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16. Abstract

The main objective of this report is to present the development of a new parameter for project-level evaluation of continuously reinforced concrete pavements (CRCP). This was accomplished through the simulation of many distress manifestations commonly found in CRC pavements by means of a discrete-element computer program. The program predicts the immediate response to any selected wheel load, in terms of maximum deflection, in the presence of every distress manifestation analyzed. This maximum deflection was the CRC pavement response used to assess the severity of a given distress manifestation, thus the parameter proposed for project-level evaluation of CRC pavements is designated as the deflection distress index (DDI).

Computer program DDI1 incorporates the major findings from this study; essentially, it reads and processes condition survey data, and estimates the DDI of every element input. Likewise, it can computerthe required condition survey sample size for the combination of allowable error and confidence level specified by the user. Program DDI1 can also predict the change in the mean and standard deviation of DDI resulting from each of five different rehabilitation strategies. An input guide for DDI1 is included in this report along with several application examples.

A project-level condition survey manual was prepared to present definitions and descriptions of the various distress manifestations considered in the scheme for project-level evaluation of CRC pavements.

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DEVELOPMENT OF A DEFLECTION DISTRESS INDEX FOR PROJECT-LEVEL EVALUATION OF CRC PAVEMENTS

by

Victor Torres-Verdin
B. Frank McCullough

Research Report 388-1

Condition Surveys and Performance Monitoring
of Existing and Overlaid Rigid Pavements
Research Project 3-8-84-388

conducted for

Texas State Department of Highways
and Public Transportation

in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by the

Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

This is the first report of work done under Research Project 3-8-84-388 at the Center for Transportation Research of The University of Texas at Austin. Essentially, this report presents the derivation of an innovative scheme for project-level evaluation of CRC pavements from condition survey data, which represents a major improvement over current methods for analysis of such field information.

The authors would like to express their gratitude to all those who helped in the preparation of this report and in particular to Lyn Gabbert, who was in charge of typing the drafts of this manuscript, Jim Long for his assistance in collecting condition survey data by means of the procedure proposed herein, and Art Frakes for coordinating the various activities required for the completion of this report. Special acknowledgement is made to Dr. W. Ronald Hudson, Professor of Civil Engineering, for his comments throughout the development of this study.

Victor Torres-Verdin
B. Frank McCullough

LIST OF REPORTS

Report No. 388-1, "Development of a Deflection Distress Index for Project-Level Evaluation of CRC Pavements," by Victor Torres-Verdín and B. Frank McCullough, presents the derivation of a new approach for project-level evaluation of CRC pavements from condition survey data. The main features of computer program DDI1, which incorporates the principal findings from the study, are discussed and an input guide for that program is provided along with a project-level condition survey manual.

ABSTRACT

The main objective of this report is to present the development of a new parameter for project-level evaluation of continuously reinforced concrete pavements (CRCP). This was accomplished through the simulation of many distress manifestations commonly found in CRC pavements by means of a discrete-element computer program. The program predicts the immediate response to any selected wheel load, in terms of maximum deflection, in the presence of every distress manifestation analyzed. This maximum deflection was the CRC pavement response used to assess the severity of a given distress manifestation, thus the parameter proposed for project-level evaluation of CRC pavements is designated as the deflection distress index (DDI).

In this study, an element was defined as that portion of a full-width CRCP lane bounded by two successive transverse cracks. Hence, there is always a finite number of these elements within a CRCP section, and for each of them a DDI can be estimated if their condition survey information is available. This element-by-element approach permits the estimation of both the mean and the standard deviation of DDI for a given CRCP section. Average crack spacing, section length, confidence level, and standard deviation of the DDI are the terms included in the statistical expressions derived for estimating the minimum number of elements that should be included in the condition survey of a CRCP section.

Computer program DDI1 incorporates the major findings from this study; essentially, it reads and processes condition survey data, and estimates the DDI of every element input. Likewise, it can compute the required condition survey sample size for the combination of allowable error and confidence level specified by the user. Program DDI1 can also predict the change in the mean and standard deviation of DDI resulting from each of five different rehabilitation strategies. An input guide for DDI1 is included in this report along with several application examples.

A project-level condition survey manual was prepared to present

definitions and descriptions of the various distress manifestations considered in the scheme for project-level evaluation of CRC pavements.

KEYWORDS: Continuously reinforced concrete pavement (CRCP), condition survey, distress, distress manifestation, deflection distress index (DDI), sample size.

SUMMARY

The Center for Transportation Research (CTR) of The University of Texas at Austin recently started to use a distress index to prioritize and schedule the maintenance and rehabilitation needs in the rigid-pavement network of the State of Texas. Although this approach is adequate at the network level, it cannot be satisfactorily extended to the project level, where analysis of the within-project variation of distress is required when trying to define the best rehabilitation strategy to be performed on a given pavement section. Several experimental CRCP sections throughout the State of Texas have been periodically monitored by the CTR for the last 10 years, and very detailed distress information has been gathered. However, condition survey data have not been properly processed to study the variation of distress within those CRCP sections. Thus, this deficiency calls for the development of a rational scheme for project-level evaluation of CRC pavements from condition survey information.

This report discusses the derivation of a parameter, designated as the deflection distress index (DDI), for project-level evaluation of CRC pavements. Computer program DDI1 facilitates the analysis of the variation of distress within a CRCP section and may also be used to estimate the change in the mean DDI for a given CRCP section due to performing various rehabilitation strategies.

A project-level condition survey manual is provided for the collection of data in the format required by DDI1 and for the description of the distress manifestations included in the scheme for estimating the deflection distress index of CRC pavements.

IMPLEMENTATION STATEMENT

A scheme for project-level evaluation of CRC pavements has been derived for the Texas State Department of Highways and Public Transportation (SDHPT), which permits analysis of the within-project variation of distress and can be used to predict the change in the distress condition of a CRCP section due to carrying out each of five different rehabilitation strategies. Computer program DDI1 was developed using FORTRAN 77 standards, which will facilitate its implementation on the Texas SDHPT computer system.

It is suggested that the deflection distress index of the experimental CRCP sections in the State of Texas be estimated by means of computer program DDI1 every time their condition survey data are gathered by CTR personnel. This long-term monitoring will help to study the relationship between distress and fatigue life of a CRC pavement. Likewise, these data could be extremely useful in research in the area of relating distress to performance of CRC pavements if data to estimate the present serviceability index can be collected for those experimental sections along with the condition survey data.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

The Texas State Department of Highways and Public Transportation (SDHPT) has about 7,000 lane-miles of continuously reinforced concrete pavement (CRCP) currently in service, and present design plans envisage the construction of many road miles of CRCP overlays and of new pavement (Ref 18). As a result, it is necessary to gather periodically condition and performance data of the CRCP sections in Texas so that they can be evaluated. The data usually recorded in a pavement evaluation include measurements of structural capacity, riding quality, skid resistance and distress (Ref 8). Deflection measurements are generally used to evaluate the structural capacity of a pavement. The riding quality of a pavement is largely a function of its roughness, which can be measured by means of a variety of methods or devices currently used in the United States. The evaluation of pavements for safety usually considers only slipperiness (in terms of skid resistance, Ref 8). Condition surveys are conducted to measure pavement distress, which is defined as the limiting response or damage in the pavement. These four different pavement evaluation measures interact and there is, of course, overlap among them. However, they should not be used interchangeably (Ref 8).

It has been observed in Texas that even when rigid-pavement sections are approaching the end of their lives, from a structural viewpoint, the riding quality sometimes remains at an acceptable level. Thus, the use of distress measures may be a more realistic way to evaluate the terminal condition of a rigid pavement (Ref 10).

The Center for Transportation Research (CTR) of The University of Texas at Austin has established the most complete data bank on CRCP distress information in the world. This impressive collection of field information is the result of periodically conducting condition surveys of CRCP sections throughout the state of Texas. In general, condition surveys are directed toward assessing the maintenance measures needed to prevent accelerated, future distress, or the rehabilitation strategies needed to improve the pavement.

A pavement management system (PMS) provides a framework for integrating the activities associated with the planning, design, construction, maintenance, evaluation, and research of pavements into a comprehensive and coordinated set of activities (Refs 8 and 10). A PMS operates at two levels, the network and the project levels. Activities at the network level are mainly the responsibility of administrators and are primarily connected with the establishment of decisions covering large groups of projects or an entire highway network. On the other hand, activities at the project level are concerned with more specific technical management decisions for individual projects (Ref 19).

Condition survey data have been used at the network level to develop a distress index for rigid pavements that is the basis of a scheme for prioritizing and scheduling the rehabilitation needs of a pavement network (Ref 10). Although this distress index is adequate at the network level, its use cannot be satisfactorily extended to the project level. At this level, analysis of the within-project variation of distress is required, and the use of a single number to represent the distress condition of a pavement section becomes meaningless as the variation of distress within that section increases. Even though CTR personnel have collected extremely detailed condition survey data on several CRCP experimental sections scattered in the state of Texas, an "aggregate" approach has been invariably followed to process this information. In this approach, distress manifestations have been lumped into per mile or 0.2-mile summaries, which reduces the value of such meticulous monitoring of distress in those CRCP sections. This serious incongruence calls for the development and implementation of a rational procedure to analyze project-level CRCP condition survey data. This procedure should account for and should provide information about the within-project variation of distress so that the best rehabilitation strategies to be performed on a given CRCP section can be selected. The development of such a procedure is presented herein.

OBJECTIVES

The primary objectives of this study are the following:

(1) A scheme for project-level evaluation of CRC pavements from condition survey data should be developed. For this purpose, an extensive factorial arrangement should be set up to predict, by means of a discrete-element computer program, the maximum deflection due to the application of a given load for the most common CRCP distress manifestations found in Texas. Such parameters as crack spacing and crack load-transfer should, also, be considered in the factorial arrangement. Deflection data from this computer simulation should be subsequently used in the derivation of an index to express the severity of each distress manifestation analyzed.

(a) Both the terminal and the ideal conditions of a CRC pavement should be clearly designated in this scheme.

(b) The scheme should provide detailed information of the within-project variation of distress of a CRC pavement.

(2) A procedure should be derived to estimate the required sample size for project-level CRCP condition surveys. This procedure should account for within-project variation of distress and CRCP section length.

(3) The scheme and the procedure for estimating the required condition survey sample size should be incorporated in a computer program. This program should be written in a language that insures compatibility with most computer systems, and should be able to process field information directly from the condition survey data forms to be developed.

SCOPE

The results of the study described herein are presented in the various chapters described below.

Chapter 2 presents a detailed description of the development of an innovative scheme for project-level evaluation of CRC pavements, based on the prediction of the immediate response to a given load by means of a discrete-element computer program, of the most common types of CRCP distress manifestations found in Texas.

The derivation of a procedure for estimating the required sample size for project-level CRCP condition surveys is discussed in Chapter 3. The recommended expressions for estimating sample size consider the variation of distress within a CRCP section, as well as section length, and can be used for different combinations of allowable error and confidence level.

Chapter 4 is devoted to describing the main features of computer program DDI1, which receives project-level CRCP condition survey data, provides information about the within-project variation of distress, and predicts the change in the distress condition of a CRCP section due to carrying out each of five different rehabilitation strategies on that section. This program also estimates the condition survey sample size by using the findings explained in Chapter 3.

Several applications of computer program DDI1 are discussed in Chapter 5, and condition survey data from two CRCP sections are used in some of the examples.

Chapter 6 presents a summary of the main accomplishments of this research, provides conclusions stemming from this study, and makes recommendations for the implementation and extension of the scheme for project-level evaluation of CRC pavements from condition survey data.

An input guide for computer program DDI1 is presented in Appendix D, and a manual for conducting a CRCP condition survey at the project level is provided in Appendix C.

The procedures presented and developed in this study should be used only for distress evaluation of CRC pavements at the project level. The distress manifestations considered in this research are those typically found in Texas. However, the findings described herein can be extended to CRC pavements in other states if the distress manifestations in those pavements are essentially the same as those included in this study.

CHAPTER 2. DEVELOPMENT OF THE SCHEME FOR ESTIMATING A DEFLECTION DISTRESS INDEX FROM CONDITION SURVEY DATA

This chapter presents a detailed description of the development of the scheme for estimating a deflection distress index (hereafter referred to as DDI) at the project level from CRCP condition survey data. The approach followed in this study included the simulation of a great variety of CRCP distress manifestations by means of a discrete-element computer program in order to predict their immediate responses to a selected load. The output data from the computer program were used in an expression derived at the AASHO Road Test (Ref 11) to compute the deflection distress index corresponding to each of the distress manifestations considered in the analysis, once the ideal and terminal conditions of a CRC pavement were defined.

Severe and minor punchouts and pumping are among the distress manifestations currently reported in CRCP condition surveys; however, no significant efforts have been directed toward studying their behavior. It has been recognized that the occurrence of such defects results in reduced fatigue life of a CRC pavement, but this has not been sufficiently supported by either empirical studies or use of discrete element methods.

DESCRIPTION OF THE ANALYSIS WITH COMPUTER PROGRAM SLAB49

The crack pattern, involving the crack spacing and the crack width, is one of the most important physical aspects of the design of CRC pavements. Longitudinal steel is placed in the slab to insure a narrow crack width, since load transfer across a given crack depends to a large extent on coarse aggregate interlock. Additionally, CRC pavements exhibiting narrow crack spacings and open cracks are considered to have a serious distress condition, which is evidenced by the occurrence of high deflections. Maximum deflection at cracks is a parameter that can be used to evaluate the distress condition of a CRC pavement since it increases with crack width and decreases with crack spacing. Likewise, deflection at a given crack increases if there is pumping or a severe punchout in either or both of the slabs adjacent to this crack.

In order to predict the immediate response of a CRC pavement to a given load, the discrete element computer program SLAB49 was used (Refs 1, 2, and 3). The discrete-element model (Fig 2.1) consists of

(1) infinitely stiff and weightless bar elements to connect the joints;
(2) elastic joints where bending occurs, made of an elastic, homogeneous,and orthotropic material which can be described by four independent elastic constants;
(3) torsion bars, which represent the torsional stiffness of the plate; and
(4) elastic support springs which provide foundation support.

SLAB49 allows for nonlinear input, discontinuities in the slab and the subgrade, and varying support in the subgrade. It has previously been used by Torres-Verdin and McCullough (Ref 4) to simulate the Dynaflect loading for a particular CRCP layout and analyze the effect of various factors on deflections.

INPUT DATA CONSIDERED

CRC pavements with both flexible and rigid shoulders were modeled with computer program SLAB49. An example of a plan layout for a CRCP with a flexible shoulder is shown in Fig 2.2, while Fig 2.3 presents one of the various layouts considered for a CRCP with a rigid shoulder.

