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Decision Support for Slope Construction and Repair Activities:
An Asset Management Building Block

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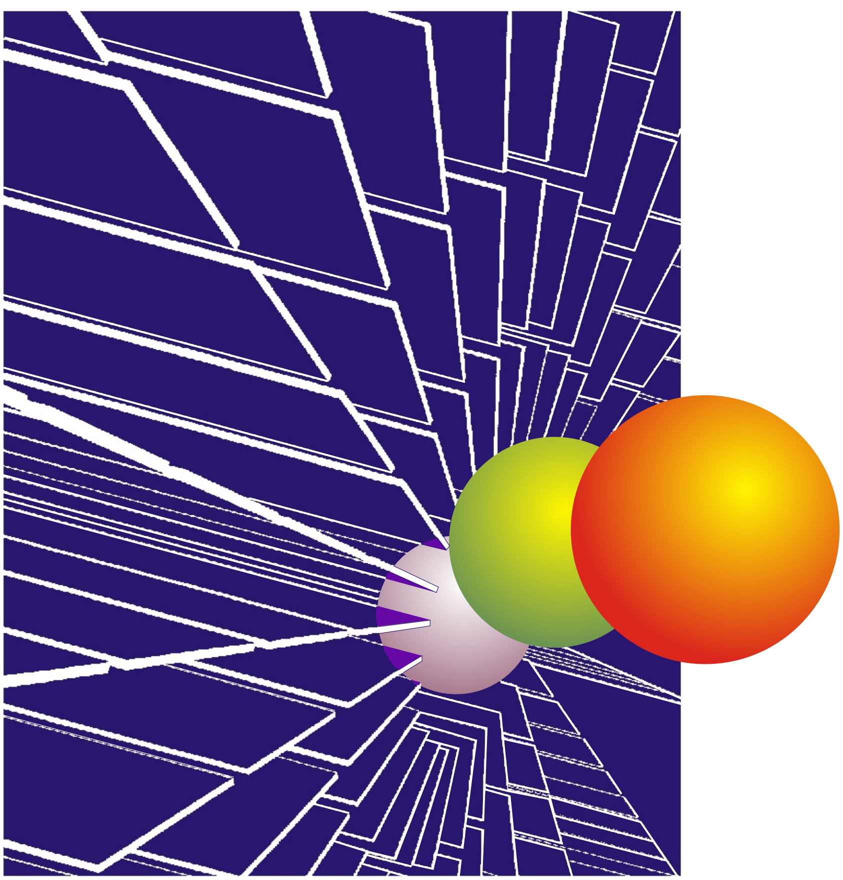

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16. Abstract

The objective of this project has been to develop a decision support framework based on asset management principles to facilitate effective decision making for selection of appropriate methods to stabilize failed earth slopes. Project activities included development of a simple asset management framework suitable for managing geotechnical assets, development of several analysis models to evaluate alternative slope maintenance and repair strategies, and evaluation of the potential for use of personal digital assistants (PDAs) for implementing geotechnical asset management systems.

A simple framework for managing geotechnical assets was developed based on mapping of a generic asset management framework proposed by the Federal Highway Administration. A number of issues that must be addressed prior to complete implementation of a geotechnical asset management system was also identified. The most significant of these issues are lack of established procedures and techniques for collecting the required data and lack of suitable analysis tools required to evaluate alternative management scenarios. Because ongoing efforts to address the required data collection and maintenance are underway, efforts for this project were focused on development of suitable analysis techniques. Two basic forms of analysis models were developed, both of which use decision trees to predict outcomes of alternative stabilization measures. The first form is referred to as the Instant in Time (IIT) form of model to reflect the fact that the model considers only a single application of a repair and, in its current form, does not model the potential costs of alternative stabilization measures over a consistent life-cycle. The second form of model is referred to as the Specific Time Horizon (STH) form of model because it provides capabilities to model the potential need for repeated application of alternative repair techniques within a specified time period. Several preliminary tools, referred to as "break-even" diagrams, were developed using the models to illustrate one potential application of the techniques by field personnel. Efforts undertaken to implement the developed models using personal digital assistants (PDAs) were unsuccessful due to current lack of portability of PC-based tools to PDAs. However, the ability to port the PC-based models to PDAs is expected to be possible in the near future.

Additional efforts should be initiated to incorporate the data collection tools and procedures being developed by others with the analysis tools developed as part of this project. Such efforts should result in a fully functional prototype geotechnical asset management system. The analysis models developed as part of this project should be modified as described in this report. Such modifications are expected to require relatively little effort, but will substantially improve the capabilities and versatility of the models. Once the analysis tools are enhanced and incorporated with appropriate data collection tools, efforts should be undertaken to develop guidance for potential users on selection of appropriate input parameters. Doing so is expected to require a period of trial implementation wherein sufficient data can be generated and evaluated to develop appropriate guidance.

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

MTC Project 2000-03

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EXECUTIVE SUMMARY

The objective of this project has been to develop a decision support framework, based on asset management principles, to facilitate effective decision making for selection of appropriate methods to stabilize failed earth slopes. Project activities included development of a simple asset management framework suitable for managing geotechnical assets, development of several analysis models to evaluate alternative slope maintenance and repair strategies, and evaluation of the potential for use of personal digital assistants (PDAs) for implementing geotechnical asset management systems.

A simple framework for managing geotechnical assets was developed based on "mapping" of a generic asset management framework proposed by the Federal Highway Administration. A number of issues that must be addressed prior to complete implementation of a geotechnical asset management system was also identified. The most significant of these issues are lack of established procedures and techniques for collecting the required data and lack of suitable analysis tools required to evaluate alternative management scenarios. Because ongoing efforts to address the data collection and maintenance are underway, efforts for this project were focused on development of suitable analysis techniques. Two basic forms of analysis models were developed, both of which use decision trees to predict outcomes of alternative stabilization measures. The first form is referred to as the Instant in Time (IIT) form of model to reflect the fact that the model considers only a single application of a repair. In its current form, the IIT model does not model the potential costs of alternative stabilization measures over a consistent "life-cycle." The second form of model is referred to as the Specific Time Horizon (STH) form of model because it provides capabilities to model the potential need for repeated application of alternative repair techniques within a specified time period. In doing so, this form of model overcomes the most severe limitations of the IIT form of model while still retaining the significant advantages of the general decision tree approach. Several preliminary tools, referred to as "break-even" diagrams, were developed using the models to illustrate one potential application of the techniques by field personnel.

Efforts undertaken to implement the developed models using PDAs were unsuccessful due to current lack of portability of PC-based tools to PDAs. However, the ability to port the PC-based models to PDAs is expected to be possible in the near future.

The following recommendations are provided to facilitate future implementation, evaluation, and enhancement of a geotechnical asset management system:

1. Additional efforts should be initiated to incorporate the data collection tools and procedures being developed by others with the analysis tools developed as part of this project. Such efforts should result in a fully functional prototype geotechnical asset management system.
2. The analysis models developed as part of this project should be modified as described in this report. Such modifications are expected to require relatively little effort, but will substantially improve the capabilities and versatility of the models.
3. Once the analysis tools are enhanced and incorporated with appropriate data collection tools, efforts should be undertaken to develop guidance for potential users on selection of appropriate input parameters. Doing so is expected to require a period of trial implementation wherein sufficient data can be generated and evaluated to develop appropriate guidance.

1. INTRODUCTION

Departments of transportation across the country are faced with the recurring task of repairing numerous erosional features and surficial slope failures, commonly referred to as nuisance slides. While often small in size and benign in appearance, these problems do 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. In addition, repair and maintenance activities required to stabilize nuisance slides are a significant staff and economic burden to infrastructure agencies. While the cost associated with repairing a single nuisance slide is generally low, total costs associated with repair of large numbers of nuisance slides may be extremely large. In the state of Missouri, it is not uncommon to have on the order of 100 nuisance slides annually. Evidence from other states suggests that this experience is not uncommon. The Transportation Research Board recently estimated that costs for repair of nuisance slides nationwide exceed costs for repair of major landslides (TRB 1996). Conservative estimates of annual costs for repair of nuisance slides exceed $100 million.

The nuisance slide problem is exacerbated by the fact that maintenance and repair measures are often performed on an ad hoc basis by personnel who lack significant training or expertise in selecting appropriate repair measures. Repair methods are often chosen based on tradition rather than for technical or economic reasons, and many slides tend to be repetitive occurrences. Formal procedural guidance to help decision makers determine whether, when, and how to repair slides is currently limited. As a result, such decisions are often made with little or no consideration given to economics from a broader, organizational perspective.

The objective of this project has been to develop a decision support framework to facilitate effective programming of slope maintenance and repair decisions based on asset management principles. The essential questions to be answered, or decisions to be made, using the framework include: “Should a slope failure be repaired?” and if so, “What repair measure(s) should be taken?” A basic premise for the project is that these questions should be answered so as to provide the greatest benefit to an agency from an overall, organizational perspective. This report documents the activities undertaken to accomplish these objectives.

The report is organized into six chapters including this introductory chapter. In Chapter 2, the development of a simple asset management framework suitable for managing geotechnical facilities is described. Justification of the need for management of geotechnical assets is provided, and comparisons are drawn between existing asset management systems and the developed framework to serve as a “state of the practice” for managing geotechnical assets. Several existing geotechnical decision support systems are described in Chapter 3, and comparisons are made between these systems and “asset management” systems. Two basic forms of decision support models developed in this project, each with different advantages and disadvantages, to analyze alternative slope maintenance. Repair decisions are presented in Chapter 4. Chapter 4 also includes discussion of the application and limitations of the respective models. Chapter 5 is a summary of results from an evaluation of the potential for implementing geotechnical asset management systems using personal digital assistants (PDAs). Finally, Chapter 6 includes a summary of the report along with conclusions drawn from the project and recommendations for future activities, needed to fully implement asset management techniques for the slope maintenance and repair problem and to improve on the analysis techniques developed for this project.

2. DEVELOPMENT OF FRAMEWORK FOR MANAGEMENT OF GEOTECHNICAL ASSETS

For most people, the term "transportation assets" brings to mind physical facilities such as pavements, bridges, and perhaps railway track. However, all of these transportation assets rest (literally) on "geotechnical assets," and the performance and costs of more traditional assets are tied, directly or indirectly, to the performance of geotechnical assets. While asset management has become a buzzword for transportation agencies, most of the schemes presented have not included geotechnical assets explicitly. This chapter provides one possible classification of geotechnical assets and some justification for using asset management principles for design and maintenance of geotechnical infrastructure. A simple framework that can be used for applying asset management techniques to geotechnical assets is then presented followed by discussion of several unique issues that arise when applying asset management to geotechnical structures. As such, this chapter, when combined with Chapter 3, serves as a "state of the practice" on the topic of geotechnical asset management.

2.1. What are geotechnical assets and why should they be managed?

Two questions that arise when considering development of a framework for managing geotechnical assets are "What are geotechnical assets?" and "Why should they be managed?" The answer to the first question is not simple due to the intimate relation between geotechnical assets and other types of assets. The boundaries between geotechnical assets and other types of assets often are blurred. Table 2.1 shows a collection of assets that can be classified as geotechnical assets. The assets are categorized in terms of function as "exclusively geotechnical," "partially geotechnical," and "minimally geotechnical" to indicate the degree of interaction with other assets. The table also includes the general purpose and fundamental performance objectives for each asset.

Perhaps the type of asset that is most clearly geotechnical is highway embankments and slopes. While one could potentially include these within "real estate" or "right-of-way," few would argue that embankments and slopes are not geotechnical structures. Furthermore, the value of these structures to the transportation system is more than the value of the land alone, since they are essentially "earthen bridges" intended to maintain appropriate roadway alignment. Embankments and slopes are designed almost exclusively by geotechnical or geological engineering professionals, and the "performance" of these structures is defined exclusively by the response of the geologic materials to environmental and loading conditions. Highway embankments and slopes interact with other assets in an indirect manner in the sense that most do not directly apply load to, or support, other assets.

In contrast, the assets listed as partially geotechnical are tied much more directly to other assets in both physical and conceptual sense. Tunnels, earth retaining structures, and foundations may be considered by some to be "structural assets" rather than geotechnical assets since their performance is likely to be judged from a structural perspective. Design of these structures involves significant structural engineering in addition to geotechnical engineering. Similarly, culverts and drainage channels could be considered "hydraulic assets" since their performance is likely to be judged from the hydraulic perspective, and their design is likely to be performed by hydraulic and structural engineers in addition to geotechnical engineers. However, the performance of these assets is closely linked to the surrounding geologic materials. As such, they reasonably may be considered geotechnical assets.

Table 2.1. Summary of highway components that can be classified as geotechnical assets (Bernhardt et al. 2003)

Asset Function Category	Interaction with Other Assets	Asset	Purpose	Performance Objectives
Exclusively Geotechnical	Indirect	Embankments and Slopes	To provide for gradual grade changes in vertical alignment	Provide satisfactory support for roadway without intruding on pavement or other transportation structures
Partially Geotechnical	Direct	Tunnels and Earth Retaining Structures	To retain earthen materials so that highway can be constructed in restricted right-of-way	Satisfactorily retain earthen materials to prevent intrusion or damage to highway structures
		Culverts and drainage channels	To provide control of surface waters	Prevent accumulation of water on pavement and prevent damage to highway structures from erosion
		Foundations	To transmit structural loads to supporting ground	Satisfactorily support structure without excessive deformations
Minimally Geotechnical	Direct	Pavement subgrade	To serve as foundation for pavement	Satisfactorily support pavement without damaging or reducing the life of the pavement

The third class of assets listed is considered minimally geotechnical. Perhaps, the best example of this category of assets is pavement subgrades. While the underlying geologic materials dramatically impact the performance of a pavement system, responsibility for dealing with subgrade quality lies primarily with pavement design professionals. Little input from geotechnical or geological engineering professionals is required beyond site characterization and determination of engineering properties. As a result, pavement subgrades are more likely to be considered within the scope of pavement assets than as geotechnical assets, although the link between the two is apparent.

Regardless of how one chooses to categorize the assets presented in Table 2.1, clearly, the performance of the assets shown is intimately tied to, and in some cases dominated by, the response of geologic materials to the environmental conditions and loads imposed. It is very likely that what are and are not considered geotechnical assets may vary among organizations according to the organizational structure and the history of the organization. Nevertheless, it is useful to try to classify the assets in some form, not for the purpose of "claiming ownership," but rather to highlight the interactions among these assets. The framework presented subsequently can be used regardless of how one chooses to classify the assets.

The second question, "Why should geotechnical assets be managed?" is addressed more easily. The primary reason for managing geotechnical assets is to reduce the lifecycle costs associated with constructing and maintaining these assets at the system-wide level. The nuisance slide problem, which is described in the introduction and is of primary interest for this project, shares many characteristics with other asset management problems. Since the problem is widespread, decision makers are often faced with the daunting task of selecting which slides should be repaired within limited construction and maintenance budgets. The problem is complicated by the fact that a wide variety of techniques are available for stabilization and repair of slope failures. The techniques range from simply replacing the failed material back on the slope and regrading, to installation of extensive drainage measures or a complete earth retaining structure. However, the costs and the long-term effectiveness of alternative repair measures vary dramatically, both overall and on a case-by-case basis.

While much work has been performed to develop guidelines on how to prevent, identify, and repair slides (e.g. Klinedinst et al. 1986; Hopkins et al. 1988), only limited procedural assistance is available to help decision makers determine whether, when, or how a slope failure should be repaired so that limited funds are applied where the most benefit will be gained (on a lifecycle basis). One impediment to development of such assistance is that the economics of constructing and maintaining transportation slopes and embankments is not well understood. For example, it is reasonable to conjecture that many slopes are simply too steep and that constructing flatter slopes would reduce long-term maintenance costs. However, the prevailing perception is that the lifecycle costs for routinely maintaining and repairing nuisance slides are smaller than the costs associated with acquiring the additional right of way and materials for flatter slopes. Alternatively, one can imagine that repetitive application of an inexpensive but temporarily effective stabilization measure, such as regrading, could be more economical that an extensive earth retention system, despite the recurring nature of the activity. Unfortunately, current record keeping of maintenance costs is generally poor (Klinedist et al. 1986; Hopkins et al. 1988; TRB 1996), so reliable evaluation of these issues is difficult. An asset management approach that includes consideration of these issues clearly has the potential to improve decision-making and reduce overall costs.

A second and perhaps equally important reason for managing geotechnical assets is to facilitate recognition of geotechnical infrastructure as having value to the transportation system. Highway embankments, retaining structures, and other geotechnical structures can be considered ancillary to the actual pavements since alone they do not directly provide the primary service required of the transportation system. However, few would argue that the transportation system would be possible without them, so their inherent value is understood, if often overlooked. While valuation of geotechnical assets is not a simple issue, failure to recognize and quantify the value of geotechnical infrastructure can lead to increased life cycle costs for all forms of transportation infrastructure. Reducing these lifecycle costs is one of the goals of asset management.

2.2. Managing Geotechnical Assets

Asset management has been defined in a number of ways. However, the Federal Highway Administration's (FHWA's) Office of Asset Management put forth the following definition in its Primer on Asset Management:

> Asset management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning. (FHWA 1997)

The foundation for asset management lies with the goals and objectives of the agency. Asset management then becomes a means for helping an agency to achieve its goals. For example, an agency goal may be "to provide the public with smooth pavement." A corresponding objective may be that no more than 25% of pavements should be rated less than 4 on a 5-point scale. The data and analysis tools of an asset management system can guide the agency in determining the investments that should be made in the system to achieve the objective. In a nutshell, "The fundamental objective is to maximize benefits for users while minimizing agency costs" (FHWA 1999). The FHWA and the American Association of State Highway and Transportation Officials (AASHTO) are focusing on asset management as a tool for strategic level administration.

Although they have not been included explicitly in discussions of transportation asset management, geotechnical assets are critical to our transportation system functioning effectively. The following sections review the components of an asset management system, propose a framework for including geotechnical assets in asset management, and identify some of the issues that need to be addressed if geotechnical assets are to be managed systematically in conjunction with other transportation assets.

2.2.1. Components of an Asset Management System

Figure 2.1 shows a simplified framework for asset management derived from the generic framework for asset management proposed by the FHWA's Office of Asset Management (FHWA 1999). In the figure, the basic components of an asset management system are subdivided into particular activities or types of data. The following paragraphs describe the intended purpose or need for each of these components in more detail.

Data are central to a comprehensive asset management system, just as they are central to a management system for any particular type of infrastructure. Data generally include both "static" data – data that seldom if ever change, such as a location or date built, and "dynamic" data – data that change frequently or continually, such as measurements reflecting current condition. In addition, a variety of cost data is important. An agency should assign value to its assets, and past, present, and projected maintenance and rehabilitation costs should be tracked. Budget data and allocation constraints also should be tracked. All data should be stored in one or more databases that, ideally, are accessible and provide useful information to personnel throughout the agency.

