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THE EFFECTS OF INADEQUATE COMPONENT INSPECTION ON FACILITY REPAIR PROJECTS

by

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B. S., Civil Engineering, University of Florida
(1980)

Submitted to the Department of Civil
Engineering in partial fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1988

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ABSTRACT

Component inspection is an important part of the facilities management process, especially as repair projects play an increasing role in the life of public facilities management organizations. The decisions facility owners make with regard to component inspection effect the eventual success of their major facility repair projects.

This thesis uses a total cost approach to evaluate the effect component inspection methods have on facility repair projects. This problem is examined by comparing the penalty cost of inadequate component inspection to the costs of alternate component inspection methods that could have minimized the penalty cost. A general framework is developed to classify the errors that occur in component inspection and predict the penalty costs.

Six major facility repair projects in which inadequate component inspection led to penalty costs are presented and analyzed. The evidence from these cases shows that owners should pursue more costly and more accurate component inspection methods. The reduction in penalty costs due to increased accuracy outweighs the added cost so that the total cost is less. These cases also point to the usefulness of automated non-contact component inspection methods in this application.

The evidence presented in this thesis supports the development of a component inspection strategy by facility owners that considers alternate component inspection methods as part of the design of facility repair projects. An understanding of the penalty cost concepts presented here will be useful to owners in the design of a component inspection strategy.

Thesis Supervisor: Kenneth R. Maser
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CHAPTER ONE

INTRODUCTION

The management of this country's infrastructure is a growing problem that will consume the talents of civil engineers well into the future. The tools and methods used to create our vast inventory of infrastructure facilities are not entirely useful for the newly emerging requirement to maintain what has been constructed. It is important that new methods and tools be developed to aid facility managers in making the decisions that will effect how billions in infrastructure reconstruction funds will be spent in the ensuing years. Recently developed technologies in sensors, computers and electronics could be used to aid the infrastructure reconstruction effort. However, these technologies have not been fully employed in this effort due to the lack of a profit motive [1]. This thesis will look at the application of these technologies to one portion of the infrastructure reconstruction process - major facility repair projects - to see if a profit motive in terms of a savings to the owner exists.

1.1 Overview Of The Problem

During the operational lifetime of a constructed facility the facility deteriorates and a certain amount of repair and maintenance work must be done to the facility to keep it operational and performing its intended purpose for the user. A number of terms are used to refer to this work; rehabilitation, renovation, repair and maintenance are just a few. In this thesis it will simply be referred to as "repair". If this repair work is to be accomplished by contract the owner must write a set of contract documents to describe the work and provide enough information so contractors can estimate and bid on the work. After the contract is awarded and the work begins, all too frequently it is discovered that the nature of the work was incorrectly described in the contract documents. The work actually required is different than that described in the contract documents. At this point the owner must take corrective action, usually by issuing a contract change, and accept the associated consequences of incorrectly describing the repair work that is required. The consequences of these errors are varied, however they usually manifest themselves in the form of project delays and additional costs.

This scenario is not unusual for anyone involved in the facilities management or the construction contracting business. It happens all to frequently. What is unusual is that little investigation has been done into the relationship between the cost of collecting more accurate information describing the work and the effects and costs of incorrectly describing the repair work. This is especially true with regard the collection of information for facility repair projects where this information is included in the contract documents to describe the nature of the work and forms the basis for the contractor's bid and the contractual agreement for the execution of the work. This activity is called component inspection or CI. Component inspection is different from condition assessment where information is collected to form the basis for a decision to select a certain project for execution. Research is ongoing to address the value of condition assessment information when making the repair or replace decision for a facility component in terms of the consequences of a wrong decision [2]. However, once the decision has been made to execute a facility repair project, how much should be spent to collect information for inclusion in the contract documents to describe the nature of the work?

The purpose of this thesis is to look at this recurrent scenario and examine the effect inadequate component inspection has on facility repair projects. This will be accomplished by determining the relationship between the cost of incorrectly describing the nature of the repair work and the cost of the component inspection methods that could better describe the repair work. This relationship will be analyzed to see if the cost of incorrectly describing the repair work can be reduced by selecting more costly component inspection methods, especially non-contact automated sensing technologies. With this insight, this thesis will examine how this relationship could be used to develop owner policies and guidelines for component inspection that could reduce the effects of incorrectly describing facility repair work.

This thesis will concentrate on that portion of facilities management that involves the repair of existing facility components by contract. In particular it will be concerned with the collection of information that will be used in the contract documents to describe the nature of the repair work. This thesis will also be concerned with the contract changes and impacts that result when the work is incorrectly described in the contract documents.

1.2 Research Approach

This thesis will look at the facilities management process to see where this problem fits into the process as a whole. This discussion will examine the decisions owners make in the design and execution of facility repair projects and how these decisions effect component inspection. This discussion will look at errors in the component inspection process that lead to changes in the contract and additional costs that otherwise would not have been incurred.

The thesis will examine several facility repair projects in which contract changes were caused by errors in component inspection. These changes resulted in additional costs to the owner that could have been avoided if there had not been an error in component inspection.

These additional costs, which are called penalty costs, will be defined and discussed later in the thesis. The thesis will examine their nature and how they can be identified. A general framework will be developed to examine the relationship between errors that occur in the component inspection process and the penalty costs that result. The purpose of this framework is to be able to predict the penalty costs a priori from the known errors that occur in the component inspection process.

The case studies will be further analyzed to determine the relationship between the penalty costs that occurred on the project and the cost of alternate component inspection methods. This will be done by comparing the penalty costs to the cost of more accurate component inspection methods that would be useful in reducing the penalty costs due to their increased accuracy in describing the work. From this analysis the thesis will attempt to draw conclusions about: 1) the benefit of employing more costly and more accurate component inspection methods, and 2) the policies that owners should adopt to minimize total cost (penalty cost plus component inspection costs). These cases will also be analyzed to see if they support the validity of the framework and show that it is useful in predicting penalty costs for facility repair projects based on errors in the component inspection process.

This thesis will restrict its discussion to two specific types of facilities; airfield pavements and concrete bridge decks. These two facilities were selected because they lend themselves to inspection by non-traditional techniques for component inspection such as non-contact automated sensing methods. They also seem to be facilities where the effects of errors in the component inspection process are pronounced in terms of the amount of change order work that results from these repair projects. Airfields and bridge decks also have many similarities:

- Both are generally owned by public or pseudo public agencies whose procurement and construction contracting procedures are inflexible and restricted by regulation.
- Both are horizontal facilities where the propensity for water and chlorides to penetrate the pavement surface is greater than a vertical facility.
- Both are made of concrete and/or asphalt.
- Both are operationally critical to their users. In the case of a bridge deck it is the critical link in a network of other facilities (roads) that is essential to the serviceability (capacity) of the network. In the case of an airfield it is critical to the serviceability of the airfield and in the case of military airfields it is particularly critical to the operational mission of the air base and national security.

- Both types of facilities constitute such a large capital investment that there is normally no redundant facilities. The additional cost of any redundancy, through either another facility or additional capacity, is not justified by the downtime associated with the need to perform repair work on the facility.
- Many of these facilities were built 10 - 30 years ago and they are now in need of major repair. The construction methods and materials used at the time they were built did not have the benefit of the years of deterioration history available today.

Airfield pavements and concrete bridge decks also differ in some respects. Although both are expansive in nature, airfield pavements tend to be larger in area than bridge decks. Both the top and the bottom of bridge decks are generally exposed to the elements, whereas only the top surface of airfields are exposed. Airfields are supported by a subgrade material whereas, bridge decks are supported by the substructure of the bridge.

Ultimately, after examining the important issues surrounding component inspection for two types of facility components, airfield pavements and bridge decks, the arguments advanced by this thesis regarding component inspection may be used to draw some parallels to the methods that should be used for other facility components where repair work is planned. The relationships developed in this thesis may be useful as a tool to design or select a component inspection strategy for a facility component repair projects in general. This could eventually help facility managers to look ahead and anticipate the effect their decisions regarding component inspection would have on a facility repair project.

1.3 Overview of remaining chapters

Chapter Two will introduce this investigation, describe its place in the facilities management process and highlight those aspects of the process that are important for further discussion in this thesis. This includes repair work, component inspection and contract changes as a part of the facilities management process.

Chapter Three will discuss repair work as it specifically applies to airfield pavements and concrete bridge decks. It will cover the defects that occur in these facility components, the repair methods that are employed and the component inspection methods that are used. Chapter Four will present actual cases where there have been changes in facility repair contracts caused by errors in the component inspection process. These cases will show the penalty costs associated with these errors. Chapter Five will discuss contract change orders in general and the penalty costs that result from incorrectly describing the nature of the repair work. This chapter will cover the various costs involved; agency, user and political costs and how each is effected by an error in describing the repair work.

Chapter Six will present the component defect analysis (CDA) framework as a method of examining the errors that occur in describing the nature of repair work to be accomplished by contract and the penalty costs that result from those errors.

Chapter Seven will return to the cases in Chapter Four and present more data concerning the component inspection methods actually used and their costs. The data from these cases will be used to analyze the costs of alternate methods versus the benefit of more correctly describing the repair work in the contract documents. In Chapter Eight the thesis will review the evidence presented and draw conclusions as to the value of increased costs for component inspection, the use of newer non-contact automated component inspection methods and the the owner policies that are needed to minimize penalty costs for facility repair projects. This analysis will also show how appropriate the component defect analysis framework is for illustrating the effects of incorrectly describing facility component defects.

CHAPTER ONE ENDNOTES:

[1] Maser, K.R., "Sensors for Infrastructure Assessment", Proceeding of ASCE workshop, Civil Engineering In the 21st Century, 11-14 November 87 Williamsburg, VA.

[2] Humplick, F., McNeil, S., Ramaswamy, R., "The Role of Uncertainty in the Management of Infrastructure Facilities", .U.S. Army Research Office Report, 6 January 1988.

CHAPTER TWO

SCOPE OF INVESTIGATION: COMPONENT INSPECTION AND THE FACILITIES MANAGEMENT PROCESS

This chapter will describe the scope of this thesis within the framework of the facilities management process. This chapter will introduce repair work, component inspection and contract change orders as key aspects of the facilities management process and show the relationship between them.

Existing facilities must be repaired from time to time. This requirement leads to the need to prepare contract documents describing the nature of the repair work for bidding purposes. These contract documents must include information regarding the deteriorated state of the facility component. In order to collect this information owners must make decisions regarding the component inspection methods that will be employed. These decisions effect the contract changes and the contractor's bid price such that the ultimate success of a project is many times determined by the decisions that are made at the outset of the project with regard to component inspection.

2.1 Component inspection

Component inspection is the process that occurs during the design of a facility repair project in which information is gathered about the state of deterioration of a facility component for inclusion in the contract documents. This component inspection information must correctly describe the nature of the repair project because it is used by the contractor to estimate the project and prepare his bid. It tells the contractor what type of work he must do and how much there is. Component inspection information also forms the basis for any contract changes that may result later in the project. It is also used by repair project designers to determine the method of repair to specify in the contract documents.

The term "component inspection" as used here should not be confused with "condition assessment" or "site investigation". Where component inspection is concerned with a particular component of a facility, condition assessment is normally associated with gathering information about the state of deterioration of a facility as a whole for use in the network level decision making process in which one project is selected for execution over another. Both condition assessment and component inspection are concerned with existing facilities. However, they are aimed at different levels of detail and the information will be used for different purposes. One can draw an analogy to the difference between condition assessment and component inspection, and the difference between schematic drawings and construction drawings. Just as schematic drawings are not sufficient to build a building, condition assessment information is not sufficient to execute a facility repair project.

Site investigation has to do with new construction. It is typically a term that refers to the gathering of information about geological conditions in preparation for new construction [1].

2.2 Categories of facility owners

This section will define several categories of facility owners and discuss why the focus of this thesis is on one particular category of owner; the informed public owner.

Facility owners can be categorized in several different ways:

- public or private
- informed or uninformed

Public owners are usually governmental bodies that are by definition nonprofit. On the other hand, an example of a private owner would be either a manufacturing corporation or a university. Private owners are usually smaller than public owners on an individual basis. The term informed owner simply means that the owner has an in-house facilities management staff and does not have to rely on outside consultants for all of their facilities management support.

There are several reasons why this thesis will focus on informed public owners. First, public owners are effected to a greater degree than private owners by errors made in describing the nature of the repair work. This is due to the contracting restrictions that public owners have that set them apart from private owners. Public owners must award to the lowest bidder; price is the primary consideration. The cooperative attitude of the contractor with regard to changes is not a factor they can consider. This requirement makes the need to correctly describe the nature work through the selection of the most appropriate component inspection methods even more critical to the public owner [2].

Secondly, informed owners tend to have greater inventory of facilities, and consequently their own facilities management staff that can make policy decisions regarding the selection of component inspection methods. Uninformed owners, on the other hand, tend to have a smaller inventory of facilities so the value of selecting the appropriate component inspection methods for their projects is less. Additionally, since they must rely on outside sources for advice regarding the development of contract documents and the appropriate component inspection methods for their projects there is little opportunity to implement new policies regarding what component inspection methods should be employed. Although many informed public owners also hire outside consultants to design repair projects, they have a staff that oversees the work and provides policy direction and approval of the component inspection methods that are employed. For this reason they have a greater opportunity to implement the component inspection policies.

Thirdly, public owners are performing increasing amounts of repair work as opposed to new work so component inspection is becoming more important to them. In the past when new construction was the predominant consideration, owners were concerned with the selection of site investigation methods and how this effected the cost of their new project construction. However, now that repair work is becoming a greater part of the work effort it is natural that these same organizations should begin to ask similar questions with regard to component inspection as they did with site investigation. In a way site investigation is to new work as component inspection is to repair work. Numerous studies in the past have discussed the effects of site investigation on new construction and made recommendations as to how to improve the decisions surrounding site investigation procedures [3][4][5]. This thesis will attempt to look at these same decisions for component inspection.

However, this is not to say that the arguments advanced by this thesis will not be of interest to facility owners in other categories, quite the opposite is true. This restriction on the category of owner simply means that the discussion will be tailored to the facilities management environment of the informed public owner.

2.3 Facilities Management process - Objectives

One of the primary objectives of a facilities management organization is to keep the existing facilities at the highest level of serviceability for the user. The execution of facility repair projects is an integral part of the facilities management process that supports this objective. However, the achievement of this objective is hampered by the structure and bureaucracy of the organizations intended to achieve this objective. The organizations that are now charged with this objective are in many cases the same organizations that were developed to construct these facilities new, and although suited for this task, they are not the best suited to perform their emerging repair objective [6].

This issue is especially true when one looks at the effectiveness of these organizations in dealing with the decision to select component inspection methods to be employed in the design of these repair projects. Selecting component inspection methods is becoming more important with the increasing quantity of repair work needed. The U.S. Military, as one of the largest single consumers of construction services, now spends more on repair than on new construction [7].

Facility management organizations in the public sector, in general have not established policies to deal with their increasing need for component inspection. They have not developed a component inspection strategy to use when designing and preparing bid documents for their major repair contracts. As these organizations transition from a period where new construction was their main emphasis to a period where reconstruction of existing facilities is a greater portion of their total effort they need to change their investigative techniques accordingly.

In selecting a component inspection method to employ, these organizations tend to only look at the additional design cost. They do not look at the impact of inadequate component inspection in terms of change order costs, project delay and the political cost of loss of credibility to the facilities organization. Considering the increasing importance of repair work to these public agencies it is surprising that more effort has not been directed towards the establishment of component inspection policies to be used in the design of facility repair projects.

The ability of facilities management organizations to achieve their objectives is also impacted by the pressure that facilities management organizations receive to force them to keep facilities operational. The users want the facilities in good condition, but operational pressures prevent them from allocating adequate time for repair. For this reason it becomes imperative that the facility owners find ways to achieve their objective and minimize the effect on the user. This includes both methods of component inspection to determine the nature of the repair work and ways of doing the work. Research that is ongoing to find materials and methods for reconstruction that could speed the actual repair effort.

This thesis is interested in examining the value of new methods for component inspection to support this repair effort.

2.4 Facilities management process - Decisions

In the course of identifying, designing and executing major facility repair projects in support of the objectives of a facilities management organization there are a number of decisions that must be made. These decision are generally made at two levels: the network level and the project level.

Decisions at the network level involve prioritizing and selecting a group of facilities repair projects for funding and execution from a larger number of available projects. The decision to repair or replace a facility component is made at this point in the process. Optimally, decisions at this level are based on the facility condition information, environmental conditions and cost data that have been collected to support these decisions [8].

This next section will examine the decisions made at the project level that are relevant to this thesis.

2.4.1 Project level decisions

Project level decisions involve the analysis and selection of the repair alternatives that will be applied to each of the projects selected above for execution. Optimally, these decisions should be based on life cycle cost analysis using actual and predicted component deterioration information and cost data that has been collected to support these decisions.

Eventually, at the project level, an individual project and a repair alternative are selected for execution. For the purposes of this thesis it will be assumed that the decision to select this individual project was made correctly and the uncertainties associated with this decision have been accounted for prior to this point in the process. This is important because the purpose of this thesis is to look at the effect of decisions made after an individual project has been selected.

Additionally, this thesis is only concerned with projects where repair of the component has been selected, as opposed to replacement. This is because the decisions an owner must make with regard to component inspection are more relevant to repair projects than replacement projects. For example, if the project calls for the complete replacement of a concrete bridge deck the nature of the work is quite easily described with minimal information concerning the deteriorated state of the existing deck. On the other hand, if a bridge deck, for example, is to be repaired knowledge about the location and quantities of deck delaminations is an important element of the nature of the work [9][10].

After an individual project has been selected for execution several decisions must be made regarding how that individual repair project will be executed. This thesis will focus on two of these decisions. They are as follows:

1) If it is to be done by contract, what type of contractual arrangement between owner and contractor should be selected for use?

2) In preparing the contract documents and doing the design for this repair project what component inspection methods should be selected for use?

The next sections of this chapter will discuss each of these decisions and the considerations that should be taken into account when making these decisions.

2.4.2 Select the contractual arrangement

This thesis is only concerned with those repair projects that are selected to be done by contract. This is because the selection of a component inspection method is not as critical if the work is to be done in-house. Basically their are three types of contracts to select from: 1) lump-sum price, 2) unit price or 3) cost-plus [11]. There are other types available, but they are simply combinations of these.

The decision to select of one type of contract over another is greatly dependent on the owner's procurement regulations. For example, cost-plus contracts are very rarely used by public agencies due to their procurement regulations and the opportunity for abuse. Additionally, the decision is dependent on the degree to which the exact nature and quantity of the work can be determined. If the scope of the repair project, including the nature and the quantity of the work, are known with certainty then a lump-sum contract can be used. If the nature of the work is known, but the quantities are not known then the a unit price contract should be selected. Many times lump-sum and unit price work items are combined into the same contract. An item of work in which the scope is known with certainty is bid on a lump-sum basis and the items of work in which there is some uncertainty as to quantity of work are bid as a unit price basis [11].

Unit price work is awarded based on an estimated quantity of work. This estimate is provided by the owner and all bidders use the same estimate so as to form a basis for comparing bids. The contractor is obligated to perform the required quantities of work even though they may differ from the estimated quantities. Depending on the procurement regulations of the owner the contract may include a provision stating that if the estimated and the actual quantities differ significantly new unit prices will be negotiated. The degree of variance at which this adjustment occurs varies from owner to owner. It can be based on the variance of each individual line item or on the total contract price.

These clauses are a part of the general conditions the owner issues with each contract and do not generally vary between individual projects. For example, the state of Vermont uses 25% of the total contract price as the threshold. The federal government uses 15% of an individual line item as the threshold. For the purposes of this thesis this threshold will be called the contract variance threshold (CVT).

The contract variance threshold will determine the accuracy with which the quantities of work must be estimated in order to avoid any additional costs associated with changing the quantity. When repair projects encounter deterioration that differs beyond the allowable contract variance threshold this results in a needed change to the contract and the associated costs must be absorbed by the owner. Determining the estimated quantity of work is the role of component inspection and decisions by the owner with regard to the component inspection methods used in the project design can have an effect on the changes caused by exceeding the contract variance threshold.

2.4.3 Select the component inspection method

During the design of the repair project and the development of contract documents the owner must select a component inspection method. In selecting a component inspection method for a particular repair project owners should consider the following factors [10]:

- the needed accuracy of the component inspection method
- the cost of the component inspection method
- the degree of user reliance on the facility
- the priority and schedule of the actual repair effort

In considering the cost of component inspection owners should evaluate the true cost of the component inspection method for a repair project. If efforts are made to cut the cost of designing a project through selecting component inspection methods that cost less and provide less accuracy this will show up as changes to the contract, project delays and embarrassment to the agency. Owners must be concerned with the effect these decisions to cut the cost of component inspection have on the total cost of the project.

One way in which owners reduce the cost of component inspection is to utilize in-house engineers to perform the component inspection. This decision fails to consider the needed component inspection accuracy for a particular repair project in comparison to the capabilities of these personnel. Although these in-house personnel may be competent in their field of expertise, component inspection for a major facility repair project, that occurs say every 15 years, is many times beyond their capabilities. They are simply not able to provide the needed accuracy. The cases to be presented in Chapter Seven will show examples of this.

If the skills required for design and component inspection are beyond the capabilities of the in-house engineers, or if expensive or sophisticated tools are needed, the owner should consider an outside consultant to perform the design. In the case of federal work the design procurement rules allow consultants to be compensated for the fair and reasonable costs associated with using expensive capital intensive component inspection equipment for the project [12].

Because the component inspection process is concerned with existing facilities the selection of a component inspection method is greatly effected by the speed of the component inspection method and the users desire to keep using the facility. The amount of downtime that can be scheduled for a component inspection activity is sometimes very limited and will determine what component inspection methods are acceptable in terms of how long it takes to perform the component inspection.

In considering the scheduling of the repair project the component inspection decisions made by owners must address the fact that deterioration is time dependent. When a repair project is delayed from starting, the deterioration is allowed to continue and when the work finally begins the designed repair may be unsuitable for the current condition of the component. Therefore, owners must select component inspection methods that identify the work at a point in time, but also address the fact that deterioration may change the work. This is particularly important with public owners where there may be a considerable delay before the execution of a repair project.

In summary, the decisions made with regard to component inspection are important to the overall success of an owner's facilities repair projects. Specifically the decisions made at this point in the facilities management process with regard to the selection of component inspection methods will affect:

1) the contractor's bid price through the application of contingency amounts.

2) the magnitude and quantity of changes to the contract as a result of inadequate component inspection.

Although the nature of increased bid prices due to component inspection decisions will be discussed in the next section, the emphasis of this thesis will be on the effect component inspection decisions have on contract changes.

2.5 Bid prices versus component inspection decisions

Bid prices for facility repair projects are effected by decisions made with regard to component inspection since component inspection forms the basis for the information in the contract documents that describes the nature of the repair work. The contractor uses this information to determine the quantities of materials, the labor hours and the equipment required to accomplish the work. This information is also used to determine the sequence of the work, the project schedule and ultimately how to optimize profit [13].

The first step any contractor takes in bidding work is to become thoroughly familiar with the contract documents in order to fully understand the overall job picture and the requirements set forth by the owner [14]. The contract documents must provide adequate information for the contractor to bid on the job [9]. If the information in the contract documents is incomplete then the contractor may be less inclined to bid on the work because of the possible problems that could result. Contractors prefer to avoid projects they know will be a problem. If they choose to bid, the prudent contractor will increase his bid price with a higher contingency to cover the uncertainty associated with the incomplete contract documents [15]. Alternatively, the less than prudent contractor may not include a contingency and hope to successfully claim for extra work after award of the contract. In either case, the owner incurs extra cost and delay in completing the repair project.

Component inspection is used to determine the estimated quantities of work for both unit price and lump-sum contracts. In unit price contracts, the contractor is obligated by the contract to provide the actual quantities of work regardless of the difference between the estimated and the actual, unless there is variance clause in the contract allowing for an adjustment in price as discussed earlier. For bidding purposes however, the amount of contingency he places in his bid will be dependent on the certainty he feels in the estimated quantities and the existence of the variance clause allowing for an adjustment in price. He will include some contingency to cover a change in quantities, but by increasing the accuracy of the estimates and including a variance clause the owner can minimize the amount of contingency [16].

2.6 Contract changes due to inadequate component inspection

This thesis is concerned with changes that result from inadequate component inspection. Inadequate component inspection is defined as occurring when errors in the component inspection process lead to incorrectly describing the nature of the repair work to such a degree that a contract change is required to correct the error. A certain degree of error exists with all component inspection methods. However, inadequate component inspection does not occur until the error is so great that a contract change is required to correct the error.

When making decisions regarding component inspection many times facility owners do not consider potential changes caused by inadequate component inspection and their impact. If owners could predict the impact of their component inspection decisions, this information could be used to help them make more informed decisions regarding component inspection for major facility repair projects.

This thesis will attempt to shed light on the decisions owners make in the component inspection process and the effects of these decisions. The errors that can be made in the component inspection process will be examined and an attempt will be made to quantify their impact in terms of dollars.

The term "penalty costs" will be used to describe this impact or the cost of changes caused by inadequate component inspection. Penalty costs are defined as the additional cost of doing the repair project as a result of changes caused by incorrectly describing the nature and the quantity of the work in the contract documents.

Penalty costs should not be equated to the total cost of the change order. Generally, only a portion of the total change order costs are penalty costs. Especially in the case of adding work to the contract where the owner would have paid some part of the change order costs to have the changed work done if it had been described correctly in the original contract documents. Penalty costs are only those costs that are attributed to changing the contract work after award.

Also included in this definition of penalty costs are the additional agency cost of administering a contract change, the user cost associated with any delay in completion of the project and any additional redesign costs. Penalty costs will be discussed and developed in more detail in Chapter Five.

Many times these penalty costs are overlooked when selecting a component inspection methods for a particular project. Changes due to inadequate component inspection are preventable and the first step towards prevention is to understand the effect of inadequate component inspection.

2.7 Relationship between component inspection costs and penalty costs

This section will present the conceptual qualitative relationship between the cost of component inspection and the penalty cost associated with inadequate component inspection.