In this study an element was defined as that portion of a full-width CRC pavement lane bounded by two successive transverse cracks. The crack spacings of two adjacent elements were varied and two 9000-pound wheel loads were applied at the transverse crack common to these elements, as shown in Figs 2.2 and 2.3. One of these loads was placed at one foot from the pavement edge for the flexible-shoulder layout so as to consider the most critical loading condition. This occurs when a truck travels close to the pavement edge. The length of the CRC pavements in the y direction was

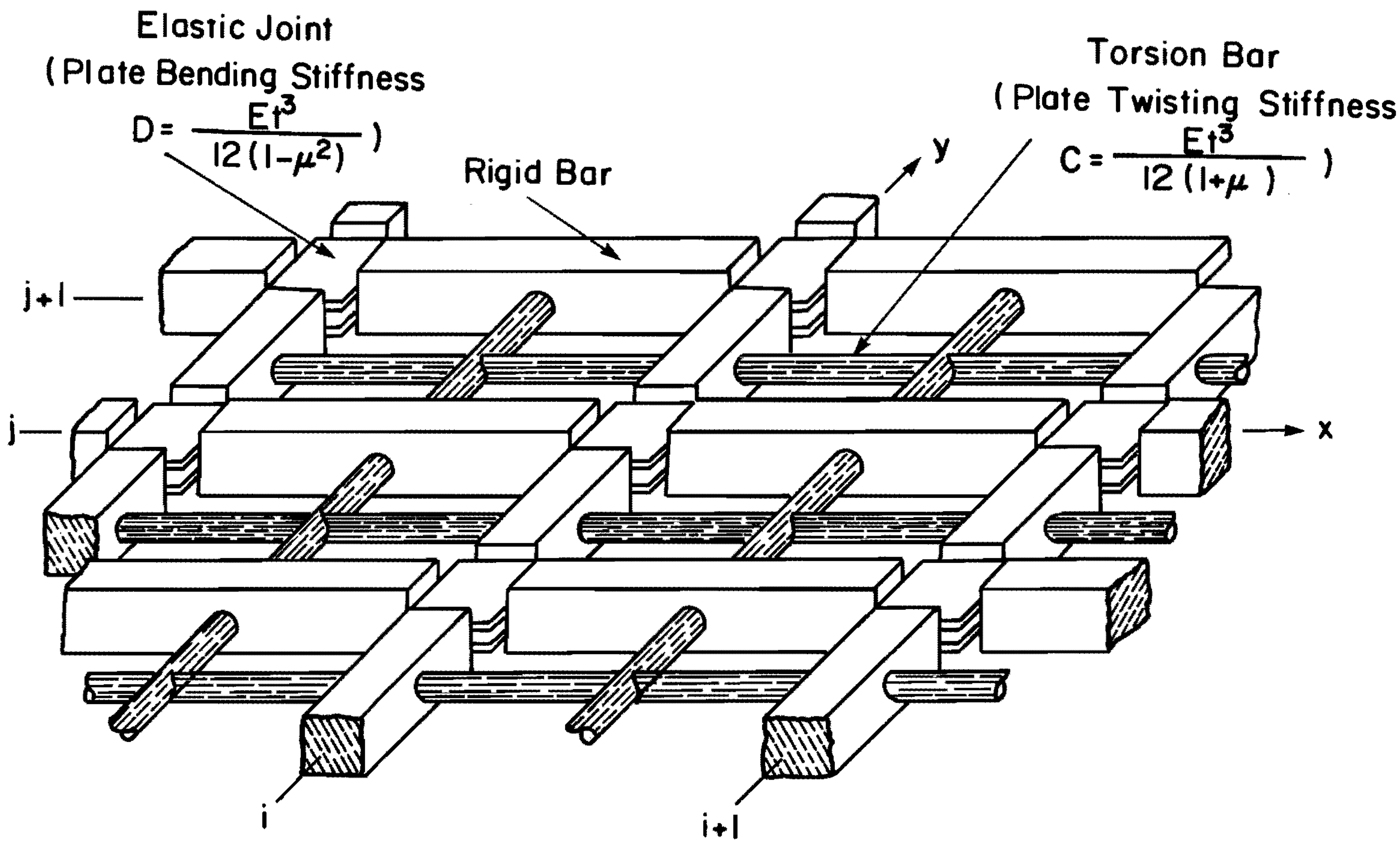

Fig 2.1. Discrete-element model of a slab (Ref 2).

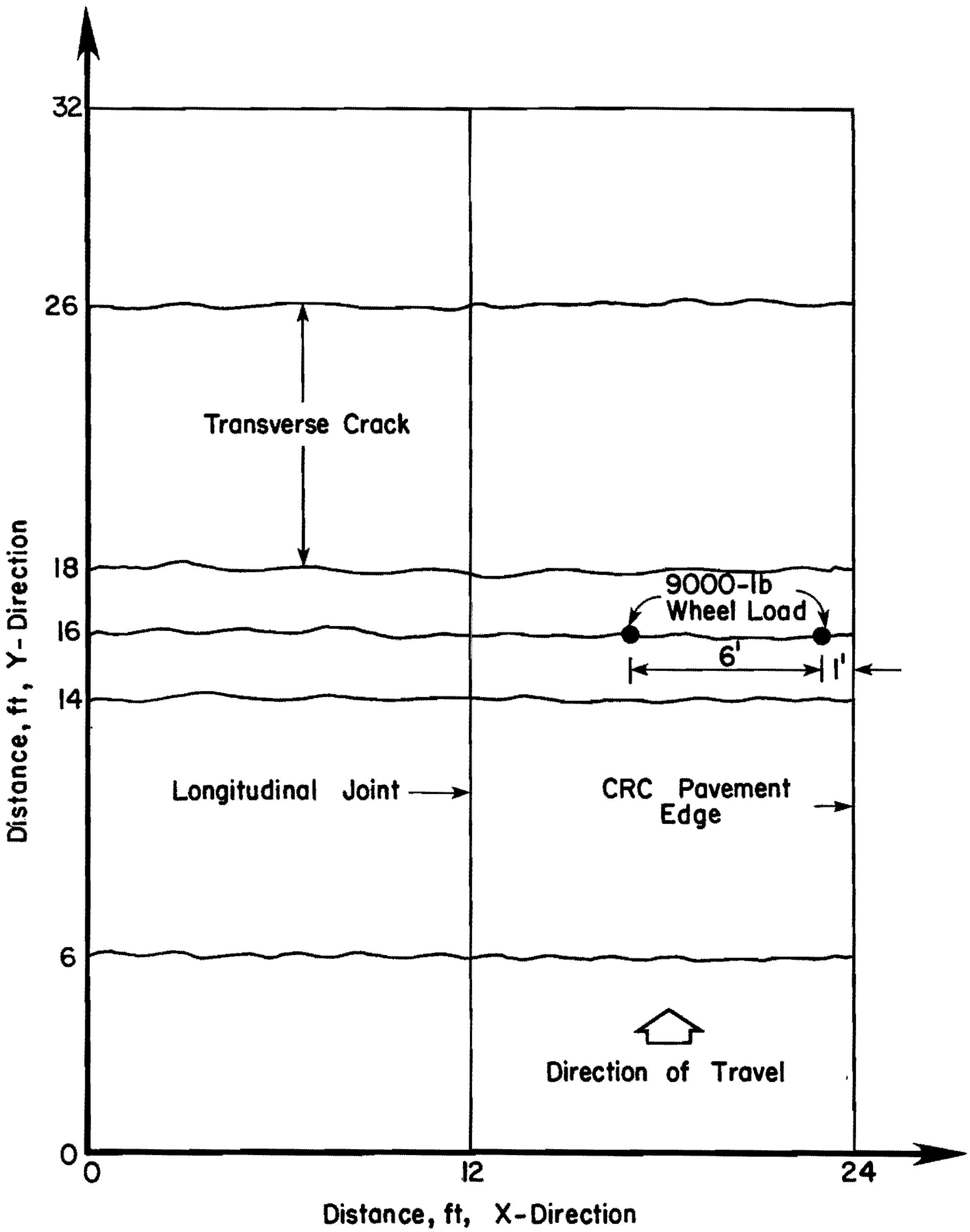

Fig 2.2. Example of a plan layout for a CRCP with flexible shoulder.

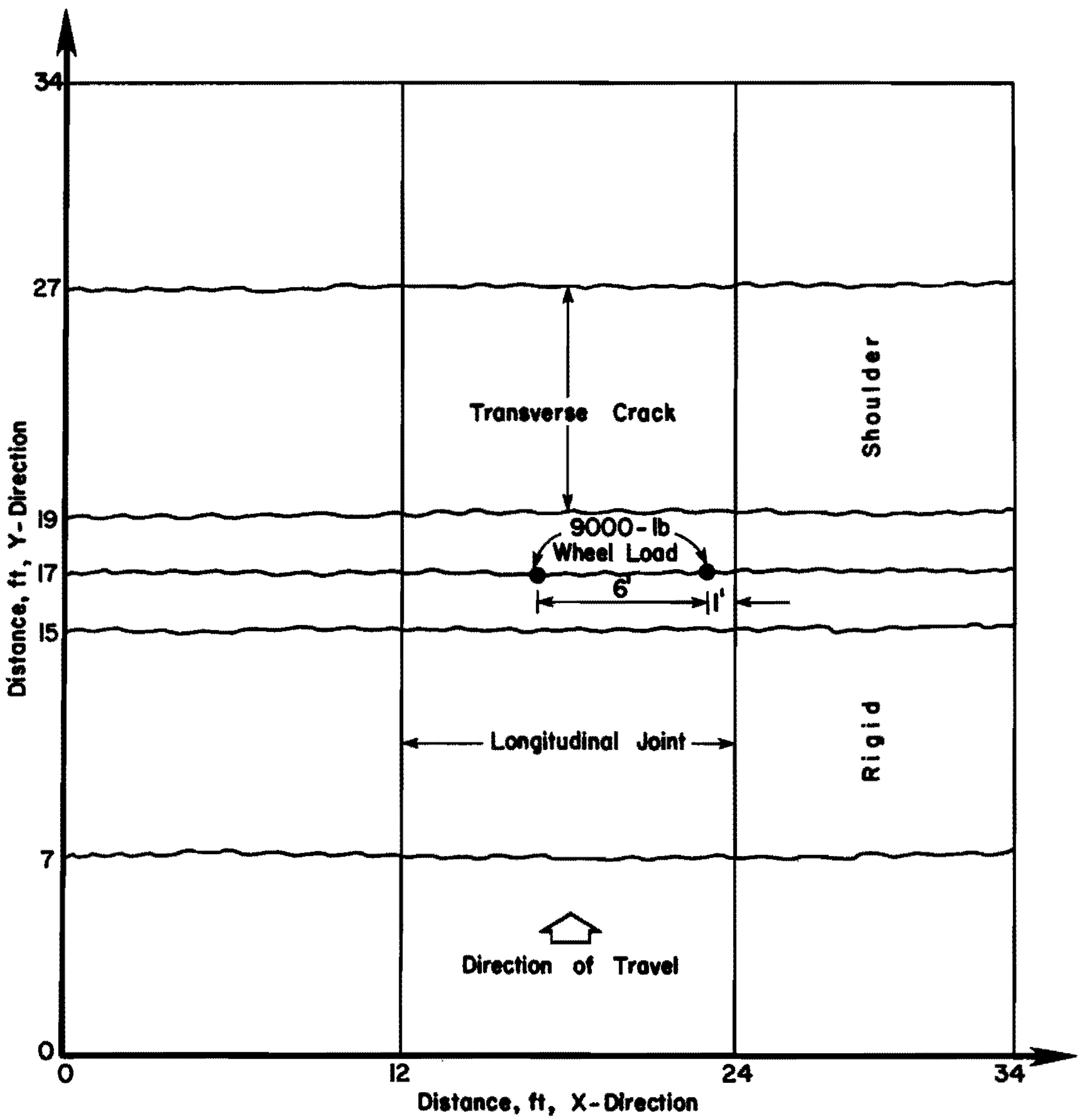

Fig 2.3. Example of a plan layout for a CRCP with rigid shoulder.

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selected in such a way that the maximum deflections at the central crack would not be affected by the pavement finite dimension in the direction of travel. Table 2.1 presents the values of the parameters held constant throughout the analysis. For practical purposes, it can be assumed that the thickness and properties of the PCC layer are constant within a given CRCP project. Essentially, as explained below in the section corresponding to the derivation of the deflection distress index, deflections are compared to assess the severity of any distress manifestation. Therefore, many values could have been assumed for the thickness and properties of the PCC layer. However, in order to take advantage of previous research, the same thickness value as that used in Ref 6 was considered. A subbase k-value of 350 psi/in. can be considered to be representative of typical conditions of in-service CRC pavements in Texas. Additionally, maximum deflections corresponding to distress manifestations, such as minor and severe punchouts and pumping, were obtained from SLAB49 for different combinations of crack spacing and crack width, as described below.

The criteria considered in Ref 2 to simulate transverse cracks and longitudinal joints are used herein to model different load-transfer conditions across discontinuities. A 90 percent reduction in the original slab bending stiffness at the discontinuity location was adopted for discontinuities with good load transfer (closed cracks or longitudinal joint), and a 100 percent reduction in the original slab bending stiffness was applied to simulate an open crack (hinged case). An open-crack condition is generally associated with the occurrence of severe spalling along a crack, it can also be the manifestation of tensile failure of the reinforcement in the pavement (Ref 5); with excessive crack width, load transfer is lost and the crack, therefore, becomes a free joint.

Distress Manifestations

Minor and severe punchouts and pumping are some of the most common types of CRCP distress manifestations in Texas. They were simulated for numerous combinations of crack spacing and crack load transfer in contiguous elements. These distress manifestations were modeled by computer program SLAB49, as described below.

TABLE 2.1. VALUES OF THE PARAMETERS HELD CONSTANT IN THE ANALYSIS

Parameter	Value
Slab thickness, in.	8
Concrete modulus of elasticity, psi	4.5×10^6
Poisson's ratio	0.20
Subbase k-value, psi/in.	350
Two wheel loads spaced at 6 ft, lb	9000 each

The definitions of punchouts (minor and severe) as stated below were used for this study only. A general definition of punchout can be found in Research Report 388-3 (to be published soon).

Minor Punchouts. A minor punchout occurs when two successive transverse cracks are connected by a longitudinal crack. The longitudinal crack was assumed at 2 feet from the pavement edge for small minor punchouts and at 6 feet for large minor punchouts. These dimensions have been normally used by the CTR to define punchout sizes.