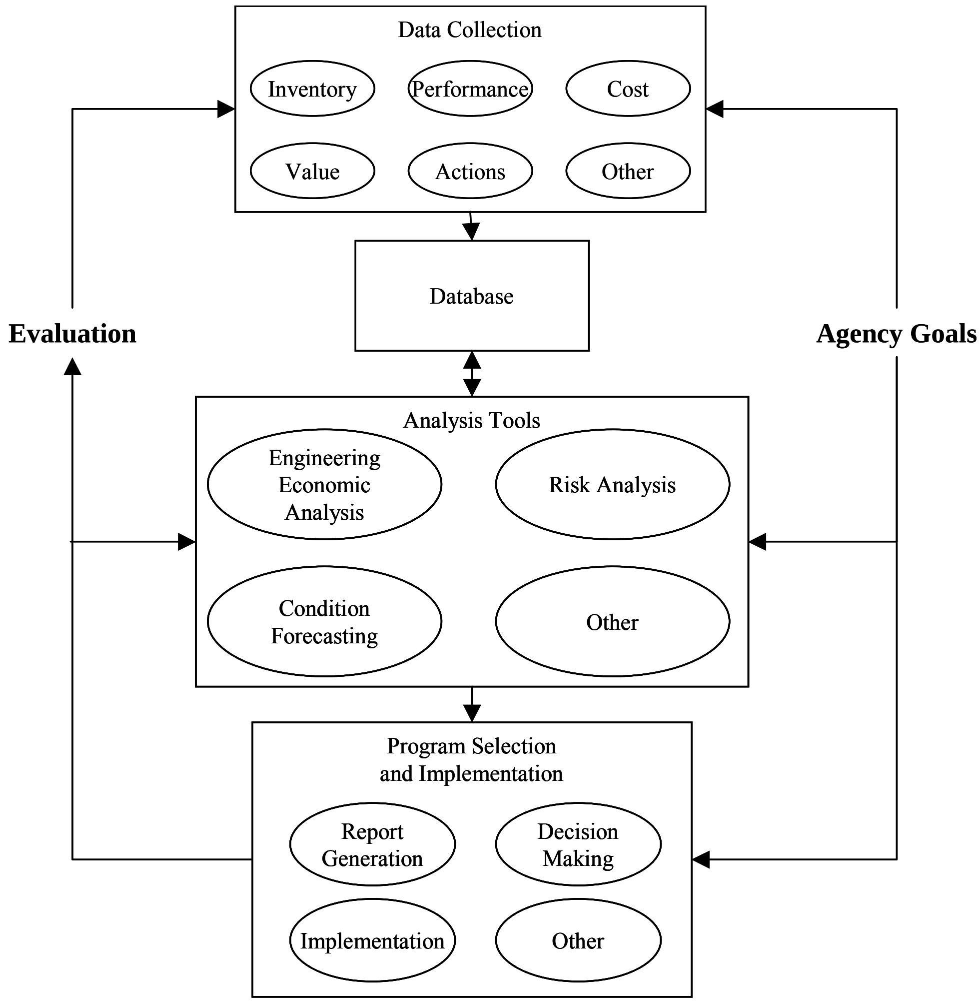

Figure 2.1. Asset management system components (Bernhardt et al. 2003)

Analysis tools apply algorithms to data extracted from the database to produce information that supports decision-making. These tools can include engineering economic analysis, risk analysis, condition forecasting, and other tools that use the agency goals as a guideline for determining appropriate use of resources. The tools should have capabilities to answer questions about the future condition of assets under different funding allocation schemes within given budget constraints, about appropriate actions to apply to particular assets, and about potential costs and probabilities of unforeseen events.

The program selection and implementation component packages the information produced by the analysis tools so it will be useful to agency decision makers. This means that reports should contain different information in different formats for different classes of users. This information forms the basis of programming decisions and subsequent implementation. Finally, top management can use the information from the reports to determine whether the data collection practices and analysis tools are sufficient.

2.2.2 *A Framework for Geotechnical Asset Management*

Current asset management systems (e.g., for pavements, bridges) are essentially single entity management systems in the sense that a limited and specific type of asset is managed independently of other assets. Geotechnical assets (however geotechnical assets are defined) are somewhat unique in the supportive role they play for other assets. As a result, effective management of geotechnical assets requires that "cross-asset" issues be addressed. If Figure 2.1 is examined in the specific context of geotechnical assets, more specific labels can be assigned to each of the components. Table 2.2 provides one possible mapping of the general functions shown in Figure 2.1 to functions specific to geotechnical assets. The table is not meant to be an exhaustive list of all aspects of the system, but rather an example of geotechnical specific components. Development of this mapping raised a number of issues within each category that must be addressed if geotechnical assets are to be integrated into an asset management system. The following sections describe these issues, as well as the mapping itself.

Table 2.2. Mapping of general asset management system components to geotechnical assets (Bernhardt et al. 2003)

Asset Management System Component	Geotechnical Asset Description/Issues
Agency Goals:	Agency unlikely to have specific goals for geotechnical assets
Data Collection:	
Inventory	Location, extent, height of embankment, soil properties, etc.
Performance	Existing erosion, stability, etc.
Cost	Maintenance budgets, cost of maintenance actions, etc.
Value	Several options available; replacement cost may be most appropriate
Actions	No action, monitor, temporary repair, permanent repair, etc.
Other	Impacts of failure (safety and mobility), etc.
Analysis Tools:	
Economic Analysis	Estimate lifecycle costs to compare various options
Risk Analysis	Evaluate risk of repair alternatives as well as risk of no repair, etc.
Condition Forecasting	Predict future condition of slope, embankment, etc. based on current and historical information, etc.
Other	Calculate level of hazard and factors of safety, etc.
Program Selection and Implementation:	
Report Generation	Tables, graphs, charts, etc.
Decision Making	Compare costs, benefits, and risks of alternatives under different budget scenarios and choose course of action
Implementation	Allocate resources and conduct projects
Other	Suggest modifications to budget to achieve performance objectives
Evaluation:	Evaluate whether data and analysis tools are providing useful information and whether goals are being met

2.2.2.a. Agency Goals

It is unlikely that transportation agencies will set direct performance goals for geotechnical assets. Rather, the performance goals for geotechnical assets will arise out of performance goals for other "primary" assets. For example, a geotechnical-related goal might be to minimize funds spent on construction and maintenance while minimizing failures that affect pavement structure. Since the geotechnical-related goals depend on the performance of other assets, geotechnical asset management must interact or be integrated with other "primary" asset management functions, as shown in Figure 2.2.

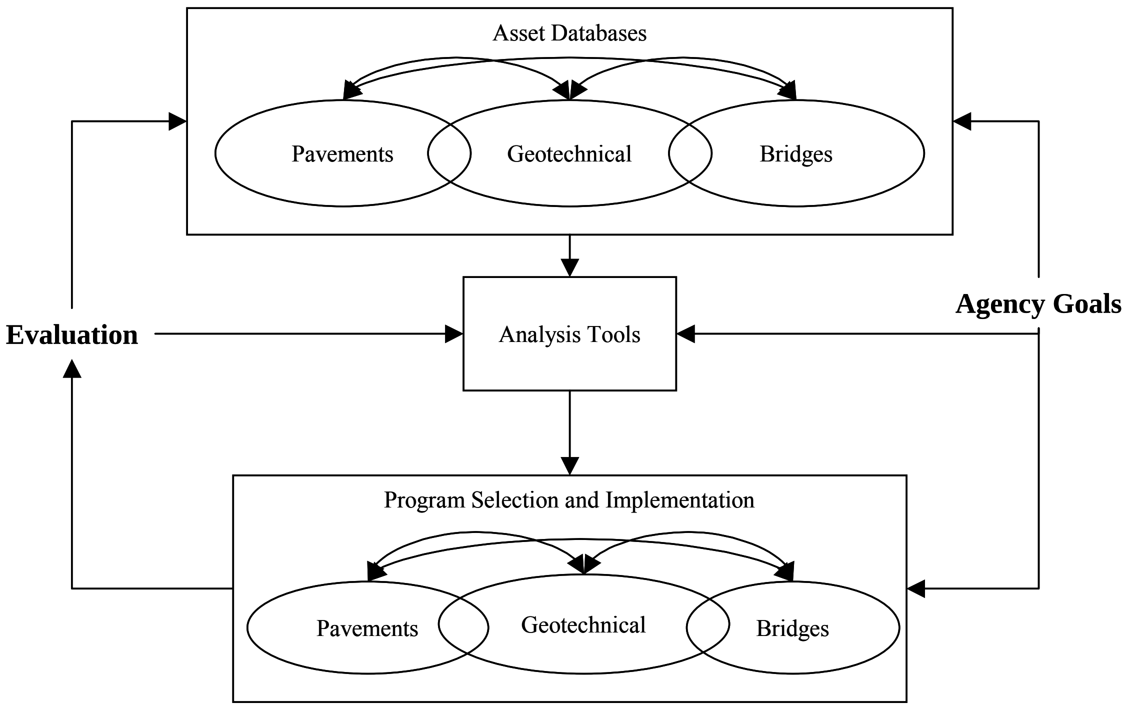

Figure 2.2. Required interaction of geotechnical asset management systems with other types of asset management systems (Bernhardt et al. 2003)

2.2.2.b. Data Collection

Several types of data that agencies will need to acquire and maintain to effectively manage geotechnical assets are noted in Table 2.2. Although some agencies collect some of the required data, many aspects of data collection will need to be improved if geotechnical asset management is to be implemented. First, few agencies currently maintain inventories of geotechnical problem sites (Hopkins et al. 1988; TRB 1996), and we are not aware of any agencies that maintain complete inventories of geotechnical assets. Similarly, many agencies do not track maintenance division costs at the level of detail required to ascertain costs for geotechnical repairs. Furthermore, agencies seldom quantitatively assess the performance of repair measures with time once they are implemented, so it is difficult to utilize current assessments in an asset management approach. While these are important issues, agencies can build on the steps that have been taken in these areas with existing geotechnical decision support systems described in more detail in Chapter 3. Other issues related to data collection are more challenging, as described in the following paragraphs.

Performance. Most agencies do not assess formally and quantitatively the condition of geotechnical assets on a routine basis. However, as demonstrated by existing asset management systems for bridges and pavements, effective management depends on knowledge and quantifiable measures of current condition, as well as other measures of current performance. Performance indicators, which may reflect physical condition, user cost, or other measures, are an essential component of any infrastructure or asset management system. More appropriate and comprehensive performance indicators must be developed for geotechnical assets, and it is important that these indicators be tied to the agency goals.

Value. Although a variety of methods can be used to value physical assets, agencies have not applied these methods to geotechnical assets. One common method for valuing physical assets is to use replacement cost. That is, if the agency were to construct the facility today, how much would it cost? This method could be applied to geotechnical assets; it would likely include the value of the land itself plus the estimated material and construction costs in current dollars. However, given that the value of geotechnical assets to the transportation system is in how well they enable other facilities to function, this may not be the most appropriate valuation method. Unfortunately, valuation methods that consider the interaction among different forms of assets are not readily available.

Other. Another issue that must be addressed in data collection is identification of potential impacts of poor asset performance. Geotechnical failures can impact both the safety and mobility of the public. For example, a serious slope failure on a heavily traveled road would have significant impacts on the traveling public, whereas a minor failure would have a lesser impact. Consistent and quantifiable measures of potential consequences are needed in such cases to enable appropriate decision-making. Several of the existing decision support systems described in Chapter 3 include such measures but additional work is needed in this area.

2.2.2.c. Analysis Tools

Table 2.2 identifies four major categories of analysis tools for geotechnical asset management: economic, risk, condition forecasting, and other. Engineering economic and risk analysis methods are used to support a variety of engineering decisions, and it is likely that these methods will serve as an integral tool for geotechnical asset management systems. Engineering economic analysis tools generally are well developed and widely accepted. Risk-based analysis methods, however, have been used only sporadically in geotechnical applications for a number of reasons, including lack of familiarity for geotechnical engineering professionals as well as difficulty in dealing with temporal and spatial variability of soil conditions (Duncan 2000). Nonetheless, in recent years, organizations such as the U.S. Army Corps of Engineers (USACE) have turned increasingly to risk-based decision making and reliability-based design tools for facilitating management decisions (USACE 1999). This trend is expected to continue as methods become better established and the geotechnical engineering profession becomes more comfortable with the shift in approach.

Reliability-based analyses are the most logical choice for forecasting the future condition of geotechnical assets because they enable the life cycle costs of very different types of conditions to be compared rationally. Conditions involving relatively low costs but with high probabilities of occurrence can be compared to conditions with relatively high cost but low probabilities of occurrence by weighting costs according to probability of occurrence. However, one issue that must be considered in reliability-based analyses is how to account for varying time horizons. A typical question that must be answered in an asset management framework is what are the costs and consequences of repairing an asset now versus repairing the asset in a year (or five years, ten years, the life of the structure, etc.). Current reliability-based analysis tools and procedures for geotechnical assets are not generally well suited to such questions, although some progress has been made in recent work (Wolff 1996). Continued advancement in this area is required if effective and accurate analysis tools are to be available for implementation in an asset management framework.

Condition Forecasting. Condition forecasting, which is often based on deterioration models, has also seen little application to geotechnical assets. The most notable work in this area to date is that by Wolff (1996). In the context of pavements, the goal of preservation is to "reduce the rate of deterioration" (FHWA 1999). One component of a pavement management system is an analysis of predicted future condition under different maintenance and rehabilitation scenarios. In these analyses, pavements are generally assumed to deteriorate slowly at first, and then the rate of deterioration accelerates as the pavement ages, as shown in Figure 2.3a. As condition worsens, the cost to return the pavement to "new" condition (or another target condition) increases, as does the uncertainty in predicting the actual condition. An appropriate maintenance strategy, then, is to try to maintain the pavement so that it never drops into the bottom portion of the curve.

The deterioration model shown in Figure 2.3a may not capture all aspects of performance decline for geotechnical assets. Since the performance of geotechnical assets is often dominated by random events, such as extreme rainfall, abrupt changes in condition may occur at any point in the lifecycle. Furthermore, the condition of some geotechnical assets may actually improve over time. An example of this phenomenon is embankments on soft foundation soils, which generally become more stable over time until the foundation soils are fully consolidated (Figure 2.3b). At this point, the embankment stability takes over as the governing factor in performance, and the asset deterioration curve may take on an entirely different form. On the other hand, the classical deterioration models (Figure 2.3a) may forecast progression of problems like erosion or geosynthetic clogging reasonably well.

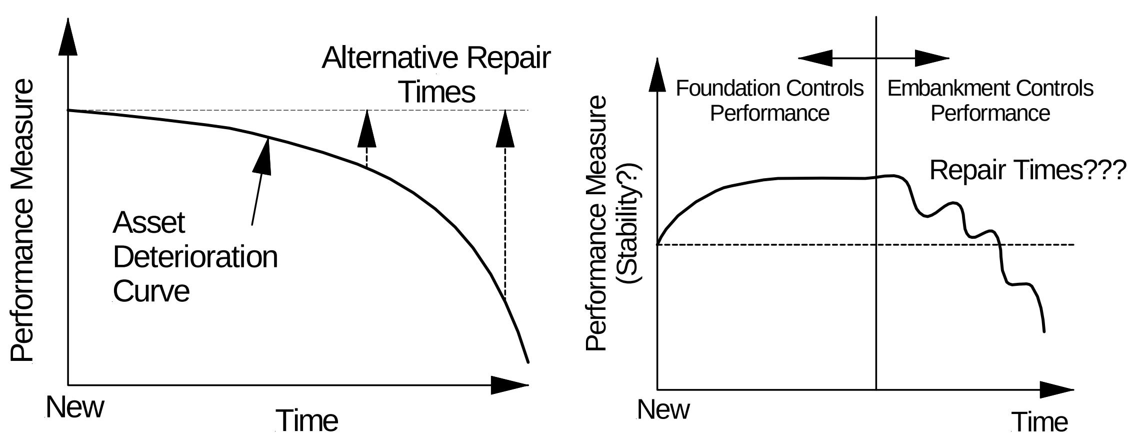

Figure 2.3. Asset deterioration curves: (a) Traditional pavement deterioration and (b) Deterioration of an embankment over soft foundation soils.

Other. Another issue that must be considered in the analysis of alternatives is the maintainability of various types of geotechnical assets. Some geotechnical assets, such as foundations, are essentially "un-maintainable." That is, there are no available methods for performing mid-level rehabilitation; any significant action requires re-construction or additional construction. With other geotechnical assets, such as embankments, this is not a problem.

Finally, analysis tools could improve decisions regarding future construction during design. Many decisions made during design and construction will significantly impact the life cycle costs, and hence the "value," of the asset. Using a highway embankment as an example, the slope angle, height, and materials selected during design, and the construction quality in the field affect the initial construction costs. These parameters also affect the required maintenance over the life of the embankment. A conservatively designed slope will tend to require more right-of-way, more or better material, and perhaps modification or improvement of existing ground, all of which will increase construction costs. However, a conservatively designed slope is expected to require less lifetime maintenance than a less conservative design, so a geotechnical asset management system should be able to improve "design time" decisions in addition to repair and maintenance decisions.

2.2.2.d. Program Selection and Implementation

Given the data and reports produced from asset management analyses discussed above, it seems reasonable to expect that program selection and implementation algorithms currently used in existing asset management systems can be applied to geotechnical assets without significant modifications. One additional consideration related to geotechnical assets exists because there is unlikely to be a separate budget for maintaining geotechnical assets. Consequently, decisions must be made considering the costs and benefits of potential repairs to other types of assets.

2.3. Discussion

As discussed above, a number of issues currently exist that must be addressed prior to implementation of asset management systems suitable for geotechnical assets. Considering these issues from an overall perspective, the most significant impediments to implementation of a geotechnical asset management system are lack of established mechanisms and tools for data collection and lack of well established analysis tools to support effective decision making. Fortunately, some progress has been made to develop data collection and data management for the specific geotechnical application of slope maintenance and repair decisions. These advances are presented subsequently in Chapter 3. Because of these advancements, work performed as a part of this project was focused on development of analysis tools to facilitate effective decision making for the slope maintenance and repair problem as described in Chapter 4.

3. EXISTING GEOTECHNICAL DECISION SUPPORT SYSTEMS

A significant amount of effort was expended during the initial portion of the project to identify existing decision support systems for geotechnical infrastructure. Work performed to develop specific systems and methods that facilitate effective decision making for geotechnical problems has been sparse, although some efforts have recently been made to improve the situation. In this chapter, the systems identified are briefly reviewed and the relationship between these systems and asset management systems is discussed.