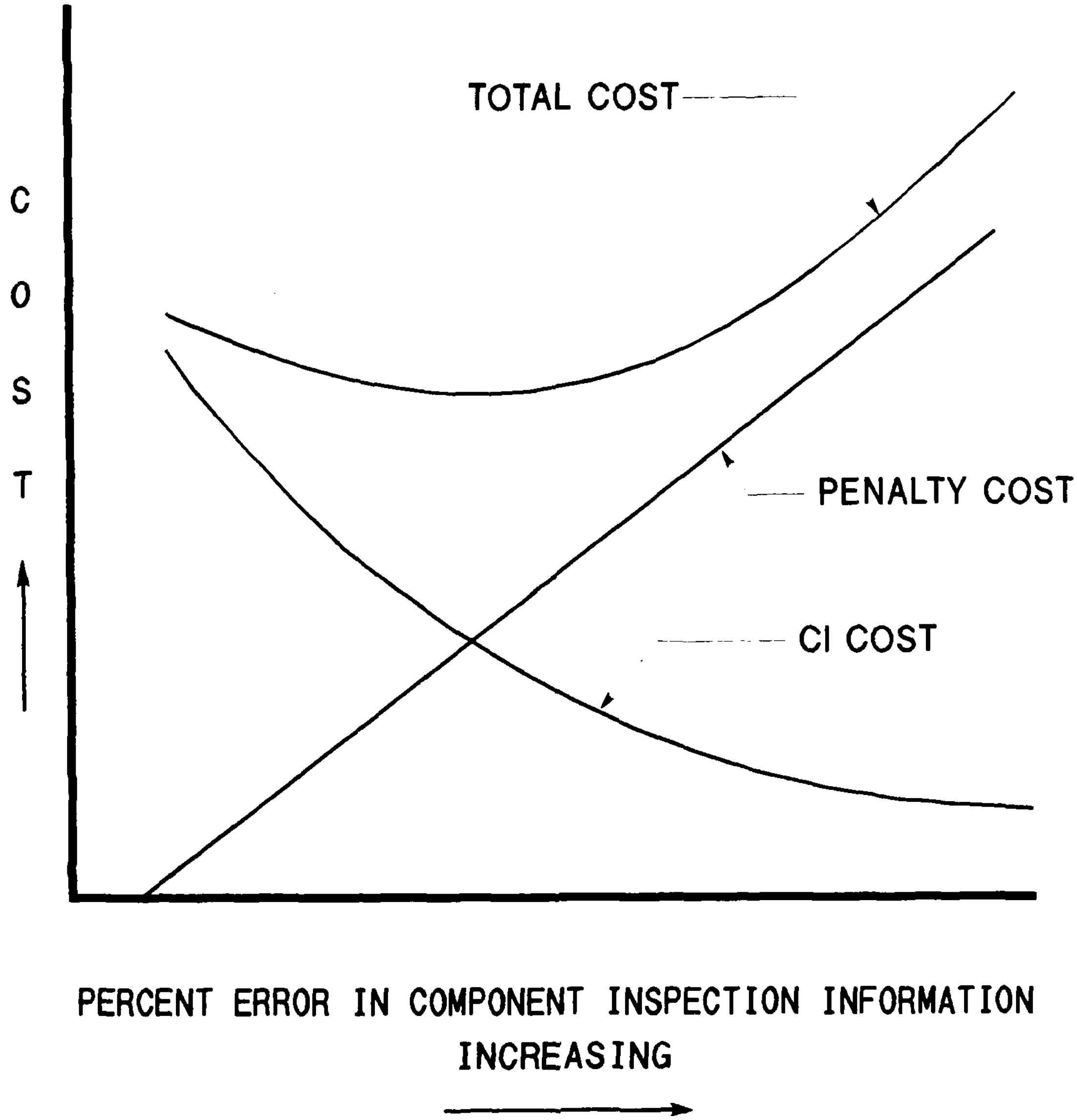
This relationship is shown in Figure 2.1. The cost of component inspection information is shown as a function of the percent error of the component inspection information. Different component inspection methods will have different costs and yield various levels of accuracy in information. These points connected together would produce the component

COMPONENT INSPECTION COST AND PENALTY COST

VERSUS

PERCENT ERROR IN COMPONENT INSPECTION INFORMATION

FIGURE 2.1



inspection cost curve shown. Methods that yield more accurate information (less percent error) tend to have a greater cost.

The penalty cost curve is also shown as a function of the percent error in the component inspection information. As the percent error of the component inspection information increases, the magnitude of the penalty costs will increase and this will produce the penalty cost curve. The total cost curve is a sum of the penalty cost and the component inspection cost at each level of accuracy of component inspection information. There is a minimum total cost which corresponds to the optimum component inspection method that yields a certain percent error of information and a certain penalty cost at the same percent error.

Through examining and understanding this relationship owners' could make decisions about the component inspection methods that are most appropriate for a project in terms of the total cost.

2.8 Summary

Repair projects play an increasing role in the life of public facilities management organizations. The unique aspects of repair work and the organizational restrictions that public owners must operate under require an examination of the component inspection decisions used in the implementation of these repair projects with the aim of minimizing the penalty costs associated with contract changes.

In order to accomplish repair work by contract the owner must prepare contract documents for the contractor to use in bidding the work. These documents must describe the nature of the work in enough detail so that the contractor can estimate the work and provide a bid. Component inspection occurs during the design to obtain the information required for the contract documents so the contractor can bid the work.

This chapter has discussed the importance of component inspection to the overall facility repair project effort in terms of its effect on contract changes and bid prices.

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CHAPTER THREE

COMPONENT INSPECTION AND REPAIR METHODS FOR DEFECTS IN CONCRETE BRIDGE DECKS AND AIRFIELD PAVEMENTS

The purpose of this chapter is to look at repair work in more detail as it pertains to the two types of facilities this thesis will be concerned with; airfield pavements and concrete bridge decks. This chapter will discuss the typical defects that occur in these facility components, the methods of repair employed for these defects and the component inspection methods that can be used to identify these defects.

3.1 Definition of repair work

For the purposes of this thesis repair is defined as anything but the replacement of the entire facility or the entire facility component. If a section of an airfield pavement or a concrete bridge deck is removed and new material put in its place this would be repair, not replacement. Replacing small sections or localized replacement in order to repair the component as a whole is considered to be repair for the proposes of this thesis. Even the replacement of an entire slab of a Portland cement concrete pavement is considered repair. Additionally since this thesis is concerned with work that is done by contract, the emphasis will be on major repair projects, as opposed to routine repair work which is many times within the capability of in-house forces or involves work of a recurring or routine nature. What will be referred to as repair work in this thesis may otherwise be known as reconstruction, renovation, rehabilitation or major maintenance. The exact term used is not so important. The important issue is to understand is that the definition does not include the wholesale replacement of a facility or a facility component. The issue of component inspection is much more important to repair projects than it is to replacement projects.

3.1.2 Key aspects of repair projects for existing facilities

Facility owners are constantly reminded that the facilities they are charged with repairing are occupied. They must keep this fact in mind when they plan repair projects and select component inspection methods. The effect these activities have on the user of the facility should be a key consideration in their planning. As discussed previously bridges and airfield are critical links in transportation networks and denying the user access is a decision that is not lightly made. Component inspection methods must be selected that minimize this downtime to the user. Repair work must be scheduled around the users requirements or alternative arrangements must be made to accommodate the user. These are key considerations for all existing facilities in which repair work is planned and not unique to airfield and bridge decks.

3.2 Bridge deck defects and repair methods

Concrete bridge decks provide the interface between the substructure of the bridge and the user. There are basically two types of concrete bridge decks. The first are bare concrete decks in which the traffic rides directly on the concrete. The concrete is a structural part of the bridge and is exposed to the elements. This is a disadvantage in that it contributes to its accelerated deterioration, however it is also a benefit because it allows direct visual inspection of the concrete surface.

The second type of deck is the asphalt covered deck in which a wearing course of asphaltic concrete has been applied over the top of the concrete. This wearing course is not a structural part of the bridge and contributes to the dead load. Between this wearing course and the concrete there may be a membrane. Asphalt wearing courses greatly complicate the inspection of a bridge deck. Defects are hidden from view and some types of defects are indiscernible from others. For example, delaminations in the concrete are mistaken for debonding between the asphalt and the concrete layer [1].

With the exception of debonding the defects found in either covered or uncovered concrete decks are the same. The following is a description of the principle defects and their causes:

Spalling is a hole in the surface of the concrete bridge deck where a delamination has progressed to a point that the concrete above it is broken away from the deck.

Scaling is the flaking or pealing away of the cement paste at the surface of the concrete. It is caused by the action of the freeze thaw cycle and the use of deicing chemicals. It can progress to the extent that the surface aggregates are loosened up.

Delamination is a separation along the plane parallel to the outer surface of the concrete. It is usually located at the elevation of the top layer of reinforcing bars and is caused by the increased pressure associated with the corrosion of the reinforcement.

Debonding is a separation at the interface between the structural concrete bridge deck and the asphalt wearing course. Although technically not a defect of the concrete bridge deck, if it is allowed to remain it will eventually become a pothole and degrade the performance of the bridge and allow the membrane, if there is one, to become damaged and degrade its performance.

Punky concrete is a term used more to describe several defects than it is a separate defect. This term is used to describe concrete that is not as strong as it should be and needs to be removed in the repair process. This loss of strength can be caused be delaminations or scaling. In any event it represents deteriorated concrete due to a number of mechanisms including infiltration of salt and water though micro cracks.

The methods of repair for each of these defects usually involves removal of deteriorated concrete and replacement with new concrete. The determination of the extent of the deteriorated concrete is the most difficult problem in planning a repair of a concrete deck [1].

After all of the areas of unsound material and delaminations have been removed most agencies employ either the installation of a concrete overlay or a membrane and an asphalt wearing course. If a concrete overlay is to be installed then the entire surface should have the top 1/4" scarified to provide a good bond. If an overlay is planned the edges of the removed areas can be made with a chipping hammer at an angle so air pockets are not produced when the overlay is put down. If a membrane and an asphalt wearing course are planned then the edges should be cut with a saw. The saw blade should be tilted slightly into the old concrete to help hold the new concrete in place. Before fresh concrete is placed the existing surface must be blast cleaned. This removal method can be used to repair spalls, delaminations and scaling.

3.3 Airfield pavement defects and repair methods

This section will discuss the defects that occur in airfield pavements and the repair methods that are commonly employed. There are two basis types of airfield pavements - flexible and rigid - and the defects that occur vary depending on the type of pavement. Many times rigid and flexible pavements will be used in different areas of the same airfield depending on the purpose for the individual section of pavement (taxiway, runway, fueling area, parking/maintenance apron). For example, maintenance and refueling areas are usually made of concrete as opposed to asphalt to prevent deterioration due to fuel spills [2].

3.3.1 Rigid pavement defects

A rigid pavement structure has two main constituent parts: the Portland cement concrete (PCC) slab and the sub-base course structure. Joints form the interface between the slabs to allow for the thermal movement of the slabs [2]. A failure of any of these parts is considered a defect in the pavement. The airfield pavement condition survey procedures used by the Navy identify 15 defects that can occur in rigid airfield pavements [3]. A description of these defects is provided in Appendix A.

3.3.2 Rigid pavement methods of repair

Rigid pavement defects, either individually and in combination, can be repaired by various methods. The methods for the repair of rigid pavements include [4]:

Localized repairs to specific portions of the rigid pavement. This work involves the removal of deteriorated areas and the placement of fresh concrete. This method requires attention to the interface between the new concrete and the existing pavement that is to remain. This work may be done on a portion of the slab that also includes a joint. In this case the joint must be rebuilt as part of the to insure the repaired joint will function consistent with the remaining portion of the joint.

Asphalt overlays are a method of repairing existing PCC pavements. In order for overlays to be effective they must be designed so that the existing defects are not reflected through to the new surface. This can be accomplished by requiring localized repairs to the badly deteriorated sections of the PCC pavement before overlaying and the use of a crack relief layer between the old PCC and the new asphalt wearing surface. The crack-relief layer provides provides a medium through which differential movements of the old PCC slab cannot be transferred.

Resurfacing is a repair method in which the existing PCC pavement is overlain with another PCC layer. Various combinations of reinforcing and bonding interfaces can be designed into the overlay depending on the desired additional pavement strength and the defects that are present on the existing pavement.

Reconstruction is a method where the existing pavement is removed and then either wasted or reused as base course, aggregate or fill. The potential for reuse of the old pavement depends on the availability of suitable virgin materials. In areas where quality aggregates are in short supply this method of repair is becoming more advantageous from a total cost perspective.

PCC joint and crack sealing is done to prevent surface water seepage into the joint and the sub-base material, protect joint fillers and to keep debris out of the joint so it can function properly. Cracks and joints must be cleaned out before sealers can be applied.

3.3.3 Flexible pavement defects

Flexible pavements have three constituent parts: the surface course, the base course and the sub-base course. Joints for the purposes of thermal expansion are not as important as in rigid pavements because the flexibility of the pavement allows for this movement [2]. The condition survey procedures used by the Navy identify 16 defects that can occur in flexible pavements [3]. A description of these defects is provided as Appendix A.

3.3.4 Flexible pavement methods of repair

Flexible pavement defects have various causes such as overloaded, age, improperly mixed asphalt concrete and user problems such as jet blast. Regardless of the cause of these defects the following repair methods can be used to repair these defects either individually or in combination [5]:

Patching - Two types of patch work are used in the repair of asphalt pavements. The first is skin patches which are temporary in nature and involve placing a seal coat over the deteriorated area. The second are deep patches which involve the removal of the deteriorated asphalt to a depth of at least 4 inches. The excavation should also extend horizontally a foot into good pavement surrounding the patched area. The edges of the excavation should be squared off. If the sub-base material is good it should be recompacted, and if it is poor or was the cause of the failure it should be replaced with new material. The edges should receive a tack coat and the sub-base should receive a prime coat before new asphalt is placed in the excavating. All types of cracking, depressions, rutting, slippage and corrugations can be repaired with patching.

Crack filling - Crack filling is a method of repair that can be used on all the commonly encountered types of cracks in asphalt. Each crack that is to be filled must be opened and cleaned. Blowing with air jets and routing are the two most frequently used cleaning procedures. Both hot and cold liquid asphalts can be used to fill the crack depending on the application. The liquid must be fluid enough to flow into the crack. Asphalt-aggregate mixtures, such as sand slurries are used to fill especially wide cracks (over 3/8").

An asphalt overlay is a method of repairing asphalt pavements and may be designed simply to improve the average pavement condition (smoothness) or it may designed with additional thickness to provide added structural capacity to the pavement. In either case, measures must be taken to retard the reflective cracking of defects in the existing pavement. One way to accomplish this is though the incorporation of a fabric under the new asphalt layer and to insure that all weak areas are repaired by a deep patching prior to overlay. This method is normally done after the removal of a thin layer of the existing asphalt by scarification.

Recycling of asphalt pavements is a method of repair that can be accomplished in three ways: 1) surface, 2) hot-mix, or 3) cold-mix.

Surface recycling consists of reworking the surface of the old asphalt pavement to a depth of less than one inch. The pavement is heated with a mobile combustion chamber and the softened materials are then scarified and mixed together. This is recompacted and an overlay is applied.

Hot-mix recycling consists of removing the existing asphalt and stockpiling these materials at a central plant. These old materials are reheated and combined with new asphalt and aggregates to produce a hot-mix that is then relayed as a new surface would be.

Cold-mix recycling removes and crushes the existing pavement to a specified particle size. The crushed pavement material is mixed without the introduction of heat with an asphalt recycling agent and new materials to produce what is considered a treated base. This treated base is placed and compacted and a hot-mix wearing course is then applied on top.

3.4 Component inspection methods for concrete bridge decks

There are two types of bridge inspections typically performed. The first is an routine inventory inspection such as the National Bridge Inventory mandated by the Congress. The second is a more detailed inspection done when the results of a routine inspection indicate a bridge is likely to be in need of work and in order to collect information for the preparation of contract documents [1]. This thesis is concerned witn the more detailed survey used in the preparation of contract documents.

In general the component inspection method that can be used for this more detailed survey can be divided into two types which will be called existing methods and new methods. The existing methods are typified by being less equipment intensive, based on a lower technology, and generally taking a longer period of time to perform the component inspection function. The new methods are faster and rely upon non-contact automated sensing technologies.

3.4.1 Existing methods

The existing methods for the component inspection of concrete bridge decks that are used frequently are described as follows:

Chloride content test is used to determine the concentration of chlorides from deicing agents that have permeated the concrete. Samples are taken to determine if the threshold concentration has been reached and at which locations. Samples are relatively expensive to take since they require a drilling rig, diamond toothed core drills and lab analysis of the samples. Unfortunately, the value obtained for each sample is only the value at that particular point. The test results are somewhat variable depending on the sample location and associated factors such as how well the deck is drained [1].

Chain drag is an acoustic technique that allows the user to find delaminations and areas of unsound concrete. Noise from traffic interferes with its use. The method is fairly accurate, but it is slow. On asphalt covered decks it is difficult to tell the difference between debonding and delamination. Delamtect is another device that can be used to detect delaminations on bridge decks. It can reportedly detect delaminations up to 4.5 inches below an asphalt wearing course and up 2.6 inches below a exposed concrete deck. However, using this method, debonding is also often mistaken as a delamination and this technique is not as accurate as chain drag [6].

Visual inspection of the bridge deck is used to locate visible defects such as spalls, scaling and cracks.

Core samples have the same disadvantages as samples taken for chloride content. Core samples can detect delamination, debonding, unsound concrete. Core samples can also be used to confirm the results of other non-destructive tests. Unfortunately core samples only provide information about the deck at the point where the sample was taken.

Selective demolition is a method in which a section of the bridge deck is ripped up to determine its condition. This method is more frequently used on asphalt covered decks where information is needed about the concrete that is hidden from view. A small section of asphalt is removed, the condition of the concrete is noted, sections of the concrete may even be taken up at this time to see if it is sound. The demolished area is then repaired with an asphalt patch until the repair work is scheduled.

Electrical resistance testing of membranes is useful for detecting their integrity if they are installed on the bridge. Any holes in the membrane that would allow current to flow would allow moisture onto the concrete. Although this test does not indicate the condition of the deck itself, the lack of a good membrane would indicate the need for a new one and the degree to which one might expect the deck to be deteriorated. The evaluation of the results is subjective and the method itself is subject to error [7].

Half-cell potential measures the corrosion activity in the bridge deck. This test is designated ASTM C876 and is described in detail in the literature [1]. It requires a hole be drilled in the asphalt wearing course and the deck membrane. The test is subject to some external variables such as temperature and the amount of free water on the deck. The test results sometimes indicate corrosion when that is not the case. The relationship between half-cell tests, corrosion and defects in a deck have been established in tests. As the half-cell readings increase the amount of corrosion and the probability of corrosion being present increase. However, the half-cell reading is not a measure of the rate of corrosion, just the presence of corrosion.

3.4.2 New component inspection methods for bridge decks

The following methods were developed in response to the need to develop new bridge deck evaluation methods. They are described as follows:

Ground Penetrating Radar (GPR) is a method based on pulsed microwave frequency energy that can detect a number of bridge deck defects. It can detect the thickness of the various layers, the depth of the reinforcement and it is sensitive to the condition of the concrete and the chloride content. The method can survey a 1.5 foot wide strip of bridge deck at 2-10 miles per hour. GPR is fast and non-destructive. However, because of the great amount of data collected the data processing a reduction costs are high [7]. A 90% reliability has been obtained in the use of this component inspection method to distinguish between sound and deteriorated concrete [8].

Infrared thermography (IR) can be used to detect delaminated and debonded areas on bridge decks. IR senses the emission of thermal radiation. Sound and unsound portions of the deck have differing heat transfer properties due to the thermal break that is filled with either water or air. This causes a difference in the amount of thermal radiation that is emitted. And by sensing differences in thermal radiation are caused by these defects and show up as with thermal discontinuity. This method is effected by external variables such as weather. It may confuse surface defects, patching and discoloration with unsound concrete. It has the advantage of being fast. It can pass over a deck at 2-10 miles per hour and survey one lane per pass [7]. In field test this method has identified 90% of the known delaminations in a concrete bridge deck [9].

3.5 Component inspection methods for airfield pavements

This section will discuss the existing and new component inspection methods for airfield pavements.

3.5.1 Existing methods

The existing methods methods are described as follows:

Chain drag is the same test for airfield pavements as described for bridge decks. This method can also be performed by dropping a metal rod, such as a reinforcing bar, on end. The accuracy of this method is fairly good, but it has the disadvantages of being difficult to use with interference from aircraft engine noise and it is also slow.

Falling weight deflectometers are used to determine the structural strength of a pavement section. It is primarily used to determine the remaining allowable capacity of an existing pavement to provide to be used to determine the required thickness of an overlay. There are several models of this device, but the all work on the basis of dropping a weight and imparting an dynamic force onto the pavement. Transducers measure the applied loads and the displacement of the pavement. There are a number of other devices such as Dynaflect and Roadrater that are based on the same principle. Some apply a impulse load and some use a vibratory load [10].

Visual inspection of an airfield pavement is fairly straight forward. The size and location of defects are noted manually during the survey. Visual inspection is the basis of the pavement condition survey procedures used by the Navy. This technique relies on examining a representative sample of the pavement to determine its overall condition. This is satisfactory for the purposes of condition assessment, however this information may not be satisfactory for component inspection purposes. If representative data is extrapolated to determine the defects that exist on the entire pavement errors in the amount of work could result [11]. Visual inspection of an entire airfield is a time consuming and laborious process, much more so than visual inspection of a bridge deck because of the greater area involved.

Test pits are a destructive method of determining the strength of the existing pavement structure. The paving materials and the sub-base materials can be tested in place and samples can be taken for lab testing. California Bearing Ratio (CBR) values can be obtained from this test. This method is quite time consuming and the test only provides information regarding the particular location tested.

3.5.2 New methods for the component inspection of airfield pavements

Several new methods are available for the component inspection of airfield pavements. Some have been adapted from methods that have already been applied to bridge decks and would be useful for airfield pavements. They are described as follows:

Ground Penetrating Radar (GPR) would also be useful to detect the same defects on airfield pavements. It can detect the thickness of the various layers, the depth of the reinforcement and it is sensitive to the condition of the concrete and the chloride content. It can also be used to detect voids under the pavement [12].

Infrared thermography (IR) can be used to detect delaminated and debonded areas in airfield pavements. IR has the advantage of being fast which is important for airfields where the time allowed for component inspection is normally restricted. It can survey a 12 foot wide path of pavement at 2-10 miles per hour [7].

Video imaging is the rapid viewing and recording of a visual inspection of the pavement. It can be used to detect any of the defects that could be detected by visual inspection. Its advantage over normal methods of visual inspection is that a permanent record is made in a short period of time to be analyzed later. The owner does not have to great periods of looking at the component and recording the defects. It allows the same defects to be detected in much less time than manual methods. This record can then be digitized and processed looking for the same defects a human inspector would look for only in much less time. This method is especially useful for facilities where the amount of time available for component inspection is severely restricted, and although existing methods would be adequate given enough time, that time is simply not available [13].

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CHAPTER FOUR

CONTRACT CHANGES DUE TO INADEQUATE COMPONENT INSPECTION

CASE STUDIES

The purpose of this chapter is to present cases studies where inadequate component inspection was the cause of change orders in facility repair projects. The existence of these cases highlight the importance of this problem and show examples of the penalty costs that are associated with inadequate component inspection. The cases have been obtained from informed public owners. The thesis will present three bridge deck cases and three airfield pavement cases.

4.1 Introduction

In discussing each of these cases the following information will be presented:

1. description of the facility and the scope of the project.
2. award amount, date of award and the duration of the project.
3. schedule constraints due to weather or user requirements.
4. how did the problem of inadequate component inspection arise or become evident.
5. how was the problem corrected.
6. what was the nature of the penalty costs that occurred due to changes issued to correct the problem.

4.2 State of Vermont - Middlesex, Plainfield and Waitsfield bridges

The Middlesex, Plainfield and Waitsfield bridges are located in the State of Vermont. Their repair was part of the annual bridge repair program by the Vermont Agency of Transportation.

4.2.1 Scope of project

A contract was awarded on 17 March 1986 for $250K to perform various items of repair work on these three bridges. The contract completion date was 1 August 1986. The contract was a unit price contract with approximately 20 line items of work. The scope of the work was the same for the three bridges and included various repairs to the bridge deck and associated work like restriping and joint repairs.

4.2.2 The problem

Of the 20 work items on the bid schedule this discussion will only be concerned with two: 1) concrete surface prep class 1, and 2) concrete surface prep class 2. These two work items include removing concrete in poor condition, preparing the exposed surface and placing new concrete. Class 1 removal is down to the top mat of reinforcement and class 2 removal is down to at least 3/4" below the top mat of reinforcement.

After the work began it became apparent that the actual quantities of removal for these two work items were significantly greater than the estimated quantities. A summary of these differences follows:

Bridge	Estimated Quant (SY) Class 1	Class 2	Actual Quant (SY) Class 1	Class 2
Middlesex	20	345	319	600
Plainfield	3	46	20	53
Waitsfield	1	7	61	20
Total each class	24	398	400	673
Total class 1 & 2	422		1072	
Percent error		154%		

The estimated quantities were determined through the standard bridge survey procedures employed by the state which include visual inspection and half-cell tests.

The actual quantities of work required at the completion of the job were 154% greater than the estimated quantities. This increase combined with other minor increases and decreases in unit quantities for other work items caused the final contract price to exceed the bid price based on estimated quantities by 50%, from $250K to $374K [1].

Although a portion of this increase is due simply to the fact that there was more work to perform and the owner would have paid this additional amount even if the quantities of work had been correctly known, a portion of this increase could have been avoided if the owner had stated the estimated quantities of work correctly on the contract documents. A portion of this increase is the penalty costs that were discussed in Chapter Two.

The other penalty costs that occurred in this case are the additional costs incurred by the owner to administer the changes and claims that occurred on this project because of the variation in the quantities. There were also penalty costs of a political nature that occurred on this project because the contractor finished later than the original completion date and the agency suffered the embarrassment of not completing the job on schedule.

4.3 Veteran's Memorial Bridge - Portland, Maine

The Veteran's Memorial Bridge is a four lane bridge carrying U.S. Route 1 over the Fore River between Portland and South Portland. It provides for a large daily traffic volume and the timely completion of this project was important to the users of the bridge.

4.3.1 Scope of project

This bridge repair project called for repairs to the substructure, concrete bridge deck, railing, lighting and other related work. This analysis is concerned with the repairs to the bridge deck. The contract was awarded on 28 June 1984 for $2,428K. The repairs to the bridge deck accounted for approximately $800K or one-third of this amount. The contractor had until 1 November 1985 to complete the work.

The contractor began work on the substructure repair first in 1984. This work was completed over the winter and the deck repairs were begun in the spring of 1985. The contract included two work items for the removal and replacement of deteriorated concrete on the deck. The first item, which will be called type 1, was removal down to the top layer of reinforcement. The second item, which will be called type 2, was to below the top mat of reinforcement.

4.3.2 The problem

After 22% of the deck work was complete it became evident that at the current rate at which deteriorated concrete was being discovered the projected actual quantity of concrete to be removed from the deck would far exceed the estimated quantities. The projected quantity was 35,000 SF. The estimated quantity in the contract was only 6,000 SF. The estimated quantities were determined by the state using the standard bridge inspection procedures, including visual inspection, coring and testing for chloride content.

If the work had proceeded as planned these additional quantities would have added $348K ($420K - $72K) to the cost of the work based on the unit prices as shown below. Furthermore, the contractor was intending to claim an additional $200K to cover the cost of accelerating the work to finish by November or the same amount to stop the work for the winter and re-mobilize in the spring of 1986.

REMOVAL TYPE	EST QUANT	UNIT PRICE	EST COST	PROJECTED QUANTITY	PROJECTED COST
1	3600 SF	8 $/SF	$28,800	21,000 SF	$168,000
2	2400 SF	18 $/SF	$43,200	14,000 SF	$252,000
TOTAL	6000 SF		$72,000	35,000 SF	$420,000

At this point the owner directed the contractor to change the method of removal for the remaining portions of the deck. Instead of continuing with the spot removal for either type 1 or 2, it was decided to perform type 1 removal over the entire deck with a milling machine as opposed to hand methods. And once complete, type 2 removal would be done where required. Afterwards the entire deck would receive an overlay of 2" of concrete [2].

This change added $515K to the cost of the contract. Although it is less than the $548 ($348K + $200K) that would have been added if the original work had continued, a portion of these costs could still have been avoided if the contractor had known that milling of the top layer of concrete was required prior to bidding the work. If the projected quantity of the deteriorated concrete had been known by the owner the decision to require the milling of the top layer could have been included in the contract documents. In this case however, the owner told the contractor how to do the work after the award of the contract and the contractor was reimbursed for his cost of doing the work. Therefore, any cost incentive on the part of the contractor was eliminated and this contributed to the penalty cost.

If the work had been correctly described in the contract documents there would have been competitive bidding on the work as it was changed and the cost of this added work would have been less.

4.4 State of Vermont - Hartland, Hartford and Sharon bridges

These bridges are located in the State of Vermont and their repair was part of the states's annual bridge repair program.

4.4.1 Scope of project

A contract was awarded in the spring of 1987 to perform various repairs to the decks of three bridges. The original amount of the contract was $327K. The contract was a unit price contract with approximately 20 line items of work. This contract was very similar in the scope of the work as the bridge repair contract in section 4.2 and included the same two work items for concrete removal as the previous Vermont case: concrete removal - class 1 and concrete removal - class 2.