Severe Punchouts. A severe punchout has the same configuration as a minor punchout. However, by definition, the portion of pavement corresponding to this distress manifestation deflects considerably under traffic loads. This is characteristic of poor load transfer across transverse and longitudinal cracks and of the occurrence of pumping beneath the slab. The effect of pumping was simulated by applying a 50 percent reduction in the subbase k-value over the whole area occupied by the severe punchout. Two different sizes of severe punchouts were analyzed: small and large, the distance from the pavement edge to the longitudinal crack for each of these two sizes is the same as that considered for the minor punchouts.

Pumping. Pumping is defined as the ejection of water and subgrade (or subbase) material through joints and cracks or at the pavement edge, caused by deflection of the slab after free water has accumulated under the slab (Ref 20). The CTR personnel have repeatedly expressed that there is a relatively low accuracy in determining the precise location at which pumping exists. Hence, it was decided to reduce the subbase k-value by 50 percent in two given adjoining elements and to assume a rectangular void with a constant width of 2 feet along both elements. Usually, the place where pumping occurs is determined while a condition survey is conducted, by observing whether there are fines along the pavement edge; because water commonly carries this material some distance from where the void is located, the task of exactly situating this area of non-uniform support is not easy. Therefore, if pumping is observed along the edge of a given CRCP element, it is reasonable to consider that there may also be pumping in its two adjacent elements.

FACTORIAL ARRANGEMENTS

Maximum deflections were obtained from SLAB49 for a great number of combinations of distress manifestations, crack spacing, and crack load-transfer. Three basic major factorial arrangements were recognized:

(1) No-punchout combinations. This group includes those combinations in which there is no punchout in either of two given adjacent elements.

(2) Single-punchout combinations. In this factorial arrangement, one punchout (minor or severe) was considered in either of two given contiguous elements.

(3) Double-punchout combinations. For a given pair of adjacent elements, one punchout (minor or severe) was simulated in each.

Deflections for the numerous combinations analyzed fall between the two cases illustrated in Fig 2.4. A CRC pavement is ideally designed to have a crack spacing of about 5 - 8 feet and adequate load transfer across transverse cracks, as shown in Fig 2.4. The smallest maximum deflection was obtained for this particular layout. In contrast, one of the worst possible conditions that can be encountered in a CRC pavement is also shown in Fig 2.4, where two adjacent elements have large severe punchouts and both the crack spacing and crack load transfer are very low, which results in very high deflections at the central crack. Cracks with good load transfer (closed) are denoted by a single line, whereas cracks with poor load transfer (open) are designated by two closely-spaced lines.

It has been commonly agreed that the addition of a rigid shoulder to an existing CRC pavement results in lower stresses and deflections (Refs 6 and 7). Thus, if we refer to Fig 2.5 and consider only the ideal condition of a lane of CRC pavement, it is evident that deflections in a rigid-shoulder CRCP will be lower than those in a flexible-shoulder CRCP, if both pavements have the same structure and material properties. This fact makes necessary the consideration of two shoulder-type levels in the factorial arrangement and the adoption of two divisions in the scheme for estimating deflection

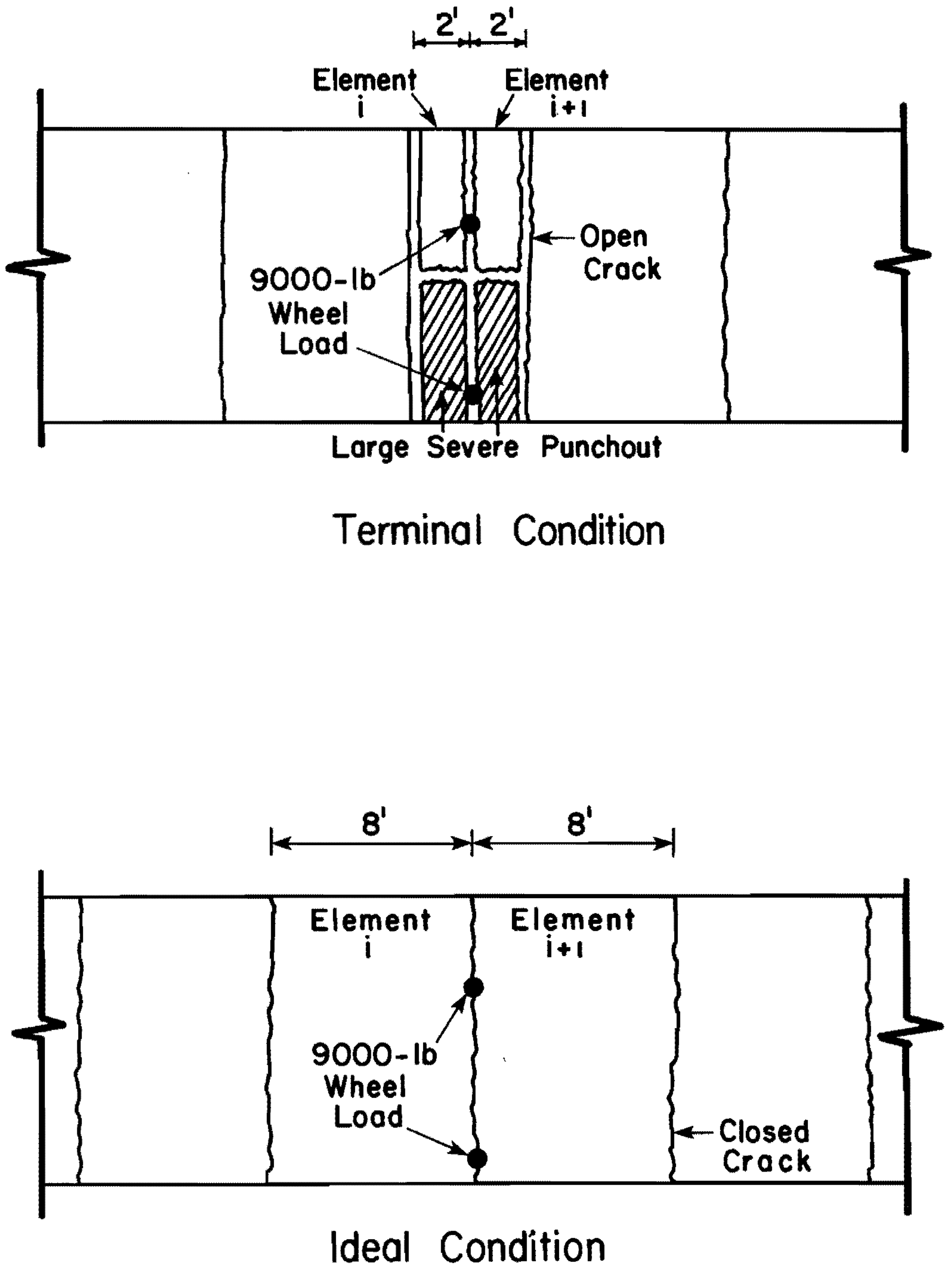
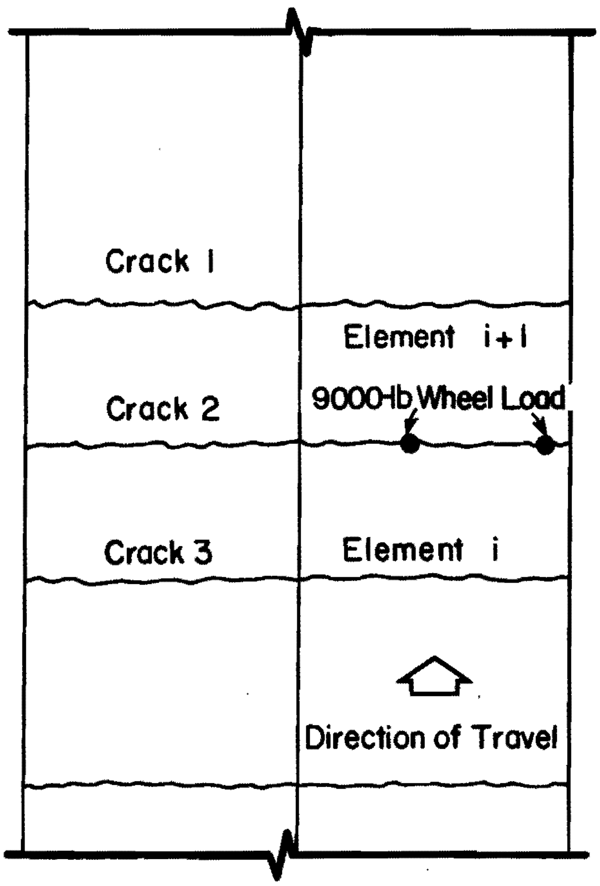


Fig 2.4. Extreme conditions of a lane of CRC pavement.



(a) Diagram of element location.

Combination	Crack Spacings ft, in Element: i+1	i
1	2	2
2	2	8
3	5	2
4	5	8
5	8	2
6	8	8

(b) Crack spacing combinations.

Combination	Crack 1	Crack 2	Crack 3
1	Open	Open	Open
2	Open	Closed	Open
3	Open	Closed	Closed
4	Closed	Open	Open
5	Closed	Closed	Open
6	Closed	Closed	Closed
7	Closed	Open	Closed
8	Open	Open	Closed

(c) Crack load transfer combinations.

Fig 2.5. Crack spacing and crack load-transfer combinations corresponding to the factorial arrangement for no-punchout combinations.

distress index; one for flexible-shoulder CRC pavements and the other for rigid-shoulder CRC pavements.

Figure 2.5 presents the characteristics of the crack spacing and crack load transfer combinations considered in the factorial arrangement for no-punchout combinations. Three different values of crack spacing were selected for the analysis. This indicates that there are nine possible crack spacing combinations for two given adjacent elements; however, three of them can be derived from the six combinations shown in Fig 2.5. The resulting factorial arrangement for no-punchout combinations is presented in Fig 2.6. It should be noted that four different levels were considered for this arrangement, depending on whether pumping occurs and on the shoulder type. There are 48 cells in each of the four levels corresponding to this factorial arrangement.

The single-punchout combinations shown in Fig 2.7 are the basic cases from which other less frequent combinations can be derived. Two punchout sizes are considered for both minor and severe punchouts. Since the two 9000-pound wheel loads are applied at the central crack, the maximum deflection for any of the combinations shown in Fig 2.7 will be the same as that of its corresponding "mirror-image" combination (i.e., in Fig 2.7, the punchout occurs in element i+1, instead of in element i, and the crack pattern is reversed). Figure 2.8 gives the final arrangement for single-punchout combinations, wherein each cell is held at four different levels.

Figure 2.9 presents the various punchout combinations considered in the factorial arrangement for double-punchout combinations. The degree of complexity of the analysis increases as the number of punchouts modeled in two adjacent elements increases from zero in the no-punchout case to two in the double-punchout case; in the latter it is necessary to evaluate the effect of having punchouts of different sizes in both elements, which is shown in Fig 2.10 . Double-punchout combination No. 4 in Fig 2.9 is similar to the terminal condition presented in Fig 2.4, if both elements have a low crack spacing. Figure 2.11 provides the factorial arrangement for double-punchout combinations. Each of the 120 cells corresponding to this arrangement was analyzed at four different levels.

Summarizing, the total number of cells for the three different factorial arrangements is 906. However, the number of SLAB49 computer-program runs

Crack Load Transfer Combination	Crack Spacing Combination					
	1	2	3	4	5	6
1	4	4	4	4	2	4
2	4	4	2	4	2	4
3	3	2	3	2	2	2
4	4	4	4	4	2	2
5	2	2	2	4	2	2
6	2	2	2	2	2	2
7	2	3	4	2	2	2
8	2	2	4	2	2	2

Level 1: No pumping, flexible shoulder.

Level 2: Pumping, flexible shoulder.

Level 3: No pumping, rigid shoulder.

Level 4: Pumping, rigid shoulder.

Fig 2.6. Factorial arrangement for no-punchout combinations. Each number indicates the number of computer runs per cell.

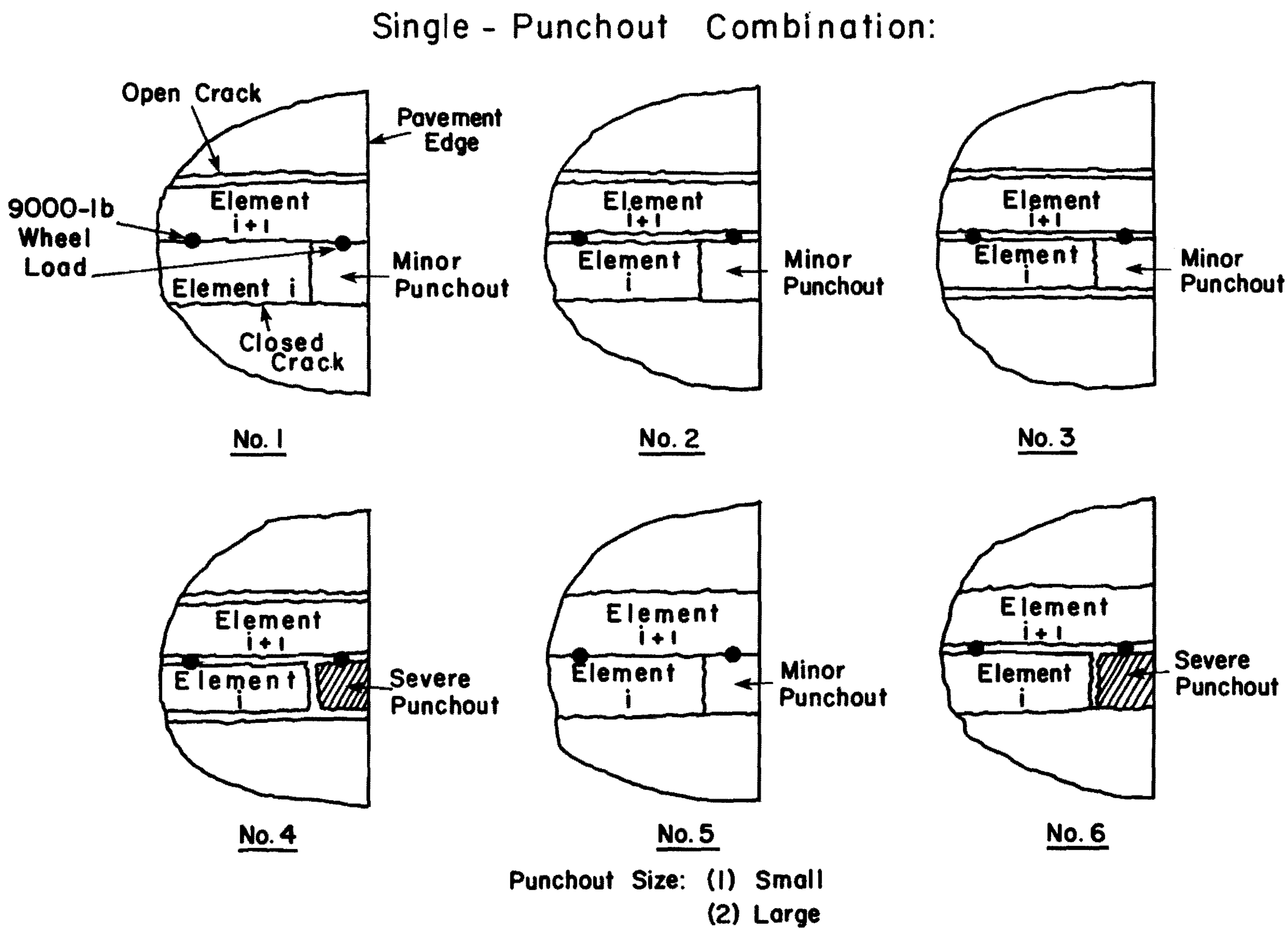


Fig 2.7. Punchout combinations and punchout sizes considered in the factorial arrangement for single-punchout combinations.