3.1. Review of Existing Geotechnical Decision Support Systems

Some of the earliest work identified was described by Adams (1988). In this work, an expert system was used to provide decision support for rehabilitation of retaining walls. Perhaps, the most comprehensive set of management systems developed to date are the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) systems developed by the U.S. Army Corps of Engineers (USACE). McKay et al. (1999) describe the development of a uniform Condition Index (CI) for assessing performance of a variety of types of infrastructure, notably including examples of steel sheet pile structures. These systems were, in large part, developed for structures and applications with acute consequences and often different level of hazard/risk (e.g., dams) as compared to more common transportation-related geotechnical structures. Nevertheless, these systems provide adaptable concepts and models that can be adapted to specific characteristics of transportation infrastructure.

In the more specific area of transportation infrastructure, the application receiving the most attention to date has been methods to improve decision-making for maintenance and rehabilitation of highway embankments and slopes. References describing several systems for ranking rock slope and landslide sites for repair were identified and studied. These references were used as a basis for preliminary development of the decision support system and as a source of information for potential hazards identification. A summary of the systems identified is provided in Table 3.1. Detailed descriptions of these systems can be found in the references cited, and a general comparison of the systems is provided in Huaco (2004).

Perhaps the best developed and most widely utilized of these systems is the Rockfall Hazard Rating System (RHRS), which was developed by the Oregon Department of Transportation (ODOT) in collaboration with other state and federal transportation agencies (Pierson and Vickle 1993). The intent of the RHRS, and subsequent revisions, is to systematically reduce the risk of rockfalls and landslides impacting the roadway on a system wide level by prioritizing sites according to the level of hazard. RHRS uses a six-step process that includes the following:

1. An inventory of all hazardous rockfall sites in the system
2. Preliminary rating of all sites according to hazard potential
3. Detailed rating of the highest priority sites identified in Step 2
4. Preliminary design and cost estimates of remedial measures for the highest priority sites
5. Project identification and development based on the results of the detailed ratings and estimated costs

6. Annual review and updating of the condition of the inventory

RHRS uses a database to manage all rockfall locations, detailed ratings, and preliminary designs and cost estimates. More recently, the RHRS was incorporated into a more comprehensive, but similar, management program that considers both soil and rock sites (ODOT 2001). This revised system incorporates economic considerations by applying multiplicative "factors" to account for relative repair and user costs among different sites to determine an overall rating.

Table 3.1. Summary of existing landslide rating/management systems

Rating/Management System	Reference	Description
ODOT Rockfall Hazard Rating System (RHRS)	Pierson and Vickle 1993	Systematic method of prioritizing rockfall sites requiring maintenance or repair
ODOT Landslide Rating System	ODOT 2001	Enhancement of the RHRS to include all landslides as well as additional improvements to RHRS
FHWA Blue Ridge Parkway Rating System	Unpublished	General rating system for prioritizing slope failure sites on the Blue Ridge Parkway
WSDOT Unstable Slope Management System	Ho and Norton 1991	System for ranking unstable slope sites that includes an "expert system" software program
Kentucky Transportation Cabinet GIS System	Hopkins et al. 2001	GIS based inventory system for slope management that includes RHRS as well as other data management and design tools

Several other similar systems have been developed, although to a lesser degree. Ho and Norton (1991) describe the development of an "Unstable Slope Management System" for the Washington State Department of Transportation that can be used to prioritize unstable slope sites. The Eastern Federal Lands Highway Division (EFLHD) of the FHWA developed a landslide rating system to evaluate and rate landslides from a technical standpoint for the Blue Ridge Parkway. More recently, the Kentucky Transportation Center is developing a state of the art Geographic Information System (GIS) based database for the Kentucky Transportation Cabinet that includes the RHRS in addition to a Landslide Data and Management System and other data management and design tools (Hopkins et al. 2001). Similar activities are being undertaken by departments of transportation in New Hampshire (Fish and Lane 2002), New York (Hadjin 2002), and North Carolina (Kuhne 2002).

3.2. Comparison between Existing Systems and an Asset Management System

The primary goal of each of the systems described is to produce a prioritized ranking of soil or rock slopes based on the general hazards associated with a particular site. In the sense that the systems are intended to prioritize rehabilitation activities, they share similar goals with asset management systems. However, the previously developed systems differ from asset management systems in several respects. The most significant difference is that the existing systems are primarily "once and for all" systems, in the sense that the highest priority sites are expected to be completely repaired, thereby effectively eliminating the hazard. The potential for application of several alternative stabilization measures with varying costs, reliabilities, and, perhaps, life-cycles is not explicitly considered within these systems; although, it can certainly be implicitly considered by the personnel using these systems. While economic considerations are implicitly included in each of the systems, the level of hazard serves as the primary basis of the rankings. As such, the systems are essentially "worst-first" systems—sites in the worst condition are expected to be rehabilitated first. While this approach is common and may be justified given that safety is of paramount importance, it is not necessarily the most effective approach from an asset management perspective. In this sense, these existing systems are really hazard assessment and management systems that focus on preventing catastrophic failures within limited funding constraints, whereas an asset management system focuses on cost-effective management of all features, whether or not failure would be catastrophic. Current systems also generally operate on the assumption that as many slides as possible should be repaired given available funding without consideration to whether the repair is cost effective independent of available funding. While this approach is understandable for "high hazard" areas such as the Pacific Northwest, it may not be as justified in areas where slope failures are more of a maintenance issue than a hazard issue (i.e. where there is little chance for personal injury or fatality). The work in this project has focused on the slope maintenance issue and consideration of several alternative stabilization measures with differing levels of reliability since it may be justified to use a marginal stabilization measure in some cases if cost savings can be realized over the life of the slope.

As an example, consider a high priority rock cut with significant potential for producing rockfalls. One approach to remedy the situation might be to install a barrier to prevent the rockfalls from reaching the roadway. An alternative may be to perform scaling on the slope to remove loose materials that have a high probability of falling. The barrier approach is likely to have substantial initial costs along with nominal and consistent ongoing costs since maintenance crews will have to routinely clear the catchment area to maintain the effectiveness of the repair. In contrast, the scaling approach is likely to have lower initial costs. However, the "effective lifetime" of scaling the rock cut is uncertain and variable since future weathering that may lead to additional material becoming loose and producing fall hazards is uncertain. The problem thus presents the dilemma of selecting stabilization measures that have higher costs but more certain outcomes versus measures that have lower costs but are more uncertain. Similar dilemmas exist for soil slopes and other geotechnical problems. None of the current "hazard assessment" systems are well suited to dealing with such dilemmas. An asset management approach can facilitate better decision making when confronted with such situations.

Despite these limitations, current systems do address some of the key asset management issues discussed in Chapter 2 such as data collection, inventory, and condition assessment. As such, they can serve as building blocks for further development of asset management based approaches with development of suitable analysis tools and techniques such as those described in Chapter 4.

The existing decision support systems also provided benefits to the current project in other ways. The existing systems identify a wide range of costs and hazards associated with maintenance and repair of slope failures. In addition, most of the systems provide some form of weighting system that is applied to different slope characteristics and hazards. These hazards and associated weighting systems serve as well documented means for assigning consequences associated with slope failures, which have been utilized in the development and evaluation of the decision support system for this project. The data collected by these agencies was also used for evaluation of alternative analysis tools since the data sets include data that is not routinely available.

4. DEVELOPMENT OF MODELS TO ANALYZE ALTERNATIVE SLOPE REPAIR DECISIONS

As discussed in Chapter 2, two of the primary impediments to application of asset management techniques for geotechnical infrastructure are lack of established procedures for data collection and lack of established analysis tools required for effectively implementing an asset management system. However, as described in Chapter 3, significant advancements are already being made with respect to developing procedures and tools for data collection and these can be expected to serve as a basis for data collection in a future geotechnical asset management system. Because development of such tools and procedures was already underway, efforts in the current project were focused on developing the required analysis tools needed for a geotechnical asset management system. One technique that can be useful for formalizing the required analyses is to use decision trees to evaluate the alternative courses of action for managing slope repair decisions. In this chapter, two alternative forms of decision tree models developed for the purpose of analyzing alternative courses of action for stabilization and maintenance of failed slopes are described. Example application of the respective decision support models are presented along with discussion of the limitations of each model. Finally, guidance regarding methods for selection of the required input for the models is provided.

4.1. Use of Formal Decision Analysis Techniques and Decision Trees

The general approach adopted for development of the decision support models has been to use formal decision analysis techniques commonly used in many business applications (Clemen 1996). For the present work, extensive use has been made of "decision trees." An equivalent alternative to decision trees is to use "influence diagrams." However, decision trees have been exclusively used throughout this work because they more explicitly present the details of the decisions to be made. A decision tree structures the components of a decision and allows a quantitative evaluation of the best outcome based on the uncertainties and consequences associated with each choice, basically providing a way to formalize complicated decisions and to incorporate different costs and risks associated with a decision. Decision trees have been previously utilized for geotechnical engineering applications (e.g., USACE 1999) and their use appears to be increasing. Use of decision trees, or other similar techniques, has the distinct advantage of allowing one to explicitly consider uncertainty when comparing alternative courses of action. It is this capability that is felt to be critical to effectively address the nuisance slide problem since there are numerous alternative methods that can be used to stabilize such slides, each with potentially different levels of reliability and different costs.

4.1.1. Basic Function of Decision Trees

A simple decision tree representing the basic slope repair decision is shown in Figure 4.1 to illustrate the basic operation of a decision tree. In the figure, decisions are represented by square "nodes" (referred to hereafter as decision nodes) where one must decide which "branch" of the tree to adopt (i.e., which decision to make). "Chance nodes," or nodes representing a chance event over which the decision maker has no control, are represented as circles. Emanating from each node are branches which represent the possible outcomes from the respective nodes. In general, each branch will have a cost, or "consequence," associated with it according to the requirements of the decision model.

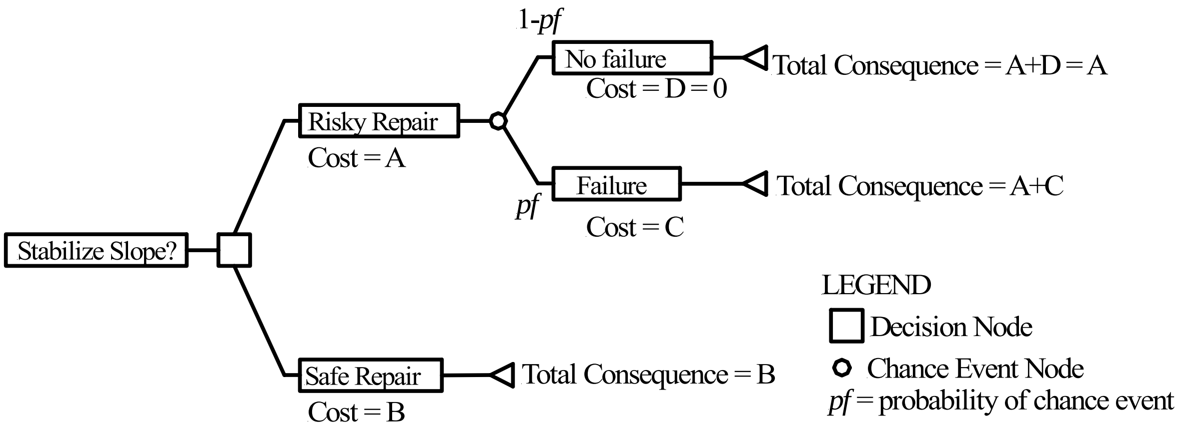

Figure 4.1. Example of a simple decision tree modeling the slope repair problem

In Figure 4.1, the basic slope repair decision is modeled by one decision node representing the decision of whether to stabilize the slope using a "safe" repair measure (i.e., a repair measure that is certain to stabilize the slope in the long-term) or a "risky" repair measure (i.e., a repair measure that may stabilize the slope, but may not!). The lower branch corresponds to the decision of stabilizing the slope using a certain repair technique (one with no chance of being unsuccessful) while the upper branch corresponds to the decision of stabilizing the slope using a risky technique. To each of these branches, a cost is assigned according to the respective costs of the repair techniques; the cost of the risky repair technique is denoted *A* while the cost of the safe repair technique is denoted *B*. Finally, for the risky repair decision, there is some probability that the repair method will be successful, and conversely some probability that the repair will not be successful. By convention, the probability that the repair will not be successful is denoted p_f, for the probability of failure. The probability of success is therefore 1- p_f since the total probability of all alternative chance events must be 1 for any chance node. Some cost may also be applied to each chance outcome (in this case, failure or no failure). In Figure 4.1, these costs are denoted *C* and *D* for the failure and no failure branches respectively.

Each branch of the decision tree, emanating from the left and following respective paths to the right, represents one possible outcome of the decision. For the decision tree shown in Figure 4.1, the possible outcomes include the following:

1. Select the risky repair method, which turns out to be successful.
2. Select the risky repair method, which turns out to be unsuccessful.
3. Select the safe repair method, which is certain to be successful.

Each of these possible outcomes has a consequence equal to the cumulative costs for the respective branch. For outcome 1, the total consequence is equal to *A*—the cost of the risky repair (assuming *D*=0). For outcome 2, the total consequence is equal to *A*+*C*—the cost of the risky repair plus additional costs due to the failure (which may include traffic delay costs, repair of appurtenant structures, and additional repair costs, among others). Finally, for outcome 3, the total consequence is equal to *B*, the cost of the safe, but certain repair.

The preferred alternative ("safe" or "risky" repair method) for the decision represented in Figure 4.1 is selected by evaluating the decision tree for a particular set of input variables (A, B, C, D, and p_f). If the initial cost of the safe repair method (B) happens to be less than or equal to the cost of the risky repair method (A), the decision is trivial since the safe repair method will be less costly than the risky repair method regardless of the values of C, D, and p_f. However, if the cost of the safe repair is greater than the cost of the risky repair, the decision is more of a dilemma and will depend on the values of the remaining variables. For this case, the decision tree is evaluated to establish overall costs for each possible decision ("safe" or "risky" in this case) by weighting the costs and consequences according to the respective probability of occurrence for each chance event. For the case shown in Figure 4.1, the total cost of the upper branch of the tree is

$$\text{Total Cost of Upper Branch} = \mathrm{A} + (1 - p_f)D + p_f C = (1 - p_f)(A + D) + p_f(A + C) \qquad (1)$$

As shown in Equation 1, the total cost of the upper branch (i.e., the decision to use the risky repair method) is computed as the initial cost (A) of the repair, plus the additional costs incurred if the repair method is successful (D) times the probability that the method is successful (1- p_f) plus the additional costs if the method is unsuccessful (C) times the probability that the method is unsuccessful (p_f). In this sense, the total cost is determined as a weighted cost according to the likelihood or probability of each possible outcome of the decision. The total cost of the lower "safe" branch of the tree is simply B, since it is assumed in the development of the tree that the safe repair method will work with complete certainty (i.e., p_f =1). The preferred alternative for a particular set of values is then established by comparing the total cost of the respective branches of the decision node and selecting the branch with the least total cost.

For example, if A is assumed to be \$50,000, B is assumed to be \$100,000, C is assumed to be \$75,000, D is \$0, and p_f =10% (=0.1), the cost of the upper branch is determined to be 0.9(\$50,000)+0.1(\$50,000+\$75,000) = \$57,500 while the cost of the lower branch is simply \$100,000. In this case, the upper branch, or risky repair method, is clearly the preferred alternative. In contrast, if the probability of failure of the risky repair method is much higher, say p_f =80%, the outcome is different. In this case, the cost of the upper branch is \$110,000 while the cost of the lower branch remains \$100,000, and the lower branch, or safe repair method, is the preferred alternative. Similar changes in the preferred alternative can also be realized by varying other input variables.

While the model shown in Figure 4.1 is simple, it demonstrates how the critical aspects of the decision, including initial costs, possible outcomes, and likelihoods of those outcomes can be logically combined and analyzed to arrive at a preferred alternative. Additional complexity, such as incorporating additional possible repair methods or additional possible chance outcomes, can be added to the decision tree without changing the basic analysis technique. More complex decision tree models can be analyzed following the same principles, only with additional computational effort. Commercial software is readily available for analyzing more complex decision tree models, as well as for performing other types of analyses (e.g., sensitivity analyses, Monte-Carlo simulations).

4.1.2. Break-even Analyses

The example presented above shows how decision tree models can be used directly to evaluate the preferred alternative for a decision based on a particular set of input variables. Another way to use decision tree models is to develop so-called "break-even" relations that serve to separate the input variable space (i.e., the range of input values) into "regions" where alternative branches of a decision are preferred. If developed for appropriate ranges of model parameters, such break-even relations can be used by personnel not familiar with formal decision analysis tools to render effective decisions without having to perform specific decision analyses.

The basic premise used to establish break-even relations is to determine what combinations of variables produce identical total costs for the respective branches of a decision node. Taking the simple example presented in Figure 4.1, this means finding the combinations of variables (A, B, C, D, and p_f) such that the value of the upper branch is equal to the value of the lower branch, or

$$B = (1 - p_f)(A + D) + p_f (A + C) = A + (1 - p_f)D + p_f C \qquad (2)$$

If B and A (the respective costs of the repair methods) are assumed to be the primary variables of interest, a break-even relation among these two variables can be established by assuming values of the remaining variables. For example, if the values of C, D, and p_f are assumed to be \$75,000, \$0, and 20%, respectively, the expression for the break-even relation is found to be

$$B = A + \$15{,}000 \qquad (3)$$

which indicates that the break-even line separating the regions where the risky and safe repair methods are preferred is linear. Figure 4.2 shows a plot of this break-even relation over one possible range of interest of values of A and B. Combinations of A and B that fall on the break-even line represent combinations where both the upper and lower branches of the decision tree produce identical total costs. Combinations of A and B that plot above the break-even line represent cases where the risky repair method is preferred (i.e., has lower total cost) while combinations that plot below the break-even line represent cases where the safe repair method is preferred. Furthermore, it should be noted that combinations that fall near to the break-even line represent cases where one alternative is only slightly preferable over the other, while combinations that fall far from the break-even line represent cases where one alternative is clearly preferable. Such information can be extremely useful to decision makers, and it provides some opportunity for applying personal judgment in using the results obtained from the decision tree models.

The primary limitation of the break-even line shown in Figure 4.2 is that it is strictly limited to the values assumed for the remaining decision variables (C, D, and p_f in this case). However, additional break-even analyses can be performed for other possible variable combinations to develop a "family" of break-even lines that are suitable for a range of possible values of the secondary variables. Figures 4.3 and 4.4 show examples of such families of break-even lines for various values of the variables C and p_f.