4.4.2 The problem

The contractor began work after award of the contract in the spring of 1987. In two out of the three bridges the estimated quantities were greater than the actual quantities of work, however the final cost of the work on each bridge was within 10% of the bid amount. However, for the Hartland bridge (58A) the actual quantity of work was far in excess of the estimated quantity and this caused the quantity of concrete removal for the entire contract to be underestimated by 172%. Class 1 and class 2 removal will be considered together as the same work item since the contractor bid the same price for each.

A summary of the increase in quantities for each of the bridges follows [1]:

	Estimated Quant (SY)			Actual Quant (SY)		
Bridge	Class 1	Class 2	TOTAL	Class 1	Class 2	TOTAL
58A	5	79	84	0	720	720
65A	9	164	173	0	130	130
15N/S	4	54	58	0	8	8
SUBTOTAL	18	297		0	858	
TOTAL			315			858
% ERROR:	172%					

The bid price for bridge 58A was $75,424 based on the estimated quantities. The final price was $176,748 or an increase of $101,324. Like the other bridges, some of the work items for this bridge had minor quantity variations, however the entire increase in price can be attributed to the increase in the quantities of Class 2 concrete removal.

In this case, like the previous cases, inadequate component inspection caused the owner to have to issue a change order to add the required quantities of work to the contract. A portion of the $101K in added cost is attributed to the work itself and the owner would have paid a portion of this amount even if the quantities of work had been correctly described. However, some of this increase in price is attributed to the penalty costs that the owner paid because the quantity of the concrete removal was incorrectly described in the contract documents.

4.5 Fairchild Air Force Base, State of Washington

Fairchild Air Force Base is located 12 miles east of Spokane, Washington, in the east central part of the state. The base provides a Military Airlift Command and Strategic Air Command air base for the U.S. Air Force.

4.5.1 Scope of project

A contract was awarded in the spring of 1983 in the amount $1,396K to perform a variety of items of repair work to the runway. There were nine items on the bid schedule. Five of the nine items were priced on lump-sum basis and four were priced on a unit price basis. Three of the unit price items consisted of the removal and repair of spalled concrete each to a different depth. The fourth unit price item was to rout and seal random PCC cracks.

4.5.2 The problem

As the work progressed it became evident that the actual quantities of three out of the four unit price items would vary significantly from the estimated quantities. The estimated quantities of work were based on a survey of approximately 10% of the areas to be worked using rodding and visual inspection. The actual quantities were determined as the project progressed through the work area. A schedule showing the quantities of work (estimated and actual) and bid unit prices and the total amount for each work item is shown below:

ITEM	EST QUANT	ACT QUANT	% ERROR	UNIT PRICE	BID AMOUNT	FINAL AMOUNT
1. 3"-9" SPALL REPAIR (SF)	29,000	45,135	56%	$12.74	$369K	$575K
2. >9" SPALL REPAIR (SF)	20,000	13,835	-31%	$19.60	$392K	$271K
3. SEAL PCC CRACKS (LF)	25,000	6,600	-73%	$1.10	$27.5K	$7.26K
BID COST					$789K	
FINAL COST (AT BID UNIT PRICE)						$853K

The owner issued changes to the contractor to add the additional quantity of work for item 1 to the contract and did not grant a time extension to the contractor, so in effect the owner was accelerating the work. As shown on the schedule above the owner agreed to pay the contractor at the bid price for the additional quantities of work. The total cost of the three items of work in which there were significant quantity variances increased $64K from $789K to $853K. The owner also had to pay a premium of $80K, in addition to the above, to cover the costs associated with accelerating the work and requiring that the added quantities of item 1 be completed without a time extension [3].

A portion of this increased cost of $144K ($64K + $80K) could have been avoided if the correct quantities of work had been known at the time the contract was bid. Although the cost of the project would have increased some extent just to cover the additional required quantities of work, a portion of this increase is the penalty cost that could have been avoided.

If the estimated quantities of work had been correct the contractor would have bid a lower unit price for the work because the fixed overhead costs could have been spread over a greater quantity of work. So by continuing to pay the contractor the originally bid price for the work the owner was overpaying the contractor's overhead costs. Although the owner agreed to this price, the fundamental principle remains that as the number of unit increase the cost per unit drops. This benefit of lower prices due to greater quantities is much easier to obtain in the bid box than at the negotiation table. Especially when the parties are under the time constraints of an ongoing project.

The $80K paid to the contractor to accelerate the work could also have been avoided if the quantity of work had been estimated to within the contract variance threshold of 15%. The contractor did not know of the additional quantities of work when he planned the job, or even in the early stages of the project, so he planned an efficient, level effort throughout the term of the contract in order to maximize his profit. Instead, because of the extra work, he had to rush in an inefficient manner during the latter period of the contract in order to complete the added work on time. This inefficient operation was the cause of the additional $80K the owner had to pay.

4.6 Minot Air Force Base, North Dakota

Minot Air Force Base is a Strategic Air Command base in North Dakota about 50 miles from the U.S./Canadian border that handles KC-135 and B-52 aircraft.

The airfield was constructed in the late 1950's and no major repair have been undertaken since construction. Minor repairs to spalled areas have been done with concrete and asphalt by in-house forces over the years.

4.6.1 Scope of project

A unit price contract to perform various repairs to the airfield pavement repairs was awarded on 22 April 1986 in the amount of $1,539K. The scope of the work included 18 various work items, however in this analysis we will only be concerned with the following two items of work that made up the greatest portion of the contract:

Item 1 Sealing of cracks in PCC pavement

Item 2 PCC pavement patches

The contractor was allowed 215 calendar days to complete the work (from 1 April 1986 to 1 November 1986). The period after 1 November was designated as a winter exclusion period in which work was not permitted due to the weather. The pavements to be worked on in this contract were divided into areas and requirements were established for the contractor as to the sequence in which these areas would be worked and how many areas could be in progress at any one time. The contractor had to complete the area he was working before he could go on. Additionally two areas could be worked on only during certain weekends when aircraft were not flying. And at the end of the weekend the work had to be finished.

4.6.2 The Problem

After the contract was awarded, during the course of the work, the actual amount of PCC patching (spall repair) required became much greater than the estimated quantity and the quantity of PCC crack repair required was much less than estimated. The owner issued change orders to the contractor throughout the course of the project to cover the additional work. Eventually the amount of the added work became so great that the contractor could not finish before the winter exclusion period. At this point the contractor demobilized for the winter and returned in the next construction season to complete the work [4].

The estimated quantities were determined through a visual inspection of a small portion of the project area. The actual quantities were determined as the work progressed and the contractor moved from one work area to the next in the sequence as discussed above. The following schedule shows the estimated and actual quantities for these work items:

ITEM	EST QUANT	ACT QUANT	% ERROR	UNIT PRICE	BID AMOUNT	FINAL AMOUNT
1 PCC (LF) crack repair	124,000	50,842	-59%	$1.25/LF	$155K	$64K
2 PCC (SF) spall repair	26,500	115,392	+335%	$12.34/SF	$327K	$1424K
BID COST					$482K	
FINAL COST						$1488K

The final contract price was $2,458K. The increase of $919K can be primarily attributed to the 335% increase in the quantity of PCC spall repair required as shown above.

A portion of the $919K increase in the price of the contract was inevitable given the significant increases in the quantity of work for PCC spall repair. However, if the estimated quantity of work had been correctly described in the contact documents a portion of these additional costs could have been avoided.

The owner paid the bid unit prices for the additional work since the contractor was entitled to some compensation associated with adding the work after award and his demobilization and remobilization in the spring. In this case the owner thought it was best to use the bid unit price rather than take the time to audit and review the contractor's new unit cost and take the likely risk that the cost could even be higher than the bid price.

At first glance one might conclude that none of the increase was a penalty cost since the contractor did not raise his unit price. However, the real issue is how much would the contractor's bid price have been if the owner had known the quantity of work to within the contract variance threshold allowed by the contract. The bid prices would have been different if the amount of work had been known.

In general, the unit price for the PCC crack repair would have been more and the unit price for the PCC spall repair would have been less. Of course, this is only a general relationship, and in this case a lower price for the PCC spall repair may have been offset by the additional costs of remobilizing in the spring to finish the work. However, if the owner had known of the large quantity of work that was required steps would have been taken to minimize the impact. The owner would not have issued a contract package knowing that the contractor would not finish in one season or would cause the contract to drag out into the next year.

Examples of the steps that could have been taken include, dividing the work into two contracts, telling the contractor at the outset what his rate of production must be or structuring the contract requirements so that a contractor can realistically finish in a season. In any event, the owner cannot make such decisions if the required quantity of the work is not known.

User related penalty costs could also have been avoided if the quantity of work had been correctly estimated. Because the work extended onto the next year there were additional interferences to the operational users of the airfield. Aircraft had to be relocated to allow the work to progress. Security arrangements had to be made for another season. Operational personnel wasted their time doing over again what should have only needed to be done once the previous year. The result is that the facilities organization lost some credibility because they are still impacting the user with a project that should have already been complete.

4.7 Naval Air Station Brunswick, Maine

Naval Air Station Brunswick is located near Brunswick, Maine in the southern coastal section of the state. The mission of the air station is to support six squadrons of P-3 Orion anti-submarine patrol aircraft.

The airfield has two parallel runways 7000 feet long and 200 feet wide. The outboard runway is not instrument equipped and is only useful in good weather. The inboard runway is equipped for instrument landings and is the only runway plowed in the winter, thus making it the most active and operationally critical runway. This discussion is concerned with the instrument capable inboard runway.

This runway was constructed in 1951. It was last repaired in 1971 by replacing sections and recycling the existing asphalt.

4.7.2 Scope of project

On 30 September 1986 a lump-sum contract was awarded for approximately $3,963K to perform repairs of the instrument runway and other electrical work. The pavement repair portion of the contract was approximately $1,400K. The contractor was allowed 435 days to complete the work and the contract completion date was 9 December 1987. It was imperative that the work be completed as quickly as possible during the summer months, not only for construction reasons, but more importantly the non-instrument equipped runway would have to be used for operations during the construction. Therefore, while the project was ongoing if bad weather set in any aircraft landings would have to be diverted to other airfields over one hundred miles away.

The scope of work called for the crack sealing of approximately 100,000 LF of cracks in the asphalt pavement and the placement of an asphalt overlay. A reinforcing fabric was called for between the new and the old pavement for the center 100 feet.

4.7.3 The problem

When the paving work began in April of 1987 the amount of pavement distress had increased considerably and the designed repair, as required by the contract documents, was no longer appropriate for this increased amount of distressed pavement. The designed repair was based on a visual inspection of the runway conducted in April 1985 that showed that estimated the amount of distressed pavement at 9,000 SF. When the amount of distressed pavement was discovered to be greater than estimated, the same firm that did the original survey was requested to resurvey. This survey showed that the amount of distressed pavement had increased to 120,000 SF. The designed repair, if executed, would have resulted in excessive reflective cracking within several years. The large amount of distressed pavement would not have provided an adequate base for the overlay, even with the fabric.

At this point a redesign of the intended repair method was required and the contract for the repair of the runway had to be changed to accommodate this new method of repair.

The new design called for the full-width reconstruction of the the first 200 LF at each end of the runway and the center 66 feet for the remainder of the runway. The reconstruction was to be done by removing the pavement, recompacting the existing base course and replacement with a binder course. The remainder of the pavement was to be repaired by milling off at least 2 1/2" and replacing with a leveling course. Then a wearing course was to be installed over the entire runway surface [5].

This change added approximately $593K to the cost of the construction contract. The penalty costs in this case are a portion of these change order costs associated with the fact that the original repair contract was awarded to do the incorrect repair and as a result the contract had to be changed and the additional costs were incurred.

A portion of the cost of this change can be attributed to the cost of deferring the repair work two years. This is the additional cost the owner would have expected to pay for waiting two years to do the work if the redesigned repair had been included in the contract documents. This cost is estimated to be $424K.

However, the remainder of the change cost, $169K ($593K - $424K), is the penalty cost of awarding a repair contract in which the method of repair had to be changed because the actual condition of the facility was different from that which formed a basis for the design in the contract. Not that the component inspection performed in 1985 itself was in error, just that the condition of the runway continued to deteriorate and the component inspection methods employed by the owner failed to take this into account. This resulted in the need for a contract change.

The penalty costs were caused primarily by the need to complete the work in the original time of the contract. This caused the contractor to have to bring all of his firm's production capacity to bear of this one project. His crews had to work 7 days a week thus lowering their productivity. The fact that the cost of this change was negotiated as the work was ongoing also contributed to this penalty cost portion. In short, purchasing this additional repair effort under after contract award instead of in the bid box accounted for this increase of $169K. This penalty cost does not include the additional internal costs the owner incurred for administering the contract changes.

4.8 Summary

These cases show examples in which errors in component inspection resulted in changes to a facility repair contract. These changes in turn caused the owner to incur additional costs, or penalty costs, that could have been avoided had the nature of the repair work been correctly described in the contract documents. And as previously discussed, the role of component inspection is to adequately describe the nature of the work in the contract documents

The next chapter will examine the source of these changes due to inadequate component inspection and the nature of the penalty costs that result. The purpose will be to understand the composition and source of penalty costs and to examine how they can be calculated or estimated.

This understanding of penalty costs will be used in Chapter Seven to calculate the penalty costs for each of the above cases. These penalty costs will be plotted against the degree of error in component inspection that occurred in each case. This will show a relationship between the penalty cost as a function of the degree of error. The actual cost of the component inspection information for that project will be calculated and shown on the same plot. The cost of alternate component inspection methods and their associated degree of error will also be plotted. The total cost curve, similar to the one shown in Chapter Two, will be used to determine if alternate component inspection methods would have lowered the total cost to the project.

CHAPTER FOUR ENDNOTES:

[1] Turner, Richard, P.E.; State of Vermont Finals Engineer, Montpelier, VT, from data provided in a 17 February 1988 letter.

[2] Couture, Edward J.; Project Review Engineer, Construction Division, Maine Department of Transportation, from data provided in a 4 May 1988 letter.

[3] Sanders, Ron; Base Pavement Engineer, Fairchild Air Force Base, from data provided in correspondence.

[4] Peep, Elvie; Base Pavement Engineer, Minot Air Force Base, North Dakota, from data provided in a 22 February 1988 letter.

[5] Sturgeon, Tom; Project Manager, Resident Officer in Charge of Construction Office, Naval Air Station Brunswick Maine, from data provided in correspondence.

CHAPTER FIVE

CONTRACT CHANGES AND PENALTY COSTS RESULTING FROM INADEQUATE COMPONENT INSPECTION

This chapter will discuss the contract change orders that occur in the execution of repair work by contract due to inadequate component inspection and further describe the penalty costs associated with these changes as introduced in Chapter Two. This chapter will describe the contract change orders costs, the different types of penalty costs and how these costs behave and their cost components.

5.1 Introduction

Contract change orders are defined as a change or a modification to the legal agreement between the owner and the contractor. Different owners use a variety of terms to describe a contract change. They are known as bilateral or supplemental agreements, modifications to the contact, construction contract changes, unilateral modifications and simply "change orders". The exact name is unimportant. The important issue is that these changes represent a situation where the originally contracted work must be changed for one reason or another. The original contract must be either added to or deleted from to accommodate different requirements. These contract changes can occur for a host of reasons. This thesis is concerned with contract changes that occur because of inadequate component inspection. If the change was caused because the nature of the work was described incorrectly to such a degree that a change is required to correct the error, it is a change this thesis is interested in. A great portion of the changes that occur on facility repair contracts are related to incorrectly describing the nature of the repair work [1]. The vast majority of these changes could be prevented if the nature of the work had been correctly described in the contract documents. Many times this could be done through the use more component inspection or the selection of different component inspection methods.

5.2 Penalty costs associated with changes

This section will further define and discuss the concept of penalty costs which were introduced in Chapter Two. In Chapter Two penalty costs were defined as the additional cost of performing the repair work as a result of changes caused by inadequate component inspection. An important point to remember when quantifying and discussing these costs is that a penalty cost is defined as the cost of doing the work less what the same work would have otherwise cost if the nature of the work had been correctly described in the contract documents.

Conceptually, when determining the penalty costs the entire cost of the change must be separated into two parts: 1) the costs that would have otherwise been incurred if the nature of the work had been correctly described in the contract documents at the outset, and 2) the portion that was paid over that amount because the nature of the work was described incorrectly, and a change was needed to get the work done. The second part is the additional expense above and beyond the work itself associated with adding work or deleting work from a contract after award. These are the penalty costs of not correctly describing the nature of the work in the contract documents.

The total cost of a change is comprised of costs from the following three categories: agency costs, user costs and political costs. Penalty costs are contained in these categories. Each of these categories can be separated into a portion that the owner would have paid had there been adequate component inspection and the penalty cost portion associated with inadequate component inspection.

Agency costs are the largest and easiest to quantify of the three categories of change costs. The penalty portion of agency costs are the additional costs that must be borne directly by the owner as a result of the change. Agency costs can be further divided into other sub-categories and these are shown in Figure 5.1. User costs are borne by the user of the facility and are associated with the time required to complete a repair project. The penalty portion is associated with the additional time required to complete the project when the contract is changed after award. Political costs are the costs related to the loss of credibility the facilities management organization suffers as a result of having to change the contract, and subject the user to delays and the owner to additional costs. Although intangible, these are real costs.

These next sections will discuss these categories of change costs in more detail, discuss the nature of these costs and identify the penalty cost portion of each category. The penalty cost portion of each category depends on the circumstances surrounding the change.

In Chapter Seven this thesis continues the analysis of the cases in Chapter Four. In this analysis some penalty costs such as direct penalty costs are evident in the analysis of the case examples. Examples of these are overtime labor costs and material costs. Other penalty costs, such as those associated with the labor learning curve, internal administration

TAXONOMY OF PENALTY COSTS

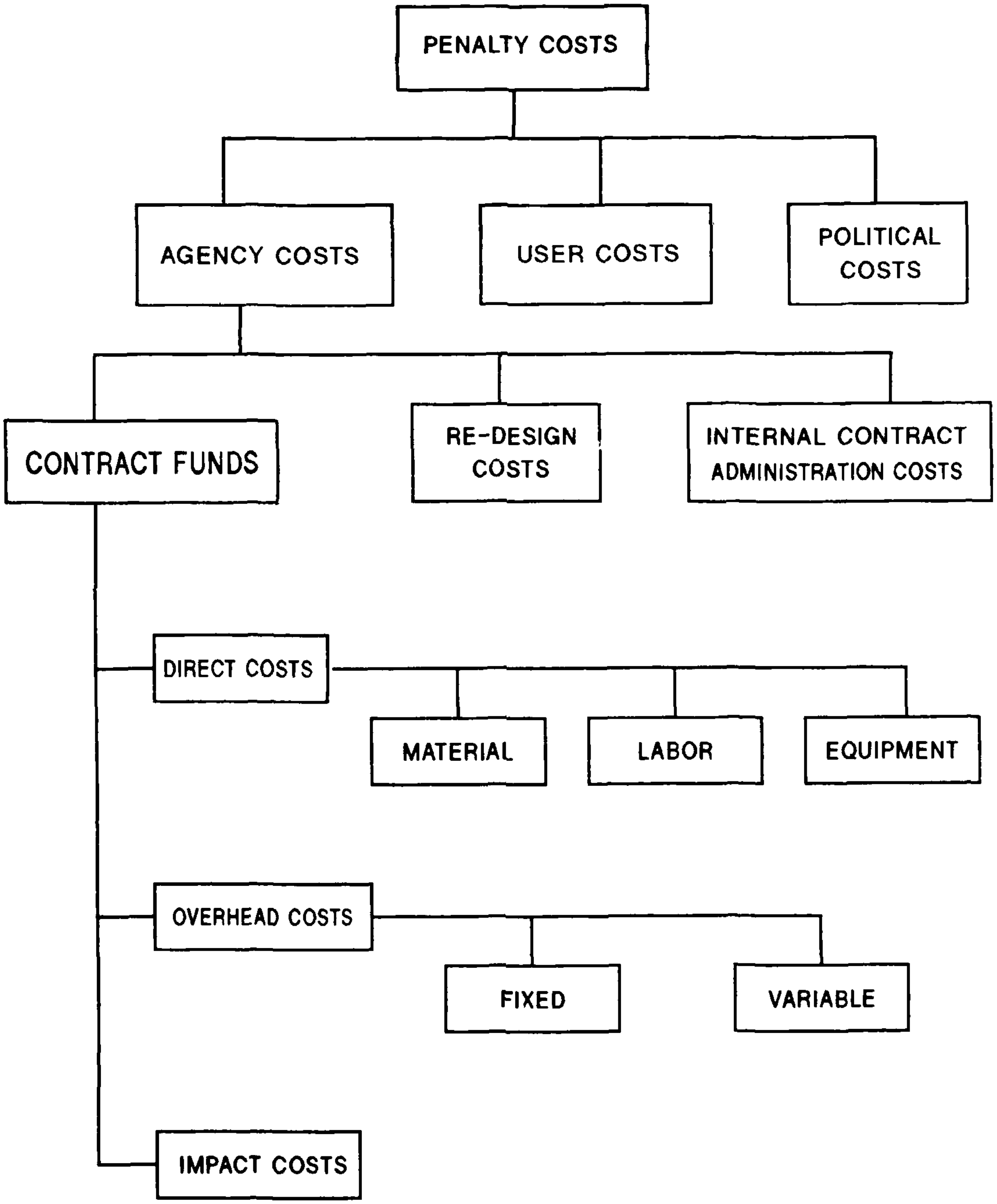

FIGURE 5.1

costs or the overhead costs, are not evident and in order to account for these in an analysis they must be calculated. The calculation of these penalty costs must be based on knowledge about the way in which these costs behave in respect to the project costs and change costs. The following sections will provide this information so that in Chapter Seven the penalty costs can be examined based on the discussion of this chapter.

For each of these penalty costs it will be assumed that they increase linearly with the increase in the degree of error in the component inspection information. Since the degree of error is related to the added quantities of work this is a reasonable relationship to assume. Although it may not be exactly linear this is a good approximation for the purposes of this thesis.

5.3 Agency costs

Agency costs are a category of the change costs that must be absorbed by the owner's facilities management organization. As shown in Figure 5.1 there are three types agency costs:

1) contract funds - funds paid to the contractor.

2) redesign costs - additional design and component inspection costs as a result of the change.

3) internal contract administration costs - internal cost of administering the contract change.

The contract funds are the largest type of agency costs that contribute to the penalty costs and they occur in most changes caused by inadequate component inspection. Redesign costs only occur when the change to the contract requires a redesign. Internal administration costs occur as a penalty cost in all changes due to the cost of administering the change. They are entirely penalty costs since if there was no change these costs would not occur.

The next sections will discuss each of these costs in more detail, show how they increase as a result of a change and show how the penalty cost portion can be identified.

5.3.1 Contract funds

The contract funds are the funds paid to the contractor to compensate him for the cost of changing the contract. Once a contract has been awarded to perform a certain specified scope of repair work this represents a legal agreement between the owner and the contractor in which they have both relied. If the terms of the contract are changed then the price of the contract must be adjusted to equitably compensate the parties for the change. These costs paid to change the contract can be divided into three categories as shown in Figure 5.1: 1) direct costs, 2) overhead costs, and 3) impact costs [2].

Direct costs can be traced and tracked directly to the work. Three types of direct costs will be considered in this thesis: labor, material and equipment costs.

Overhead costs are the costs associated with the work, but not directly traceable to any certain portion of the work. Overhead costs are either job overhead or home office overhead depending on where they occur. Job overhead can be further divided into fixed and variable overhead costs. Job overhead costs are estimated to be 15% of the cost of a project, of which 10% is estimated to be variable and 5% is estimated to be fixed [3]. Examples of variable overhead costs are supervision, insurance and bonds. Examples of fixed overhead costs are job site trailer rental, utilities and superintendent salary. Variable overhead costs change directly with the amount of work that is added or deleted from the contract. Fixed overhead costs tend to increase with the duration of the project, however they may still be reasonably estimated as a percent of the quantity or cost of the work.

Home office overhead costs are generally all fixed overhead costs. These are the costs to the contractor of being in business and are generally unavoidable. Examples of these are salaries of office employees, home office rent and utilities and general business expenses. The total cost of the home office overhead can range from 3 to 10% of the cost of the project and 5% will be used as a reasonable estimate of the home office overhead [3].

In section 5.3.1.2 and in Chapter Seven, 10% will be used as an estimate of variable overhead costs and 10% (5% from job overhead and 5% from home office overhead) will be used as an estimate of fixed overhead costs.

Impact costs are the additional compensation due the contractor because of the impact the changed work has on the originally contracted (unchanged) work [4].

Although the cost of a change order may include all of the above cost categories, the entire amount of each category is not always considered to contribute towards the penalty cost. Now that each of these cost has been defined, the thesis will discuss each one in the context of how they can be separated into the portion that contributes to the penalty costs and the portion the owner would have paid anyway if the repair work had been correctly described in the contract documents.

5.3.1.1 Direct penalty costs.

As stated earlier direct costs are composed of labor, material and equipment directly charged to the project. The cost to change a contract is composed of these costs, but only a portion of these costs are penalty costs. For example, in the Middlesex bridge case additional concrete removal was added to the project. The owner would have paid some amount for the direct costs of that added work even if the estimated quantities of work had been correct. The question of penalty cost involves what additional costs did the owner incur by adding the work after the contract was awarded.

Material costs

The penalty cost portion of material costs can be effected by changing the amount of work in the contract. If work is added and the contractor obtained a volume discount for the materials required to accomplish the originally contracted amount of work the increase may mean that he is unable to again receive this discount. In this case the price would be higher than if the work had been included in the contract documents and this increase would be a penalty cost. If the duration of the project is extended, where it otherwise would not have been, any escalation in material prices would cause material prices to increase. This would be a penalty cost since this escalation could have been avoided of the contract had not been extended to accommodate the change. On the other hand, if work is deleted or the repair method is changed and the contractor has pre-purchased materials that are no longer needed in the project, the cost of those materials or the freight to return them would be a penalty cost.

Labor costs

Labor costs to perform the changed work are affected by the amount of work that is added or deleted and whether or not a time extension is granted in connection with the added work.

If work is added to the contract and the owner does not grant a time extension and the contractor is required to perform the work on a shift work basis or by the use of overtime this would cause the contractor's labor cost to increase above what the work would have cost on a straight time basis. The entire amount of this increase would be considered a penalty cost.

On the other hand, if a time extension is granted there will be enough time to allow the contractor to complete the work at a normal schedule. This usually means that the contractor can finish the work without resorting to shift work or overtime work and other work methods that would constitute acceleration on the part of the owner. If the contractor is given adequate time to finish the job at a normal production schedule then the penalty portion of the labor costs would be zero.

The exception to this would be if the extension ran the work into bad weather or the end of the construction season which could have been avoided by the owner. In this case the additional labor costs of performing the work in the bad weather would be penalty costs and the cost of escalation in labor rates that may occur during the length of any work stoppages would be labor penalty costs. People work less efficiently in the more adverse weather. The work is still possible to accomplish, but it requires more labor per unit. A good example of this is the Middlesex bridge case where freeze protection had to be provided to cold weather concrete work.

The other labor penalty cost associated with adding work is the lost benefit the owner would receive from the learning curve. If the contractor had known that there were more quantities than estimated his labor per unit would have been lower to reflect the fact that his crews get more efficient as more quantities of the same work are done. However, when the owner adds work after award it is very difficult to get the contractor to pass this increased efficiency onto the owner in the negotiations. The penalty cost can be calculated using learning curve theory.

For example, a reasonable estimate of the slope of a learning curve for construction is 90% [5]. This means that every time the quantity of work doubles the time it takes to complete the additional units of work decreases by 10%. For example, if a contractor had bid $10/unit for the work and 40% or $4 is labor cost then the total labor cost for an estimated quantity of 1000 units would be $4000 based on his projected productivity. If the quantity was increased to 4000 units, the learning curve theory says the labor for the second 1000 units would be 10% less or a savings of $0.40 per unit on the second 1000 units. The labor cost is now $3.60/unit. When the quantity was again doubled from 2000 to 4000 the average labor cost would again go down by 10% to $3.24/unit. This would generate a savings of $0.76 per unit ($4.00 - $3.24) over the bid labor cost of $4.00/unit or a total savings of $1520 ($0.76 x 2000) for units 2000 through 4000. If these additional quantities had been known at bid time the contractor would have reflected these savings in his bid. However, since they are added after award the owner will not realize these savings at the negotiation table [4].