Punchout Size	Single-Punchout Combination	Crack-Spacing Combination 1	2	3	4	5	6
1	1	4	3	3	3	1	4
1	2	4	4	4	4	4	4
1	3	4	3	4	3	1	1
1	4	4	4	4	4	4	4
1	5	4	4	3	3	1	3
1	6	4	3	4	4	4	1
2	1	1	3	1	3	1	3
2	2	1	1	1	3	1	3
2	3	1	1	1	3	1	1
2	4	4	4	3	4	4	4
2	5	1	1	1	3	1	1
2	6	4	3	4	3	3	1

Level 1 : No Pumping , Flexible Shoulder
Level 2 : Pumping , Flexible Shoulder
Level 3 : No Pumping , Rigid Shoulder
Level 4 : Pumping , Rigid Shoulder

Fig 2.8. Factorial arrangement for single-punchout combinations. Each number indicates the number of computer runs per cell.

Double-Punchout Combination

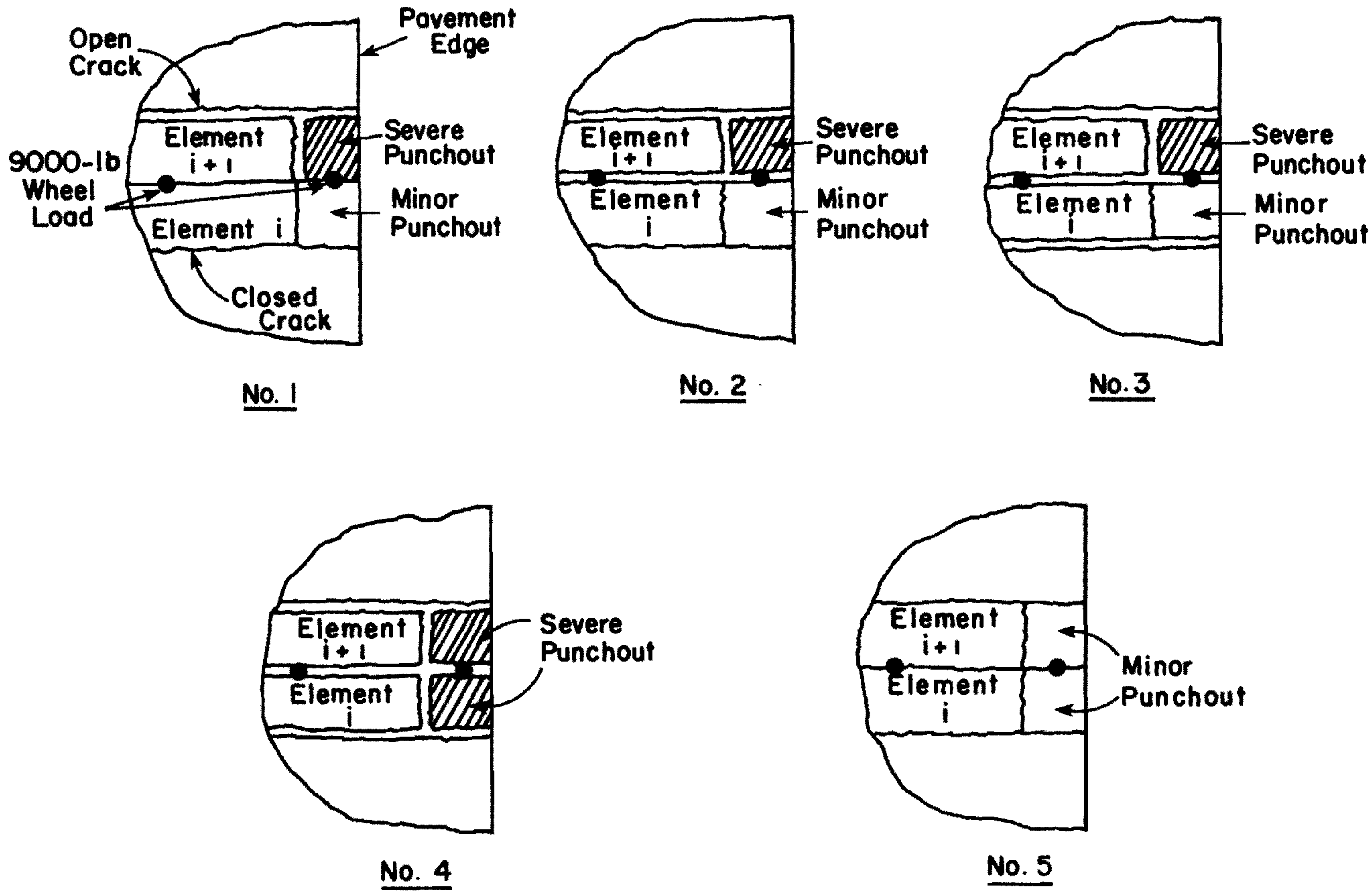
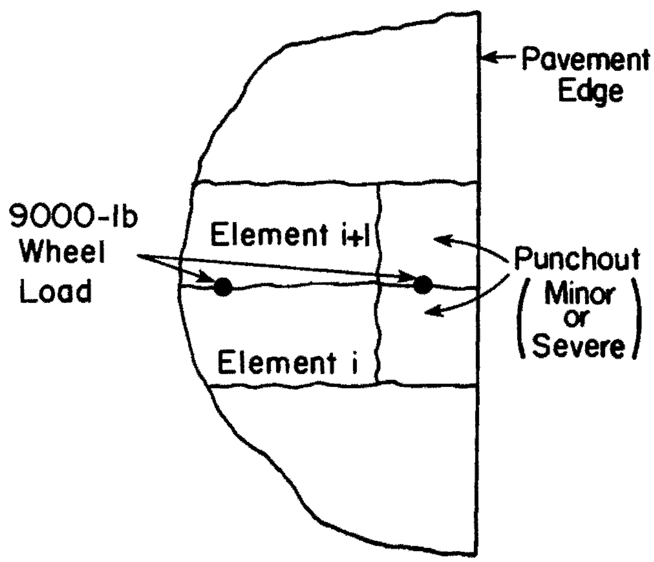


Fig 2.9. Punchout combinations considered in the factorial arrangement for double-punchout combinations.



(a) Diagram of element location.

Combination	Size of Punchout in Element	
	i+1	i
1	Small	Small
2	Small	Large
3	Large	Small
4	Large	Large

(b) Punchout size combinations.

Fig 2.10. Punchout-size combinations corresponding to the factorial arrangement for double-punchout combinations.

Punchout-Size Combination	Double Punchout Combination	Crack Spacing Combination 1	2	3	4	5	6
1	1	4	4	4	4	4	4
	2	4	4	4	4	4	4
	3	4	1	4	1	4	1
	4	2	2	2	2	0	2
	5	4	4	4	4	1	4
2	1	4	4	4	4	4	4
	2	4	4	4	4	4	4
	3	4	2	4	1	4	1
	4	2	2	2	2	2	2
	5	4	4	4	4	4	4
3	1	4	4	4	4	4	4
	2	4	4	4	4	4	4
	3	4	1	4	1	4	1
	4	0	2	2	2	2	0
	5	0	1	1	1	0	0
4	1	4	4	4	4	4	4
	2	4	4	4	4	4	4
	3	4	1	4	1	4	1
	4	2	2	2	2	0	2
	5	1	1	1	1	0	0

Level 1 : No Pumping , Flexible Shoulder
Level 2 : Pumping , Flexible Shoulder
Level 3 : No Pumping , Rigid Shoulder
Level 4 : Pumping , Rigid Shoulder

Fig 2.11. Factorial arrangement for double-punchout combinations. Each number indicates the number of computer runs per cell.

required in the analysis was reduced to 675 because some of the combinations of the various factorial arrangements were similar. For example, by symmetry, double-punchout combination 5 is the same for punchout-size combinations 2 and 3 if the crack spacing of two adjacent elements is the same for punchout-size combinations 2 and 3 if the crack spacing of two adjacent elements is the same (Fig 2.11).

MAXIMUM DEFLECTIONS FROM COMPUTER PROGRAM SLAB49

In order to facilitate the reader|s understanding of the major findings stemming from this study, it was decided to present graphically the maximum deflections corresponding to only those combinations in which the crack spacing and crack load-transfer were the same for two given contiguous elements. However, the maximum deflection value for every cell of the various factorial arrangements analyzed is presented in Appendix A.

Figure 2.12 compares the deflections for a CRC pavement with a flexible shoulder with those obtained for a CRC pavement with a rigid shoulder. It can be observed that, for similar conditions, higher deflections will exist in a flexible-shoulder CRCP than in a rigid-shoulder CRCP. Additionally, maximum deflection decreases with crack spacing for both CRC pavements.

The combined effect on maximum deflection of crack load-transfer and pumping is illustrated in Fig 2.13 for a CRCP with a flexible shoulder. In general, maximum deflection decreases with an improvement in crack load-transfer and increases if pumping occurs beneath the slab. If there is good load transfer across the three transverse cracks encountered in two given adjacent elements, then maximum deflection remains approximately constant with crack spacing. Hence, it is very important to maintain good load transfer across discontinuities in any in-service CRC pavement.

Figure 2.14 indicates that a large severe punchout with open cracks is more detrimental than a small severe punchout. This is evidenced by the higher deflections associated with the occurrence of a large severe punchout. In this instance, data corresponding to the factorial arrangement for single-punchout combinations also show that the presence of a severe punchout results in significantly higher deflections than those that would be obtained

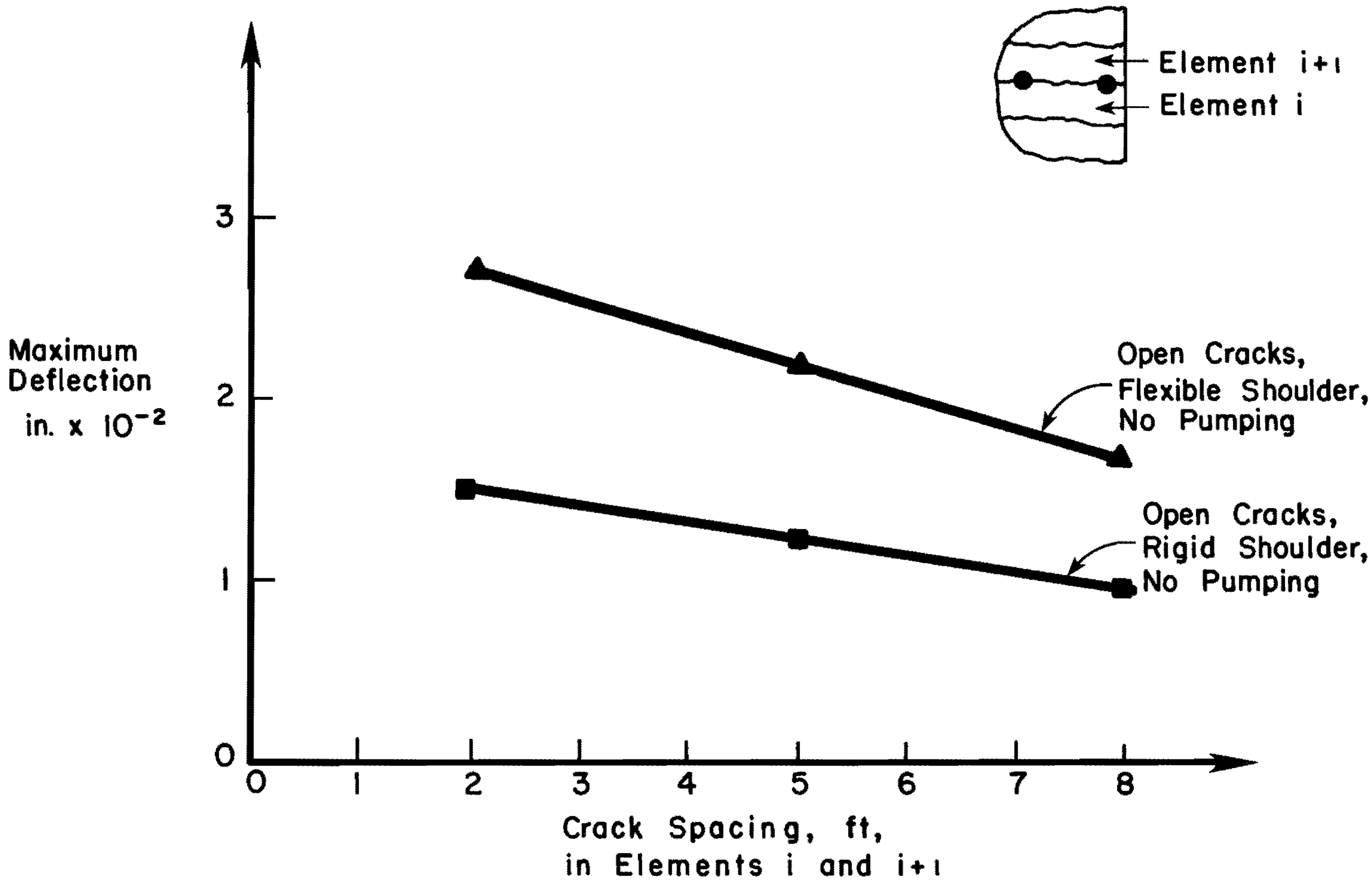


Fig 2.12. Maximum deflection for no-punchout combinations.