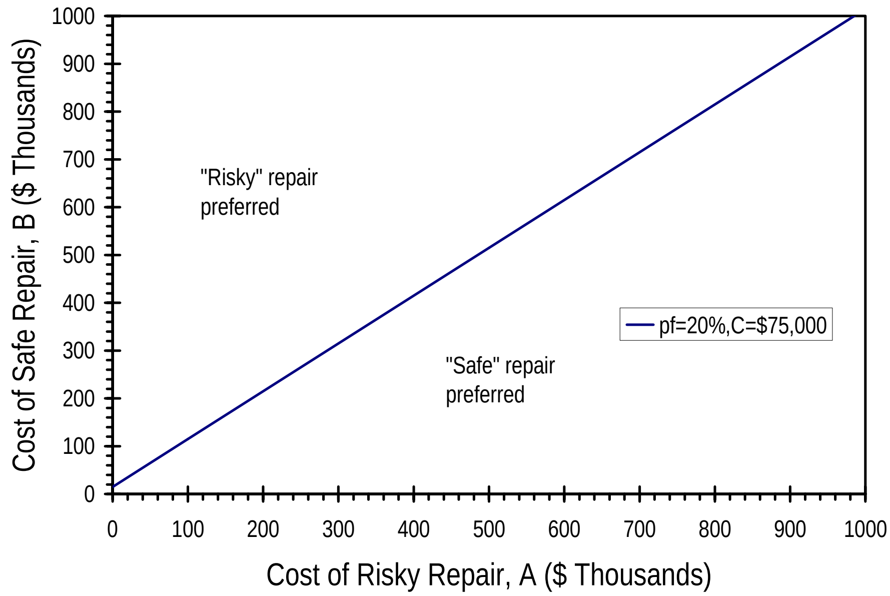

Figure 4.2. Break-even relation for simple decision tree of Figure 4.1 for *C*=$75,0000, *D*=$0, and p_f=20%

For the simple case shown in Figure 4.1, expressions for the break-even lines can be developed analytically to quickly produce break-even lines for a wide range of possible conditions. For more complex decision tree models, development of analytical expressions for the break-even conditions is more difficult, and it is often necessary to resort to specialized software or numerical calculations to develop appropriate break-even relations. Such capabilities were used to develop break-even lines for the more complex models developed for this project.

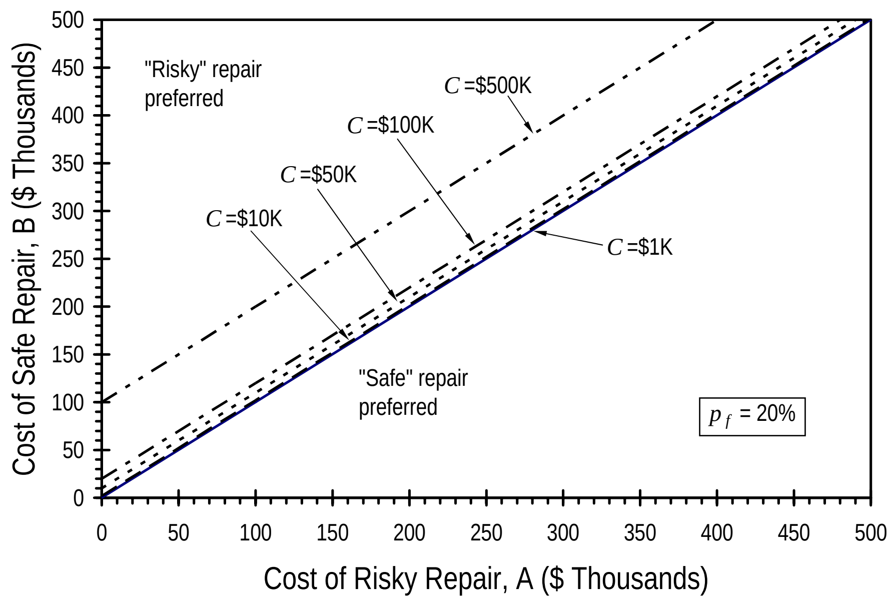

Figure 4.3. Family of break-even lines for different assumed values of *C*

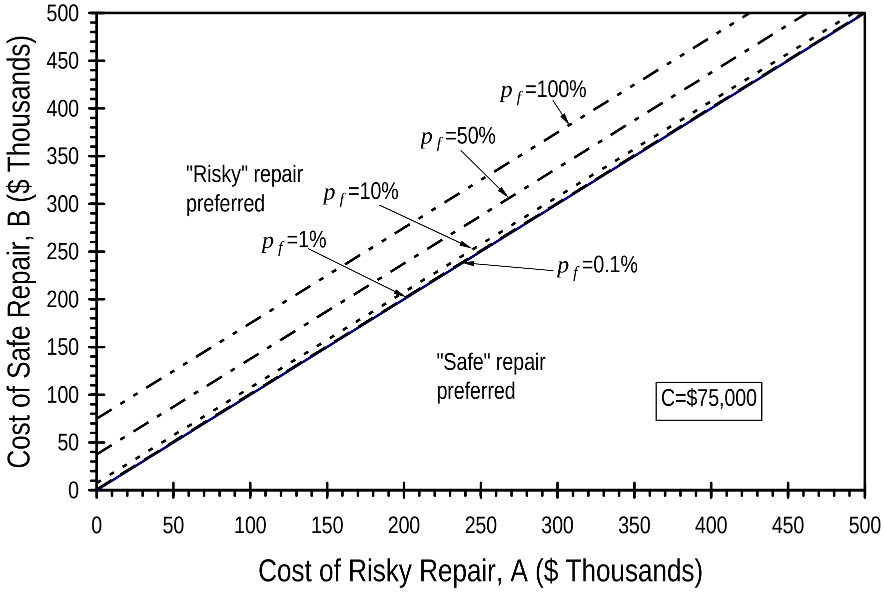

Figure 4.4. Family of break-even lines for different assumed values of p_f

4.2. Decision Models for the Slope Repair Problem

During the project, numerous different decision tree models were developed and evaluated (Huaco 2004). Of these models, two basic model forms were selected as being best suited to modeling the slope repair problem. The first model is referred to as the "Instant in Time," or IIT model because it was developed with the intent of making a repair decision at a given instant in time. The second model is referred to as the "Specific Time Horizon," or STH model because it allows for explicit consideration of the possible outcomes as a function of time. The specifics of each model are described in more detail in the following sections. All models were developed and evaluated using the commercially available decision support software suite, DecisionTools®. It consists of a number of Microsoft Excel "add-ins," as well as stand-alone programs to facilitate development and analysis of alternative decision tree models.

4.2.1. Basic "Instant in Time" Model

The basic "Instant in Time," or IIT model selected for evaluating slope repair decisions is shown in Figure 4.5. The model is similar to the example decision tree presented in Figure 4.1 and described above. However, the stabilization alternatives are now designated as Method A and Method B for more generality, and a chance node has been added to the lower (Method B) branch to allow consideration that Method B may also have some probability of being unsuccessful. As shown in the figure, the initial costs for stabilization using Method A and Method B are denoted as *A* and *B*, respectively. The probability of failure for Method A is denoted as $p_{f\text{-}A}$, while the probability of failure for Method B is denoted as $p_{f\text{-}B}$ to allow for modeling different probabilities for different methods. The consequences associated with failure and no failure following stabilization are denoted as *C* and *D*, respectively, and it is assumed that the consequences of failure or no failure will be identical for both alternative decisions. It is further assumed that the model will be applied such that Method B is the most costly of the two alternative repair measures being considered. The model is general enough to work without this assumption. However, this assumption was made to avoid confusion with negative values for break-even relations presented subsequently.

The decision model shown in Figure 4.5 provides the capability to analyze a wide range of decision scenarios simply by substituting appropriate values for the decision variables. It can be used to evaluate alternative stabilization measures by substituting appropriate values for the respective variables. It can also be used to evaluate whether or not stabilization should be undertaken at all by simply analyzing the model for a preferred stabilization technique (perhaps determined from prior analyses using the model) and for no stabilization. While it is certainly possible to develop other decision tree models with additional alternatives (e.g., a three-method tree, a four-method tree), the same result can be achieved using the two-method model by simply applying the two-method model of Figure 4.5 on a repeated basis. As such, adding additional complexity to the model does not seem warranted. Keeping the model simple also permits analytical expressions to be derived for break-even lines that can, in turn, be used to develop broad generalizations (e.g., rules of thumb), or simple decision tools (e.g., Figures 4.3 and 4.4) to facilitate effective decision making by field personnel.

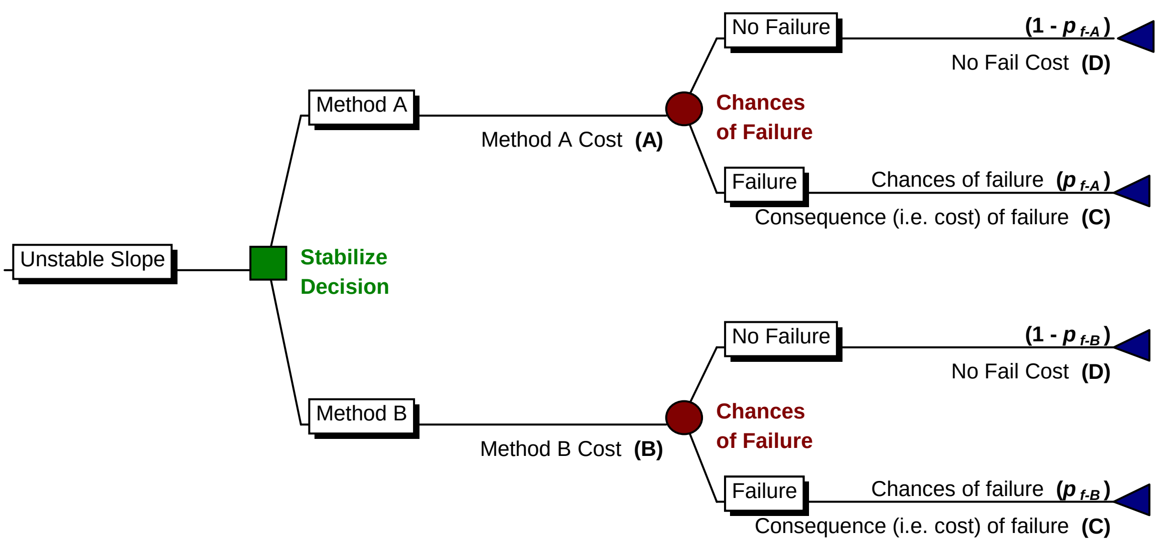

Figure 4.5. Basic Instant in Time model representing the slope repair problem

Using the techniques for analyzing decision trees described above, the total cost of the respective decisions (i.e., Method A or Method B) are found to be

$$\text{Total Cost Method A} = A + (1 - p_{f-A})D + p_{f-A}C = (1 - p_{f-A})(A + D) + p_{f-A}(A + C) \qquad (4)$$

$$\text{Total Cost Method B} = B + (1 - p_{f-B})D + p_{f-B}C = (1 - p_{f-B})(A + D) + p_{f-B}(A + C) \qquad (5)$$

From these expressions, break-even relations can be developed for different pairs of variables by simply equating Equations 4 and 5 and rearranging the expression into a convenient form. Two such relations of interest for the slope repair problem are to define the preferred alternative for different combinations of $p_{f\text{-}A}$ and $p_{f\text{-}B}$, as well as for different combinations of the relative initial costs for Methods A and B (e.g., *B-A*) and the consequences of a future failure (i.e., *C*). Break-even relations and charts for each of these sets of variables are presented in the following sections.

4.2.1.a. Break-even Relations for Basic IIT Model in Terms of $p_{f\text{-}A}$ and $p_{f\text{-}B}$

In general, expressions for break-even lines based on the basic IIT model can be derived by equating Equations 4 and 5. If the consequence of having no failure is assumed to be negligible (i.e., *D*=0), this equation can be expressed as

$$A + p_{f-A}C = B + p_{f-B}C \tag{6}$$

Rearranging Equation 6 to isolate the variables $p_{f\text{-}A}$ and $p_{f\text{-}B}$ leads to the following expression

$$p_{f-A} = \frac{(B-A)}{C} + p_{f-B} \tag{7}$$

which relates the respective probabilities of failure required to produce identical total costs for each alternative decision. Equation 7 is thus the expression for break-even lines in terms of these two variables. The relation is a linear function of the respective probabilities of failure and the term (*B*-*A*)/*C*, which involves the relative initial costs of the alternative stabilization measures and the consequence costs of a future failure (recall that these have been assumed identical for the two stabilization measures).

The form of Equation 7 is convenient because it allows a family of break-even lines to be conveniently developed for an infinite range of costs since the break-even relation is only a function of a dimensionless ratio of costs rather than the absolute magnitude of those costs. Such a family of break-even relations are presented in Figure 4.6 for several values of (*B*-*A*)/*C*. In the figure, combinations of $p_{f\text{-}A}$ and $p_{f\text{-}B}$ that plot below the respective break-even lines indicate that Method A is preferable while combinations of $p_{f\text{-}A}$ and $p_{f\text{-}B}$ that plot above the lines indicate that Method B is preferable.

The break-even line for (*B*-*A*)/*C*=0.0 represents the case where both stabilization measures have equal costs. For this condition, the break-even line is a 1:1 line, which indicates that the method with the lower probability of failure should be selected (as is intuitively obvious). Where (*B*-*A*)/*C*≥1.0, the additional cost of Method B (as compared to Method A) equals or exceeds the potential consequences of failure if Method A is selected. In this case, Method A (the least costly method) is preferable regardless of the respective probabilities since the total cost for Method A (*A*+*C*) is less than or equal to the cost of Method B. For values of (*B*-*A*)/*C* between 0.0 and 1.0, the preferred alternative depends on the relative magnitudes of the probabilities of failure and the relative cost-to-consequence ratio, (*B*-*A*)/*C*.

An interesting result arising from Equation 7 and Figure 4.6 is that as the relative cost-to-consequence ratio, (*B*-*A*)/*C*, increases, the range of probabilities for which Method A (the least costly method) is preferable increases. This suggests that, for cases where the consequences of failure are relatively small (thus making the relative cost-to-consequence ratio high), low cost stabilization measures are generally preferred over higher cost stabilization measures. However, this observation must be tempered due to the realization that the consequences of a method with a high probability of failure may in fact be higher than for a method with a lower probability of failure since repeated stabilization measures may have to be applied in the former case. This possibility is not modeled in the basic IIT model. This is a notable limitation of the basic IIT model, and one that must be addressed before the model can be implemented. Possible methods for addressing this limitation are presented subsequently in this report.

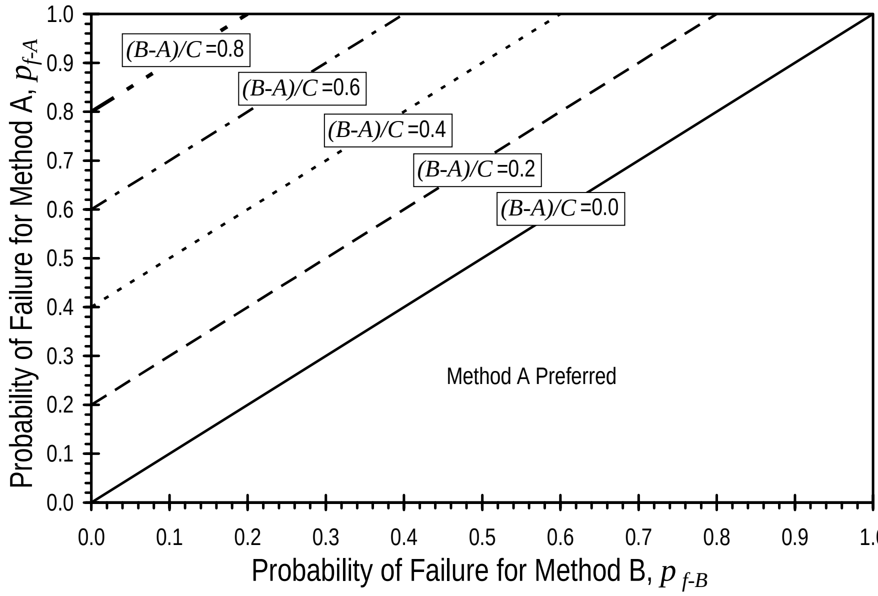

Figure 4.6. Break-even lines for Basic IIT Model in terms of $p_{f\text{-}A}$ and $p_{f\text{-}B}$

4.2.1.b. Break-even Relations for Basic IIT Model in Terms of B-A and C

Another useful form of break-even relation for the basic IIT model is to present break-even lines in relative cost (*B-A*) versus consequence (*C*) space. Rearranging Equation 7 produces the following expression

$$(B - A) = (p_{f-A} - p_{f-B})C \tag{8}$$

which defines this break-even relation. Break-even lines calculated using this relation for a range in possible relative costs (*B-A*) and consequence costs (*C*) are presented in Figure 4.7. As was the case with Figure 4.6, combinations of (*B-A*) and *C* that fall below the respective break-even lines indicate that Method A is the preferable alternative, while combinations that fall above the respective lines indicate that Method B is preferable. The extremes of the break-even lines occur for ($p_{f\text{-}A}$ - $p_{f\text{-}B}$)=0.0 and ($p_{f\text{-}A}$ - $p_{f\text{-}B}$)=1.0. For ($p_{f\text{-}A}$ - $p_{f\text{-}B}$)=0.0, the probabilities of failure are identical and the least costly method (assumed Method A in the model) will always be preferable regardless of the relative initial costs or consequence costs (this is strictly true as long as the consequence costs, *C*, are identical for methods A and B). The break-even line for this case is coincident with the vertical axis. For ($p_{f\text{-}A}$ - $p_{f\text{-}B}$)=1.0, $p_{f\text{-}A}$ must equal 1.0 and $p_{f\text{-}B}$ must equal 0.0. In this case, the break-even line is a 1:1 line, indicating that Method A is only preferable if the consequences of failure (*C*) are less than the additional costs for selecting Method B over

Method A (this is, in fact, the condition represented by the simple example presented in Figure 4.1). Break-even lines for intermediate values of $p_{f\text{-}A}$ - $p_{f\text{-}B}$ fall between these two extremes.

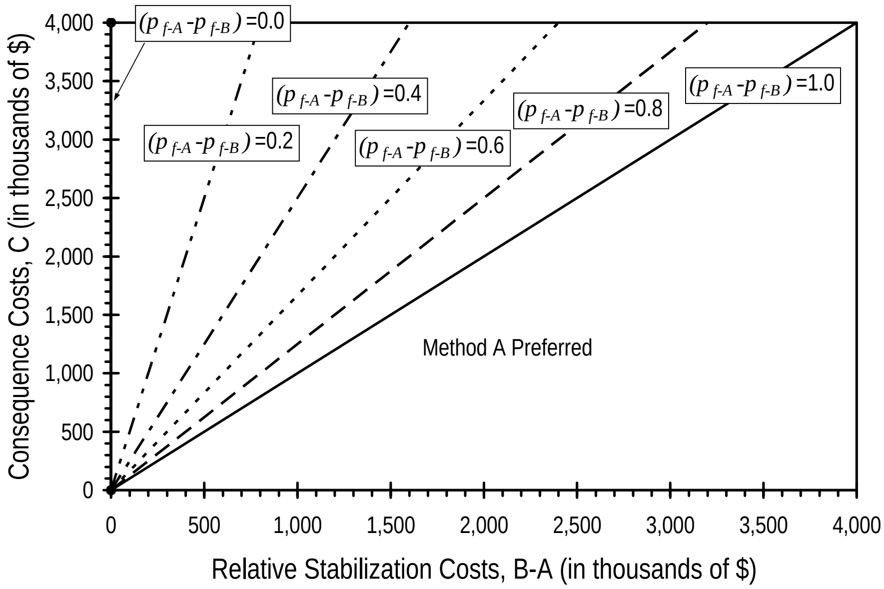

Figure 4.7. Break-even lines for Basic IIT Model in terms of (*B-A*) and *C*

Break-even lines presented in both Figures 4.6 and 4.7 produce identical results for a given set of input variables (A, B, C, $p_{f\text{-}A}$, and $p_{f\text{-}B}$, with D assumed negligible) and, thus, can be used interchangeably. However, Figure 4.6 is more generally applicable since it covers the complete range of possible input variables (i.e., any possible costs and any possible probabilities), while Figure 4.7 must be restricted to some range of possible relative costs and consequence costs.