The penalty costs associated with the learning curve theory can be estimated by assuming a reasonable slope for the learning curve and that a certain percent of the unit price is labor costs. For the purposes of the analysis presented in Chapter Seven a 90% learning curve will be assumed and labor costs will be 48% of the unit price. Although the learning curve can be applied to any size change in quantities, in this thesis, due to the approximations that are made, it will only be applied where quantities have changed by several fold.

This learning curve argument also effects labor costs when quantities are deleted from the contract. The contractor may argue that he was relying on the benefits of the learning curve to obtain lower labor costs. So because he will not do as many quantities his average labor cost per unit will be higher.

Equipment costs

The penalty portion of equipment costs are effected by the production capability of the equipment, the cost of short-term versus long-term rental periods and the fixed equipment costs such as delivery and set up expenses [3]. If the optimum amount of equipment is brought to the job and less work is required then the cost of the extra equipment that is idled on the job becomes a penalty cost since it was not needed. If more equipment is required, then the additional cost of bringing it to the project on short notice is a penalty cost.

In the case where work was added to the contract, whether or not the additional equipment costs are considered penalty costs depends on whether a time extension was granted with the change. If a time extension was granted and the contractor was allowed to complete the work with the equipment he already had on site there would be no penalty costs. However, if a time extension is not granted and he was required to rent additional equipment the penalty cost would be the portion of the cost of the equipment associated with the shorter rental periods, the cost of rushing it to the job site, and the fixed set up and delivery charges. These costs would not have been incurred if the contractor had known the amount of the work prior to bidding the job. He would not have had to rush the equipment to the job and the sizes of the equipment initially selected may have even been different so that fewer pieces would have been needed. If the time extension runs the work into the winter season and the work must stop, then there are other equipment penalty costs associated with the cost of this equipment over the period of the work stoppage and the re-mobilization costs.

In the case where work was deleted from the contract, equipment costs would be most likely to increase since there would be shorter rental periods and the fixed portion of these costs such as delivery charges would be spread over less units of work. These costs would be penalty costs since the contractor would be geared up to perform the estimated quantity of work and not until he was well into the job would it become evident that the estimated quantities would not be achieved. The extra equipment would have to be returned early. If the quantity of work had been described correctly he would not have ordered so many pieces of equipment. These costs increase as less units of work are performed.

5.3.1.2 Overhead penalty costs

Variable overhead

Variable overhead costs increase as work is added to the contract, either through the addition of more quantities or a change in the repair method. These additional variable overhead costs are not considered to be penalty costs since they are independent of the fact that the work was added after contract award due to inadequate component inspection. These variable overhead costs would have to be paid by the owner even if the work had been included in the contract at the outset.

Fixed overhead

Whether or not fixed overhead costs that are considered to be a penalty cost is dependent on the time extensions that are granted by the owner and whether the time extension would have occurred despite the inadequate component inspection.

If the time extension could have been avoided had the nature of the work had been correctly described, then the fixed overhead costs on the changed work are penalty costs since they were caused by inadequate component inspection. However, if the time extension would have been required regardless of the change, then the fixed overhead costs would have been paid by the owner in any event and they are not penalty costs.

If a time extension is not granted in conjunction with the change then fixed overhead costs are not considered penalty costs, unless the contractor continues to be paid the bid unit price which includes fixed overhead. In this case the contractor is being over compensated for his fixed overhead costs. These are overabsorbed overhead costs and they are a penalty cost. If the added quantities of work had been known this additional compensation for fixed overhead would not have been included in his bid. Therefore, this overabsorbed fixed overhead is a penalty cost of inadequate component inspection.

An example of this is the Fairchild Air Force Base case in which the contractor was paid the bid price for the additional quantities of work and thus was over compensated for his fixed overhead costs. The fixed overhead costs on that job were paid when the estimated quantity of work was completed. The price for any quantities done after this point should have decreased by the amount of the fixed overhead costs in the bid price.

When work is deleted from the contract each remaining unit must absorb a greater portion of the fixed overhead costs. These are underabsorbed overhead costs and they are penalty costs. Although, one might argue that these fixed overhead are not penalty costs since the agency would have paid for them in the bid had the nature of the work been correctly described. Realistically, however these costs would not be included in the contractor's bid if they made his mark-up so high as to make him noncompetitive. The contractor may have not bid the job if his overhead cost structure made him noncompetitive on smaller projects. Additionally, in deleting work any overhead costs that may have already been expended are penalty costs since they are not recoverable.

For the purposes of calculating the overhead penalty costs the percentages discussed in section 5.3.1 will be used. The variable overhead costs are estimated to be 10% of the cost of the work and the fixed overhead costs will be 10% of the cost of the work. These are reasonable estimates and can be used to calculate penalty costs in the case analysis in Chapter Seven.

5.3.1.3 Impact costs

Impact costs are the additional compensation due the contractor because of the impact the changed work has had on the originally contracted work. Impact costs are entirely penalty costs since they occur as a result of the change and if the changed work had been included in the contract documents at the outset there would be no change and no impact costs [2].

Impact costs are not applicable to situations where work is deleted from the contract, but they are relevant to situations where more of the same type of work is added or a new method of work is added by the change. The existence of impact costs in connection with a change is dependent on the individual circumstances of the project. The magnitude of the impact costs will depend on how the new work interferes with the originally contracted work. The magnitude of the impact costs would tend to increase with increasing magnitude of the changed work both in quantity and effort required. The greater the amount of changed work added to the contract the greater the impact costs will be. Impact costs could be minimized if the owner granted a time extension unless the extension has pushed the unchanged work out into a period where the adverse weather caused the costs to increase. This also would be an impact cost related to the quantity of work added.

5.3.1.4 Negotiated penalty costs

In general, negotiated prices for the same work are higher than competitively bid prices [6]. Therefore, if the owner determines the price of the added work through negotiation rather than using a price determined through competitive bidding the price for the added work will be higher. This same rational holds true for work that is deleted from the contract after award. The credit obtained is not as great as it would have been if it had been bid with the change reflected in the contract documents [2]. The cost of work that is priced without competition, either additive or deductive, is less beneficial to the owner than if competition had been used.

This difference between negotiated costs and bid costs contributes to the penalty costs associated with changes to the contract. Penalty costs in this category are the premium price associated with purchasing repair work at negotiated prices versus competitively bid prices. Negotiated penalty costs only occur when the price of the added or deleted work is determined through negotiation. If the price of the changed work is determined using a price that was based on competitive bidding then there is no penalty cost. Additionally, if the negotiated costs are already included as another type of penalty costs then they are not counted again as negotiated penalty costs.

Competitively bid contracts for repair are awarded on the basis of the lowest possible price. However, the price for negotiated contract or negotiated changes to contracts are awarded on the basis of a price that is fair and reasonable. These prices are higher than the lowest possible price [7]. This difference also exists because the price for work added or deleted after award is based on its estimated value at that time of the change, whereas the value of that same work if it had been purchased at the time of award would have been based on its value at the time of bidding. So when the owner either purchases (additive) or sells (deductive) work after award of the contract the price at this time is usually different than the price would have been if bid [7].

If this penalty cost is applicable to the situation it can be estimated as a percent of the cost of the change. This amount could easily be 5 to 10 percent. For the purposes of the analysis in Chapter Seven the magnitude of the negotiated penalty costs will be estimated as 7%. In some of the cases to be analyzed in Chapter Seven it will be evident what the negotiated penalty costs are, however in some cases it may be necessary to calculate this penalty cost. If so 7% will be used.

Additionally, in situations where a negotiated price cannot be agreed on or there is not time to negotiate a price for the added work, owners may have the contractor work on a "force account" or unilateral change basis. In regard to calculating negotiated penalty costs this situation is the same as if the price had been negotiated. This arrangement tends to drive up prices since the contractor realizes he will be reimbursed for all costs and the incentive to economize and run a productive operation is lost.

5.3.2 Redesign costs

Redesign costs are the agency costs associated with designing a new repair method to be used in the change that is different from the one called for in the contract documents. Redesign costs only occur where there is a change in the repair method associated with the change. In this situation the contract documents described the nature of the work incorrectly to such a degree that the method of work called for in the contract documents was no longer appropriate and a new repair method must be designed. The cost of the redesign, which may include some additional component inspection costs, are the redesign costs. The entire portion of redesign costs are considered a penalty cost. If there had not been a change due to inadequate component inspection, then there would not have been any redesign costs.

If the change simply adds more quantities of work to the contract and the repair method remains the same as called for in the contract documents then redesign costs do not occur and therefore, no penalty costs for this category. Redesign costs increase with the quantity and cost of work added to the contract. There magnitude can be expressed as a percent of the cost of the added work.

5.3.3 Internal contract administration costs

Internal contract administration costs are the cost to the agency of administering the change to the contract. The administration of changes always involves additional time spent by the owner's contract managers. Larger changes require the detailed audit and review of costs and pricing data to justify the negotiated prices. This is a very time consuming process that is a cost of changing the contract. For example, in the Middlesex bridge case the resident engineer spent 2-3 weeks reviewing the contractor's cost data to determine the new price for changed work. Many times these changes result in claims and legal proceeding the consume vast amounts of internal agency resources. Managing these changes is a major problem in the administration of facility repair contracts [1].

Although this cost is more of an opportunity cost than a true out-of-pocket expense to the agency, if the contract managers were not working on the change they could be spending their time on some more worthwhile tasks. And eventually, if there were not as many changes to administer, the number of agency personnel required would decease and the cost of administering facility repair contracts as a whole would decrease.

The Naval Facilities Engineering Command charges a fee of 5.5% of the cost of a project including changes to cover their contract administration costs which are known as supervision, inspection and overhead. The Vermont Agency of Transportation uses a fee between 5% and 15% of the contract price depending on the individual job. Other public agencies use percentages that are in the same order of magnitude. Managing the changes that occur in the course of these contract consumes a large portion of the contract management effort. Although some contract management effort would be required if the changed work was added to the contract prior to award, it would not be near as great as when work is added by change order after award. In effect, this is the additional effort required internal to the agency to add or delete work after contract award. The cost of this additional effort is a penalty cost.

From the author's experience this additional effort can consume a third of the total effort of administering a contract for facility repair work. From this a reasonable estimate of the cost of administering these changes is one third of the administration fee charged by these public owners to administer contracts. For the analysis in Chapter Seven this penalty cost will be 2% of the contract funds associated with the change. This is approximately one third of the fee these agencies charge and is a reasonable method to estimate this penalty cost.

5.4 User costs

User costs represent the costs of increased delays and inconvenience of not being able to use the facility under repair during the duration of the repair project. One example of this is delays to vehicles while a bridge has restricted capacity during lane closures for repair work. User costs in airfield pavement work are represented by delays to aircraft and reduced airfield capacity. In military airfields increased user costs show up as reduced mission capacity, increased security requirements, lower training efficiency and costs to relocate aircraft to allow the work to proceed.

The penalty portion of user costs are associated with the additional delay to the completion of the project or an extension of the project duration due to a contract change. This means user will be without the full use of the facility for an additional period of time thus increasing the user costs associated with the project from the amount estimated at the start of the project.

User penalty costs are sensitive to project time extensions. If there is no time extension, then there are no user penalty costs. If the length of the project is extended then it must be determined whether the extension was unavoidable or avoidable. If the extension was unavoidable then there are no penalty user costs because the user is not without the facility any longer than they would have been otherwise. However, if the time extension was avoidable then these additional user costs are penalty costs. There are also user penalty costs if the contract is extended over the winter season and the inconvenience that results from restarting the contract the next season. A good example of this was the Minot Air Force Base case where the contractor returned the following year to finish the work and the flight operations had to be again rescheduled, aircraft had to be relocated and additional security provided. If the quantity of work had been described correctly and the work was completed in the first year these additional user costs have been avoided.

Because of the nature of these user penalty costs they are difficult to quantify. Although sensitive to time extensions and the length of the avoidable time extension, their magnitude is a function of the individual facility. For this reason they are discussed here, but will not be quantified in the analysis in Chapter Seven.

5.5 Political costs

One of the main objectives of the owner's facility management organization is to insure that the facilities are kept at the highest levels of serviceability. When this goal is not achieved, because an existing contract must be changed due to inadequate component inspection, there is some amount of embarrassment that this organization suffers. This is a political cost and can be very damaging to the facilities management organization and the moral of its members.

Whenever the cost to complete a project or the time to complete a project increases, regardless of whether it is any greater than it would have cost without the change, ultimately this results in lowering the confidence the public has in the organizations appointed to manage their public facilities [8].

Political costs are like user costs in that they are difficult to quantify. They are also real in that they represent the loss of confidence the public has in the organizations that manage their public facilities and the lost moral of the people who work for these facilities management organizations [9]. Facilities management is very much a public relations business and when schedules slip and deadlines are not met there is a loss of confidence in the organization. Despite the fact that only a portion of the increased project costs would have occurred if the work was correctly described, taxpayers begin to wonder how efficiently their funds are being spent by these organizations when the duration and cost of projects are greater than was planned. Additionally, no one is proud to work for an organization that is constantly under criticism for not being able to live up to its commitments in terms of the time and the cost of completing projects.

5.6 Summary

This chapter has described each type of penalty cost and the sources of those costs. The agency costs can be quantified, however user and political user costs are quite variable and will not be quantified in later analysis. Figure 5.2 shows the types of penalty costs and the sources of these costs.

SOURCES OF PENALTY COSTS
FIGURE 5.2

TYPES OF PENALTY COSTS	QUANTITY INCREASING	QUANTITY DECREASING	TIME INCREASING
DIRECT COSTS:			
MATERIAL	Loss of quantity discount	Pre-purchased materials	Escalation in material prices
LABOR	Overtime, shift work, learning curve	Learning curve	Adverse weather, work interruption, Escalation in labor rates
EQUIPMENT	Set-up and delivery charges	Set-up and delivery charges	Work stoppage and demobilization
OVERHEAD COSTS:			
VARIABLE	None	None	None
FIXED	Overabsorbed fixed overhead	Underabsorbed fixed overhead	Due to avoidable time extension
IMPACT COSTS	Disruption, lower productivity	None	Moving unchanged work into adverse weather, lower productivity
NEGOTIATED	Difference between competitively bid and negotiated prices for the same work. Only applicable where cost of changed work is determined by negotiation.		
REDESIGN COSTS	Cost to design new method of repair		None
INTERNAL COST	Cost to administer work on a change order basis rather than as apart of the original contract.		

CHAPTER FIVE ENDNOTES:

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CHAPTER SIX

COMPONENT DEFECT ANALYSIS FRAMEWORK

This Chapter will discuss and explain the component defect analysis (CDA) framework as a tool to examine the penalty costs associated with inadequate component inspection and contract changes in facility repair projects. However, before discussing the framework itself the next section will discuss the three attributes that describe defects in facility components.

6.1 Attributes of component defects

Character, severity and extent are the three attributes that are used to describe a component defect and the nature of the repair work. The goal of component inspection is to obtain information about these three attributes for inclusion in the contract documents. These three attributes must be described in the contract documents in some level of detail or degree of accuracy in order for the contract documents to be considered complete.

6.1.1 Character

The character of a defect describes what type of defect it is. For example, a defect could be a spall, a crack, delamination, etc. Generally, the designer of the repair project will prescribe a repair method based on the character of the defect. The contractor will base his bid on this repair method as prescribed in the contract documents. If the character of the defect is incorrectly determined, penalty costs will occur due to the requirement to add a new repair method or to redesign a different repair method.

6.1.2 Severity

The severity attribute describes the degree to which the defect has progressed in the component. Severity is measured in relative terms. There are no specific units to measure severity. For example the severity of alligator cracking may be described as low, medium or high [1]. Severity describes the condition or state of progression of that particular defect at a given location in the component.

Like character, information about the severity of a defect is important in selecting the repair method. However, the attribute of severity is not relevant to repair methods in which the deteriorated portion of the component is completely removed and new materials are put in their place. This is opposed to repair methods where the deteriorated sections are left in place.

For example, severity is not relevant to spalls and joint repair since the method of repair involves removing deteriorated sections and putting new materials in their place. In these cases the repair method is unaffected by the severity of the defect because all of the deteriorated material is removed. On the other hand, severity is important to crack filling and overlays since the new material will come in contact with the deteriorated portions of the component. In the component defect analysis diagram severity is considered as a separate attribute, but it should be remembered that it is only relevant to certain methods of repair. If severity is not relevant then the parts of the diagram that pertain to severity simply drop out.

6.1.3 Extent

The attribute of extent describes the quantity of the defect that is present in the facility component. This attribute could be expressed in area and/or depth or simply volume. It primarily effects the quantities of work to be done by the contractor. However, if a large error is made in the extent of a defect this could cause the repair method called out in the contract documents to be inappropriate in that the method selected would not be the most efficient considering the actual extent of the defect.

6.2 Component defect analysis diagram

The purpose of the component defect analysis framework is to provide a logical method to examine errors made in component inspection and the resulting penalty costs caused by these errors. The component defect analysis diagram is a representation of this framework. The diagram begins with component inspection and shows the possible errors that could be made in describing the attributes of component defects and the penalty costs that result from these errors. The diagram is broken down into two levels. Level 1 shows the logical progression of possible errors that could occur when describing the attributes of a component defect. The possible errors lead to level 2 of the diagram where the corrective actions of the owner's facilities management organization are described.

These are the actions the owners take to rectify the errors that have occurred in the component inspection process. These corrective actions, usually a change to the contract, result in penalty costs. Each of these combinations of possible errors, corrective actions and associated penalty costs are designated error scenarios. The next sections will describe the component defect analysis diagram shown as Figure 6.1.

6.2.1 Component Defect Analysis Diagram Level 1 - Attribute errors

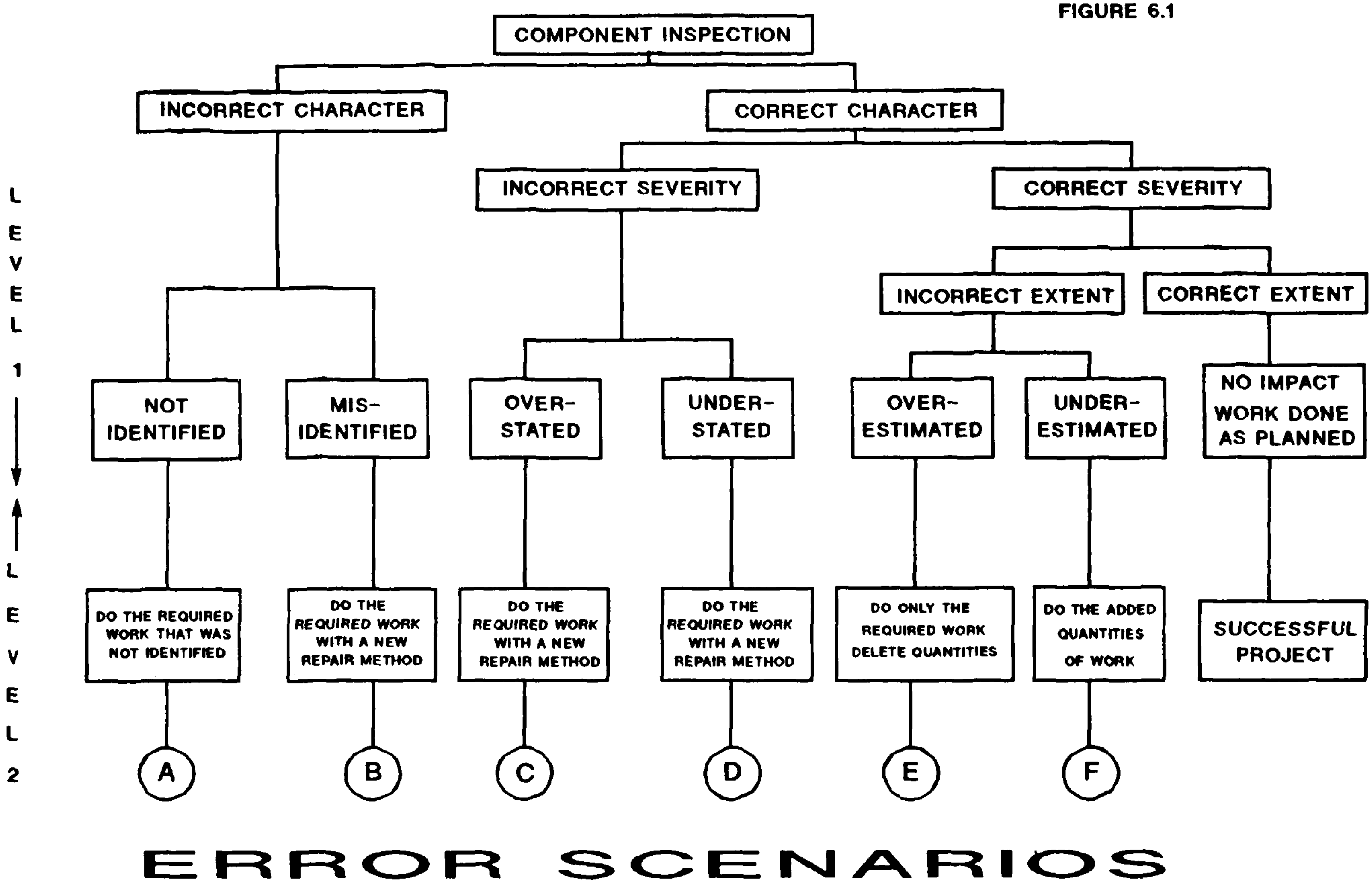
Level 1 of the component defect analysis diagram illustrates the possible errors that could occur in describing the attributes of component defects. The defect attributes are considered in the component defect analysis diagram in the order they were discussed in the previous section.

Character is the most important attribute since it has the greatest effect in determining the repair method. Severity is the second most important attribute since its purpose is almost the same. However, it is only important for certain methods of repair in which the old work remains. Extent is considered third since it only becomes important when the preceding attributes have been correctly described. Its primary importance is in describing the quantity of work and this is important only if the method of repair has been correctly determined.

On the left side of the diagram, the two possible ways for character to be incorrectly described is either 1) not identified on the contract documents, or 2) misidentified as another type of defect. Severity and extent are not considered after this point since errors in these attributes are unimportant if the character attribute is in error.

COMPONENT DEFECT ANALYSIS DIAGRAM

FIGURE 6.1



If character is described correctly then severity is considered, if it is relevant to the method of repair. Severity can be incorrectly described as either overstated or understated. In either case extent is not considered after this point because it has no effect on penalty costs. The amount of work (extent) the contractor must perform is unimportant if the method of work must be changed because the severity or character of the defect was incorrectly described.

Overstated and understated are defined to mean that the severity of the defect was in error to such a degree as to cause the designer to select a method of repair that is different from that which would have been selected had the actual severity been known. If the method of repair must be changed due to the difference between the estimated and the actual severity then the severity was incorrectly described. Even though the component inspection method may have caused an error in describing the severity of a defect it is not considered inadequate component inspection unless this error causes it to be necessary to change the method of repair.

If character and severity have been correctly described then the extent can be either incorrect or correct. If it is correct then the work is executed as planned as shown in the diagram. This is the goal of component inspection and occurs when component inspection is adequate.

The extent of a defect can be incorrectly described by either overestimating or underestimating the quantity of work. Extent is correctly described if the contract variance threshold has not been exceeded. If the threshold is based on the contract price, as in the case of the State of Vermont, it will be assumed that it applies to the quantities of work since they are closely related. This is a reasonable assumption that will facilitate the analysis in Chapter Seven.

In summary, the three attributes can be described either correctly or incorrectly. This combined with the two possible ways to incorrectly describe each attribute (e.g. over/underestimate, etc.) yields seven possible combinations. Six combinations in which an error in attribute description is identified are designated error scenarios A through F. The seventh combination results when the three attributes are all correctly identified.

6.2.2 Level 2 - Owner's corrective actions

Level 2 of the diagram shows the corrective actions that are taken by the owner to correct the errors made in describing the attributes of the defects for each of the six error scenarios A - F. These actions are taken by the owner after contract award when the error in attribute description is discovered. These actions are the change orders that are caused by inadequate component inspection.

In developing these corrective actions only the actions of a prudent owner have been considered. For each of the corrective actions shown in level 2 there exists an opposite action that is sometimes feasible, but always impractical. These imprudent actions are not considered in this diagram because they are actions that a prudent and cost conscience owner would not make.

A good example of this is when the character attribute has been incorrectly described as not identified on the contract documents. As shown on the component defect analysis diagram, the prudent owner makes the corrective decision to do the required work. However, the opposite imprudent action would be for the owner to decide not to do the required work. This would result in essentially ignoring the defect and leaving the problem uncorrected possibly until a future repair project. This is not the decision a prudent owner would make. A decision of this nature increases the life cycle cost of a facility and lowers the performance of the facility after the project is complete. This is not to say that this type of decision is not possible, or is not made under circumstances such as funding constraints. However, the component defect analysis diagram will not consider these imprudent owner actions.

In summary, this section has discussed the three attributes used to describe component defects, the possible errors that could result from incorrectly describing those attributes and the actions a prudent owner would take to correct the errors made by inadequate component inspection. This leads to the penalty costs that result from each of these corrective actions. The next section will discuss and develop equations for the penalty costs that occur in error scenarios A - F.

6.3 Penalty costs for error scenarios A though F

This section will discuss the penalty costs that are associated with error scenarios A - F. Each scenario has some or all the types of penalty costs discussed in Chapter Five associated with it. The circumstances surrounding each scenario will determine which penalty costs apply.

In the discussion of each error scenario the following outline will be used: 1) a review of the events that lead up to the error, 2) the action (contract change) required to correct the error and the associated penalty costs and, 3) the equation of penalty costs for each scenario.

In this discussion the following general equation of penalty costs will be tailored to form a penalty costs equation for each scenario:

$$PC = DC + OH + IM + NC + RE + ICA$$

The terms of the equation are defined as follows:

PC = Penalty costs

DC = Direct penalty costs

OH = Overhead penalty costs

IM = Impact costs

NC = Negotiated penalty costs

RE = Redesign penalty costs

ICA = Internal contract administration penalty costs.

Each of these penalty cost terms can be expressed as a function of the amount work added or deleted from the contract by using the proportionality factors A1 through A6 as shown below:

$DC = A1 \times Q$

$OH = A2 \times Q$

$IM = A3 \times Q$

$NC = A4 \times Q$

$RE = A5 \times Q$

$ICA = A6 \times Q$

Therefore, the general penalty cost equation can be written as;

$$PC = (A1 + A2 + A3 + A4 + A5 + A6) \times Q$$

Where the amount of changed work is represented by the variable Q. In the scenarios where both deleted and added work are considered, Q1 will denote added work and Q2 will denote deleted work as follows:

Q1 = amount of added work and PC1 = penalty cost of added work

Q2 = amount of deleted work and PC2 = penalty cost of deleted work

In the case of lump-sum contracts (primarily error scenarios A through D) the variable Q represents the entire amount of changed work. In the case of unit price contracts (primarily error scenarios E and F) it represents the amount of changed work outside of the contract variance threshold. For the purposes of this thesis it will be assumed that the factors A1 through A6 have the same value when applied to added work (Q1) as when applied to deleted work (Q2).

In Chapter Five the value of some of the proportionality factors were determined for use in the case analysis in Chapter Seven. Namely:

A2 = 10% used to calculate fixed overhead penalty cost (OH).

A4 = 7% used to calculate negotiated penalty cost (NC).

A6 = 2% used to calculate internal contract administration cost (ICA).

These known factors are important in cases where the value of a particular penalty cost term is not evident from the data, for example in the case of internal contract administration costs. However, where the value of the term can be determined from the data available the proportionality factor is not needed in the analysis.