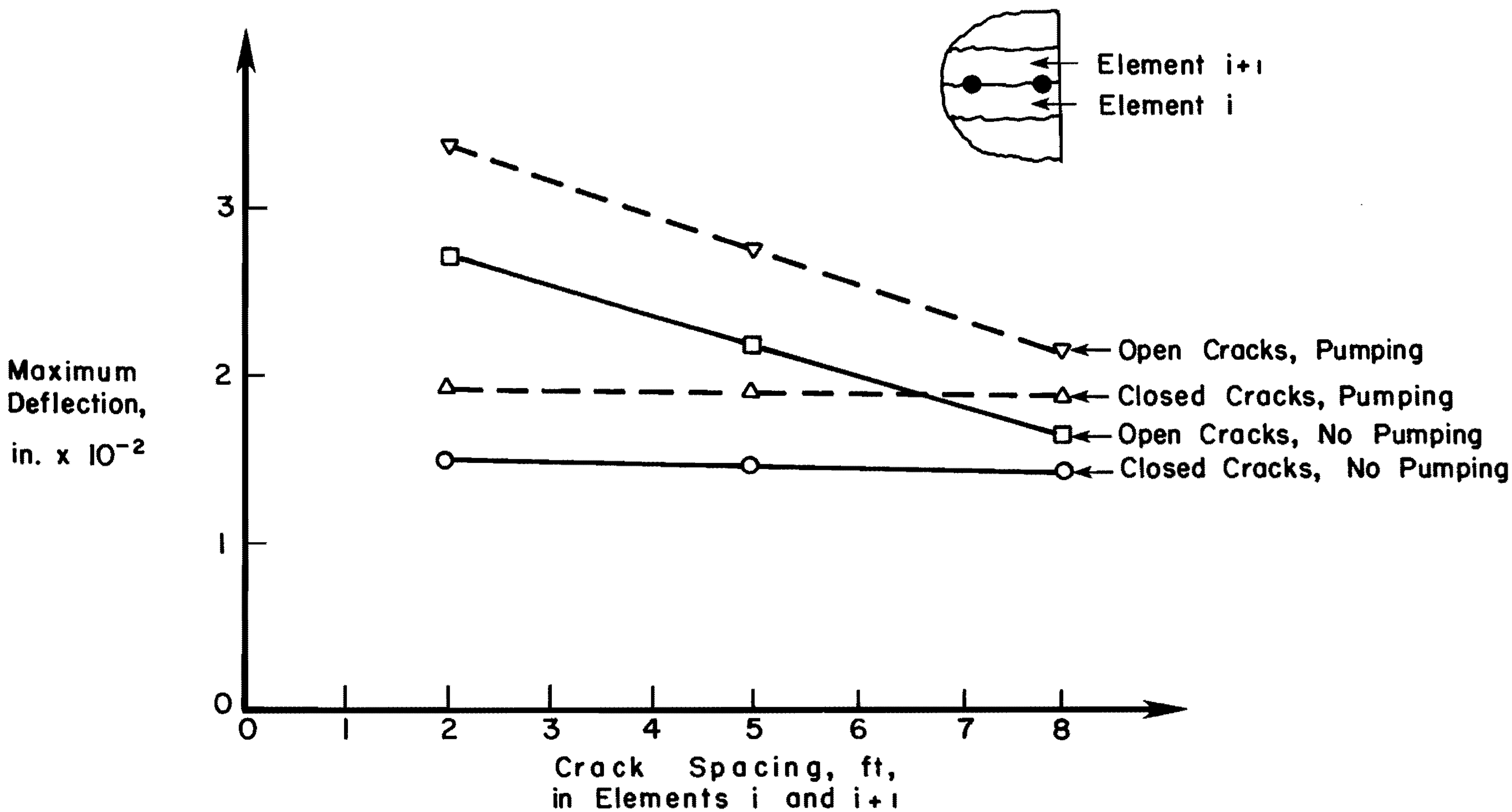


Fig 2.13. Maximum deflection for no-punchout combinations in a CRCP with a flexible shoulder.

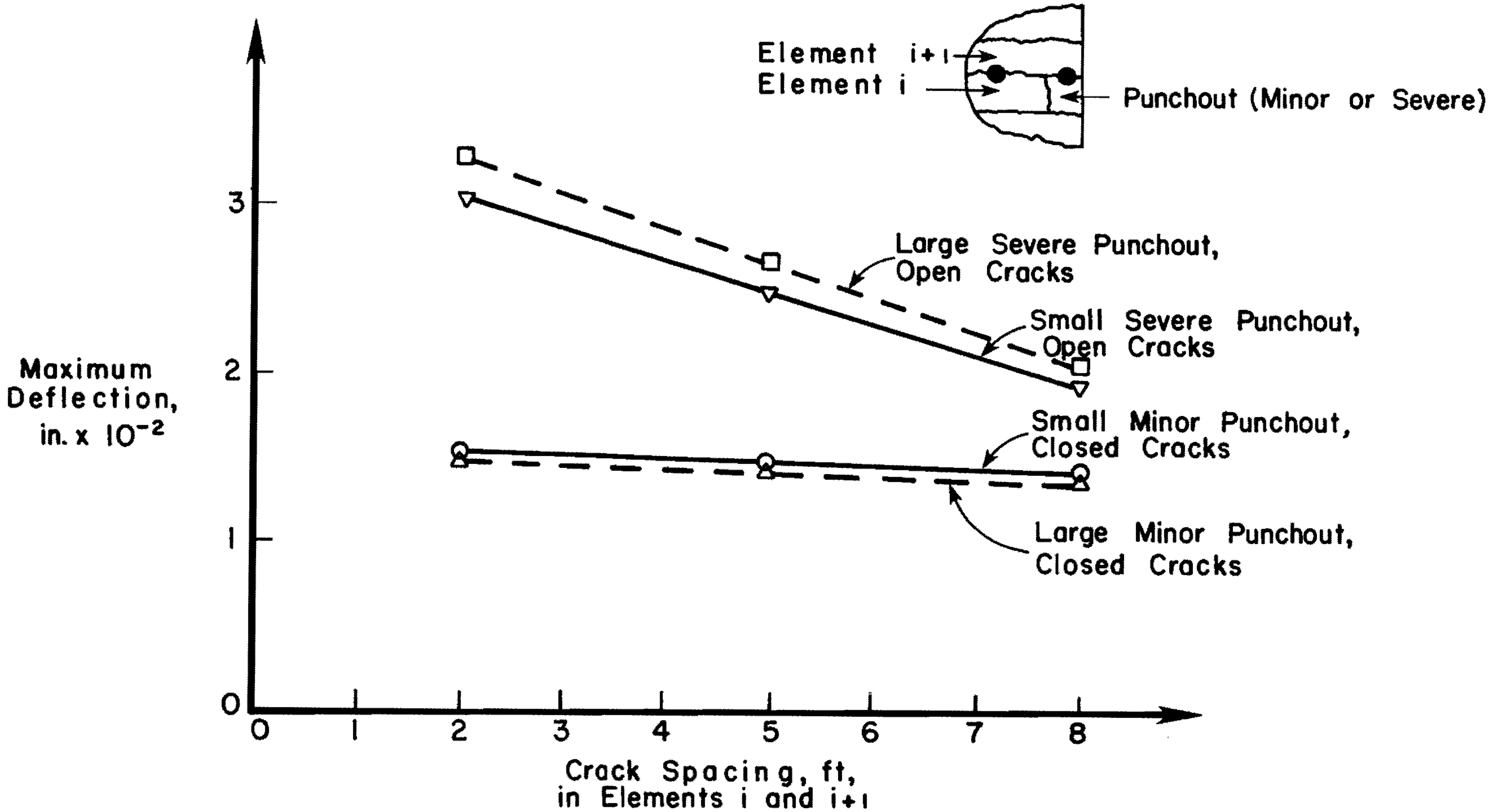


Fig 2.14. Maximum deflection for single-punchout combinations in a CRCP with a flexible shoulder.

for a minor punchout of the same size with a similar crack pattern. Deflections are slightly higher for a small minor punchout than for a large minor punchout.

The trends observed in the data for the double-punchout combinations are similar to those presented in Fig 2.14. However, as illustrated in Fig 2.15, maximum deflection increases if there are two adjacent severe punchouts.

Finally, Fig 2.16 permits a comparison of the maximum deflection to be expected under the simulated 9000-pound wheel loads for the three different punchout combinations considered in the analysis. Deflection increases with an increase in the number of large severe punchouts. This figure includes the deflections corresponding to the conditions defined as ideal and terminal in Fig 2.4. A condition is ideal when adjacent elements have both a crack spacing of 8 feet and good load transfer across transverse cracks; the terminal condition, on the other hand, is represented by a double-punchout combination in which both punchouts are large and severe and crack spacing tends to have a very low value (2 feet in this study). Subjective labelings about the distress condition of a CRCP are also provided in Fig 2.16. This is done to simplify the reader|s understanding of the severity of different distress manifestations; since the severity of a distress manifestation is related to its predicted maximum deflection.

DERIVATION OF A DEFLECTION DISTRESS INDEX FOR PROJECT-LEVEL EVALUATION OF CRC PAVEMENTS FROM CONDITION SURVEY DATA

Condition surveys measure various types and degrees of severity of distress (Ref 8) and are directed toward assessing the maintenance measures needed to prevent accelerated, future distress, or the rehabilitation strategies needed to improve the pavement. From information gathered in the condition survey of a particular pavement section, a distress index is computed; the index is the combination of distress manifestations to ascertain with a single number the amount of pavement deterioration (Ref 9).

A relatively new approach to estimate distress index of a CRC pavement at the network level is presented in Ref 10. This distress index, incorporated in a computer program, has been used to prioritize and schedule

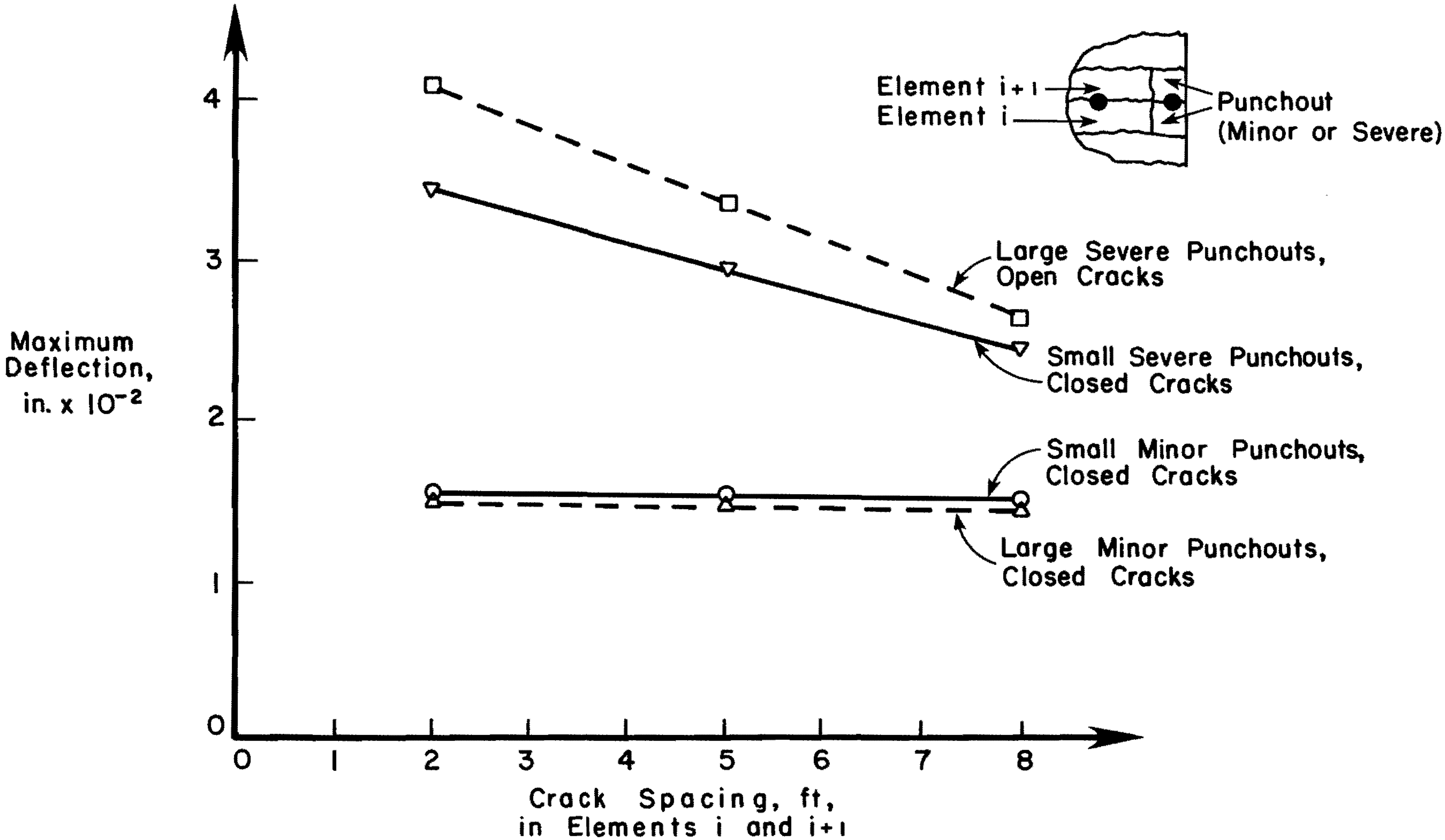


Fig 2.15. Maximum deflection for double-punchout combinations in a CRCP with a flexible shoulder.