4.2.1.c. Application of the Basic IIT Model

Given the values of the input variables, A, B, C, $p_{f\text{-}A}$, and $p_{f\text{-}B}$, application of the basic IIT model is relatively straightforward. The variable values can be directly substituted into either of Equations 7 or 8 to establish the preferred decision, or alternatively, the variable values can be used to compute the relevant parameters for Figures 4.6 and 4.7 to establish the preferred alternative. To demonstrate application of the model, data acquired from the Oregon Department of Transportation (ODOT 2001) can be used as a "case study" for application of the basic model.

In this case study, the decision to be made is whether to stabilize a slope using a hypothetical risky stabilization technique or using a "tried and true" technique believed to provide certain stabilization. The cost of the risky stabilization is assumed to be \$350,000 (i.e., A=\$350,000), while the cost of the "tried and true" technique is assumed to be the average cost of all stabilizations in the ODOT database, or \$589,794 (i.e., B=\$589,794). Since the cost of the risky stabilization method is lower than that of the tried and true method, the risky method is assigned as Method A and the tried and true method as Method B. As is assumed in all existing slope decision support systems, the probability of failure of the tried and true method, $p_{f\text{-}B}$, is assumed to be zero to reflect the belief that the stabilization measures are certain to stabilize the slope. In contrast, the probability of failure of the risky stabilization method, $p_{f\text{-}A}$, is assumed to be 30%.

The consequences of future failure, cost *C*, was taken to be the average of the 24-hour traffic delay costs for all cases in the ODOT database, or \$603,819 (i.e., *C*=\$603,819). (While other costs could be included in the consequence costs as described subsequently, the 24-hour delay costs tend to dominate the consequences so for this example consequence costs were simply assumed to be the 24-hour delay costs.)

For these variables, the relative cost-to-consequence ratio is found to be

$$\frac{(B-A)}{C} = \frac{(\$589{,}794 - \$350{,}000)}{\$603{,}819} = 0.4 \qquad (8)$$

which is one of the break-even lines plotted in Figure 4.6. Plotting the point for the respective probabilities of failure ($p_{f\text{-}A}$ =0.3 and $p_{f\text{-}B}$ =0.0), as shown in Figure 4.8, reveals that the point lies below the appropriate break-even line, which indicates that the risky stabilization technique (Method A) is preferred in this case.

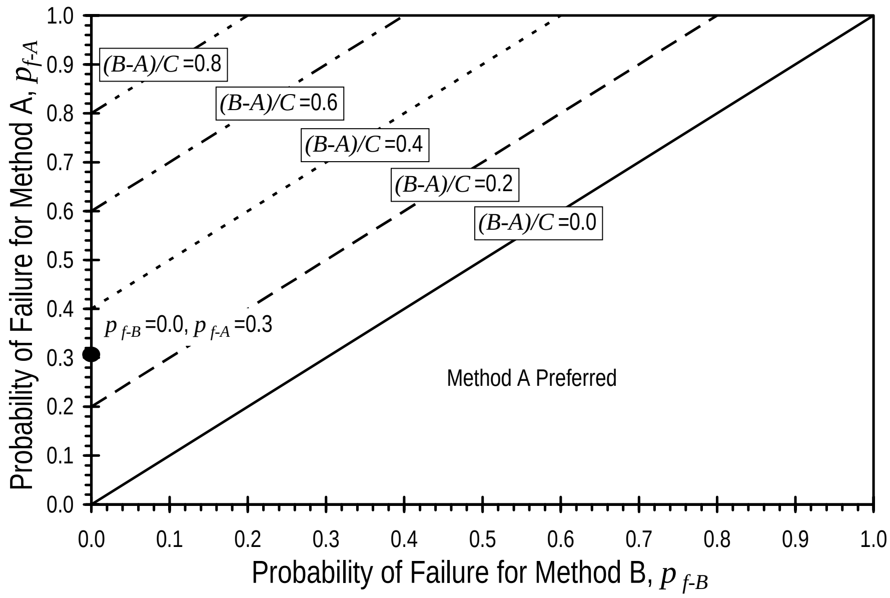

Figure 4.8. Application of basic IIT model using input from ODOT database

Also from Figure 4.8, it can be noted that the same conclusion (decision) would be reached if the probability of failure of the risky method ($p_{f\text{-}A}$) were as high as 0.4 in this case. This observation would give the decision maker some comfort in knowing that the decision would remain the same even if a slightly higher probability of failure were assigned to the risky method. If the results were such that the decision might change for small changes in $p_{f\text{-}A}$ or $p_{f\text{-}B}$ (e.g., if $p_{f\text{-}A}$ were instead 0.4), the decision maker might then decide to more rigorously evaluate $p_{f\text{-}A}$ and $p_{f\text{-}B}$ instead of simply assuming rough values.

A similar technique can be used with Figure 4.7 to establish appropriate ranges of the relative costs of stabilization where the decision would remain the same. As shown in Figure 4.9, the appropriate point for the input data provided corresponds to (*B*-*A*)=\$239,794 and *C*=\$603,819. The appropriate break-even line for ($p_{f\text{-}A}$ - $p_{f\text{-}B}$)=0.3 lies halfway between the break-even lines for

($p_{f\text{-}A}$ - $p_{f\text{-}B}$)=0.2 and 0.4. Following the line shown for consequence costs of *C*=\$603,819 suggests that the same decision would be made for *B-A* less than approximately \$175,000. This again provides useful information to the decision maker regarding the importance of the input variables and the need for possible additional analyses to refine the input values.

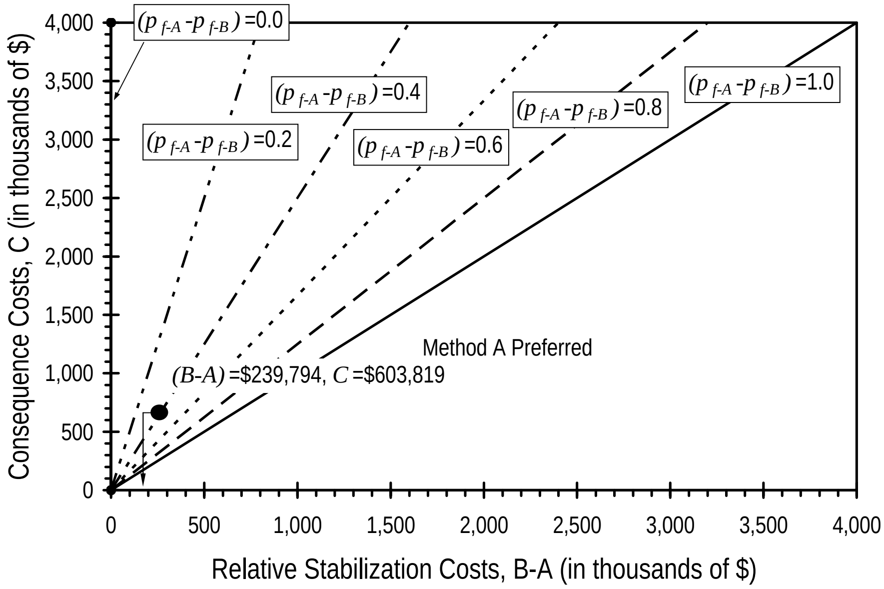

Figure 4.9. Application of basic IIT model using input from ODOT database

It is also important to note that use of the basic IIT model, or any decision tree model for that matter, does not necessarily imply that the recommended decision will always be successful when played out in reality. The recommended decision is simply the decision that is preferred if applied to a large number of cases on a consistent basis. It is certainly possible for a recommended stabilization to experience a failure, and if so, the costs for the recommended procedure may in fact be greater than the costs that would have been encountered had the alternative stabilization technique been implemented. However, over 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.

4.2.1.d. Limitations of the Basic IIT Model

The basic IIT model, as presented above, is subject to two primary assumptions. The first assumption is that the consequences of having no future failure are negligible (i.e., *D*=0). Consequences of having no failure may include such costs as maintenance costs (e.g., mowing, painting, and general upkeep). There may be instances where such costs may be a significant component of the decision. In such instances, the basic IIT model must be modified to incorporate such costs in addition to the initial costs and consequence costs. These instances are believed to be relatively rare, however, so this limitation is not believed to be significant.

A more significant limitation of the model as presented is the assumption of having identical consequences for both branches of the model regardless of the probabilities of failure associated with each branch. As discussed above, this assumption limits the applicability of the model analysis to a “one-time” repair, in essence comparing the cost of applying each stabilization technique only once. However, the consequence of more interest is really the cost of making a decision over some finite time horizon (e.g., a “design” life). For this question, the consequences associated with a more risky repair method may include having to repeatedly apply a stabilization technique over the time horizon of interest, while a less risky repair method may have to be applied less frequently and perhaps only once. Therefore, the basic IIT model, as presented, does not accurately consider life-cycle costs and must be modified to include such considerations. The Specific Time Horizon, or STH model described below represents one approach for more accurately comparing alternative stabilization methods by incorporating life-cycle costs. Other modifications could also be incorporated into the IIT model to account for life-cycle costs. However, these modifications were not considered in the current project.

4.2.2. Basic “Specific Time Horizon” Model

The basic “Specific Time Horizon,” or STH decision tree model was developed following a similar logic to that used to develop the IIT model, but with modifications to account for the possibility of having to apply a specific repair technique multiple times over a specific time horizon. In developing the STH model, the basic assumption was made that the minimum recurrence interval for slope failures at a specific site is one year. Therefore, the model incorporates a yearly cycle upon which the possibility of having a slope failure for a particular stabilization method is evaluated. While it is certainly possible that multiple failures can occur within a single year, experience with nuisance slides suggests that having multiple failures per year at a given site is rare. This assumption therefore seems justified. Consideration of having multiple failures per year can be incorporated into the model in the future if such consideration is deemed important.

Two alternative forms of STH models developed as a part of this project are presented below. Each is intended to evaluate the slope repair problem over specific time intervals. However, the two forms differ slightly in projecting possible future outcomes over the time horizon of interest.

4.2.2.a. Three-Method STH Model

The first form of the STH model is referred to as the “Three-Method STH” model because it can be used to evaluate among three alternative stabilization methods over specified time horizons. Figure 4.10 shows the Three-Method STH model for a time horizon of two years. Referring to Figure 4.10, the “root,” or primary decision of the model is to select the preferred method among three different possible methods being evaluated (Methods A, B, and C). As was the case with the IIT model, each method has some initial costs associated with constructing the repair that are denoted as A, B, and C for Methods A, B, and C, respectively. Each method also has some probability of failure, which is now an “annual” probability of failure since each chance node now represents the possibility of having a failure within one year. The respective probabilities of failure are denoted as $p_{f\text{-}A}$ for Method A, $p_{f\text{-}B}$ for Method B, and $p_{f\text{-}C}$ for Method C. The consequences of failure for each method are similarly represented by the variables X, Y, and Z for Methods A, B, and C, respectively, and the consequences of no failure are represented by the variables T, U, and V for the respective methods.

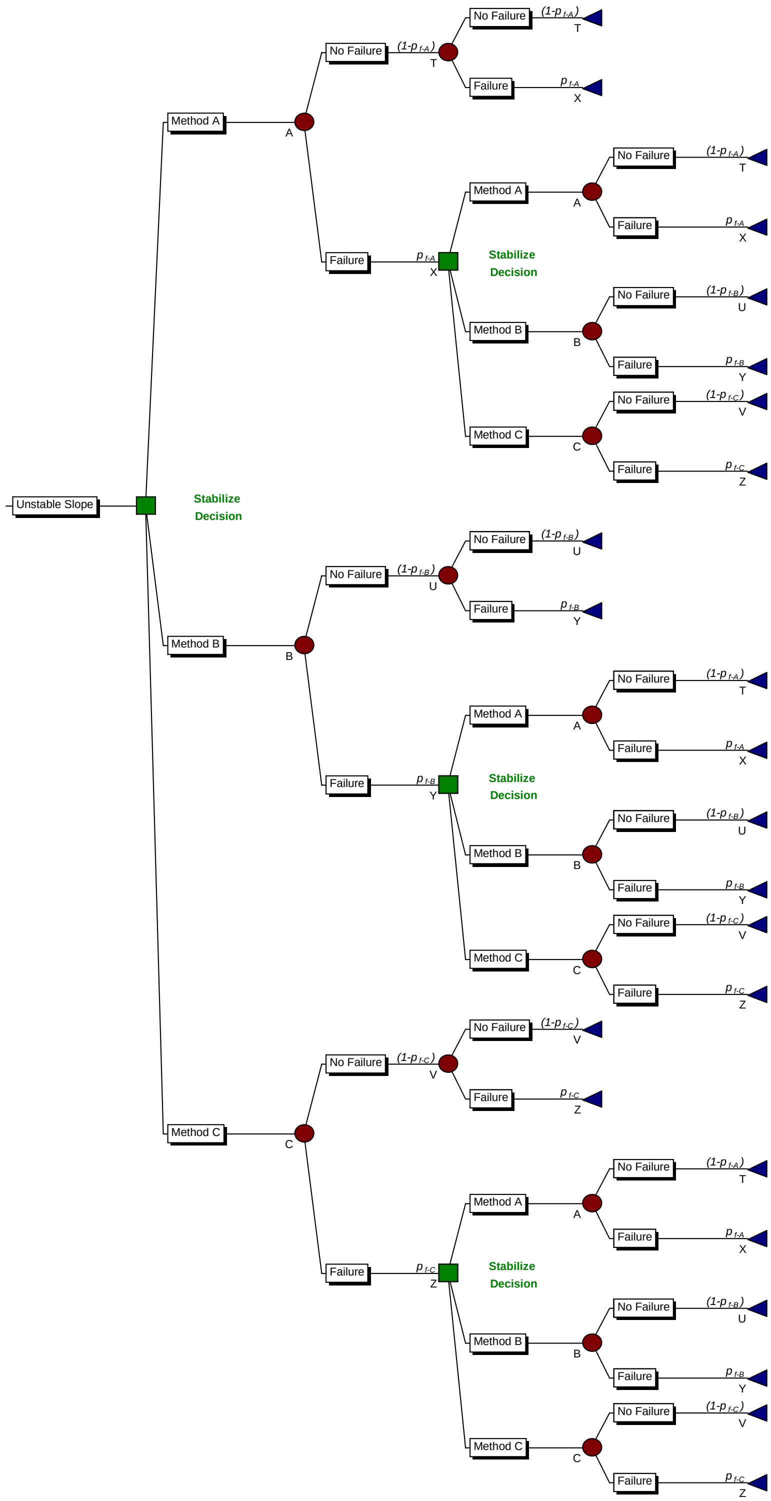

Figure 4.10. Three-method Specific Time Horizon model for two-year time horizon

The basic form of the model from the root decision through the first series of chances nodes (working from left to right) is identical to that used for the IIT model except that a third, Method C, branch has been added for simultaneous comparison of three methods. This first level of the model is used to represent the first year after application of the stabilization scheme. Beyond the first level, an additional level of branches has now been added to represent a second year after application of the stabilization scheme. In this second level, additional decision and chance nodes are added to model the second year depending on whether a failure has occurred during the first year or not. In cases where no failure has occurred during the first year (i.e., at a "no failure" branch in the first level of the tree), a chance node is added to the respective branches to represent the chance of having a failure during the second year. In cases where a failure has occurred during the first year (i.e., at a "failure" branch in the first level of the tree), it is assumed that the decision maker will again decide among the three alternative methods being considered. Therefore, a decision node is added to the respective branches to represent the three possible choices and the associated chance nodes and consequences of those choices (in effect, adding a complete level to the tree for the second year). In all cases, all variables have been assumed to remain constant throughout the specified time horizon.

Additional levels can similarly be added to the decision tree model to represent additional years within the time horizon of interest. However, it is obvious from comparison of the one-level model in Figure 4.5 and the two-level model in Figure 4.10 that the number of branches, and therefore the number of possible outcomes of the root decision, grows dramatically with each added level (or year). Even for the relatively short two-year time horizon considered in Figure 4.10, the use of numerical tools to evaluate the decision tree models is imperative. Even with numerical methods, the computational effort required to evaluate the three-method STH model for reasonable time horizons of interest can become substantial, often requiring on the order of 20 minutes to evaluate the model for a given set of input variables.

For this project, three-method STH models were developed for time horizons of up to 5 years. The primary advantage of these models is that they are capable of modeling the actual decisions as a function of time with reasonable accuracy by incorporating consideration of multiple stabilization methods throughout the time horizon of interest. However, this accuracy comes with the substantial costs of additional complexity and computational effort as discussed previously. In addition, the three-method STH models are not readily extended to incorporate additional methods (e.g., a four-method or five-method STH model) without reformulating the entire model, which requires extensive effort for time horizons that are likely to be of interest (perhaps 20 years or more). Because of these limitations, efforts to develop similar models for longer time horizons were abandoned in preference to a simpler, although slightly more approximate model as described subsequently.

4.2.2.b. Break-even Relations for Three-Method STH Model in Terms of $p_{f\text{-}A}$ and $p_{f\text{-}B}$

The three-method STH model was used to develop break-even relations similar to those shown for the basic IIT model in Figure 4.8 for time horizons of up to five years. For all of these analyses, the initial cost and probability of failure for Method C were artificially set to be very high so that, in effect, the three-method model becomes a two-method model. Furthermore, the consequence costs for each method were assumed to be identical (i.e., X=Y=Z). While the latter assumption may not hold for all possible analysis conditions, it is believed to be reasonable for "typical" applications where break-even relations are expected to be useful. It is important to emphasize that the model itself is not subject to these assumptions, only the break-even relations presented in this section. Thus, special cases where the consequences of alternative repair methods differ, or where the "base values" used to develop the break-even relations differ appreciably from those appropriate for the special case, could be analyzed individually using the basic model with appropriate input parameters.

