset management system through the enhancement of the models shown in this thesis, the following recommendations are presented:

1. Considering the lack of data, it would be optimum to develop a data collection system that could be linked to the decision tree model input or could be used through tables and charts as information for the judgment of the model users.
2. Temporary variability in the variable values should be included in the STH models. The variability of variables such as initial costs and consequence cost

could be calculated with the use of the time value of money concepts. However the probability of the slope failure variable will be more complicated considering that this variable could vary singularly for different slopes

3. It is necessary to perform modifications for the SPIT model so that it could include life-cycle costs similar to the STH models. Considering that SPIT models are less complex and required less computational effort than SHT models, this modification would be advantageous.
4. More studies need to be done to improve the user data input spreadsheet or some other type of input system. This will allow obtaining decisions that are standard with less user involvement or judgment.

CHAPTER 7 - REFERENCES

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