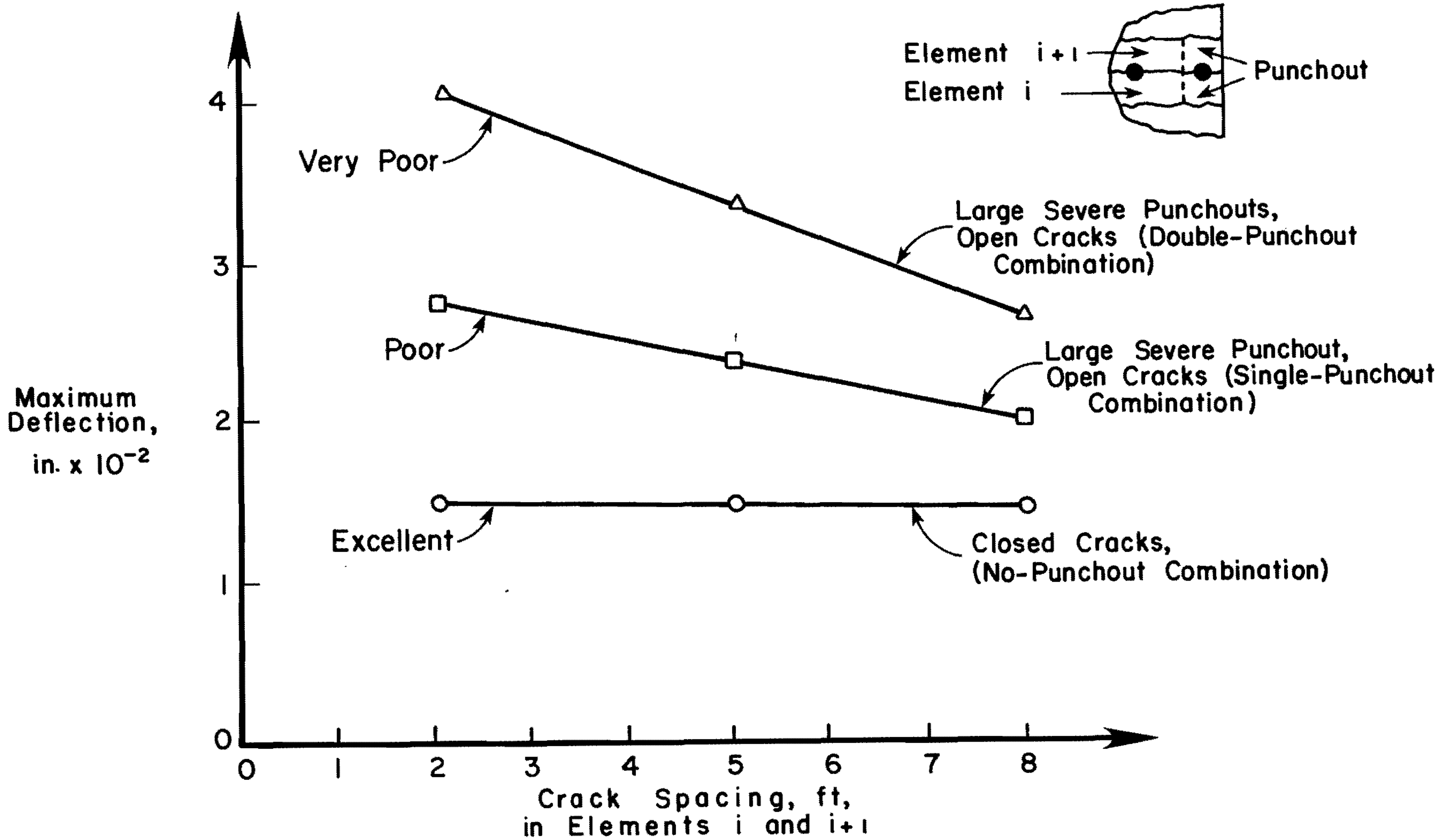


Fig 2.16. Maximum deflection for different punchout combinations in a CRCP with a flexible shoulder. Subjective labelings of the distress condition are also shown.

maintenance and rehabilitation needs in the rigid-pavement network of the state of Texas. However, this approach does not provide any information concerning the within-project variation of distress in a given pavement section, which becomes especially important when we are trying to define in a precise way the most adequate rehabilitation strategies to be performed in that section.

The Center for Transportation Research of The University of Texas at Austin has periodically conducted CRCP condition surveys throughout the state of Texas during the last 10 years, and several experimental sections have been included in this monitoring, in which very detailed distress information has been gathered. However, when these data have been analyzed, an aggregate approach has been followed and distress manifestations have been lumped into per mile or 0.2-mile summaries, which has resulted in reduced knowledge about the within-project variation of distress.

An original method was developed and is reported in this study to derive a new distress index through the prediction of the immediate response of a multitude of distress manifestations to a given loading pattern by means of computer program SLAB49. Since maximum deflection is the response considered in this approach, the proposed parameter is designated as a deflection distress index (DDI). The use of deflection in the derivation of this distress index will permit, to a certain extent, the verification of the assumptions implicit in the analysis, because deflection is the pavement response more commonly measured in the field by means of different devices currently available.

PERFORMANCE FROM STATIC EDGE DEFLECTION AT THE AASHO ROAD TEST

Given the two boundary conditions of the scheme for estimating deflection distress index presented in Fig 2.4, and being consistent with the distress index derived in Ref 10, a DDI value of 100 percent is assigned to the ideal condition of a CRCP lane, whereas a DDI value of 0 percent is specified for the terminal condition of a CRCP lane. Nevertheless, it is necessary that the DDI value of every cell of the various factorial arrangements of distress manifestations be computed by means of a rational scheme. Deflection cannot be directly used to compute the DDI value of the factorial cells falling between the two boundary conditions, basically because the damage caused by deflections is not linear. For example, for a given pavement, a two-fold increase in the original deflection will cause significantly more than a 100 percent increase in the damage to that pavement.

The first objective of the AASHO Road Test asked for relationships between the performance of the pavement and the pavement design variables for various loads. The term "present serviceability" was adopted to represent the momentary ability of a pavement to serve traffic, and the performance of the pavement was represented by its serviceability history in conjunction with its load application history. A serviceability rating is defined as the judgement of an observer as to the current ability of a pavement to serve the traffic it is meant to serve. An estimate of the mean of serviceability ratings made by a panel of judges is designated as a serviceability index. A present serviceability index formula is used to determine the estimate of the serviceability rating of a section (Ref 11). Studies made at the AASHO Road Test have shown that about 95 percent of the information about the serviceability of a pavement is contributed by the roughness of its surface profile (Ref 8).

Several expressions were developed at the AASHO Road Test (Ref 11) to predict performance from deflection following one of the objectives of the Road Test. The equation used herein is that corresponding to the performance from static edge deflection, namely,

$$\log W_{2.5} = 0.74 - 3.15 \log \tilde{d}'_e \qquad (2.1)$$

where

$\log W_{2.5}$ = the logarithm of the number of unweighted axle load applications at which $p = 2.5$ (p is the present serviceability index), and

$\log \tilde{d}'_e$ = the logarithm of the static edge deflection, in.

Unweighted axle load applications is a term used to indicate that the cumulative number of axle load applications has been determined by using a seasonal weighting function whose value is always one. The seasonal weighting function is used to describe the relative serviceability loss potential of a pavement during a specified time interval.

The number of unweighted load applications at which p equals 2.5 for the two boundary conditions illustrated in Fig 2.4 can now be estimated by means of Eq 2.1, if the maximum deflections computed by SLAB49 are input into that expression. Eq 2.1 requires as input the static edge deflection measured by means of a Benkelman Beam. However, the maximum deflections predicted by program SLAB49 can be assumed to be approximately equal to those that would be measured in the field for the conditions considered in the various factorial arrangements. Therefore, $W_{2.5}$ can be estimated for any of the cells of the factorial arrangements analyzed. Additionally, if it is assumed that deflection distress index varies linearly with $W_{2.5}$ between the $W_{2.5}$ value corresponding to the terminal condition and that for the ideal condition of a CRCP lane, then DDI for every distress manifestation simulated by SLAB49 can be computed, as shown in Fig 2.17.

The DDI for CRC pavements can be computed by means of an expression corresponding to the straight line shown in Fig 2.17. The equation to compute the DDI for flexible-shoulder CRC pavements is written as

$$DDI = -3.82 + 2.92 \times 10^{-5} W_{2.5} \qquad (2.2)$$

where

DDI = deflection distress index of flexible-shoulder CRC pavements, percent, and

$W_{2.5}$ = as defined above.

Equation 2.3 should be used to compute the deflection distress index of rigid-shoulder CRC pavements.

$$DDI = -7.63 + 4.67 \times 10^{-6} W_{2.5} \qquad (2.3)$$

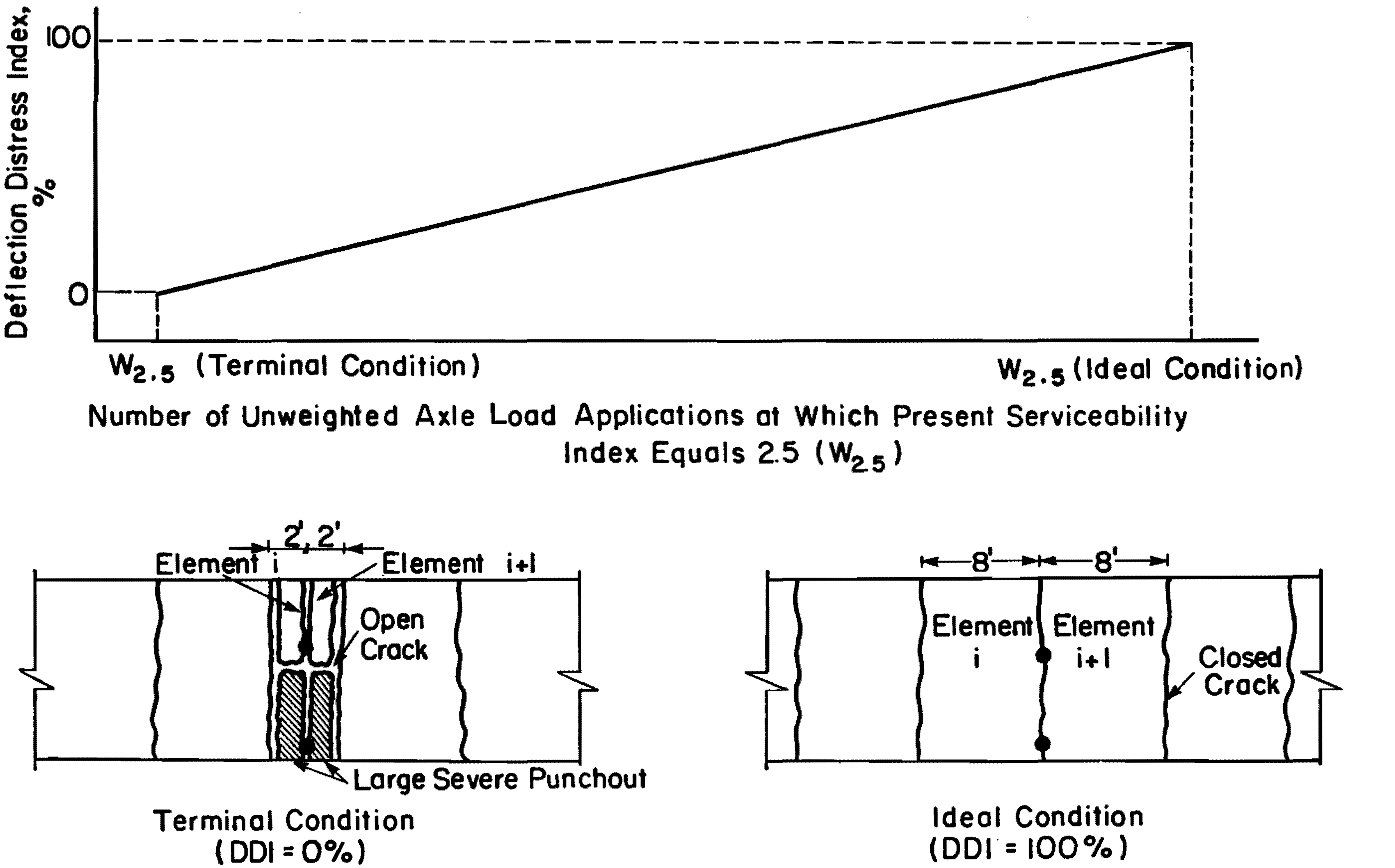


Fig 2.17. Computation of deflection distress index.

where

DDI = deflection distress index of rigid-shoulder CRC pavements, percent.

It is important to point out that Eq 2.1 was used only as a means for arriving at the DDI values of those distress manifestations falling between the two boundary conditions. This expression permits the evaluation of the severity of every distress manifestation as evidenced by its corresponding maximum deflection predicted by SLAB49. Equation 2.1 also considers the fact that the relationship between deflection and pavement damage is a nonlinear one.

Figures 2.18 to 2.22 show the DDI values corresponding to those factorial cells in which the crack spacing and crack load transfer are the same for two given contiguous elements, in the same way as Figs 2.12 to 2.16 presented the maximum deflection data. Due to the fact that different criteria are used for deriving the DDI in flexible and rigid-shoulder CRC pavements, the curves of DDI versus crack spacing presented in Fig 2.18 for both pavement types lie very close to each other, even though the maximum deflection obtained for a rigid-shoulder CRCP was much lower than that corresponding to a flexible-shoulder CRCP for a given crack spacing. Figures 2.18 to 2.22 present the general trends of DDI versus crack spacing for different punchout combinations. The DDI values corresponding to the factorial cells that are not plotted in this series of figures, are included in Appendix B. Subjective labelings are used in Fig 2.22 to indicate the severity of the distress manifestations plotted, and explain the relationship between the severity and the DDI values for these distress manifestations.

DEFLECTION DISTRESS INDEX FOR REPAIR PATCHES IN GOOD CONDITION

At the present time, very few approaches consider repair patches in the computation of distress index of a CRC pavement. Nevertheless, it is highly desirable to include repair patches in the scheme proposed in this study, because their occurrence is equivalent, in many instances, to a distress manifestation, such as a punchout, with a severity depending on its condition

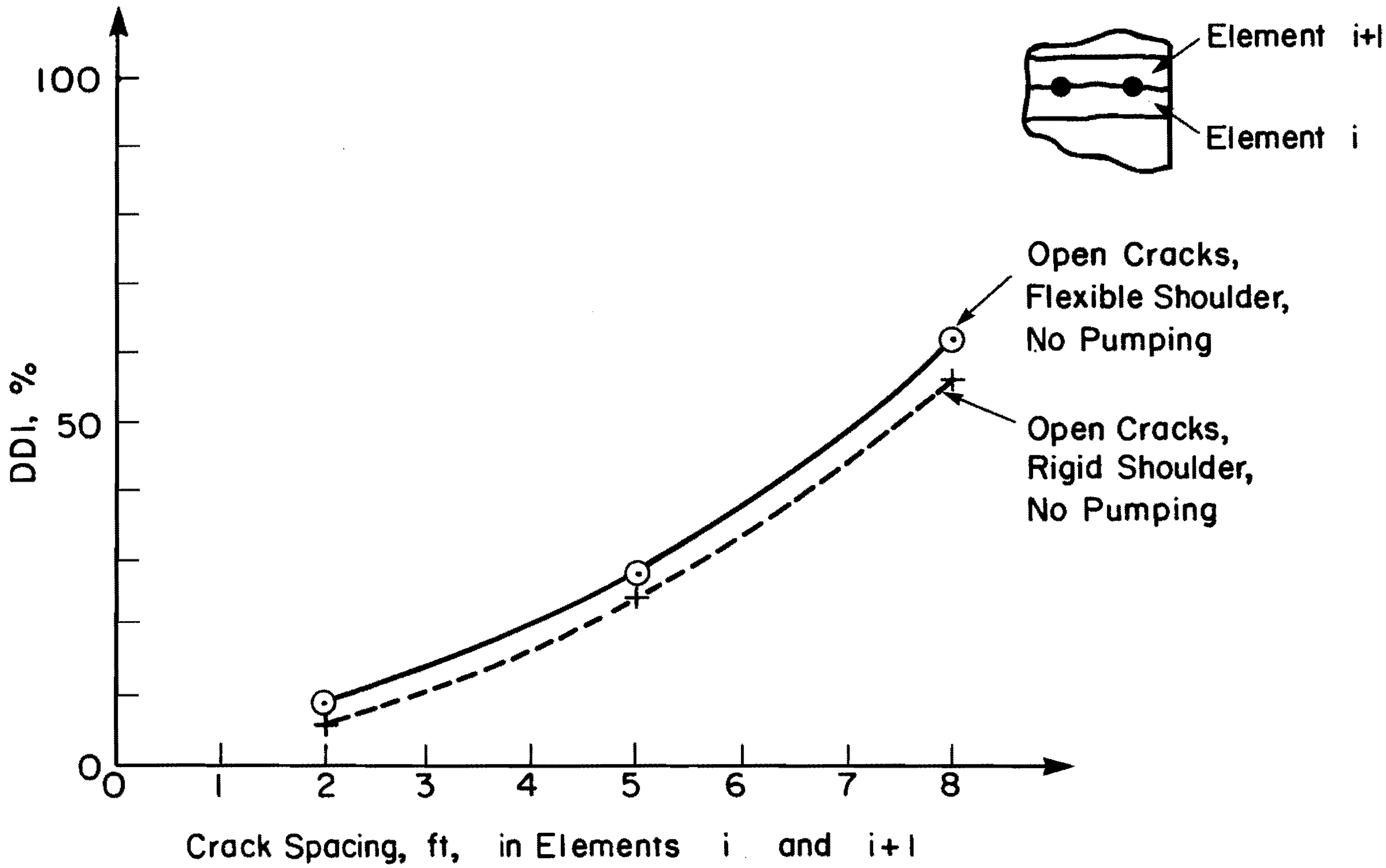


Fig 2.18. Deflection distress index (DDI) for no-punchout combinations.