Figure 4.11 shows the specific break-even relations determined using the three-method STH model for a five year time horizon. In the figure, break-even lines are shown for relative cost-to-consequence ratios, $(B\text{-}A)/X$, of 0.1, 0.5, and 0.9, which were calculated assuming that both B and X were equal to \$600,000. It is not currently known whether these relations are generally applicable for other assumed values of these variables. However, evidence from a series of evaluations using alternative values of B and X indicates that the break-even relations are not sensitive to the assumed values and, therefore, are applicable over a reasonably large range. Additional evaluations are still needed to definitively confirm or refute whether these relations can be used for broad ranges in costs. If these analyses show that the break-even relations vary substantially for different cost levels, it will be necessary to develop several sets of break-even relations that can be applied over different ranges in costs.

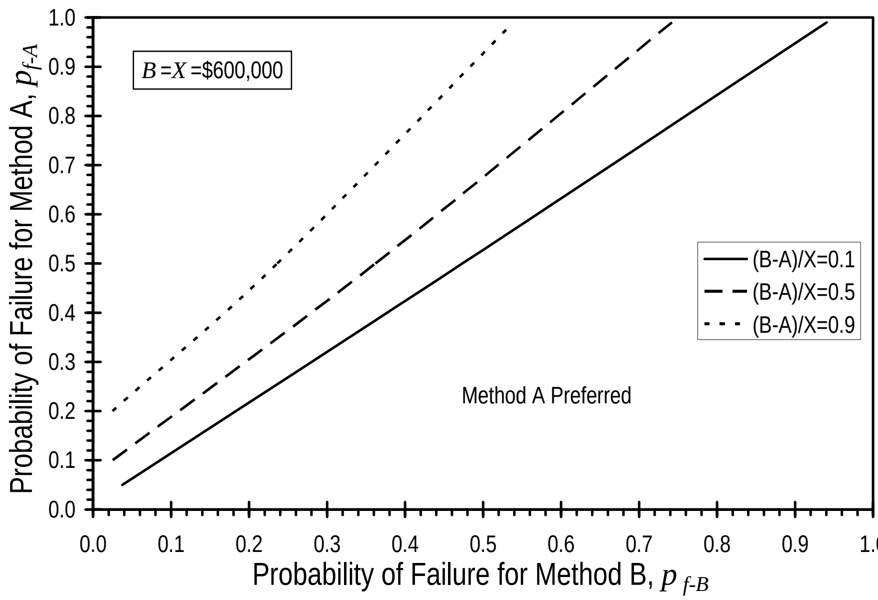

Figure 4.11. Break-even lines determined using the three-method STH model for a five-year time horizon with B=X=\$600,000

As was the case with break-even lines for the IIT model (Figure 4.8), the break-even lines are observed to rise with increasing relative cost-to-consequence ratios. However, unlike the break-even lines for the IIT model, the break-even lines for the three-method STH model are not parallel and do not increase in direct proportion to the relative cost-to-consequence ratio. Furthermore, the break-even lines determined using the three-method STH model are slightly non-linear as a result of the possibility of "switching" between stabilization methods during the specified time horizon.

In the extreme case of $(B\text{-}A)/X$ equal to 0.0, which corresponds to having identical costs for Methods A and B, the break-even line again corresponds to a 1:1 line in Figure 4.11, which indicates that the most reliable method should be selected (as again is intuitively obvious). The break-even relations for the three-method STH model also do not predict an obvious "upper limit" on the relative cost-to-consequence ratio above which the preferred alternative becomes obvious. Additional break-even lines may therefore be needed for relative cost-to-consequence ratios above 1.0.

4.2.2.c. Constant-method STH Model

The constant-method STH model represents a simplification of the three-method STH model described previously. The simplification adopted for the constant-method STH model is to assume that a single stabilization method will be adopted throughout the specified time horizon rather than permitting the stabilization method to be changed within the time horizon as is modeled in the three-method STH models. While this simplification somewhat restricts the accuracy of the model in that a decision maker might choose to use an alternative repair method after unsuccessful application(s) of one stabilization technique, the constant-method model addresses several of the distinct disadvantages of the three-method STH model discussed above. In the worst case, it is believed that the constant-method STH model can serve as a reasonable approximation to the more rigorous three-method STH model (or future "n-method" STH models).

Figure 4.12 shows one branch of the constant-method STH model for a two year time horizon. In general, the model is composed of similar to the three-method STH model components, except that the method is assumed to remain the same. In fact, only one branch of the model is needed for comparison of any number of different methods since appropriate variable values for a method can simply be substituted for the variables shown. The total costs determined for different methods using the model shown in Figure 4.12 can then simply be compared to establish the preferred alternative. Furthermore, the model in Figure 4.12 can be used to develop break-even relations numerically by simply varying the variable values until the total costs for different methods become equal. This approach was used to develop the break-even relations presented subsequently.

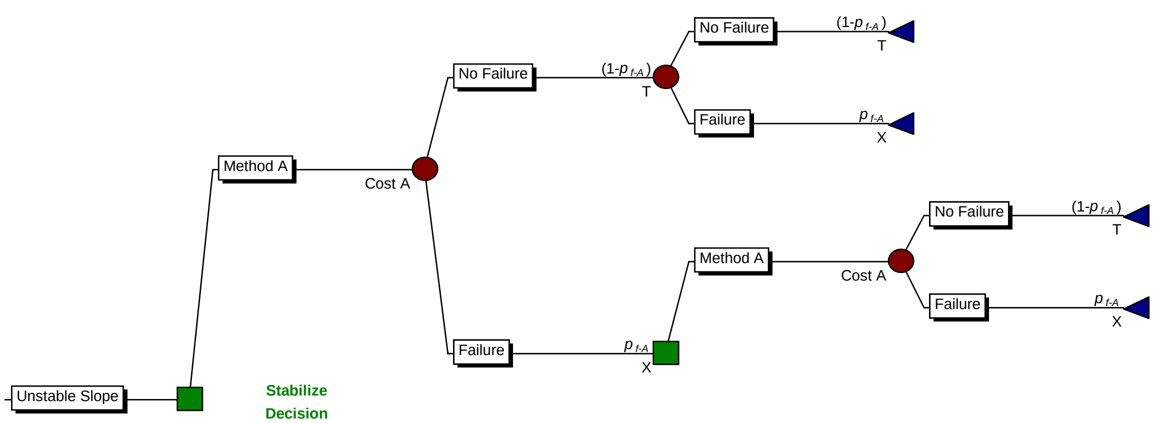

Figure 4.12. Method A branch of constant-method Specific Time Horizon model for two-year time horizon

As was the case with the three-method STH model, additional levels can be added to the model to represent increasing time horizons with one level being added for each year in the time horizon. Adding additional levels again increases the size of the model. However, as can be observed by comparison of Figures 4.10 and 4.12, the constant-method STH model grows at a dramatically lower rate with increasing time horizons, which limits the computational effort required to analyze cases with large time horizons. Furthermore, the simplified form of the constant-method STH model permits analytical algorithms for computing the total costs (now life-cycle costs) to be developed. At present, such algorithms have been implemented in Microsoft Excel for time horizons of up to 20 years. Implementation of the algorithms for longer time horizons will require additional effort, but much less so than with the "n-method" STH models. Finally, the constant-method STH model can be used to compare any number of possible stabilization methods since the total life-cycle costs for each method are independent in the constant-method model.

4.2.2.d. Break-even Relations for Constant-method STH Model in Terms of $p_{f\text{-}A}$ and $p_{f\text{-}B}$

Break-even relations in terms of $p_{f\text{-}A}$ and $p_{f\text{-}B}$ were again determined numerically for the constant-method STH model. However, since the constant-method model is much simpler, break-even relations could be developed for time horizons of both 5 and 20 years. Figures 4.13 and 4.14 show the break-even relations determined for time horizons of 5 and 20 years, respectively. These relations were again computed assuming that B=X=\$600,000 and are therefore strictly only applicable to cases with costs that are reasonably close to these values. In cases where the "base values" of B and X are substantially different from those assumed, alternative break-even relations could be developed, or the basic model could be applied directly using the appropriate input values. The break-even relations shown for time horizons of 5 and 20 years again follow the general trends exhibited in Figures 4.8 and 4.11. For the constant-method STH model, all break-even relations were found to be linear in $p_{f\text{-}A}$ versus $p_{f\text{-}B}$ space but were not found to increase linearly with the relative cost-to-consequence ratio.

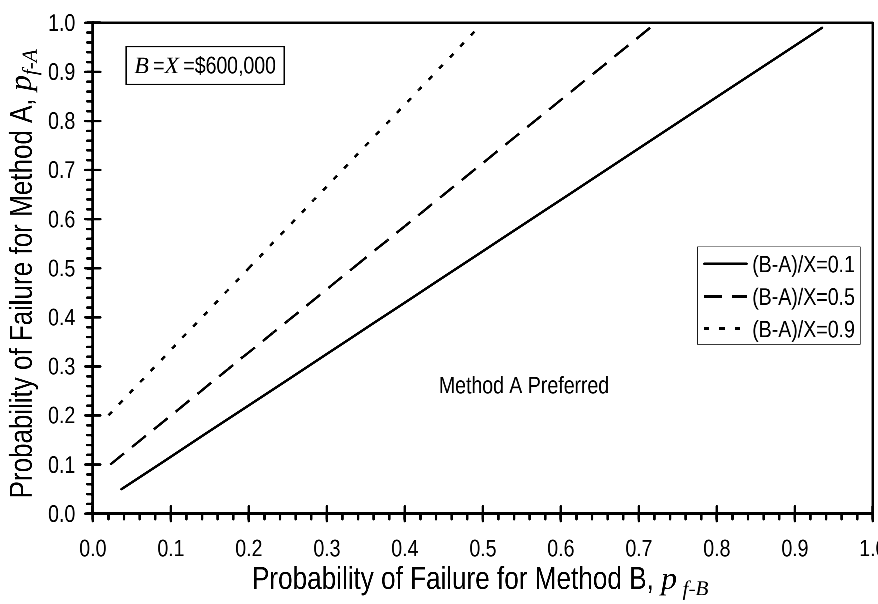

Figure 4.13. Break-even lines determined using the constant-method STH model for a five-year time horizon with B=X=\$600,000

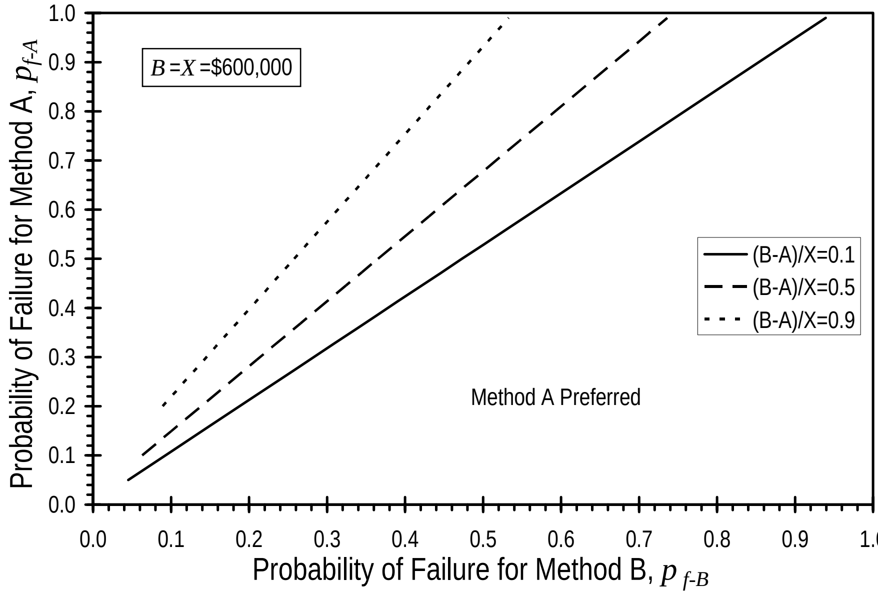

Figure 4.14. Break-even lines determined using the constant-method STH model for a twenty-year time horizon with *B*=*X*=$600,000

4.2.2.e. Comparison of Break-even Lines for Alternative STH Models

It is of interest to compare the break-even lines determined using the various STH models to draw conclusions regarding the different assumptions inherent in the respective models. Such comparisons are provided in Figures 4.15 and 4.16. Figure 4.15 shows a comparison of the break-even lines determined using the three-method and constant-method STH models for a time horizon of 5 years (recall that the break-even lines for the three-method STH model were determined using arbitrarily high values for the initial cost and probability of failure for Method C, so the results are in fact representative of a two-method STH model). In the figure, break-even lines determined with the three-method STH model are shown using heavy lines, while the break-even lines determined with the constant-method STH model are shown using light lines with similar dash patterns used for identical relative cost-to-consequence ratios. As shown in the figure, the break-even lines determined using the two models are reasonably consistent, although the difference tends to increase with increasing relative cost-to-consequence ratio. As expected, the break-even lines for the three-method STH model are consistently below those of the constant method model which indicates some preference towards Method A (the less costly, more risky method) for the constant-method model. This is a result of the fact that, for some possible outcomes of the model, switching stabilization methods during the specified time horizon can provide slightly lower total costs. However, when viewed from the perspective of the likely precision of the respective model input values, the results determined using the three-method and constant method models can, for practical purposes, be viewed as being identical.

Break-even lines determined using the constant-method STH model for time horizons of 5 and 20 years are compared in Figure 4.16. In this figure, heavy lines are used for break-even lines for a 20 year time horizon while light lines are used for break-even lines for a time horizon of 5-years. Similar dash patterns are again used for break-even lines determined for the same relative cost-to-consequence ratios. The figure shows potentially significant differences in the break-even lines determined for the two time horizons. The break-even lines are very similar for a relative cost to consequence value of 0.1, but become less similar as the relative cost-to-consequence ratio increases. This observation is consistent with that drawn from Figure 4.15, which suggests that the assumptions employed in the respective models are less important when the consequences are high relative to the differences in costs of the method (i.e., as conditions approach those of equal costs for different methods). It is also apparent that the break-even lines for the two different time horizons have different slopes. At relatively high values for the probability of failure, the respective break-even lines are reasonably close, while at low values of the probability of failure the differences are substantial. It can also be noted that the break-even lines for a 20 year time horizon are consistently lower than those for a 5 year time horizon. These observations suggest that the duration of the time horizon is particularly important for relatively low values of the probability of failure and that some preference should be given to Method A (the less costly, more risky method) for short time horizons (e.g., for temporary slopes or sites where future construction is planned), while more preference should be given to Method B (the more costly, less risky method) for longer time horizons (e.g., for permanent slopes).

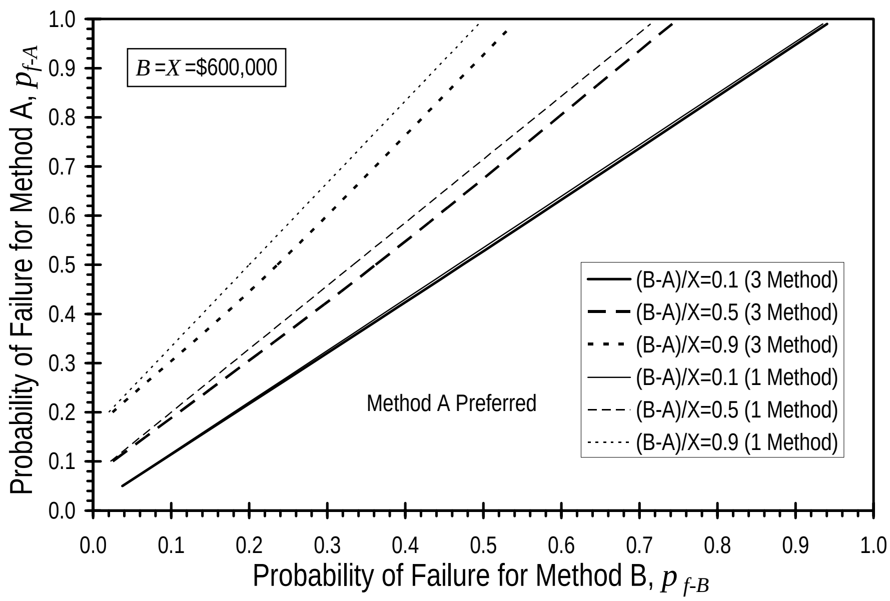

Figure 4.15. Comparison of break-even lines determined for a time horizon of 5 years using the three-method and constant-method STH models

4.2.2.f. Application of the STH Models

Application of the STH models is again relatively straightforward given appropriate values for the input variables. The most direct method for applying the models is to simply input appropriate variable values into the respective numerical models, all of which are implemented in Microsoft Excel and commercially available "add-ins." This method has the distinct advantage of enabling the decision maker to compute values for specific decision conditions without requiring approximations due to simplifying assumptions (other than those involved in the models themselves) or interpolation. However, the approach requires the availability of the numerical models and can require significant personal and computational effort for some scenarios. The "direct application" approach is therefore recommended only for cases where the decisions are deemed critical (e.g., where significant cost is involved and where significant effort can be justifiably put into determining the respective model variables). For more common applications, we recommend that decision makers utilize the break-even graphs presented above, or similar graphs developed for enhanced models designed to address the limitations of current models. This approach has the distinct advantage of being relatively simple and quick and is expected to produce results (decisions) that are generally consistent with those that would be obtained from direct application of the models, particularly with respect to the precision that can be expected of the various input parameters. The following hypothetical examples developed using the database acquired from ODOT illustrate application of the break-even graphs for a "typical" scenario.

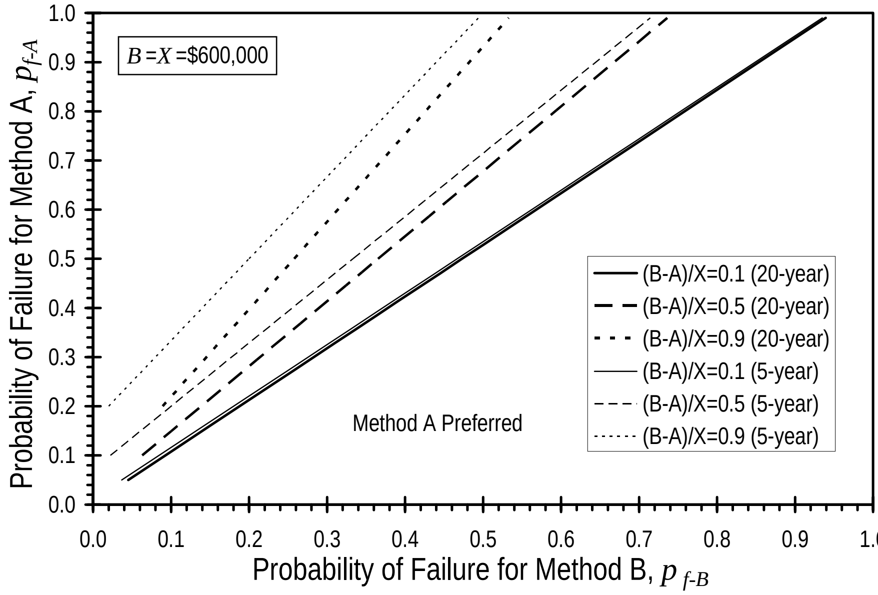

Figure 4.16. Comparison of break-even lines determined for time horizons of 5 and 20 years using the constant-method STH model

The first example involves the same scenario as the previous example used to demonstrate application of the IIT model. In this example, the cost of the "risky" stabilization method (deemed Method A) is assumed to be \$350,000 (i.e., A=\$350,000), while the cost of the "tried and true" stabilization method (deemed Method B) is again assumed to be the average cost of all stabilizations in the ODOT database, or \$589,794 (i.e., B=\$589,794). The probability of failure for Method A ($p_{f\text{-}A}$) is assumed to be 30%, while the probability of failure of Method B ($p_{f\text{-}B}$) is assumed to be zero since the method is assumed to be a "certain" stabilization. The consequences of future failure, cost X, was taken to be the average of the 24-hour traffic delay costs for all cases in the ODOT database, or \$603,819 (i.e., C=\$603,819) and was again assumed to be identical for both methods (i.e., X=Y). (The fact that the consequences of a future failure are assumed identical for application of the STH models does not present the same limitations as discussed previously for the IIT model because the *number* of failures, and hence the cumulative costs of future failures, can be different for different methods and outcomes in the STH models.) Based on these values, the relative cost-to-consequence ratio $(B\text{-}A)/X$ is again equal to 0.4. For this instance, the break-even lines developed for $(B\text{-}A)/X$ equal to 0.5 were therefore used as a reasonable approximation for the break-even lines to determine the appropriate decision. (In reality, break-even lines for (B-A)/X=0.4 would fall just slightly below those presented for (B-A)/X=0.5; however, given the expected precision of the input variables, such an approximation seems justified.)