User penalty costs and political costs are not quantified in this general penalty cost equation. For this reason they will be discussed here as a whole as opposed to individually in each scenario. As described in Chapter Five, whether user penalty costs occur or not is dependent on the time extension that is granted. The magnitude of the user penalty cost is dependent on the characteristics of the individual facility. These costs will not be included in the penalty costs equations of each scenario due to their individual nature as discussed in Chapter Five.

Political costs were discussed in detail in Chapter Five. Since it is difficult to attach a dollar value to these costs, they are not included in the equations of penalty costs for each error scenario.

6.3.1 Error scenario A - Incorrect character/ defect not identified

In this error scenario the component defect was not noted on the contract documents. The defect was discovered after award of the contract to repair other defects in the facility. This scenario requires that a method of repair be designed based on the newly discovered defect. The contract is modified to add the requirement for this new repair method. If the extent of the new defect is known a lump-sum price may be agreed on; if the extent is unknown then a unit price may be negotiated. In either case the cost of the new work is a negotiated price established without the benefit of competition.

Penalty costs

In this scenario the total contract price will increase to reflect work that was not included in the contract. There would be no penalty cost portion of direct costs unless a time extension was not granted. If a time extension was not granted the labor costs and the equipment costs would expected to include penalty costs. These would be a percentage of the added work and they would increase with the amount of the new work.

The overhead penalty costs would depend on whether a time extension was granted as discussed in Chapter Five. If there was an avoidable time extension these fixed overhead costs would be a penalty cost. These fixed overhead costs would also increase linearly since they are a percent of the cost of the added work.

Design costs for the added work would not be a penalty cost since no repair method for this defect was designed with the original design effort. Therefore, this design is a cost that would have been incurred even if the defect had been known.

Penalty cost equations

The following equations describe the penalty costs for this scenario for each of the following circumstances regarding a time extension:

No time extension: $$PC = DC + IM + NC + ICA = (A1 + A3 + A4 + A6) \times Q \quad (1)$$

Unavoidable time extension: $$PC = IM + NC + ICA = (A3 + A4 + A6) \times Q \quad (2)$$

Avoidable time extension: $$PC = OH + IM + NC + ICA = (A2 + A3 + A4 + A6) \times Q \quad (3)$$

6.3.2 Error scenario B - Incorrect character - defect misidentified

In this scenario a certain defect and method of repair have been described in the contract documents. However, after contract award it is discovered that the actual defect is different from the type described in the contract documents and as a result the method of repair is no longer appropriate. The corrective action in this scenario is to repair the defect actually discovered. In order to accomplish this the method of repair specified must be deleted from the contract and a new method of repair added. This involves a deductive and an additive change order to the contract.

Penalty costs

In general the penalty costs in this scenario involve the penalty costs for the deleting the specified repair method, plus the penalty cost associated with adding a new repair method.

The penalty cost for the deleted work include the cost of any work, direct or overhead, that has already been expended in the pursuit of the deleted repair method and is no longer useful to the project. This could include pre-purchased materials or the fixed costs associated equipment already delivered to the site.

The negotiated penalty cost also applies to the value of the deleted work if the price was determined through negotiated prices. This is a penalty cost of changing the work.

Redesign costs in this scenario would be penalty costs since the repair method for this defect should have been designed with the original design. Redesign costs are a percent of the contract funds for the change and would increase linearly with the added work.

Penalty cost equations

From the above discussion the equation for the penalty costs in this scenario must include the penalty cost for the deleted work (PC1) and the penalty costs for the added work (PC2). This is expressed as:

$$PC = PC1 + PC2$$

$$\text{Where: } PC2 = DC + OH + NC + ICA \qquad (4)$$

$$= (A1 + A2 + A4 + A6) \times Q2$$

Note that PC2 is calculated using the amount of the deleted work Q2.

PC1 can be calculated using the general equation for penalty costs. The equations for these penalty costs would vary depending on whether a time extension was granted as did scenario A. The following equations describe the penalty costs for the added work (PC1) in this scenario for each of the following circumstances regarding a time extension:

$$\text{No time extension: } PC1 = DC + IM + NC + RE + ICA \qquad (5)$$

$$= (A1 + A3 + A4 + A5 + A6) \times Q1$$

$$\text{Unavoidable time extension: } PC1 = IM + NC + RE + ICA \qquad (6)$$

$$= (A3 + A4 + A5 + A6) \times Q1$$

Avoidable time extension: $PC1 = OH + IM + NC + RE + ICA$ (7)

$$= (A2 + A3 + A4 + A5 + A6) \times Q1$$

6.3.3 Error scenario C - Correct character/ incorrect severity - overstated

In this scenario the contract documents have correctly described the character of the defect, however the severity has been incorrectly described by being overstated. After contract award the severity of the defect is correctly determined to be less than that described in the contract documents. The result of this error scenario is that the repair method selected is inappropriate. The repair method specified was based on the belief that the defect was worse than it actually is. The corrective action is to design an appropriate method of repair and substitute it for the contracted method of repair.

Penalty costs

In this scenario the specified method of repair must be deleted from the contract and a new method of repair designed and added to the contract. This involves a deductive change and an additive change to the contract. In this regard this scenario is very similar to error scenario B.

In general, the total cost of the contract in this scenario will decrease since the severity was overstated the new method of work will presumably be designed to address a lesser degree of severity, and this will require less effort and cost. In this scenario there is not likely to be a time extension since the total effort required of the contractor is less than originally contracted for.

The penalty costs for the deleted work (PC2) and the added work (PC1) would include the same elements as discussed in scenario B.

Penalty cost equations

The penalty cost equation for this scenario must include the penalty cost for the deleted work and the penalty costs for the added work. This is expressed as:

$$PC = PC2 + PC1$$

$$\text{Where: } PC2 = DC + OH + NC + ICA \tag{8}$$

$$= (A1 + A2 + A4 + A6) \times Q2$$

PC1 can be calculated using the general equation for penalty costs. The following equation describes the penalty cost for the added work in this scenario with various time extensions:

$$\text{No time extension: } PC1 = DC + IM + NC + RE + ICA \tag{9}$$

$$= (A1 + A3 + A4 + A5 + A6) \times Q1$$

$$\text{Unavoidable time extension: } PC1 = IM + NC + RE + ICA \tag{10}$$

$$= (A3 + A4 + A5 + A6) \times Q1$$

$$\text{Avoidable time extension: } PC1 = OH + IM + NC + RE + ICA \tag{11}$$

$$= (A2 + A3 + A4 + A5 + A6) \times Q1$$

6.3.4 Error scenario D - Correct character/ incorrect severity - understated

In this scenario the contract documents have correctly described the character of the defect, however the severity has been incorrectly described by being understated. After contract award the severity of the defect is discovered to be greater than described in the contract documents. The method of repair specified was based on the severity being less than it actually is and would be inadequate if performed as specified.

In this scenario the corrective action is much like scenario B and C. The specified repair must be deleted from the contract and the new method of repair added to the contract. The significant difference in this case is the total price of the contract is likely to increase due to the greater level of effort required because of the greater than anticipated severity of the defect.

Penalty costs

Again in this scenario the penalty costs can be discussed in terms of a cost to delete the specified repair method and the cost to add a new repair method. The penalty costs associated with deleting work will behave like those discussed in scenario C and B.

Penalty cost equations

The penalty cost equation for this scenario must include the penalty cost for the deleted work and the penalty costs for the added work. This is expressed as:

PC = PC2 + PC1

Where: PC2 = DC + OH + NC + ICA (12)

= (A1 + A2 + A4 + A6) x Q2

PC1 can be calculated using the general equation for penalty costs. The following equation describes the penalty cost for the added work in this scenario with various time extensions:

No time extension: PC1 = DC + IM + NC + RE + ICA (13)

= (A1 + A3 + A4 + A5 + A6) x Q1

Unavoidable time extension: PC1 = IM + NC + RE + ICA (14)

= (A3 + A4 + A5 + A6) x Q1

Avoidable time extension: PC1 = OH + IM + NC + RE + ICA (15)

= (A2 + A3 + A4 + A5 + A6) x Q1

6.3.5 Error scenario E - Character correct/ severity correct/ extent incorrect - overestimated

In this scenario the character and severity (if relevant) of the defect were described correctly on the contract documents. However, the extent of the defect was overestimated. The actual quantity of work is less than the estimated quantity of work. In this scenario the owner directs the contractor to perform only the work that is required and estimated quantities of work are decreased to the required amount by a contract change.

Penalty costs

Direct penalty costs would occur in this scenario. They would occur if the contractor lost a quantity material discount due to the change or the contractor already has pre-purchased materials. This penalty cost will increase linearly with decreasing quantities of work.

Labor penalty costs could be expected for higher unit costs based on the lack of the benefit of the learning curve. The contractor could claim that he was relying on doing a greater number of units, and thus his crews would become more efficient and his overall per unit labor costs would decrease.

Equipment penalty costs would occur in this scenario due to shorter rental periods. The fixed equipment costs such as delivery charges would be spread over less units of work. These penalty costs would increase as less and less units of work are performed.

The overhead penalty costs would occur in this scenario due to a portion of the fixed overhead costs.

Redesign penalty costs would not occur in this scenario.

Penalty cost equations

The penalty cost equation for this scenario is the penalty cost for the deleted quantities of work. In this scenario:

$$PC = PC2$$

$$\text{Where: } PC2 = DC + OH + NC + ICA \tag{16}$$

$$= (A1 + A2 + A4 + A6) \times Q2$$

In this scenario there would not be a time extension since the total effort required of the contractor is less than originally contracted for.

6.3.6 Error scenario F: Character correct/ severity correct/ extent incorrect - underestimated

In this scenario the character and severity of the defect were described correctly in the contract documents. However, the extent was underestimated. The actual quantity of work required is greater than the estimated quantity. The owner decides to perform the required quantities of work and the estimated quantities are increased to the actually needed amount. In this scenario a time extension is normally justified because of the addition of work to the contract. Therefore, if the owner chooses not to grant one this would require the contractor to accelerate the work and the owner could expect to pay the associated acceleration costs which are considered penalty costs.

Penalty costs

The amount of penalty costs associated with a change in this scenario are most sensitive to whether or not the owner grants a time extension in conjunction with the change. Generally in this scenario the owner must decide to either: 1) require the contractor to complete the additional work by the original completion date and pay the added labor costs (overtime, shift work) and impact costs, or 2) grant the contractor a schedule extension and pay the additional overhead costs. If he allows a schedule extension this may put the completion date into the less desirable season of the year for construction work and the work may become more costly as a result. Alternatively, a time extension may extend the project into a period of the year when construction is not feasible and the contractor must demobilize and return in the next construction season. This issue was discussed in Chapter Five with regard to the effect time extensions had on the penalty costs associated with a change.

This decision the owner must make can be described as several options. These various options determine the penalty cost equation that applies to each scenario. Each of the options of this error scenario will be designated 1 - 3. First the three options will be described.

The first option the owner has is to require the added work to be completed in the original contract time with no time extension. Assuming that more time was justified, which is a reasonable assumption in this scenario, there are penalty costs associated with the selection of this option.

The second option is to grant a time extension and the length of the extension does not run the completion date into adverse weather so that the cost of the work increases or the work must be stopped. If the length of the time extension in this option is the same as it would have been had the quantity of work been known then the penalty costs are minimal (unavoidable time extension). If however, the length of the time extension could have been reduced or completely eliminate had the quantity of the work been known then the penalty costs will increase since this time extension could have been avoided (avoidable time extension).

The third option is that the time extension is granted and the length of the extension runs the project into adverse weather and either: 1) the work had to be stopped and started again in the next season; or 2) the work continued in the adverse weather and experienced delays and lower productivity. Either of these would cause the cost of the work to increase. If the quantity of work had been known by the owner the additional cost caused by this adverse weather situation could have been avoided. In this option the costs of encountering this adverse weather situation are penalty costs.

OPTION 1: In this option there is no time extension, therefore the contractor must accelerate the work to complete in the original time period. Direct penalty costs would occur because of the acceleration of the work.

The fixed overhead costs would not increase, and therefore these are penalty costs if they are paid to the contractor.

Option 1 penalty costs equation

No time extension: $PC = DC + OH + IM + NC + ICA$ (17)

$$= (A1 + A2 + A3 + A4 + A6) \times Q$$

OPTION 2: In this option work is added to the contract and the schedule is extended so that the work continues without encountering adverse weather that could impede progress or cause the work to stop. If the length of the time extension granted by the owner is the same as it would have been had the quantity of work been correctly known, then the penalty cost would be due to negotiated instead of competitively bid costs and internal contract administration.

On the other hand, if the time extension could have been avoided if the quantity of the work had been correctly known at bid time then there are other penalty costs.

Direct penalty costs and overhead penalty costs would occur. Impact costs would not occur since the schedule has been extended and thus the effect on the other work has been reduced.

Option 2 penalty cost equation

Unavoidable time extension: $PC = NC + ICA$ (18)

$$= (A4 + A6) \times Q$$

Avoidable time extension: $PC = DC + OH + NC + ICA$ (19)

$$= (A1 + A2 + A4 + A6) \times Q$$

OPTION 3: In this option, like Option 2, the owner adds additional quantities of work to the contract and grants a schedule extension. However, in this case the length of the schedule extension is such that the completion date runs into adverse weather that increases the costs of the work over what it would have been, or causes the work to stop and restart the next season. This involves demobilization and remobilization in the next season. In this option the time extension is avoidable since if the quantity of work had been known the owner would not have contracted the work such that this adverse weather problem was encountered.

Penalty overhead costs would occur. Variable overhead costs would increase because of the additional quantities of work, but would not be penalty costs. Fixed overhead costs would be a penalty cost since the time extension was avoidable.

Impact costs in this option would be likely to occur and would be penalty costs.

Option 3 penalty cost equation

$$\text{Avoidable time extension:} \quad PC = DC + OH + IM + NC + ICA \qquad (20)$$
$$= (A1 + A2 + A3 + A4 + A6) \times Q$$

6.4 Summary

This chapter has identified the six different error scenarios that can occur in component inspection and developed equations for the penalty costs that result from these errors. In the next chapter each of the cases discussed in Chapter Four will be classified as to the error scenario that occurred and the penalty costs will be determined using the appropriate penalty cost equation.

CHAPTER SIX ENDNOTES:

[1] "Condition Survey Procedures for Navy and Marine Corps Airfield Pavements", prepared by U.S. Army Engineer Waterways Experiment Station, prepared for Naval Facilities Engineering Command, October 1985.

CHAPTER SEVEN

CASE STUDIES:

ANALYSIS OF PENALTY COSTS AND COMPONENT INSPECTION COSTS

This chapter will reexamine the cases presented in Chapter Four. From a conceptual perspective the goal will be to develop a plot similar to the one shown in Figure 2.1 for each case. The penalty cost and the component inspection cost will be expressed as a function of the percent error in the component inspection information.

The understanding of penalty costs developed in Chapter Five and the equations in Chapter Six will be used to calculate the penalty costs for each of the cases. These penalty costs will be plotted against the percent error that occurred in each case. This will show a relationship between the penalty cost as a function of the percent error.

The cost of the component inspection method actually used for a project will be shown on the same plot. The cost of alternate component inspection methods will be estimated along with the degree of error an owner might expect to obtain from that particular method. These costs and their associated percent error will also be plotted. This data will produce a total cost curve, similar to the one shown in Figure 2.1. Analysis of this total cost curve for each project will enable the thesis to draw conclusions as to the effect alternate, more costly component inspection methods have on the total cost of the project.

The component inspection cost used in this analysis will be the cost of the method itself, not including any costs associated with the speed of the method or how long the user is without the facility while the component inspection is being conducted. Although the speed of a method is a decision criteria for selecting a component inspection method as discussed in section 2.4.3, this criteria will not be quantified in this analysis. The importance of this factor varies for each individual facility and it is difficult to quantify. None the less, it is a factor that owners should remember when selecting a component inspection method. Although one component inspection method may result in a lower total cost than another method, if the time to perform the component inspection is so great that it is unacceptable to the user the first method should not be selected.

Additionally, by presenting, discussing and analyzing the details of these cases this thesis will show that the component defect analysis diagram shown in Chapter Six, with error scenarios (A-F) and the penalty cost equations (1-20), is adequate as a tool for looking at the penalty costs associated with errors in component inspection.

7.1 Introduction

This chapter will discuss each case using the following format:

1. Give an overview of the case from Chapter Four. Classify the case according to the error scenarios presented in Chapter Six and show the penalty cost equation that applies.
2. Describe and calculate the penalty costs that occurred.
3. Draw a plot of the penalty costs versus the degree of error in the component inspection information. Discuss whether the penalty costs are those that were predicted in the penalty cost equation.
4. Describe the component inspection method actually used and estimate its cost. Show this as the initial component inspection cost point.

5. Calculate data points corresponding to alternate component inspection methods that could have been used. Estimate costs of these alternative methods and the accuracy they would yield.

6. Plot the total cost curve.

7. From this analysis draw conclusions as to the appropriateness of the component inspection method actually used in the case and the benefits in terms of lower total cost that could be achieved by spending more on component inspection and employing alternate methods. This conclusion could support a more costly investigation using the existing component inspection methods, newer non-contact methods or maintaining the method actually used.

7.2 State of Vermont - Middlesex Bridge

The scope of this project was the repair of the deteriorated sections of concrete bridge decks on three bridges in Vermont. The extent of the deterioration was underestimated in the contract documents. The contractor was granted a time extension to complete this additional work. However, the time extension ran the work into the winter weather. This time extension could have been avoided if the quantity of work had been known at the outset.

This case is an example of error scenario F - option 3 as discussed in Chapter Six. The penalty cost equation that applies to this scenario is equation number 20 shown below:

$$PC = DC + OH + IM + NC + ICA \tag{20}$$

7.2.1 Penalty costs

The original amount of the contract was $250K. This increased to $374K primarily due to the increase in the quantity of work for concrete removal as shown below:

BRIDGE	ESTIMATED QUANTITY (SY) CLASS 1 1	CLASS 2 2	TOTAL	ACTUAL QUANTITY (SY) CLASS 1 1	CLASS 2 2	TOTAL	% ERROR
MIDDLESEX	20	345	365	319	600	818	124%
PLAINFIELD	3	46	49	20	53	73	49%
WAITSFIELD	1	7	8	61	20	81	912%
SUBTOTAL	24	398		400	673		
TOTAL CLASS 1 AND 2			422			1072	
TOTAL PERCENT ERROR							154%

Both classes of removal involve removing deteriorated concrete, preparing the exposed surface and placing new concrete. Class 1 removal was down to the top mat of reinforcement and class 2 was down to at least 3/4" below the top mat of reinforcement.

As a result of the increase in the quantity of work the contractor was entitled to request additional compensation in the adjustment to the unit prices. He requested an increase in the unit price for class 1 and 2 concrete removal due to the fact that the additional quantities pushed the work into the winter and the work was more expensive. His crews worked less efficiently, he had to work overtime and the concrete work now required freeze protection thus, driving his unit costs higher than if the work had been completed in the less adverse weather.

He also requested additional equipment costs for rental of more traffic control devices. He was planning to work the bridges consecutively, however, with the additional quantities of work they had to be worked concurrently. This additional rental cost would not have been incurred if not for adding the additional quantities after contract award during the course of the contract. Because the contractor had to work the bridges concurrently, due to the additional quantities, he now needed two sets of control devices vice the one set he had planned on if work had gone according to his schedule.

Review of the contractor's request and his detailed cost records by state engineers showed that the justified cost increase for concrete work was $7.30/SY or a total of $7822 (1072 SY x $7.30/SY) in labor penalty costs. As for the traffic control devices the state established that the contractor would have been 31 days late on the contract considering his actual production rate if the quantity of work had been unchanged. So because of contractor's low production rate the extra devices were needed in spite of additional work. However, to complete extra work required 90 days beyond the contract completion date.

Therefore, because of the joint responsibility for the cost of additional traffic devices, the penalty cost is the cost of the added traffic devices less the 31 days that the contractor would have been late in any event or $8640 in equipment penalty costs.

The owner also lost the benefit of the learning curve associated with the additional quantities. Assuming a 90% slope of the learning curve and 48% of the unit price ($100/SY) is labor this is a penalty cost of $3121 as calculated below:

CALCULATION OF PENALTY COSTS DUE TO LEARNING CURVE

UNITS FROM	UNITS TO	QUANT	AVERAGE LABOR COSTS PER UNIT	SAVINGS PER UNIT	SAVINGS TOTAL
1	422	422	\$48 (48% X \$100)	0	0
423	844	422	\$43.20 (90% X \$48)	\$4.80	\$2096
845	1072	228	\$43.20*	\$4.80	\$1095
Total saving due to learning curve that is penalty cost:					\$3121

* Assume no further reduction in labor costs associated with increase in quantities since quantity of work added would have to increase to 1688 (844 x 2) to obtain another 10% reduction.

The above penalty costs for labor, equipment, and the learning curve represent direct penalty costs (DC) in the penalty cost equation.

There were no penalty costs associated with variable overhead since this cost would have been paid if the quantities had been correct. However, the fixed overhead paid on the additional quantities of work is a penalty cost. If the quantity of the work had been known at the outset the time extension could have been avoided and the additional fixed overhead would not have been paid. Fixed overhead penalty costs are calculated using proportionality factor A2 and the relationship from Chapter Six as shown below:

$$A2 \times Q = OH$$

$$10\% \times (1072SY - 1.25 \times 422SY) \times \$100/SY = \$5,445$$

The internal administration costs of reviewing the contractor's cost records and the cost of administering the change to the contract are penalty costs. These are calculated as 2% of the increase in the contract funds using the proportionality factor A6 as shown below:

A6 x Q = ICA

2% x (1072SY - 1.25 x 422SY) x \$100/SY = \$1,230

There were no negotiated penalty costs in this case since the price of the added work was determined using the bid prices. Impact costs also did not occur as predicted by the penalty cost equation. In this case three out of the five penalty cost terms in the penalty costs equation occurred and they are summarized as follows:

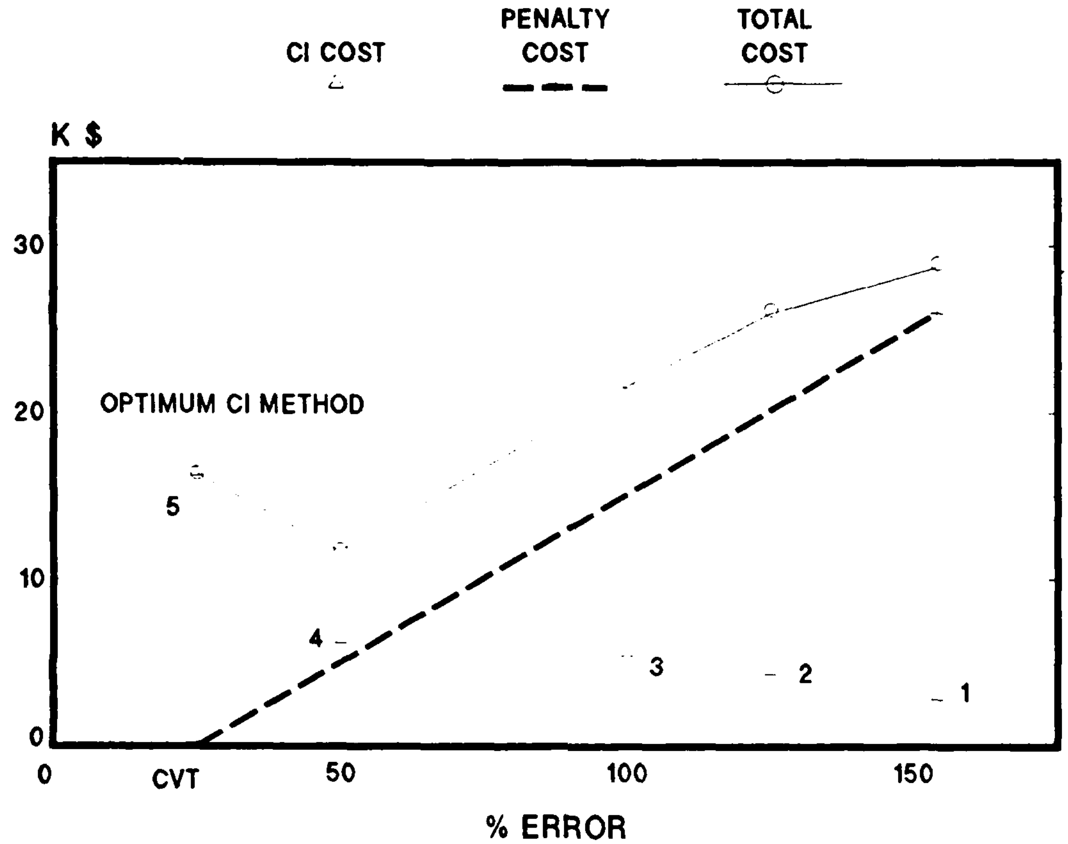
Direct penalty costs - DC		\$19,583	
Labor	\$7,822		
Equipment	\$8,640		
Learning curve	\$3,121		
Fixed overhead - OH		\$5,445	
Internal contract admin cost - ICA		\$1,230	
Total penalty costs - PC		\$26,258	or say \$26K

A penalty cost of \$26K and the percent error in describing the extent of the defect of 154% is used to plot the penalty cost curve shown as Figure 7.1. The penalty costs are zero at the contract variance threshold. The penalty costs increase to \$26K for the 154% error. The behavior of the penalty costs between these two points are assumed to be linear in nature. This is a reasonable assumption given the cost elements involved and the fact that penalty costs increase with the increase in the degree of error.

7.2.2 Actual component inspection method and cost

For this project Vermont used its standard bridge inspection procedures to estimate quantities of work. This includes a complete visual inspection of the bridge and half-cell potential readings on a 5 foot grid. A reasonable estimate of the cost of these tests would be

COST VS. PERCENT ERROR
VERMONT - MIDDLESEX BRIDGE



PENALTY COST = $26K AT 154% ERROR

COMPONENT INSPECTION METHOD	POINT	CI COST $ K	PERCENT ERROR
ACTUAL METHOD	1	3.0	154%
ACTUAL AND HALF-CELL ON 2" GRID	2	4.5	125%
ACTUAL AND IR	3	5.6	100%
ACTUAL, IR AND GPR	4	6.4	50%
ACTUAL, IR, GPR, SELECTIVE DEMOLITION AND CORING	5	16.4	25%

FIGURE 7.1

$1,000 per bridge [1]. Using this actual component inspection method, the state was able to achieve a percent error of 154% at a cost of $3,000 for the three bridges in this contract.

7.2.3 Alternate component inspection methods and costs

In this section the cost of alternate component inspection methods and their expected degree of error will be examined.

Vermont could have reduced the grid size for their half-cell tests to 2 feet from 5 feet. The remainder of the survey procedure would have remained the same. This would have increased the cost of the entire method to an estimated $4,500 and increased the accuracy of this method to an estimated 125% percent error.

Vermont could have selected infrared thermography (IR) as an alternate method to use in conjunction with their standard method. The area of the three bridge decks is 26,000 SF and IR is estimated to cost $0.10 per SF on bridge decks. The total cost of this method would be $5,600 ($3,000 + $2,600). A reasonable estimate of the percent error for this method is 100%.

Vermont could also have selected a component inspection method that would use both ground penetrating radar (GPR) and IR together. A cost of $0.13 per SF will be used as reasonable for this combination of sensors. With this method the data processing costs would be almost the same, but there would be a longer data collection time for the GPR since the path width of the sensor is less. The cost for this method, combined with the standard method, would be $6,380. The percent error using this method would improve over the previous method to an estimated 50%.

As a final method the state could have used IR and GPR in conjunction with selective demolition of portions of the deck and extensive coring to confirm the results of the IR and GPR data. This would have added $10,000 to the cost of the previous method, for a total of $16,380. The demolition would have cost an estimated $5,000 and the taking of a large number of core samples another $5,000. The degree of accuracy obtained with this method could be estimated as 25%.

The costs and the percent error for each of these alternate component inspection methods are shown and plotted on Figure 7.1.