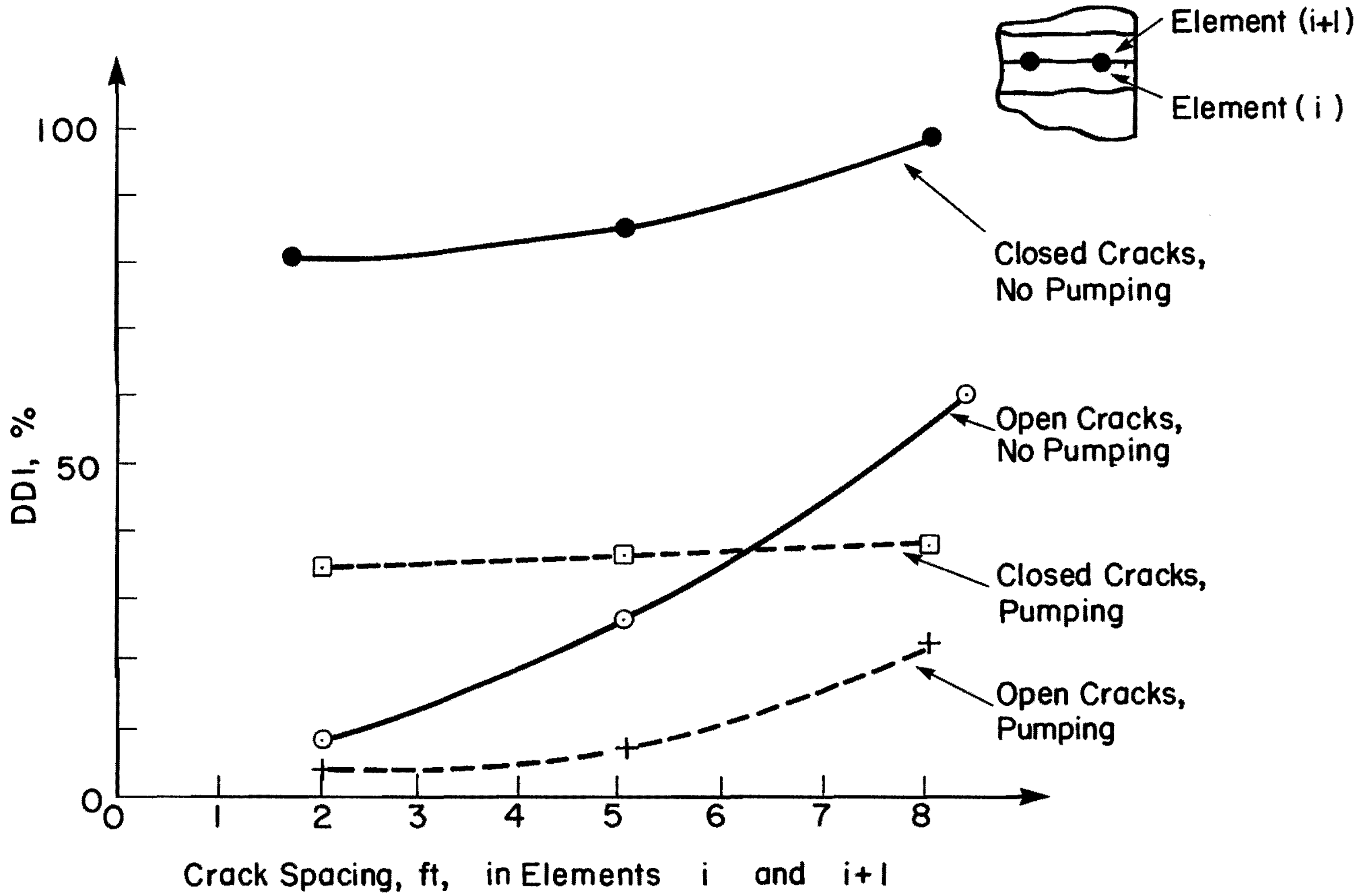


Fig 2.19. Deflection distress index (DDI) for no-punchout combinations in a CRCP with a flexible shoulder.

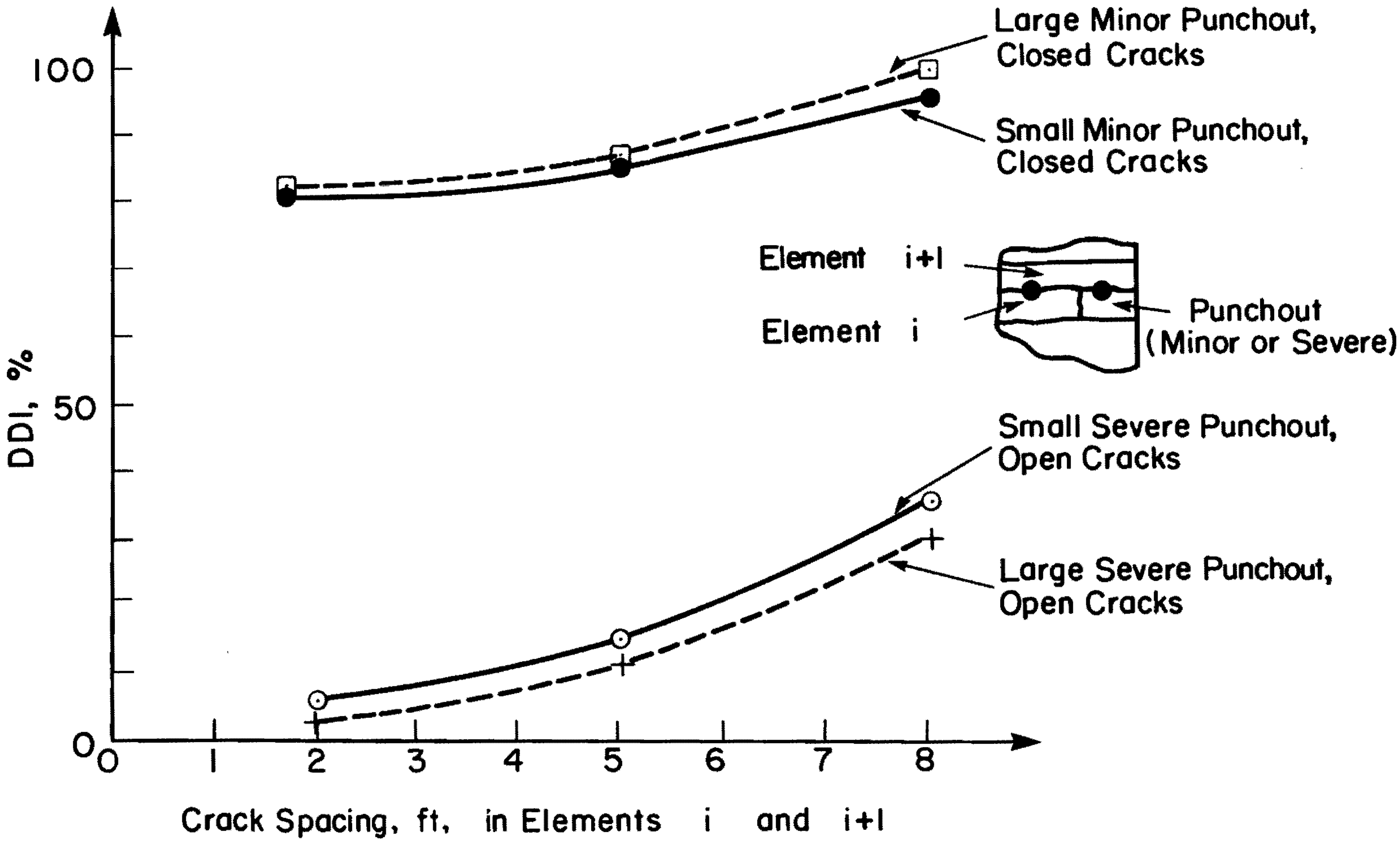


Fig 2.20. Deflection distress index (DDI) for single-punchout combinations in a CRCP with a flexible shoulder.

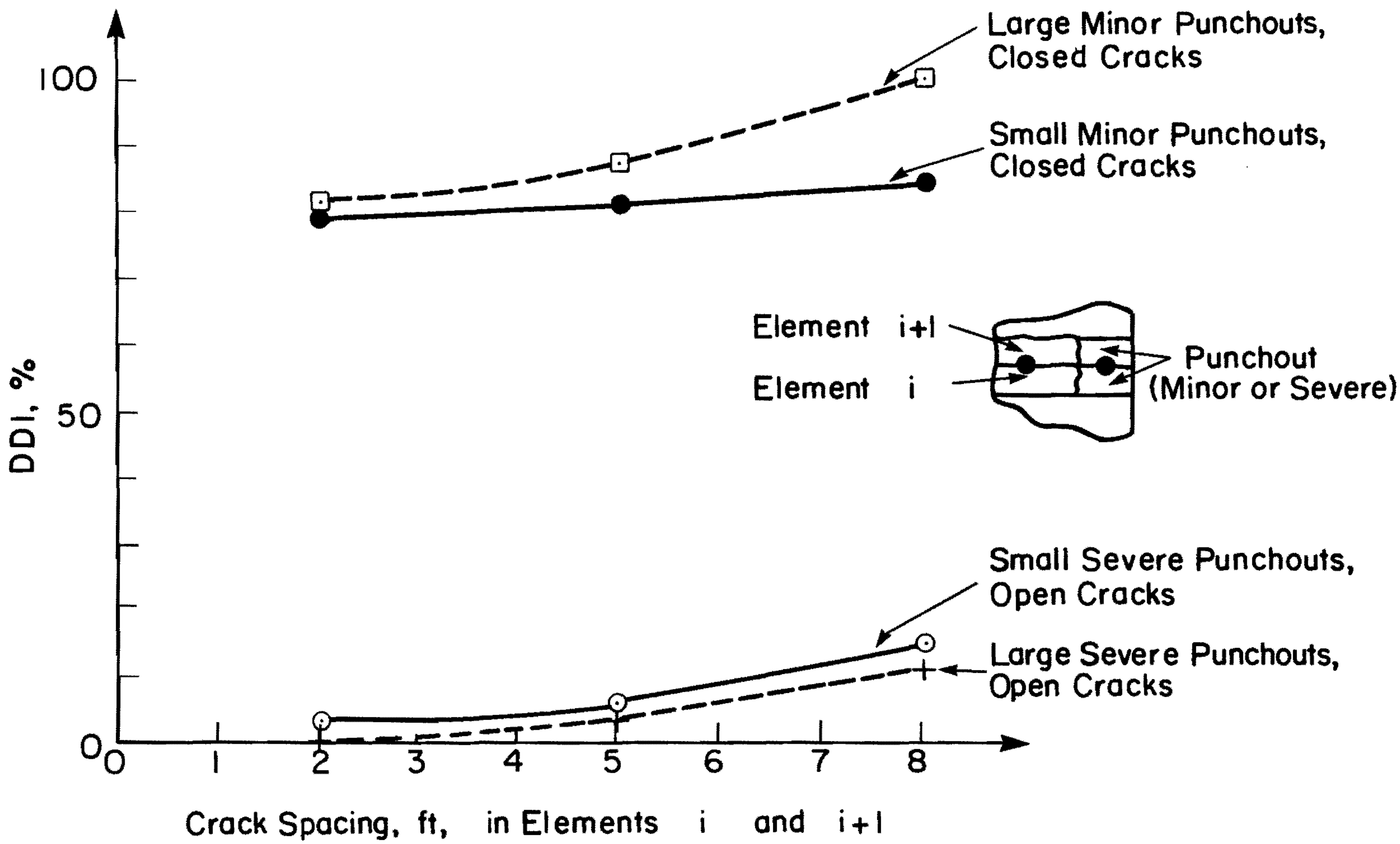


Fig 2.21. Deflection distress index (DDI) for double-punchout combinations in a CRCP with a flexible shoulder.