Figure 4.17 shows the point corresponding to $p_{f\text{-}A}$ =0.3 and $p_{f\text{-}B}$ =0.0, plotted on the break-even lines developed using the constant-method STH models (Figure 4.16). As shown, the point corresponding to $p_{f\text{-}B}$ =0.0 and $p_{f\text{-}A}$ =0.3 lies well above the break-even line for (*B*-*A*)/*X*=0.5 for both the 5 year and 20 year time horizons, which indicates that in both cases the preferred decision is to stabilize the slope using the tried and true (more costly, more reliable) stabilization method. This conclusion is in contrast to the decision predicted by the basic IIT model, which only considers the possibility of having a single future failure. The difference in the recommended decisions is a result of more accurately accounting for the fact that multiple future 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. It is also important to note that the same conclusion would be drawn using break-even lines determined from the three-method STH model or from a more accurately determined break-even line for (*B*-*A*)/*X*=0.4.

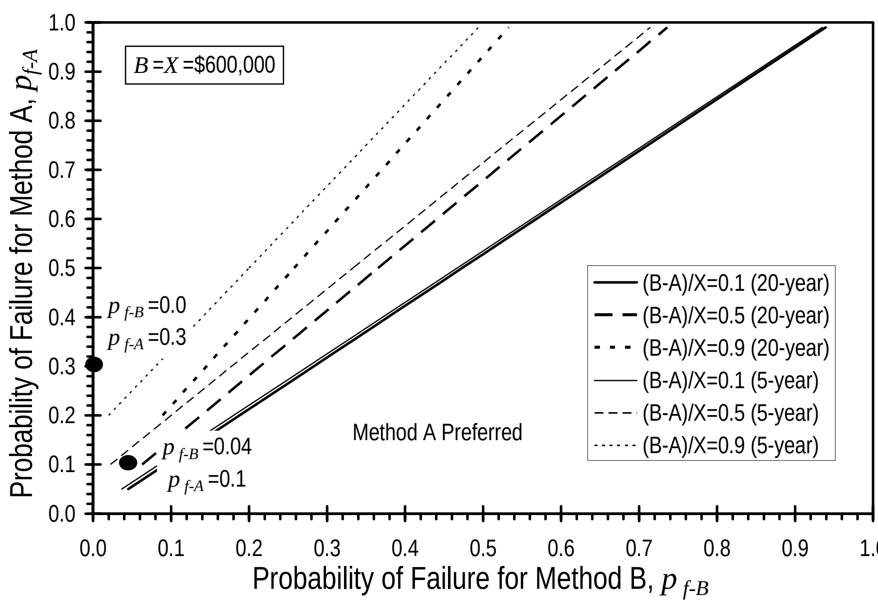

Figure 4.17. Application of constant-method STH model for two example problems based on input from ODOT database

The second example considered is similar to the first example, except that the probabilities of failure are assumed to be 10% for Method A (i.e., $p_{f\text{-}A}$ =0.1) and 4% for Method B (i.e., $p_{f\text{-}B}$ =0.04). These probabilities are more typical of what might be expected for most commonly applied stabilization methods. The point corresponding to this situation is also indicated in Figure 4.17. The results of this example are not as straightforward. When comparing the appropriate point to the break-even lines determined using the constant-method STH model for a 20 year time horizon, the preferred decision is to select Method B since the point lies above the appropriate break-even line. However, the preferred decision when considering a 5 year time horizon is to select Method A. In instances such as this, judgment is required on the part of the decision maker to select which decision is appropriate. In making this judgment, the decision maker should consider a number of issues, some of which may give preference to selecting Method A (the less costly but more risky method) and some of which may give preference to selecting Method B. Issues that may give some preference to selecting the less costly but more risky method include the possibility of future construction at the site or having limited available budget for slope repairs versus other repair needs, among others. Issues that may give some preference to selecting the more costly but more reliable method include having temporary budget surpluses or perhaps political considerations in cases where repeated failures may lead to substantial negative public sentiment. Other issues may obviously also be important, and such dilemmas might warrant additional study of the site's specific conditions which may give some preference to one type of repair over another. In general, however, it is important for the decision maker to remember that in these cases the conditions are generally close to the break-even line, which implies that the overall outcome (when viewed in an "average" sense) is likely to be similar regardless of the final judgment made.

4.2.2.g. Limitations of the STH Models

The STH models overcome the primary limitation of the basic IIT model in that the STH models explicitly consider the potential life-cycle costs of alternative stabilization methods over a specified time horizon. In doing so, the STH models are believed to produce much more realistic decisions for the most common scenarios under which slope stabilization applications are made. These improvements come at some cost in terms of effort required for development of the models and simplified decision tools, such as the break-even charts presented in this report. Once these tools are developed, however, use of the tools is essentially identical regardless of which particular model was used to develop the tools.

Several additional limitations still remain for the STH models, however. Perhaps the most significant limitation of the presented models arises from the assumption of having constant variable values throughout the specified time horizon. It is certainly reasonable to expect that the values of these variables may need to change over time, especially for relatively large time horizons. For example, the costs of addition future stabilization can be expected to increase with time due to inflation. Similarly, it is not unreasonable for the probabilities of failure for alternative methods to change over time (either increasing or decreasing depending on the type of slope and the specific repair method). Incorporating changes to the current models to include such considerations and evaluating the significance of those changes is an important step that must be taken prior to implementation of the developed models. Fortunately, several possible methods for incorporating such changes have recently been developed, which will facilitate making the appropriate enhancements to the current models. An additional limitation of the STH models is the assumption of having a maximum of one failure per year. While this assumption is not believed to play a significant role in the models, some effort to verify this belief seems warranted.

4.3. Selection of Parameters for the Decision Support Models

Given appropriate values of the input variables, application of the models is relatively straightforward whether they are applied directly or using simplified decision tools such as the break-even charts. The critical step in applying these models therefore lies in selecting appropriate values for the input parameters. In this respect, establishing the initial costs for alternative stabilization measures (costs A and B, etc.) is relatively commonplace and can be accomplished using established cost-estimation techniques. Establishing values for the consequence costs (C) and the respective probabilities of failure ($p_{f\text{-}A}$ and $p_{f\text{-}B}$) is much less common and more challenging at present.

Perhaps the best method for estimating the consequences of failure would be to track the costs associated with prior failures with similar characteristics (i.e., failures in similar slopes with similar size in similar geographic areas). Unfortunately, this is currently rarely done by most state departments of transportation. Estimates of appropriate consequences may, therefore, have to be made directly by decision makers, preferably using a somewhat standardized approach so the models can be consistently applied across an organization. Such an approach is utilized in the Blue Ridge Parkway rating system, where estimated annual maintenance costs are used as a measure of the cost consequences. A more formal approach is adopted by the Oregon Department of Transportation (ODOT 2001), where the 24 hour traffic delay costs (which are estimated using a standardized formula) and an estimate of the length of the delay are used to estimate the consequences associated with a particular failure. Regardless of the approach used, it is important that the method be consistent and that *all* costs associated with a failure are considered. Such costs may include costs to repair and/or clear the roadway, costs to repair and/or replace associated roadway hardware (e.g., signs, guardrail, barriers), costs to temporarily respond to the failure (e.g., personnel and other costs to investigate the problem and perhaps install warning signs), and, finally, possible traffic delay costs and other user costs. Additional consequences must also be considered for cases where the safety of the public is involved and perhaps even political consequences, which likely are tangible but often indeterminate. Such consequences can be established in terms of dollar values, or in terms of some other value that can be incorporated with more easily established consequences. In the STH models, consequence costs should not include costs for possible future repairs because these costs are already included elsewhere in the models.

Selection of appropriate probabilistic parameters (e.g., $p_{f\text{-}A}$ and $p_{f\text{-}B}$) is also somewhat daunting at present, primarily because technical personnel are not yet comfortable in dealing with problems probabilistically. However, current initiatives to adopt Load and Resistance Factor Design (LRFD) and reliability-based design (RBD) approaches are expected to improve this condition over time. In fact, the developed models fit in well with the LRFD approach in that LRFD-based designs are intended to produce specific probabilities of failure. The developed models can therefore play a role in establishing appropriate probabilities of failure for different scenarios which then can be used to develop load and resistance factors to produce designs with these probabilities of failure. One issue that must be addressed in synthesizing the developed decision support models and LRFD is that it may be necessary to establish several "sets" of load and resistance factors for designing specific stabilization measures, so that designers can design using appropriate target reliabilities that are established based on analyses using the decision support models.

Other options for selecting appropriate probabilistic parameters include using empirical data to estimate appropriate reliabilities, estimating reliabilities using reliability-based analyses, as well as simply using judgment (referred to as "expert elicitation" in the probability literature). Of these options, the most accurate approach is obviously using empirical data (preferably from within the same organization for similar slopes) to develop appropriate reliabilities. Unfortunately, appropriate empirical data is not readily available in most organizations at present. However, some data is available, and it is not overly ambitious to expect that such data could be acquired, even from relatively meager studies (which could be improved over time by collecting additional data). Estimating reliabilities using reliability-based analyses is also believed to be a reasonable expectation in the short-term. Such analyses are becoming much more common in the geotechnical engineering field, so it is not unreasonable to expect that such analyses could be performed. It may also be possible to estimate reasonable ranges of reliabilities for different methods simply by performing reliability-based analyses for “typical” conditions that are encountered within an organization and then utilize these values until more accurate empirical data can be collected. Finally, it is possible to simply estimate the values of reliability for different methods using judgment of personnel with significant experience using alternative methods of stabilization (i.e., expert elicitation). Studies have shown that while most individuals are not terribly adept at estimating probabilities, probabilities determined by “averaging” probabilities estimated by a group of individuals are generally quite reasonable. One possible method for facilitating selection of appropriate probabilistic parameters, at least in the short term, may therefore be to develop estimates for alternative stabilization methods using expert elicitation.

5. EVALUATION OF IMPLEMENTATION USING PDAs

Aside from developing the models presented above, a significant task undertaken during the project was evaluating possible methods of implementation of decision support systems. The ultimate goal of developed decision support tools, such as the ones presented in this report, is to provide accessible decision support to users in the field. As a result, potential methods by which the models developed on a PC could be exported or implemented to a mobile computing platform were explored – in this case using personal digital assistants (PDAs). This work was performed primarily by Dr. Kristen Sanford Bernhardt and Erin North, an undergraduate research assistant funded by Lafayette College. This chapter describes this work including the selection of hardware and software, development of a prototype, the final version of the prototype system that has been implemented, and suggestions for further development.

5.1. Hardware

PDAs were examined rather than laptop computers because of the desire to minimize the size and weight of the device. The two most widely used types of PDAs operate using either the Palm Operating System (Palm OS) or Microsoft's Pocket PC operating system. After investigating both systems, we chose to implement the prototype on a system running the Palm OS. Based on our research, the Palm OS is more commonly used for similar types of applications, and a greater variety of decision support software is currently available for the Palm OS. In addition, PDAs operating on a Palm OS tend to be less expensive than Pocket PCs, which would decrease costs for implementing the system in the field.

5.2. Software

As described in this report, the PC-based decision tree models were developed in Microsoft Excel using several commercially available add-ins. Preference was therefore given to using the same software on PDAs. While a number of spreadsheet programs exist for PDAs, unfortunately, none of them are currently compatible with the add-ins used to develop the decision models. As an alternative, a number of programs that allow the user to develop forms were explored, with the idea that these could be used to transmit information from the PDA in the field back to the PC in the office (or maintenance vehicle) for analysis. One of the programs, HanD Base, could actually be used to develop forms that could then be programmed to recommend decisions using one or more of the models developed during this project. This program could also be downloaded into a PC, and the information could be "hot synced" between the handheld and the PC. However, after more in-depth investigation, it was determined that the software was not very flexible and would not be suitable for our purposes. As a result, prototype development was pursued using Microsoft Excel on the PC and a compatible spreadsheet program for the PDA.

5.3. Prototype Development

The prototype is similar to the system developed by the Oregon Department of Transportation (ODOT) in many ways. ODOT uses a hazard rating system in order to inventory slopes. The slopes are given identification numbers and rated based on various characteristics. For the prototype, a data table was developed consisting of various characteristics of the slope failure and point values for each. It should be noted that the categories chosen and the point values assigned in the prototype are arbitrary and should be modified before implementation to reflect the priorities of the user.

Several macros were developed within Excel to facilitate the user entering information and the processing of that information. Options explored include:

- The color of a cell changes according to the severity of the situation for various categories. To use this macro, the user enters a specific number or types in the characteristic that describes the particular situation in the appropriate column. The macro can then be run, making the cells the appropriate color. A major problem with this prototype is that there is no way to restrict what is typed in the columns. A separate worksheet with a list of the possible choices could be provided, and the user could then pick from this list and type it in manually. This would take extra time and leave room for data entry errors. Another problem with this prototype is that it does not correspond very closely to existing hazard rating systems that were being used as a basis for the evaluation.
- A macro assigns point values to a description typed in a column. When the macro is run, the numerical value replaces the description the user types in the cell. This model relates more closely to the hazard rating system in that numbers are assigned to certain criteria. Although this prototype imitates the point assignment system, it still does not allow for a quick and easy way to ensure that only allowable values are chosen for the cells.
- In order to guarantee that everyone using the model would choose from the same set of data, we decided that it would be best to utilize some form of control within the spreadsheet. Specifically, the drop down box offers a number of desirable characteristics, including appropriately restricting user choices and providing a user-friendly interface. The drop down box allows the user to pick from a list of options and place choices in the drop down box. Once this list is developed and the command placed in the drop down box, the associated point value is recorded in a cell next to the corresponding drop down box. This prototype is the most user-friendly and functional of those explored in Excel.

After evaluating a number of spreadsheet programs for PDA that were compatible with Excel, we chose to use “Documents to Go” from DataViz. Unfortunately, none of the available spreadsheet programs, including Documents to Go, supports either macros or controls. According to a technical support employee from DataViz, the company is currently working on including support for controls in future versions of this program. As a result, the prototype built in Excel can not be transferred to the PDA with currently available software. However, it is hoped that with continued development of more powerful tools for the PDA, it will soon be possible to do so. The same limitations were present with tools provided for the Pocket PC PDA operating system.

5.4. Final Prototype Description

The main obstacle with implementing a user-friendly application in Documents to Go was finding a way to present a limited number of choices to the user. A similar database to that in the PC was created, which contained criteria and corresponding point values. Again, several possible implementations were investigated:

- A function was created that would connect the description chosen to its corresponding point value. The user would make the choice by placing an “x” in the column next to the best fitting characteristic. This model worked well, but there were three major problems: 1) the letter “x” is one of the more difficult figures to create in the handheld with graffiti writing, 2) the view on the handheld was confusing and contained information that the user didn’t need to see, and 3) a final result calculation was not included in the model.
- The three problems discussed above were addressed as follows. First, instead of making a choice by placing an “x” in the column, we changed the function so that a “1” could be placed next to the best choice. To correct the second problem, we created a separate worksheet for each category and moved the point values out of the normally visible screen area. Finally, we created a summary worksheet that contains a function to sum all of the point values in the previous sheets to give a final result. This final result can then be used to evaluate a particular site, and a decision can be made based on this final result.

5.5. Suggestions for Further Development

A remaining problem with the prototype implemented on the PDA is that there is no way to restrict the number of choices made. The user should, theoretically, place a “1” next to only one description. If the person using the device does not know this, he/she could pick more than one, and the final result will be affected. One way this could be fixed in Excel is by placing a validation restriction on the column. This particular tool is a pop-up that shows up when the person places the cursor in a certain cell. It gives instructions as to what the person should do. In the example developed, it instructs the person to “pick one” when working in the B column. Although this feature is not supported currently in the Documents to Go program, it may be in the future, and this would be another possible solution to the problem of restricting choices.

Based on the investigation of possible implementation of the decision models on PDAs, the model we recommend is one similar to the prototype form created in Excel. Although this type of control is not yet supported by the handheld, it seems that it will be in the future. If this type of control were supported in the handheld, this would be the most “user-friendly” design. Until then, the model that is now presented in the handheld is the best option. It should be noted, however, that we designed the categories in the prototype to be representative rather than prescriptive. The point values given to these criteria are arbitrary and should be changed accordingly to create a sensible rating system.

6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1. Summary

The objective of this project has been to develop a decision support framework based on asset management principles to facilitate effective decision making for selection of appropriate methods for stabilization of failed earth slopes. Particular focus has been paid to “nuisance” slides, which generally have limited size and consequences when viewed on a case by case basis, but represent a substantial staff and economic burden to many private and governmental organizations when viewed on a collective basis. Project activities included development of a simple asset management framework suitable for managing geotechnical assets, development of several analysis models to evaluate alternative slope maintenance and repair strategies, and evaluation of the potential for use of personal digital assistants (PDAs) for implementing geotechnical asset management systems.

In developing the simple asset management framework for geotechnical assets, a number of issues that must be addressed prior to complete implementation of a geotechnical asset management system were identified. The most significant of these issues are lack of established procedures and techniques for collecting the data required for implementation of a geotechnical asset management system and lack of suitable analysis tools required to evaluate alternative management scenarios. Fortunately, efforts currently underway by several agencies are making notable strides to address the lack of data collection. Efforts for this project were therefore focused on addressing development of suitable analysis techniques for which little has been done.