7.2.4 Total costs

Review of the total cost curve shows that the optimum component inspection method was the actual survey method combined with IR and GPR. The additional $3.4K (for a total of $6.4K) spent on component inspection to reduce the percent error would have been worth the investment. This would have lowered total cost to $11.8K versus the $29K that was spent on the standard component inspection method and the associated penalty costs. Even if the percent error for the optimum method had been greater than the 50% estimated, up to as high as 125%, the total cost would still have been lower using this method rather than the standard method alone.

Looking further at the trend of the total cost curve below 50% error their is no further benefit to be gained by spending more on component inspection. The total cost curve begins to increase at this point. In this case it was beneficial for the owner to spend more on component inspection in order to achieve a more accurate estimate of the quantity of work.

7.3 Veteran's Memorial Bridge - Portland, Maine

This project was a unit price contract to perform repairs to the Veteran's Memorial bridge in Portland, Maine. The project included work items to repair the deteriorated sections of the concrete bridge deck. After the work started it became evident that the amount of removal required would far exceed the estimated quantity. For this reason the owner directed the contractor to change from spot removal above and below the reinforcement to complete removal of concrete above the reinforcement with a milling machine and spot removal below the reinforcement by hand where required. In this case the owner changed the removal method in an effort to minimize the penalty costs associated with requiring the contractor to complete the tremendous increase in quantities of work on an accelerated basis without a time extension.

This case is an example of error scenario F - option 1. From Chapter Six the penalty cost equation that applies to this case is equation number 17 as shown below:

$$PC = DC + OH + IM + NC + ICA \tag{17}$$

7.3.1 Penalty costs

If the work had continued as it was intended the owner would have added \$548K to the price of the contract. However, with the change in removal method the cost of the added work was reduced to \$515K. This included $479K for the cost of milling the deck and placing the concrete overlay and $36K for the added quantities of removal that were paid at the bid price.

The estimated quantities and actual quantities paid at the bid price are shown below:

REMOVAL TYPE	ESTIMATED QUANT	BID PRICE	ESTIMATED PRICE	ACTUAL QUANT	ACTUAL PRICE
1	3,600 SF	$8/SF	$28,800	5,400 SF	$43,200
2	2,400 SF	$18/SF	$43,200	3,600 SF	$64,800
TOTAL	6,000 SF		$72,000	9,000 SF	$108,000

The $479K cost included payment for 8038 SF of additional type 2 removal in the areas of the deck where it was required after milling. This added amount of type 2 removal is shown below combined with the amount of removal paid at the bid price:

REMOVAL TYPE	ESTIMATED QUANT SF	ACTUAL QUANTITY (SF)			PERCENT ERROR
		AT BID PRICE	IN MILLING COST	TOTAL	
1	3,600	5,400	0	5,400	50%
2	2,400	3,600	8,038	11,638	384%
TOTAL	6,000	9,000	8,038	17,038	184%

The above table shows that the percent error in the estimated quantities of work for this contract was 184%. In this analysis type 1 and 2 removal will be considered together as the same defect since the available data does not allow the penalty costs to be apportioned between them.

The added amount of removal, both at the bid price and as a part of the milling cost, include the type 1 and 2 removal that was encountered before the change and all the type 2 removal in the milled areas. Although the milling procedure is actually type 1 removal over the entire deck, the quantity of type 1 removal shown in the milling cost column is zero because this analysis is concerned with estimating the extent of a defect that is actually in the bridge deck. In this case it is impossible to determine how much type 1 defect was actually present in the milled areas since type 1 was done over the entire deck. Milling of the top 1" of the deck removed a lot of good concrete and it would be unfair to include this amount in the measure of the error.

Maine Department of Transportation contracts do not state a definite contract variance threshold. The contract allows the state to increase or decrease the quantities of work at the bid price unless this substantially changes the character of the work. For the purposes of this analysis a contract variance threshold of 25% will be used as reasonable. In order for a change to be substantial the magnitude of the change must lie between 10% and 50% [2]. This assumption will facilitate calculating the penalty costs and drawing the penalty cost curve for this case.

The direct penalty costs (DC) in this case are generated by the learning curve efficiencies gained by the contractor because of the excess quantities of type 2 removal. This amount is $22.1K as calculated below. Type 1 removal is not considered in this learning curve penalty cost analysis since the quantities did not increase by several fold and the work was switched from being labor intensive to equipment intensive. When the type 1 removal is done by milling machine the equipment costs are 63%

of the cost. Any learning curve benefit for this work item was insignificant. If the removal method had not been changed the direct penalty costs associated with the learning curve would have been greater.

CALCULATION OF DIRECT PENALTY COSTS DUE TO LEARNING CURVE

UNITS FROM	UNITS TO	QUANT	AVERAGE LABOR COSTS PER UNIT	SAVINGS PER UNIT	SAVINGS TOTAL
0	2400	2400	\$8.64 (48% x \$18.00)	0	0
2401	4800	2400	\$7.78 (90% x \$8.64)	\$0.86	\$2064
4801	9600	4800	\$7.00 (90% x \$7.78)	\$1.64	\$7872
9601	11,638	2038	\$7.00*	\$1.64	\$3342

Total saving due to learning curve that is penalty cost: \$13,278

* Assume no further reduction in labor costs due to additional quantities.

The penalty overhead costs (OH) are the overabsorbed fixed overhead costs on the amount of added work greater than the contract variance threshold. This is calculated using the proportionality factor A2 as follows:

$$A2 \times Q = OH$$

$$10\% \times [\$108K - (1.25 \times \$72K)] = \$1.8K$$

These penalty costs also would have been much greater if the removal method had not be changed.

The negotiated penalty costs (NC) incurred in this case are associated with the fact that the price for the milling was determined based on negotiations. The amount of this penalty cost is calculated using the proportionality factor A4 as follows:

A4 x Q = NC

7% x $479K = $33.5K

The internal contract administration penalty cost are calculated using A6 as 2% of the amount of added work as follows:

A6 x Q = ICA

2% x [$515K - (1.25 x $72K)] = $8.5K

Although the penalty cost equation included the impact cost term (IM), it did not occur in this case. However, four out of the five terms did occur. These four penalty cost terms are summarized below:

Direct penalty cost - DC	$13.3K
Overhead penalty cost - OH	$1.8K
Negotiated penalty cost - NC	$33.5K
Internal contract administration - ICA	$8.5K
Total penalty costs - PC	$57.1K

If the owner had continued with the spot removal method the magnitude of the change and the magnitude of the penalty costs would have been much more. However, by telling the contractor to do the work a different way a great portion of the penalty costs were avoided. In any event, the work still cost more than it would have if the required quantity of work had been correctly called out in the contract documents. The above penalty costs represent this additional amount.

7.3.2 Actual component inspection method and cost

Maine DOT uses a standard bridge inspection procedure to determine the estimated quantities of work for a bridge deck repair project. These inspection procedures include a visual inspection of the top and bottom of the deck and coring for chloride content and testing for compressive strength [3] [4]. The cost for these test procedures is approximately $3,000 per bridge and requires approximately 10 man days of effort [5]. The percent accuracy obtained was 184%.

7.3.3 Alternate component inspection methods and costs

The owner could have chosen infrared thermography (IR) as an alternate component inspection method. The cost of this method would have been $0.10 per SF. The area to be surveyed was 108,000 SF. The total cost would have been $13,800 when combined with the standard procedure. This method is reported to have very good accuracy, however for this analysis 100% will be used as an estimate.

The owner could also have selected a combination of infrared thermography and ground penetrating radar (GPR) as an alternate method. The cost of this method would have been $17,040 based on a cost of $0.13 per SF. The percent error generated by this method could be assumed to be 50%.

The owner could have chosen to combine IR and GPR with some of the existing methods for component inspection. Extensive core sampling, half-cell potential tests and selective demolition could have been added to confirm the results of the IR and the GPR. The addition of these methods would have increased the component inspection cost by $13K to a total of $30,040. The half-cell tests are estimated to costs $3,000. The combination of these method would have provided an estimated accuracy of 25%.

These alternate component inspection methods are plotted with the penalty cost curve on Figure 7.2.

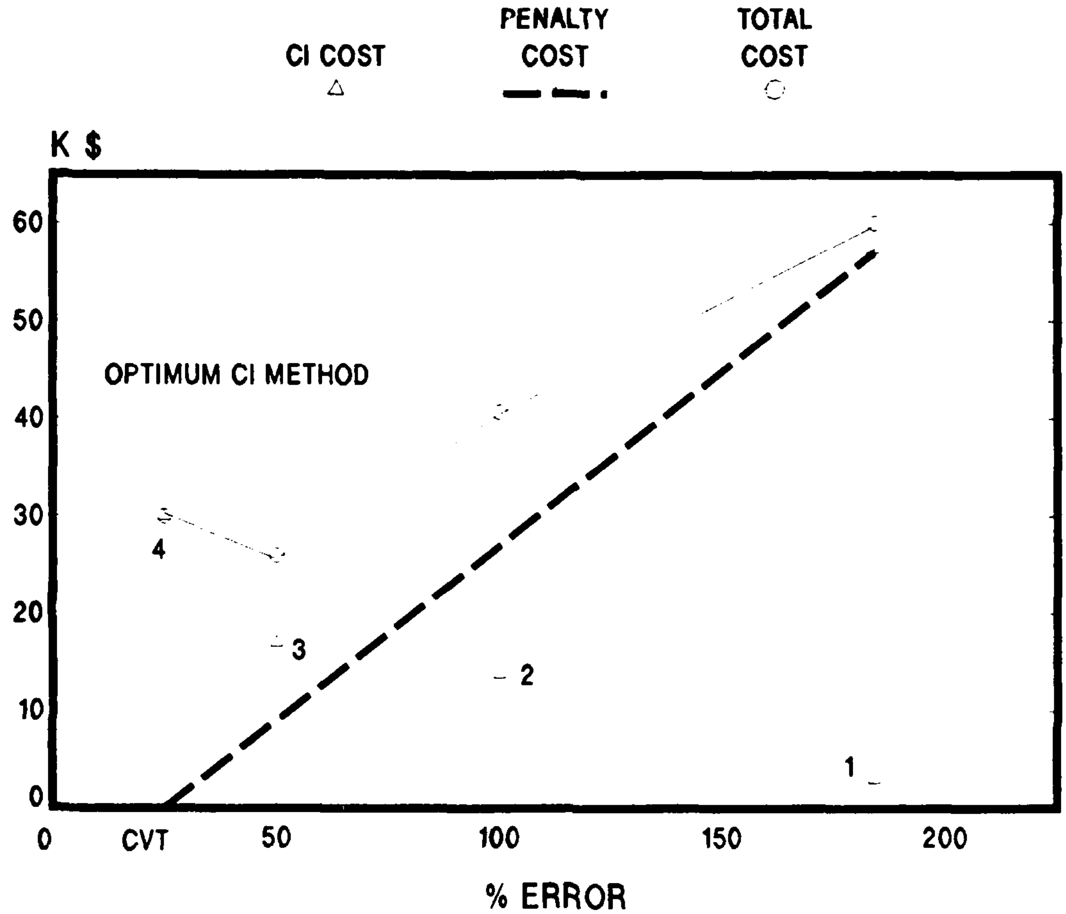
7.3.4 Total costs

Review of the total cost curve shows that if the owner had selected some of the alternative component inspection methods penalty costs would have been lower and the total cost to the project would have decreased.

The optimum component inspection method was the actual method combined with IR and GPR. The total cost was lowered from $60.1K to $26K by investing $14K in a more accurate component inspection method at the beginning of the project. The use of more accurate component inspection methods past this optimum point result in a higher total cost.

This case also shows that in spite of inadequate component inspection owners should take steps to minimize the penalty costs even after award of the contract. In this case if the resident engineer had allowed the contractor to continue with spot removal the cost of the change would have been greater and the quality of the final product would have been less.

COST VS. PERCENT ERROR
VETERAN'S MEMORIAL BRIDGE - MAINE



PENALTY COST = $57.1K AT 184% ERROR

COMPONENT INSPECTION METHOD	POINT	CI COST $ K	PERCENT ERROR
ACTUAL	1	$3.0K	184%
ACTUAL AND IR	2	$13.8K	100%
ACTUAL, IR AND GPR	3	$17.0K	50%
ACTUAL, IR, GPR, EXTENSIVE CORING, HALF-CELL AND SELECTIVE DEMOLITION	4	$30.0K	25%

FIGURE 7.2

7.4 State of Vermont - Hartland, Hartford and Sharon bridges

The scope of this project was the repair to deteriorated sections of concrete bridge decks on three bridges in Vermont. The extent of the deteriorated concrete on these bridges was underestimated in the contract documents. The percent error between estimated and actual quantities was 172%. The owner granted a time extension to complete the added work and the time extension did not run the work into adverse weather. However, the time extension would have been avoidable if the quantity of work had been known. Therefore, this case is an example of error scenario F - option 2 as discussed in the component defect analysis framework. The penalty cost equation that applies in this case is equation number 19 as shown below:

$$PC = DC + OH + NC + ICA \tag{19}$$

7.4.1 Penalty costs

The cost of the work for bridge 58A increased by \$101K from the original bid amount of \$75K to \$176K. The increase is attributed to the increase in the quantities of class 2 concrete removal that were required.

In this case the amount of penalty costs were minimized by the contact provisions the owner had included in the contract. Normally in this error scenario the owner would have been subject to similar penalty cost having to do with all the terms shown in the penalty cost equation. However, in this case the owner was able to avoid some of these penalty costs by including a provision in the contract that pre-priced the added work if the required quantities increased dramatically. This was done by stating that if upon removal of the asphalt wearing course the extent of the deteriorated concrete was discovered to be greater than estimated the ownercould order class 1 or 2 removal over the entire deck and the price would be 90% of the bid price for that bridge only. So instead of spot removal and replacement of concrete, concrete would be removed over the entire deck to either class 1 or 2 and then replaced with a continuous concrete overlay and the contractor would be paid 90% of the bid price.

Without this contract provision the owner would likely have paid the bid unit price for the additional work on bridge 58A and the associated penalty costs. It would have been far more difficult for the owner to obtain any price concessions at the negotiation table for the benefits the contractor receives from the learning curve and overabsorbed overhead costs. By recovering 10% of the bid unit price up front the owner avoided some of these penalty costs and minimized the cost of adding these quantities of work after the award of the contract.

This analysis will calculate the penalty costs with and without the 90% contract provision to see how effective this contractual arrangement was in lowering the penalty costs as compared to how effective other component inspection method would have been.

A summary of the increases in the quantities and the extended prices for removal with and without the 90% contract provision on bridge 58A is shown below:

	QUANTITY SY		BID PRICE $/SY		EXTENDED PRICE $		
ITEM	EST	ACT	100%	90%	EST	ACT @100%	ACT @90%
CLASS 1	5	0	180	162	900	0	0
CLASS 2	79	720	180	162	14,220	129,600	116,640
TOTAL	84	720			$15,120	$129,600	$116,640

If the 90% contract provision had not been included the penalty costs would have included the following, as explained below:

Direct penalty cost - DC	$12,451
Overhead penalty cost - OH	$11,070
Internal contract administration - ICA	$2,214
TOTAL	$25,735

The direct penalty costs (DC) are associated with the learning curve and represent the lower cost the contractor would have bid if he had known the quantities were going to be this great. The calculations for this amount are shown below:

CALCULATION OF DIRECT PENALTY COSTS DUE TO LEARNING CURVE

UNITS FROM	UNITS TO	QUANT	AVERAGE LABOR COSTS PER UNIT	SAVINGS PER UNIT	SAVINGS TOTAL
0	84	84	$86.40	0	0
85	168	84	$77.76 (90% x $86.40)	$8.64	$726
169	336	168	$69.98 (90% x $77.76)	$16.42	$2756
337	672	336	$62.99 (90% x $69.98)	$23.41	$7866
673	720	47	$62.99*	$23.41	$1100

Total saving due to learning curve that is penalty cost: $12,451

* Assume no further reduction in labor costs associated with additional quantities since quantity of work added would have to increase to 1,344 (672 x 2) to obtain another 10% reduction.

The overhead penalty costs (OH) are based on fixed overhead costs that would have been paid on the added quantities of work. They are calculated using the proportionality factor A2 as follows:

$$A2 \times Q = OH$$

$$10\% \times [\$129,600 - (1.25 \times \$15,120)] = \$11,070$$

The internal administration penalty costs (ICA) are calculated using A6 as follows:

$$A6 \times Q = ICA$$

$$2\% \times [\$129{,}600 - (1.25 \times \$15{,}120)] = \$2{,}214$$

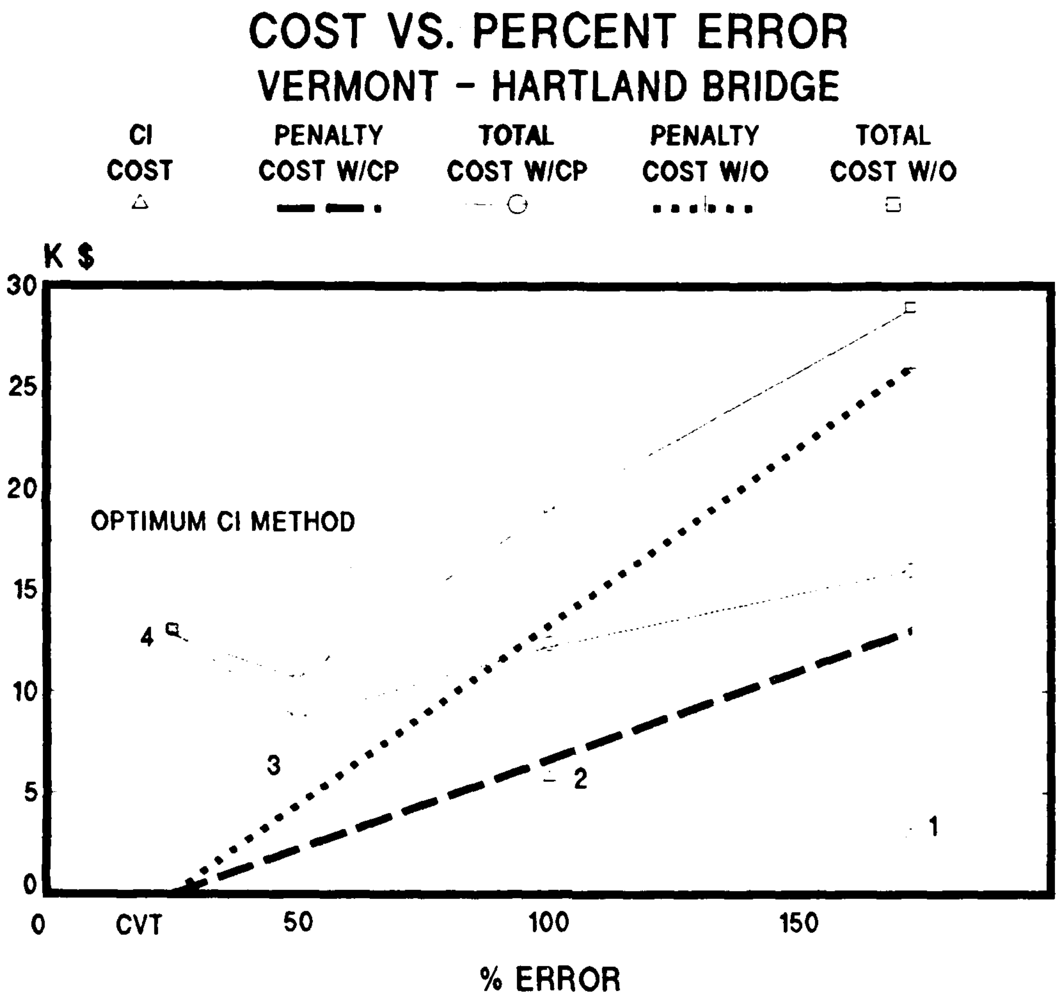
The penalty costs calculated above ($25,811) assumed that the 90% contract provision was not included in the contract. However, with the 90% contract provision a portion of these penalty costs were recovered through the reduction in the unit price. The amount of penalty cost recovered by this contract provision is the price for the work at the unit price less the price the same work at the 90% unit price. Therefore, the penalty costs incurred with the 90% contract provision are the penalty costs calculated above less the penalty costs that were recovered as shown below:

$$\$25{,}735 - (\$129{,}600 - \$116{,}640) = \$12{,}775$$

The penalty costs with the contract provision were half of the amount without the contract provision. Figure 7.3 shows the penalty costs curve both with and without the 90% contract provision.

7.4.2 Actual component inspection method and cost

For this case the standard bridge inspection procedures were used to estimate the quantities of work. As in the previous case this is estimated to be $1000 per bridge or a total of $3000. Therefore using this component inspection method the state was able to obtain a percent error of 172%.



PENALTY COST WITHOUT CONTRACT PROVISION = $26K AT 172% ERROR

PENALTY COST WITH CONTRACT PROVISION = $13K AT 172% ERROR

COMPONENT INSPECTION METHOD	POINT	CI COST $ K	PERCENT ERROR
ACTUAL	1	3.0	172%
ACTUAL AND IR	2	5.8	100%
ACTUAL, IR AND GPR	3	6.6	50%
ACTUAL, IR, GPR, SELECTIVE DEMOLITION AND HALF-CELL TEST	4	13.1	25%

FIGURE 7.3

7.4.3 Alternate component inspection methods and costs

The state could have used infrared thermography (IR) as an alternate component inspection method and used this in conjunction with their standard bridge inspection procedures. The size of the three bridge decks is 28,000 SF. The cost of the IR would be $2,800 based on $0.10 per SF. The total cost of these two methods would have been $5.8K. The percent error using this method could reasonably be estimated at 100%.

The state could also have used ground penetrating radar and IR in conjunction with the standard method. The estimated cost of this multiple sensor method would be $0.13 per SF. The cost for the IR and GPR survey is $3,640, for a total cost of $6.6K. The estimated accuracy of this method is 50%.

The state could also have supplemented the last method with selective demolition and half-cell potential tests. This would have added $6.5K to the cost of the previous method; $5K for the selective demolition and $1.5K for the half-cell tests. The addition of these method would have lowered the percent error to an estimated 25%.

These alternate component inspection methods and their costs are shown on Figure 7.3.

7.4.4 Total costs

Review of the total cost curve in this case shows that the combination of the actual method with IR and GPR produced the optimum total cost. This was true with and without the 90% contract provision. The total cost with the 90% contract provision (W/CP in Figure 7.3) was lowered from \$16K to \$8.8K by investing \$3.6K more in component inspection at the beginning of the project. Without the contract provision (W/O in Figure 7.3) the total cost was lowered from \$29K to \$11K by investing \$3.6K more in component inspection.

This case also shows that creative contract provisions can be significant in recovering the penalty costs the owner would have paid due to inadequate component inspection methods. The use of the 90% contract provision cut the penalty costs in half. This reduced the total cost from \$29K to \$16K with no investment in component inspection. The fact that no added component inspection cost is needed makes the benefit obtained from these provisions greater than the benefit of more accurate component inspection methods.

7.5 Fairchild Air Force Base

This project provided various repairs to the concrete portions of the runway. The extent of three of the work items in this contract were incorrectly described in the contract documents as shown below. Work items 2 and 3 were overestimated and item 1 was underestimated. In all three cases the degree of error in describing the extent of the defect exceeded the contract variance threshold. This particular contract is typical of most federal contracts in that the contract variance threshold (CVT) is 15%.

ITEM	EST QUANT	ACT QUANT	% ERROR	UNIT PRICE	BID AMOUNT	FINAL AMOUNT
1. 3"-9" SPALL REPAIR (SF)	29,000	45,135	56%	$12.74	$369K	$575K
2. >9" SPALL REPAIR (SF)	20,000	13,835	-31%	$19.60	$392K	$271K
3. SEAL PCC CRACKS(LF)	25,000	6,600	-73%	$1.10	$27.5K	$7.26K

7.5.1 Penalty costs

Penalty costs for this case are derived from each of the three work items in which an error in the estimated quantities was made. This section will look at the penalty costs for each of these work items separately.

Item 1 - Spall repair 3" - 9"

This is an example of error scenario F - option 1 in which the extent of the defect was underestimated and the owner did not grant a time extension. The penalty costs equation that applies to this case in equation number 17 as follows:

$$PC = DC + OH + IM + NC + ICA \qquad (17)$$

The premium of $80K discussed in Chapter Four represents the direct penalty costs. This cost was caused by the owner's requirement for the contractor to finish the work without a time extension. This requirement caused the contractor to have to work overtime and additional shifts to complete the added quantities. This additional cost is attributed to the overtime and shift work, the loss of labor efficiency, additional material and freight costs, and additional equipment rental costs. These costs would not have been incurred if the owner had not required that the added work for this item be completed within the original schedule.

The overhead penalty costs stem from the fact that the contractor was paid at the bid price for the additional quantities of work over 115%. At 115% all fixed overhead costs have been paid by the preceding units of work and any further compensation represents overabsorbed fixed overhead costs. These overhead penalty costs are calculated as 10% of the cost of the added work greater than the contract variance threshold as follows:

$$A2 \times Q = OH$$

$$10\% \times [45{,}135 \text{ SF} - (1.15 \times 29{,}000 \text{ SF})] \times \$12.74/\text{SF} = \$15{,}014$$

The internal contract administration penalty costs are calculated as 2% of the added amount of work or:

$$A6 \times Q = ICA$$

$$2\% \times [45{,}135 \text{ SF} - (1.15 \times 29{,}000 \text{ SF})] \times \$12.74/\text{SF} = \$3{,}013$$

Impact costs and negotiated penalty costs did not occur in this case. The total penalty costs for this item of work are:

Direct penalty costs - DC	80,332
Overhead penalty costs - OH	15,014
Internal contract administration - ICA	3,013
TOTAL Penalty costs work item 1	$98,359

Item 2 - Spall repair greater than 9"

The extent of this defect was overestimated and the error is classified as error scenario E. The penalty cost equation for this work item is equation number 16 that considers the penalty costs associated with the deleted work (PC2) using the variable Q2 as follows:

$$PC2 = DC + OH + NC + ICA \tag{16}$$

In this case there were no direct penalty costs associated with this work item. This could be explained by the fact that work item 1 and 2 are similar in nature. Thus the causes of direct penalty costs in work item 2 may have been eliminated. An example is pre-purchased materials for work item 2 that could be used in work item 1, thus eliminating any penalty costs for work item 2.

The overhead penalty costs in this work item are associated with the underabsorbed fixed overhead costs. This amount is calculated as 10% of the deleted work as follows:

$$A2 \times Q2 = OH$$

$$10\% \times [(85\% \times 20{,}000 \text{ SF}) - 13{,}835 \text{ SF}] \times \$19.60/\text{SF} = \$6{,}203$$

The internal contract administration penalty costs are calculated as 2% of the added amount of work or:

$$A6 \times Q2 = ICA$$

$$2\% \times [(85\% \times 20{,}000 \text{ SF}) - 13{,}835 \text{ SF}] \times \$19.60/\text{SF} = \$1{,}241$$

For a total of $7,444 in penalty costs for this work item.

Item 3 - Random PCC Cracks.

Like item 2 the extent of this defect was overestimated which is error scenario E. Using the same equation number 16 the underabsorbed .xed overhead costs and the internal administration costs are calculated as follows:

$$10\% \times [(25{,}000\text{LF} \times 85\%) - 6{,}600\text{LF}] \times \$1.10/\text{LF} = \$1{,}612 = OH$$

$$2\% \times [(25{,}000\text{LF} \times 85\%) - 6{,}600\text{LF}] \times \$1.10/\text{LF} = \$267 = ICA$$

For a total of $2,017 in penalty costs for this work item. There were no direct penalty costs for this work item due to the minor cost of this work item (1% of the contract value).

For all of these work items there are no negotiated penalty costs since the amount of the changed work was priced based on bid unit prices. The $80K that was a negotiated costs was included as a direct penalty costs, so therefore it is not counted twice.