The analysis models developed during this project make use of formal decision analysis techniques, and more specifically “decision trees,” commonly used in business applications. Decision tree models, and the associated analyses that can be performed using them, provide the capability to compare alternative stabilization techniques with appropriate consideration of the costs, consequences, and reliability of the techniques from an organizational perspective. As such, these models serve as effective means for making rational and consistent decisions across an organization that can produce substantive cost savings.

As a part of this project, two basic forms of decision tree models were developed. The first form is referred to as the Instant in Time (IIT) form of model to reflect the fact that the model considers only a single application of a repair and, in its current form, does not model the potential costs of alternative stabilization measures over a consistent “life-cycle.” The second form of model is referred to as the Specific Time Horizon (STH) form of model because it provides capabilities to model the potential need for repeated application of alternative repair techniques within a specified time period. In doing so, this form of model overcomes the most severe limitations of the IIT form of model, while still retaining the significant advantages of the general decision tree approach.

During the project, numerous trial models of both forms were developed and evaluated. The three most promising were described in this report. One of these models is the basic IIT model. While extremely limited in its current form, several possible modifications could be incorporated into the model to account for life-cycle costs. If these modifications are successful at representing life-cycle costs, the simplicity of the approach offers notable advantages over the more complicated STH models. The other two models are STH models that are referred to as the three-method STH model and the constant-method STH model. The three-method STH model has the capability of comparing repeated application of three-alternative stabilization measures with the possibility of “switching” between methods during the specified time horizon of interest. In contrast, the constant-method STH model is restricted to repeated application of a single stabilization measure over the specified time horizon.

Example cases based on available cost data from the Oregon Department of Transportation were presented for each of the most promising decision tree models to demonstrate application of the models for realistic input values. In addition, a series of preliminary charts were developed and presented to illustrate the type of simplified decision tools that can be developed using the models for use by field personnel and to evaluate and draw preliminary conclusions regarding the slope repair problem.

Finally, efforts undertaken to investigate the potential for implementing a decision support system using personal computers and personal digital assistants (PDAs) were described. At present, no tools are available for fully implementing the decision tree models using PDAs. However, new and improved tools and capabilities for these devices are being introduced at a rapid pace, so there is hope that capabilities for doing so will be available in the near future.

6.2. Conclusions

Based on the work performed as a part of this project and the results of analyses performed using the developed decision tree models, the following conclusions are drawn:

1. The most significant impediments to implementation of a geotechnical asset management system, and more specifically a “slope” asset management system, are lack of established tools and procedures for collecting and maintaining required data and lack of established analysis procedures for evaluating alternative maintenance and repair strategies.
2. Ongoing efforts by several agencies have resulted in significant advances in tools and procedures for collecting and maintaining the types of data required for implementation of a geotechnical asset management system. Work to develop and evaluate suitable analysis procedures is extremely limited outside of this project.
3. In general, the basic approach of using decision trees to model the slope repair problem is believed to capture all of the important considerations for the problem. As such, decision trees are deemed to be an effective technique for performing analyses required in a geotechnical asset management system.
4. While the general approach of using decision trees to model the slope repair problem is sound, several limitations exist with the current models which limit the practical applicability of the models at present. Nevertheless, the developed models do provide the basis upon which future enhancements can be made with relative ease to produce effective and practical models upon which to base future decisions.

5. Analyses performed using the developed models indicate that, under certain conditions, repeated application of a less costly, but more risky stabilization technique can be more cost effective on a life-cycle basis than application of more costly but less risky methods from an organizational perspective. This conclusion is true regardless of the time horizon of interest, but is especially true for relatively short time horizons.
6. While implementation of the developed analysis models using PDAs is not currently possible, the potential for future implementation on this platform appear feasible.

6.3. Recommendations for Future Work

Finally, several recommendations for future work to facilitate future implementation of a geotechnical asset management system, to enhance the developed models, and to provide improved guidance on selection of appropriate input parameters for the models include the following:

1. Additional work should be undertaken to incorporate the data collection tools and procedures being developed by others with the analysis tools developed as part of this project. Such efforts should result in a fully functional prototype geotechnical asset management system. Once developed, the geotechnical asset management system should be implemented on a trial basis for a limited time to allow for evaluation and enhancement of the system prior to widespread implementation.
2. Continued efforts should be directed towards implementation of the geotechnical asset management system using PDAs. Such devices provide significant capabilities for providing convenient, efficient, and cost effective application of geotechnical asset management systems.
3. The STH models should be modified to incorporate consideration of having temporally varying parameter values including costs, consequences, and probabilities of failure. Since the STH models are essentially numerical models, doing so requires only that minor modifications to the model be implemented such that the models use values defined as some function of time (which is already a part of the models) rather than constant values. One then simply has to define how the parameter values are expected to change with time with the model input. In the case of costs and consequences, it is relatively straightforward to predict values of costs and consequences at future times by simply estimating a logical rate of inflation (something for which procedures are currently in place within most transportation organizations) and applying that to "current" values. For probabilities of failure, the problem is more complicated because some slopes may have probabilities of failure that increase with time, while others may have probabilities of failure that decrease with time. Fortunately though, recent work performed for the U.S. Army Corps of Engineers (Wolff 1996) provides significant guidance on selection of functions describing how the probability of failure may change with time. It is believed that similar techniques can be implemented into the STH models with relative ease.

4. Additional modifications and evaluations of the IIT model to incorporate methods for including life-cycle costs should be performed. While the STH models already consider life-cycle costs, the IIT models are in general much less complex and computationally intensive. If methods for reasonably incorporating life-cycle costs can be implemented in the IIT models, the models will have significant advantages over the more complicated STH models.
5. Finally, significant work is required to provide additional guidance to potential users on selection of appropriate input parameters. Among other work, this will require better record keeping of the initial and consequence costs associated with nuisance slides, as well as work to establish the actual "field" probabilities of failure for different types of methods.

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APPENDIX A. ANNOTATED BIBLIOGRAPHY OF APPLICATIONS OF PDAs

A Handheld for Every Pocket. 12 Nov 2001. *Business Week 3757*. Expanded Academic Index. Infotrac. http://web2.infotrac.galegroup.com.
This article describes the uses the Palm VII wireless handheld in Lincoln, Nebraska. This city uses these devices in order to keep animal records, house appraisal records, and soon for vehicle records. The article also describes various devices, including the new m-series from Palm, which range in price form $149 to $449. All except for the m-100 have an expansion slot and the m-125 uses AAA batteries rather than rechargeable ones. The article states that if integration with desktop applications is needed, a PocketPC is a better choice.

ArcPad. 21 Jan 2002. http://esri.com/software/arcpad/index.html.
ESRI describes one of their products, ArcPad, which costs $495.00. With this software, the user can update maps and collect information for the GIS database in the field using a PocketPC, cellular phone, PDA or anything using a TCP/IP connection. When the user is finished, the new data can be uploaded directly into the master database in an office PC equipped with ArcView software.

Brown, Bruce, and Mary Brown. 22 May 2001. Quick PDA Data Exchange- Trade business cards, swap files, book a date, or even share photos using your PDAs infrared port. *PC Magazine*: 93. Expanded Academic Index. Infotrac. http://web2infotrac.galegroup.com.
In this article, the authors describe a feature of PDAs that enables the user to send information, such as a Microsoft Excel spreadsheet, from one PDA to another by way of an infrared port. Many of the most recent PDAs are equipped with an infrared port and infrared transfer applications are available for those that are not for as low as $14.95.

Compton, Jason. Sept 2000. *Quickspins: ArcPad 5*. Mobile Computing Online. http://www.mobilecomputing.com/showarchives.cgi?56:2.
This article describes certain features of the ArcPad software. In order to use the software, the users PocketPC must have a color display and Windows CE 2.11 or later installed. The stylus of the PocketPC can be used to scroll on the map, call up information on a certain feature, and to make changes or additions with ArcPad's data collection forms. The program is also equipped with a Layers tool that enables the user to add or delete individual data sets or images. Location data from a Trimble GPS unit may be integrated for more precision.

Electronic Design. 3 Dec. 2001. Database Development Software Functions For Next-Generation PDAs. *Electronic Design* 49: 90. Expanded Academic Index. Infotrac. http://web3.infotrac.galegroup.com.
This article describes the Visual CE database software, which now supports the Windows-powered PocketPC 2002. The cost of the software ranges form $79 to $599 depending on the Edition. The software adds development tools such as pop-up word lists, grid control, and forms that can be developed to run on a desktop or handheld. It allows users to easily access and update server data in real-time.

Palm Enterprise. 27 Dec 2001. Demos Consulting, Productivity Experts, Rely on Palm Handhelds for Email and Internet Access. Palm Enterprise. http://www.palm/com/enterprise/studies/study 38.html.
This article describes the successful use of Palm Pilots for email and Internet purposes within a financial consulting company, Demos Consulting. The company chose PDAs operating with Palm OS rather than Windows CE because of their reliability, low cost, compact size, and access to a Microsoft Exchange Server. The use of these devices gave the users real-time access to any type of information they needed. According to the company, the devices also provided better and more efficient service to the customer.

Fieldsmart Connect: A New Way to Communicate in the Field. 21 Jan 2002. http://www.mapframe.com/fsconnect.htm.
Mapframe Corporation describes one of its products with “Fieldsmart” technology, the Fieldsmart Connect. This product allows the user to send maps, map data, engineering drawings, and diagrams over wireless network. This product provides a way to send time sensitive information from the field in a cost effective way.

Fieldsmart Design: Brings New Efficiencies to the Distribution Design Process. 21 Jan 2002. http://www.mapframe.com/fsdesign.htm.
Mapframe Corporation describes the Fieldsmart Design system. This system allows users to create designs at the job site on a laptop or PDA. A materials list and cost estimate is then automatically created. Engineering calculations, task qualifiers, and access to reference materials may also be included in the Fieldsmart Design system.

Fieldsmart Inspect: Increases the Efficiency and Effectiveness of the Inspection Process. 21 Jan 2002. http://www.mapframe.com/fsinspect.htm.
Mapframe Corporation describes the Fieldsmart Inspect software. This software allows users to update and correct data using maps or sketches in the field.

Fieldsmart View: The Smart Simple Way to View Maps and Facility Data in the Field. 21 Jan 2002. http://www.mapframe.com/fsview.htm.
Mapframe Corporation describes the product, Fieldsmart View, which runs on all versions of Windows (95, 98, NT, 2000, CE). This program allows the user to add data to a map in a quick and simple way. The user does not need extensive training and the software is easily customized for specific uses, with symbology and interface dialogs controlled by external tables.

Freudenrich, C.C. 8 Jan 2002. How Personal Digital Assistants (PDAs) Work. http://www.howstuffworks.com/pda.htm.
In this article, the author explains how PDAs function. He also describes the difference between the Palm OS and PocketPC operating systems. The Palm OS runs faster, is easy to use, and takes up less memory. The PocketPC on the other hand is more complicated and slower, but it can support miniature Windows packages, color displays, and graphics. Specific types of software described, includes medical software and decision-making software. According to the author, PDAs are designed to compliment desktop or laptop computers rather than replacing them.

Gargiulo, Robert, B.A. Myers, H. Stiel. 27 Dec 2001. Collaboration Using Multiple PDAs Connected to a PC. http://www.cs.cmu.edu/~pebbles.
This publication describes the research being done with PDAs at Carnegie Mellon University. The devices used for the research were 3Com Palm Pilots. The two applications described are the: "Remote Commander," which allows users to send data from their PDA to a PC as if they were using a keyboard and mouse, and "Pebbles Draw," which allows users to send data to a PC simultaneously.

Graham, L.A. 2000. Life in the Fast Lane. *GEOWorld*: 30-35.
This article describes various uses of both Palm Pilots with the Palm operating system (OS) and Microsoft Windows CE devices. Handhelds may now have World Wide Web browsers and versions of Microsoft Office applications. Some special features may include color displays and/or daylight-visible displays for field use. The article also discusses the use of GIS, Auto CAD, and GPS programs with a handheld, replacing the use of bulky laptops for these applications. The author discusses various types of software that may be used for these applications, such as ArcPad, VoCarta Forms, and Fieldsmart software.

Hardesty, Larry. 21 Jan 2002. Apps on the Fly. *Technology Review* 104.5: 32. Expanded Academic Index. Infotrac. http://web2.infotrac.galegroup.com.
The author describes a new network architecture, "application streaming," which will enable users of PDAs to run applications without having the software stored locally in the PDA. Citrix Systems and Nortel Networks Application Management Solutions were separately working on this new network architecture that was supposed to be adopted by June 2002, according to the author.

Hughes, J.R. 2000. Field Computing Options Abound. *GEOWorld*: 8.
The author states that the use of PDAs and handheld computers with mapping technology has become less expensive and much easier to use for even those with minimal computing skills. He also states that many of the problems that initially caused many project managers to be wary of the products have now been sorted out. He explains that because of these facts, in some cases PDAs and handhelds have taken the place of desktops and laptops.

Johnson, Russ. 10 April 2001. Firefighters Pioneer Pocket-Sized GIS Collection. http://www.esri.com/news/arcuser/0401/viejas.html.
The article describes an application of ArcPad and a Compact IPAQ PocketPC. Firefighters used the ArcPad software in order to digitally map the perimeters of an ongoing wildfire in Southern California in January 2001. Using ArcPad and the GIS database, firefighters can map a wildfire in real-time, predict the spread of the fire, and provide visual reference for team strategy discussion.

Kinast, J.A. 2001. Applications of Handheld Computers to Gas Distribution Business. *Pipeline and Gas Journal* 228.7: 46-47. http://firstsearch.oclc.org.
In this article, the author describes the use of PDAs, which have replaced laptops in the gas distribution business. The PDAs allow the user to collect field data such as meter readings and inspection reports. The results of the use of the PDAs were an increase of

productivity of field staff, elimination of costly errors, reduction of administration effort, and a reduction in the delays or data processing.

Lewis, Peter. 21 Jan 2002. Ring In the New: Handspring's clever Treo pocket communicator is just my type: voice, email, browsing, and more. *Fortune* 45.2: 123. Expanded Academic Index. Infotrac. http://web1.infotrac.galegroup.com.
The author describes the Hanspring Treo PDA, which can be used to make calls, email, organize, send SMS messages, and browse the Web. This PDA is smaller than the smallest current Palm organizers at a cost of $399. The email system is only adequate for consumers as of now due to security issues. A larger version, the 180g model, is also available for $599.

McCracken, Harry. 2001. Get Organized: PDAs for Any Budget. *PC World* 19.12: 66. Expanded Academic Index. Infotrac. http://web1.infotrac.galegroup.com.
The author describes and compares four different Personal Digital Assistants: the Visor Neo and Visor Pro from Handspring, the Casio Cassiopeia Pocket Manager BE-300, and the Toshiba PocketPC E570. The Handspring PDAs are relatively inexpensive ($200 or $300) and very simple. With weak backlights they are not good in dim environments and the pop-off covers are very easy to lose. The Casio model, which costs $300, operates with the Windows CE system. The Toshiba is the top of the line at a cost of $569. It runs many versions of Microsoft office applications, has a screen visible outdoors, and comes with CompactFlash and Secure Digital slots for memory and modems.

Ollerton, J.A. 12 Jan 2001. Fire Hydrant Inventory Made Simple With ArcPad. http://www.esri.com/news/arcuser/0101/arcpad.html.
This article describes an application in which the Compaq IPAQ PocketPC, a Sokkia GIR 1000 GPS unit, and the software ArcPad form ESRI are used together. The Elsinore Valley Municipal Water District in Southern California uses these devices and software to develop a map of the entire system of fire hydrants in the area in the GIS database. The user can locate hydrants not already in the GIS, and then can add them to the GIS database while in the field using the ArcPad software. A form was created in the PocketPC for the user to collect the data needed for each hydrant.

PDAbuzz.com Discussion Forums. 8 Jan 2002. PocketPC Users Can Now Print on the Road With the SiPix Portable Printer A6. PDAbuzz.com Discussion Forums. http://www2.pdabuzz.com.
This article describes a compact and lightweight pocket printer that supports PocketPC versions 2.0 to 3.1 and most notebook PCs. The printer has a retail price of $149 with a $20 rebate if purchased before February 28, 2002.

PQuake- An Integrated System for Earthquake Damage Reconnaissance Using Palm Technology. 3 Jan 2002. http://www.prism.gatech.edu/~sd89/doctoral .html.
This article describes the PQuake system, which integrates GPS, GIS, and digital photography for both quantitative and qualitative information. Detailed maps of the area of interest can be made and even printed in the field with the use of a digital camera, a handheld GPS, a Palm Pilot, and a portable printer.

Roe, A.G. 5 Nov 2001. Handhelds Hold Up Well for Variety of Site Uses. *ENR.*

In this article, the author describes applications of PDAs used by the California Department of Transportation. PDAs are more practical than laptops in the field and can aid in the design, data collection, project management, and inspection of job sites. Limitations include hard-to-read screen displays, durability, and the connectivity.

Dick Builds. Jan 2002. Turnpike Project Adds Value Through Technology. *Dick Builds* 20.4: 2.
This article describes the successful use of Palm Pilot technology by the Dick Corporation in the Construction Management of the Ohio Turnpike. For this project, inspectors receive a Palm Pilot to record daily data obtained on the jobsite. A folding keyboard is also used for longer data entries and each Palm Pilot is programmed with sketchpad capability. At the end of the day the inspectors return to the field office to download the data in his or her Palm Pilot, which becomes part of an overall job report after the project manager reviews it.

VoCarta Forms. 21 Jan 2002. http://www.datria.com/products/forms/index.htm.
Datria Systems describes one of their products, VoCarta Forms. This voice-to-data software enables mobile users to enter data into their handhelds with the recognition of their voices. This allows for quicker data entry and accurate collection of data.

Business Week. 15 Oct 2001. What's Making Palm Sweat. *Business Week* 3753: 24. Expanded Academic Index. Infotrac. http://web2.infotrac.galegroup.com.
This article describes and compares three different PDAs (the Hewlett-Packard Jornada 560, the Compaq iPAQ 3800, and the Toshiba E570). All have the same basic software, a 240 by 320 pixel color display, and an Intel StrongARM processor. The iPAQ has the broadest range of communications and the brightest screen. The Jornada is the only PocketPC with a removable battery. The Toshiba model is designed for two types of expansion cards, the SD and CompactFlash. Though they are much alike, each model has its own strengths.

Young, J.R. 7 Dec 2001. High-Tech Methods are Used to Assess Damage After Terrorist Attacks. *The Chronicle of Higher Education* 48.15.
http:// chronicle.com/free/v48/i15/15a02801.htm.
In this article, the author describes various technologies used in assessing the damage in New York, after the terrorist attacks. One of the technologies mentioned is a program developed by an engineering professor at Georgia Tech to log building damage done by earthquakes, called PQuake. This software was developed for PDAs and can be used to record structural characteristics of buildings while the user is in the field. The information can also be sent to others electronically. GPS software can also be used to match exact locations with data, making it easy to keep notes and pictures organized.