In summary, the penalty costs for each work items are as follows:

	PENALTY COST	%ERROR	ERROR SCENARIO
ITEM 1	$98,359	+56%	F - 1
ITEM 2	$7,444	-31%	E
ITEM 3	$1,879	-73%	E

A comparison of the penalty costs for the three work items shows that the penalty costs for work item 2 and 3 are relatively insignificant compared to item 1. The penalty costs for work items 2 and 3 are also insignificant compared to the costs of alternate component inspection methods that could improve the accuracy of the estimate for these work item and thus lower these penalty costs. In other words, the cost of the more accurate component inspection method would be more than any savings that could be obtained by lowering the penalty cost. Because of this comparative insignificance work items 2 and 3 will not be considered in the remainder of this analysis. The penalty cost associated with work item 1 is significant, and alone it makes the consideration of alternate more costly component inspection methods worthwhile.

7.5.2 Actual component inspection method and cost

The estimated quantities for this contract were identified through a visual inspection. During this inspection "rodding" was used to detect spalls. This method is based on the same principle as chain drag. The survey also used the presence of asphalt patches to identify areas that had been temporarily repaired and needed to be permanently repaired with concrete.

This component inspection method was restricted by the needs of the user. The survey team was allowed on the runway for approximately 30 minutes and then required to get off to allow aircraft to use the runway for approximately the same time. With this restriction approximately 10% of the runway was surveyed and this data was extrapolated to obtain the estimated quantities. This survey took five men one month to complete.

At an estimated $40,000 per year for each man, or $14 per hour, the component inspection method cost:

$14/HR x 5 men x 8HR/day x 5days/week x 4 weeks = $11,200

7.5.3 Alternate component inspection methods and cost

An alternate method that could have been used would be for the owner to continue as they were and do twice as much of the rodding. This would have doubled the cost of the effort to $22.4K. If this was done twice the amount of the airfield would have been surveyed and the degree of error could have been improved to an estimated 50%.

The owner could have selected infrared thermography (IR) as an alternate component inspection method. Although a reasonable cost for this method on a bridge was discussed in the previous case as $0.10 per square foot, this does not take into account the economies of scale that can be obtained on an airfield pavement. The unit cost of this component inspection method can be lowered by the sheer size of the facility. Figure 7.4 shows how this lower price can be calculated. This calculation gives an order of magnitude cost per SF for this component inspection method.

In this project there was 1.6 million SF of PCC pavement to survey. Using the above unit cost for this method the total cost would be:

$$1.6 \times 10^{6} \text{ SF} \times \$0.021 \text{ per SF} = \$33{,}600$$

Although this method is able to detect thermal discontinuity in pavement, it is unlikely that it could have detected the depth of the spalls or effectively identified the PCC cracks. Therefore, the percent error that this method alone could achieve is estimated to be 35%. There are other component inspection methods and sensors that are better suited to determine the depth of spalls and to more clearly identify cracks.

To improve this percent error the owner could have selected an alternate component inspection method for this project that employed a van equipped to perform several methods simultaneously. Several sensors and the data recording equipment could be mounted on the same van. This van would contain ground penetrating radar, infrared thermography and video imaging sensors and recorders. These methods combined could readily detect all defects on this project including the three for which there were errors.

COST OF AIRFIELD IR SURVEY

FIGURE 7.4

Calculate the reasonable cost of an IR survey of an airfield due to the economies of scale gained in through the sheer size of the airfield.

Given: IR cost for bridge decks: \$0.10 per SF

A van equipped with IR sensors and data recording equipment can do 10 average bridges per day. An average bridge is estimated to be an area 56′ x 600′ = 33,600 SF.

Calculate: Area covered in one day is:

33,600 SF/bridge x 10 bridges/day = 336,000 SF/day

Cost of one day of work is:

336,000 SF/day x \$0.10 per SF = \$33,600 per day

Therefore: One day of data collection, processing and interpretation costs \$33,600. Most of the day is spent setting up the van and traveling from bridge to bridge. In fact at 5 MPH and a 10′ path width only 8 minutes is spent actually collecting the data for one bridge.

If IR was used on an airfield there would be no travel time between facilities and the set up time would be minimal. Therefore most of the day, say 6 out of 8 hours a day, could be spent collecting data. There is a tremendous economy of scale to be gained when this method is used on an airfield as compared to a bridge deck.

Calculate: How much airfield pavement could be surveyed in a 6 hour day at 5 MPH.

10′path x 5280′/mi x 5MPH x 6 hour/day = 1.584×10^6 SF/day

Therefore: If one day of IR survey costs \$33,600, then a approximate estimate of the cost per SF is:

\$33,600 per day / 1.584×10^6 SF per day = <u>\$0.021 per SF</u>

As in the previous bridge case the cost of the method increases somewhat when additional sensors are added to the process. For airfields a unit cost of \$0.03 per SF will be used as reasonable. This is an increase of 40% over the single sensor survey of \$0.021 per SF. Therefore, the cost of this multiple sensor component inspection method would be:

$$1.6 \times 10^6 \text{ SF} \times \$0.03 \text{ per SF} = \$48,000$$

Because of the increase in the amount of information produced and the capabilities of the sensors in this method it is assumed that this method would yield a 20% error for each of the three defects.

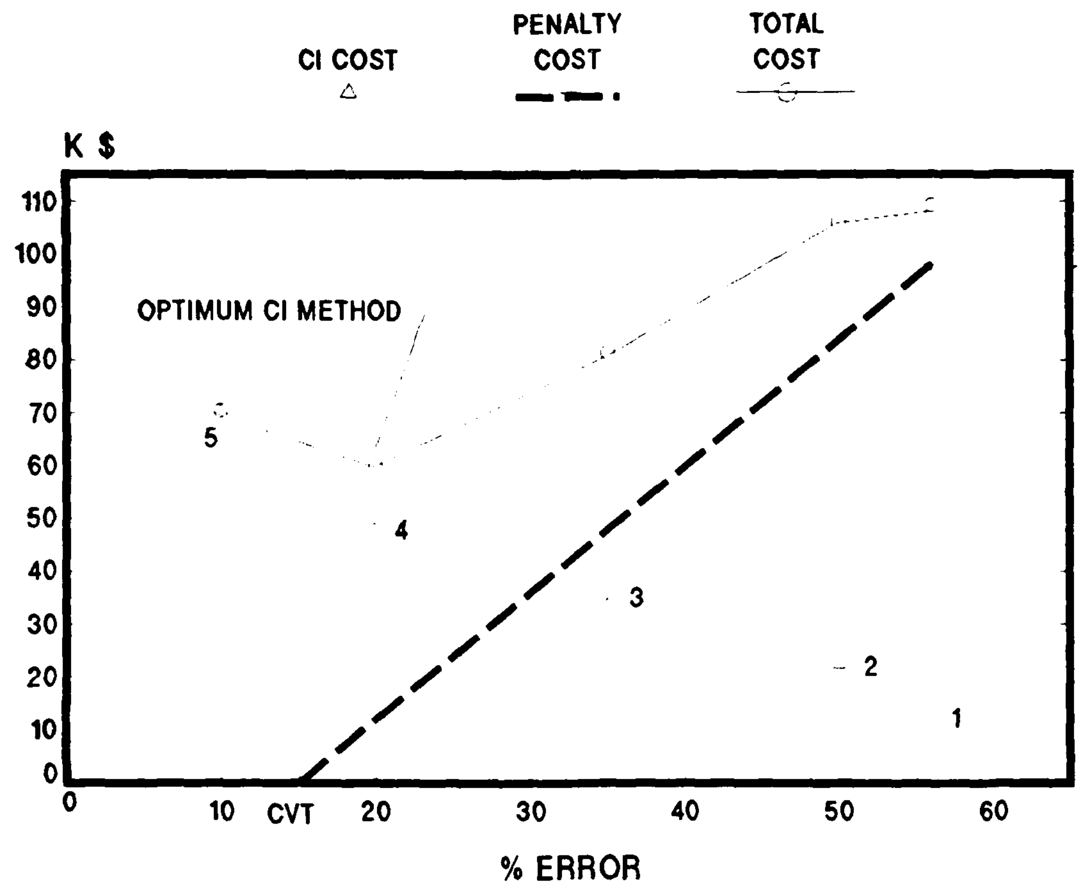
In an effort to increase the accuracy of the estimate for this work item even further the owner could have selected the previous method for \$48,000 and combined it with more rodding. The rodding could have confirmed the results of the non-contact method and increased the accuracy of this combination of methods to an estimated 10%.

These alternative component inspection methods are summarized with the plot of the penalty cost curves on Figure 7.5.

7.5.4 Total costs

Review of the total cost curve in this case shows that the multi-sensor method is the optimum component inspection method providing the minimum total cost. The total cost is reduced from \$109.2K to \$59.9K by investing \$36.8K more on component inspection at the outset of the project. Spending more on component inspection past this point in an effort to reduce penalty costs causes the total costs curve to increase.

COST VS. PERCENT ERROR
FAIRCHILD AIR FORCE BASE



PENALTY COST = $98K AT 56% ERROR

COMPONENT INSPECTION METHOD	POINT	CI COST $ K	PERCENT ERROR
ACTUAL METHOD	1	3.0	56%
MORE RODDING	2	22.4	50%
IR	3	33.6	35%
MULTI-SENSOR CI	4	48.0	20%
MORE RODDING AND MULTI-SENSOR CI	5	70.4	10%

FIGURE 7.5

More rodding is beneficial, but only to a minor extent. The total cost curve is reduced only $3.1K. The multiple sensor method is the optimum component inspection method from a total cost perspective.

7.6 Minot Air Force Base, North Dakota

The scope of this project was repairs to the airfield pavements at the Minot Air Force Base. The unit price contract was awarded in April of 1986. Errors were made in describing the extent of two of the unit price items of work on the contract. The owner granted a time extension to complete the extra work and this extension ran the work into a winter exclusion period in which the work had to be halted until the spring. The contract included the standard federal contract clause regarding a 15% contract variance threshold.

7.6.1 Penalty costs

The repair contract was awarded for $1,539K and the final contract price was $2,458K. This increase can be attributed to the added quantity of PCC spall repair (work item 2) required. The following schedule shows the estimated and actual quantities for these work items:

ITEM	EST QUANT	ACT QUANT	% ERROR	UNIT PRICE	BID AMOUNT	FINAL AMOUNT
1. PCC CRACK REPAIR (LF)	124,000	50,842	-59%	$1.25/LF	$155K	$64K
2. PCC SPALL REPAIR (SF)	26,500	115,392	+335%	$12.34/SF	$327K	$1,424K

The penalty costs for each of these defects will be examined separately.

Item 1 - PCC crack repair

Item 1 was overestimated which is an example of error scenario E in the component defect analysis framework. The penalty cost equation that applies is equation number 16 as follows:

$$PC2 = DC + OH + NC + ICA \qquad (16)$$

In this case there were no direct penalty costs associated with this work item. In this case the magnitude of work item 2 overshadowed any direct penalty costs associated with work item 1.

The overhead penalty costs in this work item are associated with underabsorbed overhead costs. This amount is calculated as 10% of the deleted work using the relationship from Chapter Six as follows:

$$A2 \times Q2 = OH$$

$$10\% \times [(124,000 \text{ LF} \times 85\%) - 50,842 \text{ LF}] \times \$1.25/\text{LF} = \$6,820$$

The internal contract administration costs penalty costs are calculated as 2% of the cost of the change:

$$A6 \times Q2 = ICA$$

$$2\% \times [(124,000 \text{ LF} \times 85\%) - 50,842 \text{ LF}] \times \$1.25/\text{LF} = \$1,605$$

For a total of $8,425 in penalty costs for this work item.

Item 2 - PCC spall repair

Item 2 is an example of error scenario F - option 3. The quantity of work was underestimated and the owner granted a time extension which ran the work into the winter and the adverse weather made it impractical to continue with the work. The contractor demobilized for the winter and returned in the spring to finish. The penalty cost equation that applies in this case is number 20 as follows:

$$PC = DC + OH + IM + NC + ICA \tag{20}$$

The direct penalty costs associated with the benefit the contractor gained from the learning curve that was not passed on to the owner are calculated below:

CALCULATION OF DIRECT PENALTY COSTS DUE TO LEARNING CURVE

UNITS			AVERAGE LABOR	SAVINGS	
FROM	TO	QUANT	COSTS PER UNIT	PER UNIT	TOTAL
1	26,500	26,500	\$5.92 (48% X \$12.34)	0	0
26,501	53,000	26,500	\$5.33 (90% X \$5.92)	\$0.59	\$15,635
53,001	106,000	53,000	\$4.80 (90% x \$5.33)	\$1.12	\$59,360
106,001	115,392	9,392	\$4.80*	\$1.12	\$10,519

Total saving due to learning curve that is direct penalty cost: \$85,514

* Assume no further reduction in labor cost due to increase in quantities.

In this case the contractor did not request any additional compensation for direct costs as in the previous airfield case. It is possible that since a time extension was granted, and the contractor did not have to accelerate the work, he did not incur any additional direct costs that were not covered by the unit price. This is quite likely since the owner did not force the contractor to increase his output to meet the original completion date.

The overhead penalty costs are those fixed overhead costs paid on the units of work in excess of the contract variance threshold. If the extent of this defect had been known at the time of award the owner would have made arrangements to insure that the work did not take two seasons to complete. Examples of this include, dividing the work into two contracts, telling the contractor at the outset what his rate of production must be or structuring the contract requirements so that he can realistically finish in a season. For this reason these fixed overhead costs are penalty costs. These overhead penalty costs are calculated using A2 in the following relationship:

A2 x Q = OH

10% x [(115,392 SF - (1.15 x 26,500 SF)] x $12.34/SF = $104,787

The internal contract administration penalty costs are as follows:

A6 x Q = ICA

2% x [(115,392 SF - (1.15 x 26,500 SF)] x $12.34/SF = $20,959

There were no impact penalty costs in this case.

In summary the penalty costs for these defects was as follows:

WORK ITEM 1	Overhead penalty costs - OH	$6,820
	Internal administration - ICA	$1,605
	Total penalty costs item 1	$8,425
WORK ITEM 2	Direct penalty costs - DC	85,514
	Overhead penalty costs - OH	$104,778
	Internal administration - ICA	$20,959
	Total penalty costs item 2	$211,251

As in the previous case the penalty costs associated with work item 1 are insignificant when compared to the penalty costs for work item 2 and the cost of alternate more component inspection methods that could lower the penalty costs. For this reason work item 1 will not be considered any further in this analysis.

7.6.2 Actual component inspection method and cost

The component inspection method used to determine the estimated quantities for this contract were chain drag combined with a visual inspection. The work was done in house by the base pavement engineer. No consultant was hired to assist or perform the work. The pavement engineer related a number of problems with this method:

1) This method is very time consuming so the entire airfield area could not be surveyed in the time that was available.

2) The time spent in surveying impacted on the airfield operations and restricted the time that could be spent on the survey.

3) Interference from jet aircraft noise makes the chain drag method especially difficult to use.

For these reasons only a small portion of the airfield was surveyed. The extent of the defects obtained from this limited survey was extrapolated to obtain the quantity of the defects for the entire airfield pavement to be repaired under this contract.

This component inspection method involved the one person for the period of four weeks. The cost of this method based on an annual salary of $40,000 is $3,077.

$40,000 x 4 weeks / 52 weeks per year = $3,077

7.6.3 Alternate component inspection methods and costs

The owner could have selected more of the visual survey as an alternate component inspection method. In this case more personnel could have been assigned to the survey. If the four people had been assigned for the same period of time the cost would have increased to $12,308. Using this method it is reasonable to assume that the accuracy of the estimated quantity would have improved by 20% to 268%.

A second component inspection method that that would have been appropriate for the defects in this repair project would have been the multiple sensor van used in the previous airfield case. This analysis will look at several combinations of accuracies and costs for this method.

In this project there were 6.8 million SF of pavement to survey. Using the cost per SF for this similar type of survey from the Fairchild case the cost would be:

6,800,000 SF x $0.03 per SF = $204,000

As in the Fairchild case a percent error of 20% will be assumed as reasonable. This type of survey of the entire area would have taken three days at a 12 foot path width and 5 miles per hour.

If however, the owner wished to reduce the time and cost for the survey by having the sensor van travel at a faster speed this would be expected to increase the degree of error. If the speed of the van was doubled to 10 miles per hour, the cost would decrease by approximately 25% since the cost of data processing would remain. The degree of error would be expected to increase with this alternative to an estimated 50%.

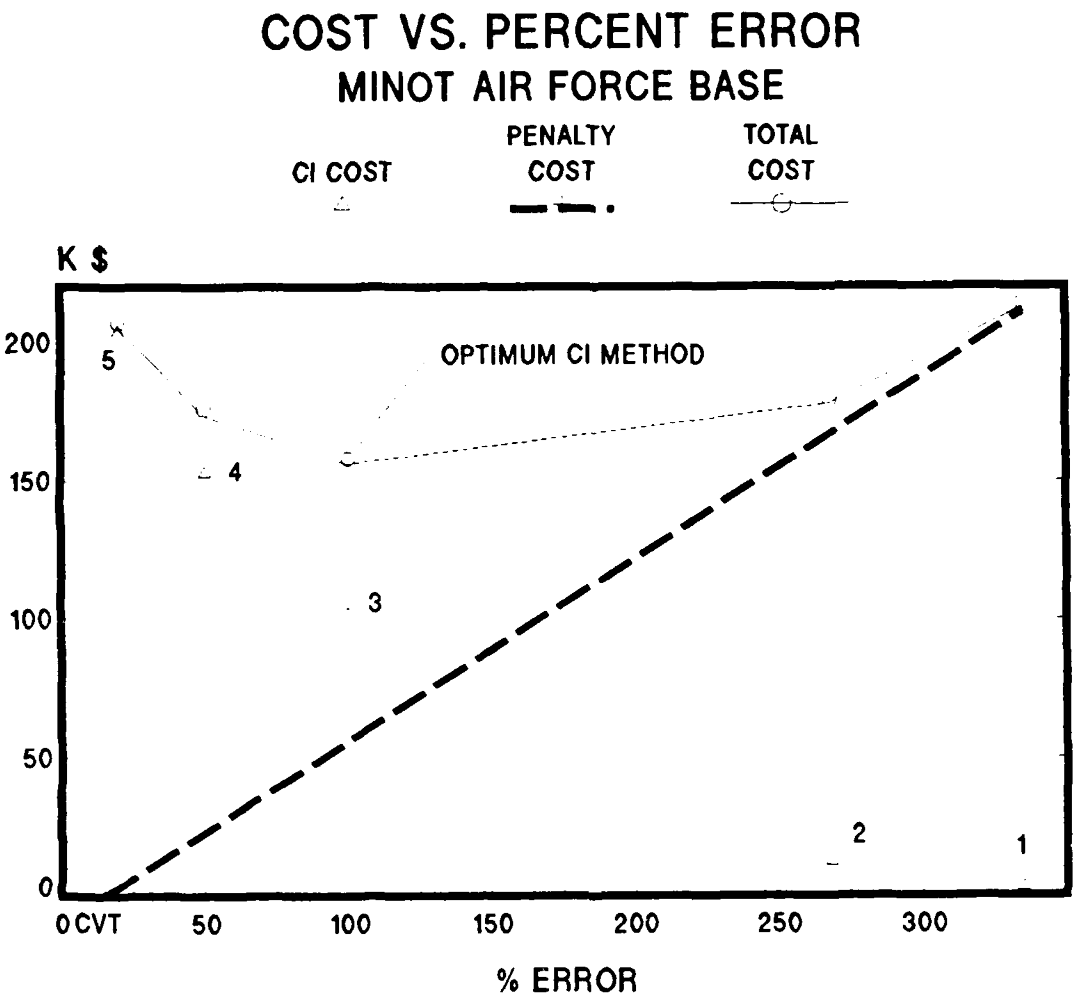
The owner might also survey only half of the airfield pavement and then use the quantities obtained from this to estimate the total quantities for the project. This method would also reduce the cost and the time to perform the component inspection. With this approach the cost would be half since the amount of data processing would also be reduced. The degree of error would increase again and could reasonably be estimated as 100%.

CI METHOD	% ERROR	CI COST $
Multi-sensor @ 5 MPH	20%	$204,000
Multi-sensor @ 10 MPH	50%	$153,000
Multi-sensor 1/2 AREA	100%	$102,000

These methods are shown with the plot of the penalty cost curve on Figure 7.6.

7.6.4 Total costs

Review of the total cost curve for this case shows that a multi-sensor method covering only one half of the airfield yielded the optimum total cost. The penalty costs were reduced from $211K to $158K by investing $102K in component inspection to utilize the multi-sensor method. The investment in more accurate component inspection methods past this point result in increased total costs.



PENALTY COST = $211K AT 335% ERROR

COMPONENT INSPECTION METHOD	POINT	CI COST $ K	PERCENT ERROR
ACTUAL METHOD	1	3.1	335%
ACTUAL - FOUR TIMES MORE AREA SURVEYED	2	12.3	268%
MULTI - SENSOR 1/2 AREA	3	102	100%
MULTI - SENSOR @ 10 MPH	4	153	50%
MULTI - SENSOR @ 5 MPH	5	204	20%

FIGURE 7.6

7.7 Naval Air Station Brunswick

This project was a lump-sum contract to provide repairs to the instrument runway. This is an example of error scenario F - option 1 in which the degree to which the extent of the defect was underestimated and the owner did not grant a time extension. However, this case is slightly different in that the underestimate was so large that the method of repair was inappropriate and had to be changed. Normally in error scenario F the additional quantities of work are added to the contract and the contractor continues with the same method of repair. In this case however, it was infeasible to continue with the designed repair. The original design was based on 9000 SF of distressed pavement. When the work was started the extent of the distressed pavement had increased to 120,000 SF.

From Chapter Six the penalty cost equation that applies in this case is equation number 17:

$$PC = DC + OH + IM + NC + ICA \tag{17}$$

7.7.1 Penalty costs

The amount of the change to the contract was \$593K. If this added work had been included in the contract documents it is estimated that the added work would have cost \$424K. The difference, \$169K, is a penalty cost. This added cost represents the penalty cost terms DC and NC that were incurred by the owner in adding this work to the contract after award.

The direct penalty costs (DC) are associated with the overtime and shift work the contractor had to perform in order to get the work done within the original schedule. The contractor worked seven days a week on this job throughout the summer. Long hours such as these lower the productivity of a contractor's crew and this increased labor cost must be added to the cost of the work. The contractor had to mobilize all of his productive effort, men and equipment, on this job in a short period of time. This was not his plan when he bid the job. The fixed costs of this increased mobilization effort and increasing the amount of equipment on the job contributed to the cost.

The $169K cost also includes the negotiated penalty costs (NC) associated with purchasing what under normal circumstances would have been $424K worth of paving work on a negotiated basis.

There were no impact penalty costs (IM) or overhead penalty costs (OH) in this case.

There were internal contract administration penalty costs. These are 2% of the cost of the added work:

A6 x Q = ICA

2% x $593K = $12K

A summary of the penalty costs in this case are:

DC and NC	$169K
ICA	$12K
Total penalty costs	$181K

Since this was a lump-sum contract no contract variance threshold had been established that applied to the increased amount of distressed pavement. However, there is a certain increased quantity of component defect that would trigger the start of penalty costs. In effect the contract variance threshold is the level of error at which penalty costs are incurred as a result of a contract change caused by inadequate component inspection. In this case if the amount of distressed pavement had increased up to an estimated 30,000 SF the designed repair still would have been acceptable. However, the increase to 120,00 SF was too great to continue with the designed repair. Therefore, 30,000 SF will be used as the contract variance threshold for this case. At this point the designed repair had to be changed and penalty costs were incurred. The amount of these penalty costs increase with increasing degree of error in describing the extent of the defect.

For this analysis 0% error will be at 9000 SF of distressed pavement. The contract variance threshold is 233% error calculated as:

$$[(30{,}000 - 9{,}000) / 9{,}000] \times 100\% = 233\%$$

The percent error at $181K penalty costs is based on 9,000 SF and 120,000 SF calculated as follows:

$$[(120{,}000 - 9{,}000) / 9{,}000] \times 100\% = 1233\%$$

Therefore, the penalty cost will be zero at 233% error and will increase linearly up to 1,233% error.

7.7.2 Actual component inspection method and costs

As stated in Chapter Four the the component inspection method used in 1985 was not itself inadequate, it correctly identified the extent of the defects in the airfield at that time. However, to be considered adequate the component inspection decisions made by the owner must take into account the fact that deterioration is time dependent. In this case the methods used by the owner after 1985 failed to detect this change in the amount of distressed pavement. Therefore, the series or combinations of component inspection methods the owner selected for use were inadequate since the final result was that the extent of the distressed pavement was incorrectly described and this resulted in a contract change.

The actual component inspection method used in 1985 included a visual inspection, topographic survey and soil borings to confirm the strength of the sub-base material. This survey noted that the pavement was beginning to show signs of deterioration. The major areas of concern were longitudinal and transverse cracks, and alligator cracking. The method used in this survey determined that there was 100,000 LF of transverse and longitudinal cracks and 9,000 SF of distressed pavement such as alligator cracking. The cost of this method was $15K.

7.7.3 Alternate component inspection methods and costs

The most obvious alternate component inspection method that the owner could have used to prevent these penalty costs would have been to perform a confirmation survey prior to advertising this contract. This type of survey would involve simply confirming if the conditions are the same or worse than those described on the contract documents. The estimated cost of this method would be $3K. If this method had been selected by the owner the increased extent of the deterioration would have been detected and the contract could have been amended prior to bid. The contractor would have bid on the correctly described work and the owner would have avoided the penalty costs.

On the other hand, it is possible that the increased deterioration occurred after the contract was awarded, during the second winter, prior to the start of work (contract award was in fall 1986). In this case a confirmation survey in 1986, prior to the award, would not have detected this accelerated deterioration.

However, if a confirmation survey had been done in 1986 it is quite likely that some additional quantities of work would have been detected. It is doubtful that the entire amount of pavement distress occurred over the second winter and that none occurred over the first winter. Therefore, it seems reasonable that a confirmation survey would have at least informed the owner about a portion the increased extent of distressed pavement and alerted to the possibility of increased deterioration during the upcoming winter. With this information arrangements could be made to halt the deterioration during the second winter or to plan for the likelihood of increased quantities of work in the upcoming contract and examine the effect that would have on the designed repair.

The owner could also have considered an alternate contractual arrangement that may have enabled a portion of the penalty costs to be avoided. If the owner had included a unit price item for additional asphalt patching work, at least the price for the this work would have been pre-priced. The disadvantage to this approach would be if the estimated quantities failed to materialize then there would have been penalty costs associated with a error scenario E situation.

In summary, it would be reasonable to say that if the owner had employed a confirmation survey in 1986 the increased amount of distressed pavement would have been detected. If this had been done presumably the owner would order a second complete survey as was done in 1987 at a cost of $15K. The amount of distress would have been measured and as a result of this combination of methods the degree of error would be reduced to an estimated 300% and the penalty cost would have been lower as shown on the penalty cost curve. The total cost of this combination of component inspection methods is now $33K; $30K for the first and second surveys and $3K for the confirmation survey.

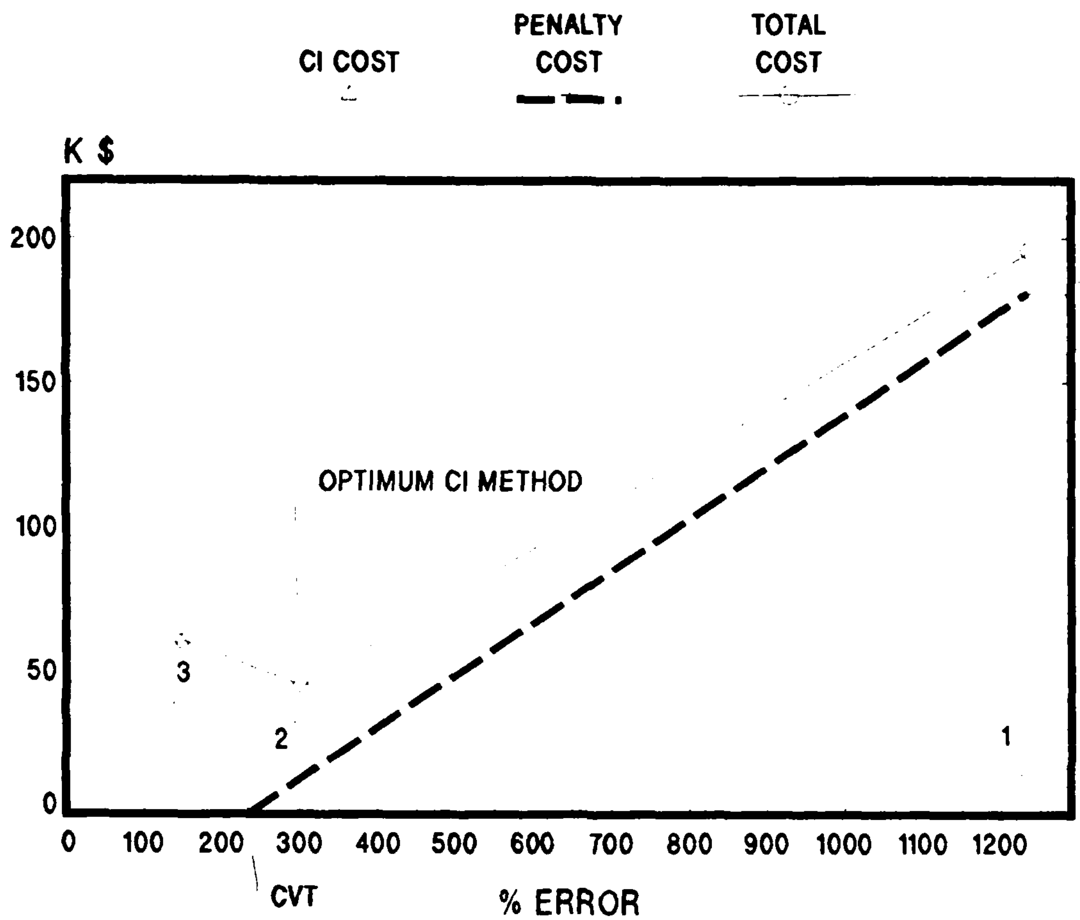
An alternate component inspection method the owner could have used in the original survey was video imaging. The cost would have been $37.8K assuming a unit cost similar to that of previous non-contact methods.

200 LF x 7,000 LF x $0.027 PER SF = $37,800

If this had been done in 1985 a confirmation survey in 1986 could have used the same method and the data collected could have simply been compared. This would have told the owner more accurately the increase in the distress. The owner could have used this information to determine if the contract documents were still adequate. The cost of this second survey would be less since it was a resurvey and the cost could be estimated as 60% of the original survey or $22.8K. The accuracy of using this method could reduce the degree of error again by approximately one half to 150%

These alternate component inspection methods are shown with the plot of the penalty cost curve in Figure 7.7.

COST VS. PERCENT ERROR
NAVAL AIR STATION BRUNSWICK



PENALTY COST = $181K AT 1233% ERROR

COMPONENT INSPECTION METHOD	POINT	CI COST $ K	PERCENT ERROR
ACTUAL METHOD	1	15	1233%
CONFIRM AND RESURVEY	2	33	300%
VIDEO IMAGE	3	60	150%

FIGURE 7.7

7.7.4 Total costs

Review of the total cost curve for this case shows that it is worthwhile for the owner to employ a combination of component inspection methods to address the issue of deterioration being time dependent. This is true even if this involves repeating the same methods at a later date.

If the owner had decided to use a confirmation survey and then had followed up with a resurvey the savings in penalty costs would have been significant. This action would have reduced the total costs from $196K to $45K by investing $18K more in component inspection. If the owner had invested in a video survey the total costs, although higher, would still have been significantly less than $196K.

7.8 Summary

This chapter presented six major facility repair projects in which inadequate component inspection caused a contract change and penalty costs. The penalty costs were calculated using the penalty cost equations developed in Chapter Six. The cost of the component inspection method actually used in the case and the cost of alternate component inspection methods were calculated. The penalty costs and the component inspection costs were combined to produce a total cost curve. Analysis of the total cost curve revealed an optimum component inspection method for each scenario. In all the cases the optimum method was more expensive than the actual method, however this resulted in lower total costs. The existence of this optimum component inspection method showed that it was beneficial for the owner to spend more on component inspection in order to lower the penalty costs associated with inadequate component inspection and reduce the total cost of the project.

Each of these cases was classified by error scenario (A - F) as described in the component defect analysis framework. Although there were six cases, two of these involved errors made in more than one defect so there are nine error scenarios in all. Of the nine error scenarios six were classified as error scenario F and three error scenario E. There were no examples of error scenarios A through D.

From this one might conclude that error scenarios A through D are not representative of the errors that occur in component inspection. However, it is quite likely that if an exhaustive search was conducted that numerous examples of the other scenarios could be found. It may be that error scenarios E and F are more prevalent in airfield pavement and bridge deck repair projects. These two scenarios may also occur more frequently when dealing with unit price contracts, since the very nature of a unit price contract lends itself to situations where there is some uncertainty associated with the quantity of work. Although the cases presented here have not proven the existence of error scenarios A - D, it would be erroneous, because of the small number of cases presented, to conclude they have been disproved.

The component defect analysis framework did a fairly good job of predicting the types of penalty costs that would occur in each of the nine error scenarios. In most cases the penalty costs terms that were indicated in the equations did occur. The exceptions were the impact cost (IM) and the negotiated penalty cost (NC) terms. These two terms did not occur in many of the cases simply because of the circumstances surrounding that individual project.

The direct penalty cost term also did not occur in the error scenarios classified as E, although it was shown in the equations. This is attributed to the fact that any direct penalty costs on the error scenario E work items were overshadowed by the magnitude of the direct penalty costs for the error scenario F work items in the same project. If this overshadowing had not happened it is quite likely that the direct penalty cost term would have occurred and the penalty costs for this error scenario would have been more significant.

The minimal nature of the penalty costs in the error scenario E cases caused by the lack of direct penalty costs might lead one to conclude that to reduce penalty costs the owner should purposefully overestimate the quantity of work. Although this may be true, the evidence presented here does not entirely support such a conclusion. Unfortunately there were no cases where the error scenario E was independent of any other errors. The penalty costs of error scenario E were always effected by the association with an error scenario F work item within the same contract. Therefore, the penalty costs associated with the error scenario E work items were in all likelihood artificially lower than they should have been.

In conclusion, it would be fair to say that in these cases if the owners had known the outcome of their decisions with regard to component inspection they would have made different decisions. They would have selected another component inspection method, restructured the contract for the work or inserted a creative contract provision. The question after reviewing these cases seems to be how can situations like these be prevented in the future? How can facility owners anticipate these penalty costs and take measures prior to the award of the contract to avoid these added costs and delays? What component inspection decisions should owners be making to minimize changes due to inadequate component inspection?

CHAPTER SEVEN ENDNOTES:

[1] Discussions with Don Perkins on 2 May 1988 and minutes from a 21 January 1986 meeting with representatives of the Vermont Agency of Transportation.

[2] Mr. J. Miller, "Law in the Construction Industry", A class at MIT, Spring semester 1988.

[3] Minutes of a 30 January 1986 meeting with representatives of the Maine Department of Transportation.

[4] Conversations with Jim Chandler, Bridge Design Engineer, Maine DOT on 12 February 1988.

[5] Conversation with Don Kennedy, Materials and Research Division, Maine DOT on 6 May 1988.

CHAPTER EIGHT

CONCLUSION

This chapter will review the evidence presented in this thesis and evaluate the thesis objectives.

8.1 Overview of thesis

The purpose of this thesis is to examine the effect of inadequate component inspection on major facility repair projects. The methodology for doing this was to determine the relationship between the cost of component inspection methods and the penalty costs associated with inadequate component inspection. This relationship was analyzed to see if it supported the selection of more costly component inspection methods, especially methods that employ non-contact automated sensing technologies. With this insight, this thesis explored how this relationship between component inspection cost and penalty cost might be used to help owners make a priori decisions regarding the selection of component inspection methods for facility repair projects.

Although the scope of this investigation has been limited to airfield pavements and concrete bridge decks, the concepts regarding component inspection have been general in nature and applicable to a wide variety of facility types.

8.2 Relationship between component inspection cost and penalty cost

Through the use of the concept presented in Chapter Two, showing the total cost curve as the sum of the component inspection cost and the penalty cost, the thesis was able to examine how the selection of more costly component inspection methods effected the total cost curve. In each of the six cases the application of more costly component inspection methods produced a total cost curve in which an optimum method was evident.

Figure 8.1 shows a summary of the data obtained from the six cases. In each case, for both the actual and the optimum component inspection methods, the component inspection cost and the percent error are shown. The difference in the total cost between the actual and the optimum method is also shown. This difference is the savings that the owner could have expected if the more costly optimum component inspection method had been used. This savings is further expressed in Figure 8.1 as: 1) a percent of the additional component inspection cost required to employ the optimum method as opposed to the actual method, and 2) as a percent of the project cost when completed (including changes). The first percentage shows the owner's rate of return on the investment in more costly component inspection methods. In only one case, number 5, was the amount of the savings in total cost less than the investment in component inspection. None the less, in all cases there was a savings to the owner by employing the optimum method.

The second percentage shows the percent savings on the entire project that the owner could expect by investing in the optimum component inspection method. This percentage ranges from 1.7% to 7.6% of the

SAVINGS BASED ON OPTIMUM CI METHOD

FIGURE 8.1

CASE	CI METHOD	% ERROR	CI COST $K	SAVINGS IN TOTAL COST $ K	SAVINGS IN TOTAL COST % OF ADDED CI COST*	SAVINGS IN TOTAL COST % OF FINAL PROJECT COST
1 VERMONT MIDDLESEX	ACTUAL	154	3.0	17.2	506%	4.6%
	OPTIMUM	50	6.4			
2 VMB MAINE	ACTUAL	184	3.0	34.1	243%	2.6%
	OPTIMUM	50	17.0			
3 VERMONT HARTLAND	ACTUAL	172	3.0			
		WITHOUT CP		18.0	500%	4.2%
		WITH CP		7.2	200%	1.7%
	OPTIMUM	50	6.6			
4 FAIRCHILD AFB	ACTUAL	56	11.2	49.3	133%	3.1%
	OPTIMUM	20	48.0			
5 MINOT AFB	ACTUAL	335	3.1	56.1	57%	2.3%
	OPTIMUM	100	102.0			
6 BRUNSWICK MAINE	ACTUAL	1233	15.0	150.9	838%	7.6%
	OPTIMUM	300	33.0			

* Calculated as follows:
SAVING IN TOTAL COST / [(CI COST OPTIMUM - CI COST ACTUAL)]

project cost. This evidence shows that in this application it is beneficial to select more costly component inspection methods.

This total cost relationship and the data presented here illustrate the importance of owner's decisions with regard to component inspection methods and the impact these decisions have on major facility repair projects. In each of these cases the owner could have saved several percent of the project cost by selecting more costly methods.

The total cost relationship used in this analysis was dependent to some degree on the percent error and cost that was estimated for each of the alternate component inspection methods that were selected for analysis. The percent error estimated for each of the alternate component inspection methods used in the analysis were reasonable, however, they are not known with any degree of certainty. By using these methods in the field and comparing the actual and estimated quantities for numerous projects, the day to day accuracies produced by these methods could be determined with some level of certainty. This is an area where additional research needs to be done.

The costs used for the component inspection methods evaluated in this analysis are reasonable estimates. The actual cost of the in-house methods may be greater than estimated because they are subsidized to some degree and the estimate does not reflect the true cost of the effort. On the other hand, the cost of the newer non-contact automated methods will decrease in the foreseeable future because of the dependence these methods have on sensors and computers that are becoming less expensive each year in the general market place.

The percent error estimates used in the analysis also indicate what the performance capabilities of these methods must be in order to make a difference. Because of the nature of the total cost curve in most cases it is not necessary to reduce the degree of error to the contract variance threshold in order to have any benefit. Simply lowering the degree of error from the stratospheric levels will lower the total cost. It is interesting to note accuracies in the range of 25% to 50% would have improved the total costs of the cases that were analyzed.

In summary, this evidence indicates that as an owner it would be beneficial to select component inspection methods that are more costly and yield improved levels of accuracy. The added cost of these methods will be paid for by the reduced penalty costs that result from their use. It is more cost effective from the perspective of total cost to fund component inspection than to pay the penalty costs.

As an added point, the total cost does not consider the penalty costs that were not quantified, such as user and political costs. If these are taken into consideration it would seem even more appropriate to select more costly component inspection methods that would increase the accuracy of the estimated amount of work and allow the owner to avoid project delays and loss of credibility.

8.3 Existing versus new component inspection methods

Evaluating the effect that more costly component inspection methods have on facility repair projects also indicates something about the use of existing methods versus the use of the newer non-contact automated methods. In five of the six cases the optimum component inspection method included non-contact automated sensing technologies. This shows that although these methods are typically more expensive than traditional methods, they would be useful in this application. By selecting these methods owners can reduce the total cost curve even though this will require more funds for component inspection at the outset of the project. The benefit of these methods will become even greater in the future as the cost of these methods decrease.

8.4 Owner policies for selecting component inspection methods

This section will analyze the general owner policies that should be instituted based on the evidence presented in this thesis. These policies are especially important now that facility repair work is taking up more of these agencies resources and more facility repair projects are being undertaken.

8.4.1 The selection of a component inspection method

The selection of a component inspection method is a decision the owner must make during the design of a major facility repair project. In making this decision owners should carefully consider all of the component inspection methods that are available.

The evidence presented indicates that in a majority of the cases the decision to select the component inspection method used was done without a great deal of analysis. Many times the component inspection method used was selected because that was the status quo. This was the case in Vermont and Maine. The selection of a component inspection method in the

Minot and Fairchild cases was also done without any formal analysis. However, in these cases there was no precedent and the lack of experience in performing the component inspection for this size repair effort may have adversely effected the decision. In all cases failure to analyze and consider the alternative component inspection methods available was a factor.

Cost cutting seemed to be a motivational theme that existed to some degree in all the cases, especially through the selection of in-house methods for component inspection. This is to be expected since these organizations are under extreme pressure to cut costs. However, as the evidence in Figure 8.1 showed, selecting the least costly component inspection method resulted in greater total costs. Selecting the more costly optimum component inspection method lowered the total cost. The decision to select one component inspection method over another should be based on some objective analysis. An objective and logical analysis is also necessary to justify the added cost of the more accurate component inspection methods in the early stages of the project.

8.4.2 A component inspection strategy

This discussion regarding the selection of component inspection methods prompts the another question that needs to be considered. What about all the other projects in which the standard component inspection methods were used, the actual quantities were within the contract variance threshold and there were no penalty costs? Although this thesis did not look for these cases, it would be fair to say that plenty of these cases exist. So if they do exist, are they successful because the owner selected the best component inspection method based on a logical analysis of the project characteristics, or are they successful because the best component inspection method for that project just happened to be the one that is the standard method?

This thesis has shown in the six cases presented that if alternate component inspection methods had been selected the owner would have benefited. However, this determination was made after the fact. If some logical analysis had been used to select the component inspection method would a better method have been selected during the design of the repair project thus preventing the penalty costs.

This question points to the need for owners to establish a component inspection strategy during the design of facility repair project. This strategy would be specific to the project and describe the component inspection method(s) that should be employed. The development of this strategy would go hand in hand with the design of the repair project and would be dependent on the defects the repair project was aimed at. This strategy would be based on the logical analysis of the alternate component inspection methods that are available.

The selection of a component inspection method should include the development of a component inspection strategy that considers the penalty costs of errors that could occur in the component inspection process. This is where the use of the component defect analysis framework as an analysis tool should become a part of the decision process to select a component inspection method. A component inspection strategy for each project should be developed and analyzed to see if it will provide the lowest total cost to the project based on the estimated costs of the component inspection method and the penalty costs that are likely to occur.

As shown in Chapter Seven, the component defect analysis framework does a fairly good job of predicting the various types of penalty costs that occurred in most of the cases. The penalty cost equations for each scenario were useful in determining the magnitude of the penalty costs. Therefore, this framework would be useful as a tool to help owners design a component inspection strategy and select component inspection methods for their facility repair projects.

8.4.3 The component defect analysis framework as a tool

The owner could use the component defect analysis framework as a tool to design a component inspection strategy and choose between several component inspection methods. This section will present an example of where this would be useful by looking at the Vermont - Middlesex bridge case.

This example will start with the things that are known by the owner. First the defects that the project is trying to fix are known from previous preliminary surveys, but the extent of the defects are still unknown. In this case the defects are delaminations and punky concrete. Both of these are repaired by the same method of repair, removal and replacement of the concrete. This is the work item which an estimated quantity must be determined.

Next the penalty costs are determined by reviewing the component defect analysis diagram. For this defect the characteristic of severity is not relevant, so the error scenarios that could occur are A, B, E and

F. Error scenario A is not possible since the owner already knows that some type of defect is present in the component and it is believed to be the above. Error scenario B is possible since all the defects that are believed to be delaminations could be debonding. This is not very likely, but possible. Error scenarios E and F could also occur. The penalty cost equations for each of these scenarios can be used to calculate the penalty costs for each error scenario as a function of the degree of error. In regard to error scenario F, a "what if" approach could be used to look at the effect of granting time extensions, whether they are avoidable or unavoidable time extensions and the effect of adverse weather. From this information the penalty cost curves can be determined.

The owner then selects several component inspection methods that would be appropriate for the defects in the bridge deck. The expected degree of accuracy of these alternate component inspection methods and their costs would then be estimated.

This data could be combined with the penalty cost curves for each error scenario to plot the total cost curve for each scenario. Analysis of these total cost curves would indicate the optimum component inspection method that would produce the lowest total costs for each error scenario that could occur.

The design of a component inspection strategy, performed before the component inspection method is selected, could reduce the total cost of a project. It could also be used to justify the expense associated with the more accurate component inspection methods or the expense using an equipment intensive component inspection methods, such as infrared or ground penetrating radar, that may require an outside consultant to perform.

This design strategy does not account for the penalty costs that were not quantified in the penalty cost equations; user and political. If the selection of one method over another was close based on the total cost curve then these considerations could effect the decision.

Additionally, in proposing alternate component inspection methods to include in the strategy it is important that they be acceptable. For example, if closing the bridge to do coring is unacceptable to the user then it should not be considered as an alternate component inspection method even though it may produce the lowest total cost.

Owners should require their facilities organizations to adhere to policies that consider alternate component inspection methods in the design of major facility repair contracts. The requirement to develop a component inspection strategy for each major facility repair project is one of those policies.

8.4.4 Contractual arrangements

The Brunswick and the Vermont - Hartland cases point to the importance of selecting the contractual arrangement for the work and the bearing this can have on penalty costs. It appears from the evidence that it may be possible for owners to achieve some of the same goals in regards to reducing penalty costs through contractual arrangements as they can through the use of more costly component inspection methods. Additionally, these contractual arrangements sometimes take no more than the stroke of a pen and can be accomplished at a fraction of the cost of alternate component inspection methods with the same positive effect on the total cost curve. As a part of the development of a component inspection strategy the contractual arrangement for the work should also be considered.

One of the aspects of the contractual arrangement is the selection of a contract variance threshold. Although in the cases presented the contract variance threshold was standard for a contract issued by the same owner, these owners should evaluate their contract variance threshold policies in the light of the evidence presented here. They should consider selecting contract variance thresholds individually for each project based on the expected accuracy of the component inspection method that is selected for use. This would be another way to minimize penalty costs through the establishment of a contractual arrangement.

Owners should include arrangements to pre-price quantities work outside the contract variance threshold. The state of Vermont did this with success in the Hartland bridge case. In doing this they were able to recover a portion of the penalty costs that they would have paid if the arrangement had not been included.

The execution of lump-sum contracts for facility repair contracts should be avoided when possible. The objective of repair projects is to restore the effects of deterioration which in most cases is time dependent. With the funding restrictions that public owners operate under it quite normal for delays in award and early award of contracts to result. Lump-sum contracts are not as adaptable as unit price contracts when this occurs. Lump-sum contracts also tend to amplify the effects of changes in the quantity of work. There is no established contract variance threshold to dampen the effects of inaccuracies in component inspection methods or the effects of time dependent deterioration. The case at Brunswick was an example of this.

Although these contractual arrangements are not component inspection methods, they must be included as part of the component inspection strategy for a facility repair project and instituted as part of the design process. These contractual methods can be just as effective in reducing the total cost as the selection of more accurate component inspection methods at a fraction of the cost.

APPENDIX A

COMPONENT DEFECTS OF AIRFIELD PAVEMENTS

This appendix provides a brief description of the component defects that occur in rigid and flexible airfield pavements as referenced in Chapter Three.

RIGID AIRFIELD PAVEMENT DEFECTS:

The airfield pavement condition survey procedures used by the Navy identify 15 defects that can occur in rigid airfield pavements:

A **blow up** occurs at a transverse crack or joint that is not wide enough to permit expansion of the concrete slabs. The insufficient width is usually caused by infiltration of incompressible materials into the joint space. When expansion cannot relieve enough pressure, a localized upward movement if the slab edges (buckling) or shattering will occur in the vicinity of the joint. This type of distress is almost always repaired immediately because of severe damage potential to aircraft.

A **corner break** is a crack that intersects the joints at a distance less than or equal to one-half of the slab length on both sides, measured from the corner of the slab. A corner break differs from a corner spall in that the crack extends vertically through the entire slab thickness, while a corner spall intersects the joint at an angle. Load repetition combined with loss of support usually cause corner breaks.

Longitudinal, transverse and diagonal cracks divide the slab into two or three pieces and are usually caused by a combination of load repetition and shrinkage stresses.

"D" cracking is caused by the concrete's inability to withstand environmental factors such as freeze-thaw cycles. It usually appears as a pattern of cracks running parallel to a joint or linear crack. A dark coloring can usually be seen around the fine durability cracks. This type of cracking may eventually lead to disintegration of the concrete within 1 to 2 feet of the joint or crack.

Joint seal damage is any condition which enables soil or rocks to accumulate is the joints or allows significant infiltration of water. Accumulation of incompressible materials prevents the slabs from expanding and may result in buckling, shattering, or spalling. A pliable joint filler bonded to the edges of the slabs protects the joints from accumulation of materials and also prevents water from seeping down and softening the foundation supporting the slab.

A **patch** is an area where the original pavement has been removed and replaced by a filler material.

A **utility cut** is a patch that has replaced the original pavement because of placement of underground utilities.

Popouts are small pieces of pavement that break loose from the surface due to freeze-thaw action in combination with expansive aggregates.

Pumping is the ejection of material by water through joints or cracks caused by deflection of the slab under passing loads. As the water is ejected, it carries particles of gravel, sand, clay, or silt resulting in a progressive loss of pavement support. Surface staining and base or subgrade material on the pavement close to joints or cracks are evidence of pumping. Pumping near joints indicates poor joint sealer and loss of support, which will lead to cracking under repeated loads.

Scaling, mapcracking or crazing refers to a network of shallow, fine, or hairline cracks that extend only through the upper surface of the concrete. These defects may be caused by deicing salts, improper construction, freeze-thaw cycles, and poor aggregate. Another recognized source of distress is the reaction between the alkalies in some cements and certain minerals in some aggregates. Products formed by the reaction between the alkalies and aggregate result in expansions that cause breakdown in the concrete. This generally occurs throughout the slab and not just at joints where "D" cracking normally occurs.

Settlement or faulting is a difference of elevation at a joint or crack caused by upheaval or consolidation.

Shattered slab are intersecting cracks that break the slab into four or more pieces due to overloading and/or inadequate support.

Shrinkage cracks are hairline cracks that are usually only a few feet long and do not extend across the entire slab. They are formed during the setting and curing of the concrete and usually do not extend through the depth of the slab.

Spalling joints are the breakdown of the slab edges within 2 feet of the side of the joint. A joint spall usually does not extend vertically through the slab but intersects the joint at an angle. Spalling results from excessive stresses at the joint or crack caused by infiltration of incompressible materials or traffic load.

Spalling corner is the raveling or breakdown of the slab within approximately 2 feet of the corner. A corner spall differs from a corner break in that the spall usually angles downward to intersect the joint, while a break extends vertically through the slab.

FLEXIBLE AIRFIELD PAVEMENT DEFECTS:

The condition survey procedures used by the Navy identify 16 defects that can occur in flexible pavements:

Alligator cracking is a series of interconnecting cracks caused by fatigue failure of the asphaltic concrete (AC) surface under repeated traffic loading. The cracking initiates at the bottom of the AC surface where tensile stress and strain are highest under a wheel load. The cracks propagate to the surface initially as a series of parallel cracks. After repeated traffic loading, the cracks connect, forming many sharp-angled pieces. Alligator cracking occurs in areas that are subjected to repeated traffic loadings, such as wheel paths.

Bleeding is a film of bituminous material on the pavement surface that creates a shiny, glass like, reflecting surface that usually becomes quite sticky. Bleeding is caused by excessive amounts of asphalt cement in the mix.

Block crackings are interconnected cracks that divide the pavement into approximately rectangular pieces. Block cracking is caused mainly by shrinkage of the asphaltic concrete and daily temperature cycling. The occurrence of block cracking usually indicates that the asphalt has hardened significantly.

Corrugation is a series of closely spaced ridges and valleys occurring at fairly regular intervals along the pavement. The ridges are perpendicular to the traffic direction. Traffic action combined with an unstable pavement surface or base usually causes this type of distress.

Depressions are localized pavement surface areas having elevations slightly lower than those of the surrounding pavement. Depressions can be caused by settlement of the foundation soil or can be built during construction. Depressions when filled with water can cause hydroplaning of aircraft.

Jet blast erosion causes darkened areas on the pavement surface where bituminous binder has been burned.

Joint reflection (PCC) is a distress that occurs where flexible pavements are placed over a PCC slab. Joint reflection cracking is caused mainly by movement of the PCC slab beneath the asphaltic concrete surface because of thermal and moisture changes.

Longitudinal and transverse cracking - Longitudinal cracks are parallel to the center line or the direction in which the pavement was laid down. They are caused by 1) a poorly constructed paving lane joint, 2) shrinkage of the AC surface due to low temperatures or hardening of the asphalt, or 3) a reflective crack caused by cracks beneath the surface course, including cracks in PCC slabs. Transverse cracks extend across the pavement at approximately right angles to the center line or direction of laydown.

Oil spillage is the deterioration or softening of the pavement surface caused by the spilling of oil, fuel, or other solvents.

A **patch** is considered a defect, no matter how well it is performing.

Polished aggregate is caused by repeated traffic applications. Polished aggregate occurs when a portion of aggregate extends above the asphalt and there are no rough or angular aggregate particles to provide good skid resistance.

Raveling and weathering are the wearing away of the pavement surface caused by the dislodging of aggregate particles and loss of asphalt or tar binder. They may indicate that the asphalt binder has hardened significantly.

Rutting is a surface depression in the wheel path. In many instances ruts are noticeable only after a rainfall. Rutting stems from a permanent deformation in any of the pavement layers or subgrade, usually caused by consolidation or lateral movement of the materials due to traffic loads.

Shoving of a AC pavement occurs when PCC pavements increase in length at the ends where they adjoin flexible pavements. This increase in length shoves the asphalt pavement and causes swelling and cracking. The expansion of the PCC slab is caused by a gradual opening up of the joints as they are filled with incompressible materials.

Slippage cracks are crescent-shaped cracks having two ends pointed away from the direction of traffic. They are produced when braking or turning wheels cause the pavement surface to slide and deform. This usually occurs when there is a low strength surface mix or poor bond between the surface and next layer of pavement structure.

Swell is characterized by an upward bulge in the pavement's surface. A swell may occur sharply over a small area or as a longer, gradual wave. Either type of swell can be accompanied by surface cracking. A swell is usually caused by frost action in the subgrade or by swelling soil, but a small swell can also occur on the surface of an asphalt overlay (over PCC) as a result of a blowup in the PCC slab.

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