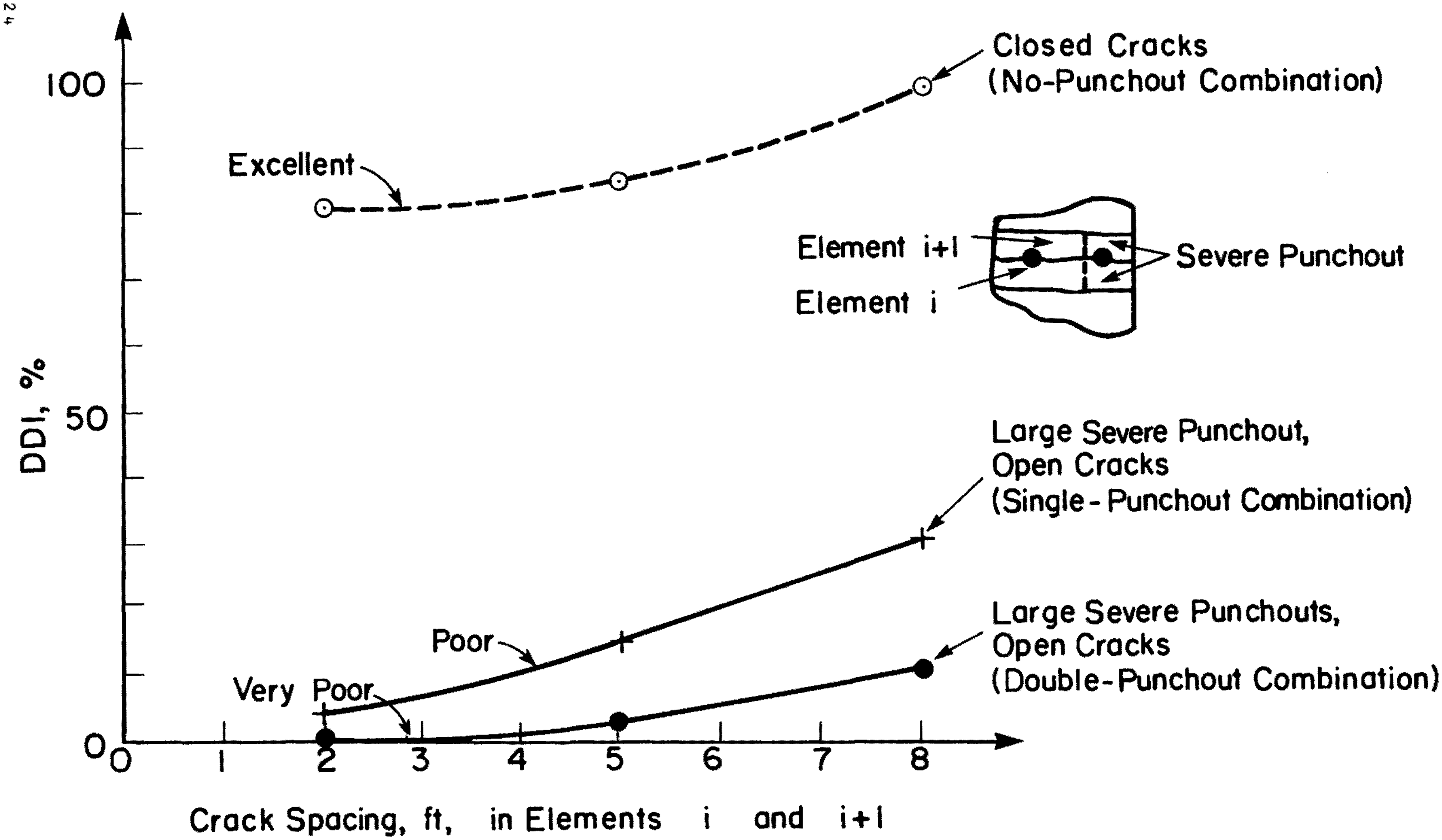


Fig 2.22. Deflection distress index (DDI) for different punchout combinations in a CRCP with a flexible shoulder. Subjective labelings of the distress condition are also shown.

at the time of the survey. Owing to the considerable amount of computer time required for simulating a distress manifestation by means of program SLAB49 and taking into account the total cost of this research, repair patches in good condition are assumed, in the DDI scheme, to be equivalent to minor punchouts, as shown in Fig 2.23. An asphalt patch in good condition is considered to be equivalent to a minor punchout with open cracks, because an asphalt patch, basically, does not provide any load transfer to the surrounding CRC pavement. In Fig 2.23(b), as an example, a PCC patch in good condition is assumed to have an open and a closed crack; this repair patch is treated in the DDI scheme as if it were a minor punchout with the same load transfer characteristics as those of the original PCC patch.

Repair patches in poor condition are considered in the scheme for estimating DDI to be equivalent to severe punchouts. Hence, any time there is a repair patch in poor condition in a given CRCP element, a very low DDI value will be assigned to that element.

DISCUSSION OF RESULTS

This chapter has presented the development of an innovative scheme for project-level evaluation of CRC pavements from condition survey data. A very detailed approach has been followed to predict the immediate response, in terms of maximum deflection, for a variety of combinations of CRCP distress manifestations, when they are subjected to the action of the same load. This consistency in the analysis has permitted the simulation, under similar conditions, of the behavior of every distress manifestation included in the various factorial arrangements considered. Consequently, this process has resulted in the development of the DDI concept for CRC pavements.

Since an element-by-element approach has been followed, it is now possible to estimate both the mean and the standard deviation of the present DDI of a given CRCP section. Figure 2.24 is a plot of DDI versus element number, which represents the DDI within-project variation. In this example plot, it is assumed that DDI was estimated for every element in the section. However, as discussed in Chapter 3, the required number of elements to be sampled can be estimated if the sample standard deviation is available and an

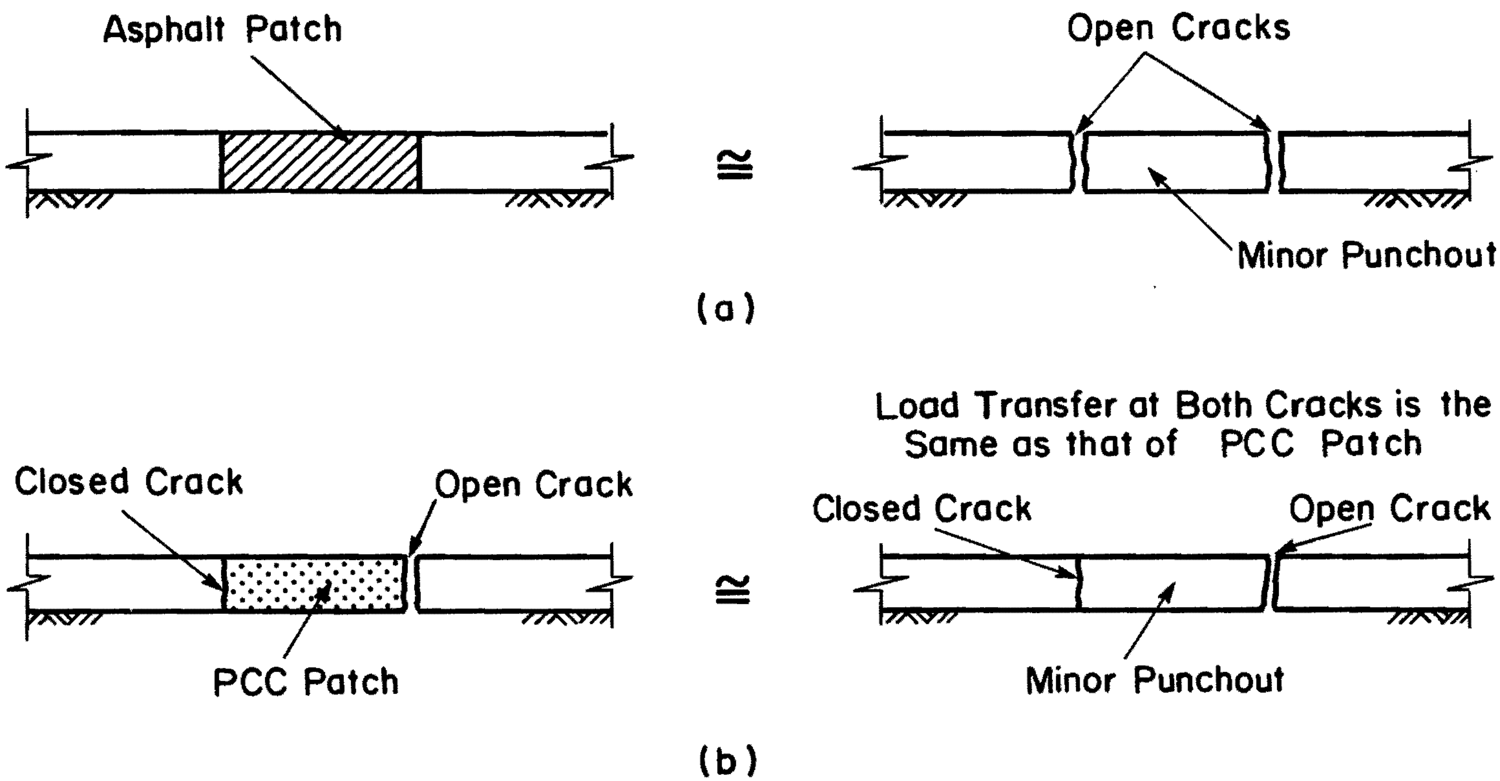


Fig 2.23. Deflection distress index (DDI) for repair patches in good condition.

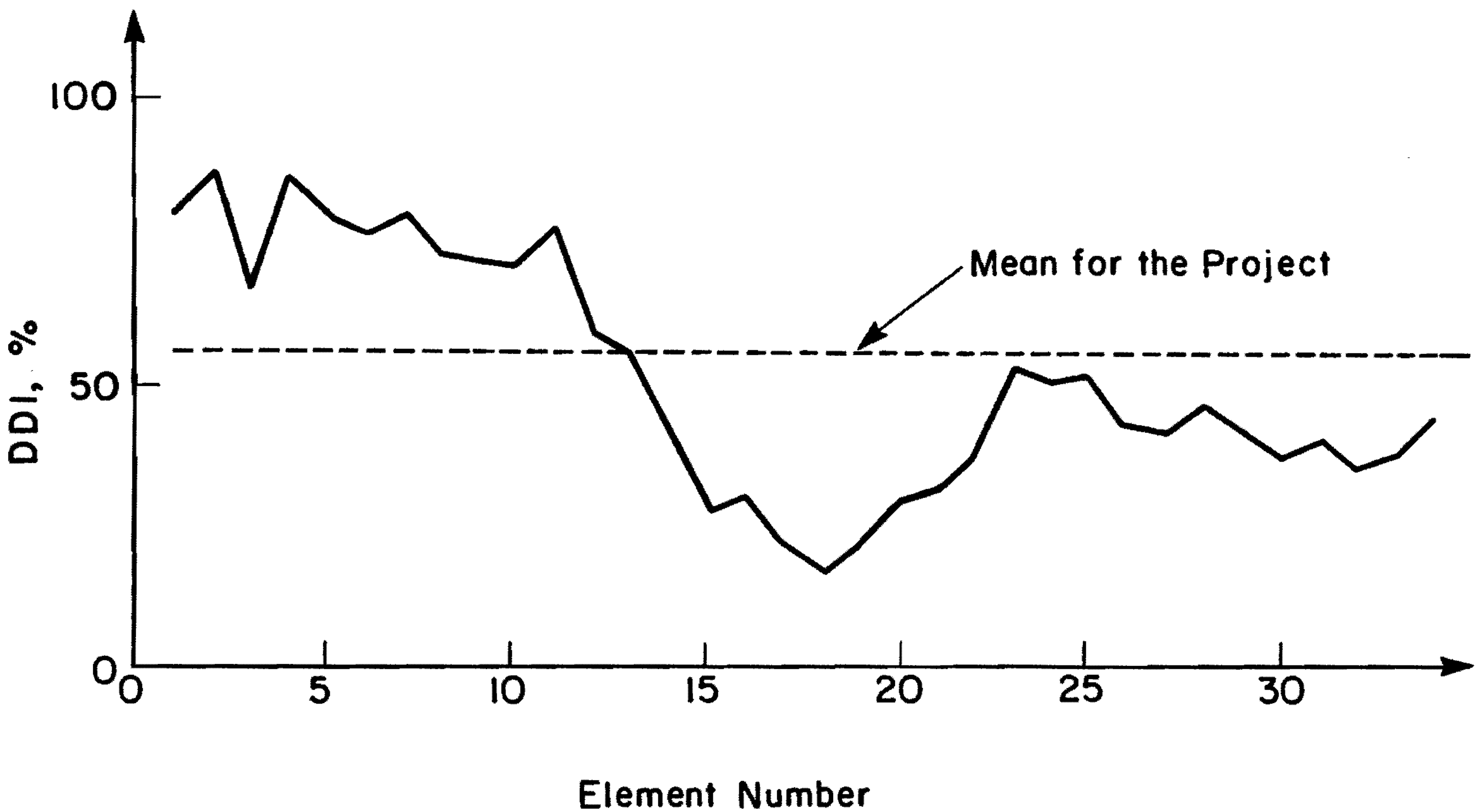


Fig 2.24. Conceptual illustration of the DDI within-project variation.

allowable error and a confidence level are selected. At the network level, a single number is used to describe the distress condition of a CRCP section. Nonetheless, it becomes necessary to obtain information about the within-section variation when defining the most adequate rehabilitation strategies for a CRCP section at the project level.

Finally, new criteria have been used to establish the terminal and ideal conditions of a CRCP element. A terminal condition exists when a large severe punchout occurs in both of two adjacent CRCP elements. Hence, in order to estimate the DDI of a given CRCP element, it is necessary to consider the distress condition of its adjoining elements.

CHAPTER 3. ESTIMATION OF SAMPLE SIZE FOR CONDITION SURVEY OF CRC PAVEMENTS

One of the major deficiencies of the current condition surveys procedures is the lack of a rational method for estimating the number of observations that are required in order to obtain a representative sample. This estimation of condition survey sample size has not been possible, largely because a single parameter or index is commonly used to express the distress condition of a given pavement section, without accounting for the variation of distress within that section. The approach presented in Chapter 2 permits the estimation of both the mean and the standard deviation of the deflection distress index values for a CRCP section. These statistical parameters can be used in the various expressions available for sample size estimation. The purpose of this chapter is to describe the development and use of a new method for estimating the sample size for a condition survey of a CRCP section by means of the DDI mean and the standard deviation for that section.

DEVELOPMENT OF EXPRESSIONS FOR ESTIMATING THE SAMPLE SIZE FOR CONDITION SURVEY OF CRC PAVEMENTS

The expressions presented herein are based on recent research related to the estimation of the deflection sample size for in-service rigid pavements, which is presented in Refs 4, 12, and 13.

Generally, if the value of the universe standard deviation is known, a level of confidence is specified, and the allowable error in estimating the universe mean is given, then a confidence interval of the universe mean can be produced by selecting a sample of the correct size (Ref 14). Under the assumption of a normal distribution, the formal expression to determine the required sample size is written as

$$n_r = \left[\frac{Z_\alpha \sigma}{e} \right]^2 \tag{3.1}$$

where

n_r = required sample size,

Z_α = abscissa of the normal curve that cuts off an area (level of significance, α) at the tails,

σ = universe standard deviation, and

e = allowable error.

The unbiased estimate of the universe standard deviation is obtained from a representative sample by

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{n - 1}} \tag{3.2}$$

where

$\hat{\sigma}$ = unbiased estimate of the universe standard deviation,

X_i = value of the sample's i^{th} observation,

$\overline{X}$ = sample mean, and

n = sample size.

Since $\hat{\sigma}$ is the parameter commonly available, a Student's t distribution should be used according to statistical theory; thus, Eq 3.1 can be modified as follows:

$$n_r = \left[\frac{t_\alpha \hat{\sigma}}{e}\right]^2 \tag{3.3}$$

where

t_α = t-value corresponding to a certain combination of level of significance, α, and number of degrees of freedom.

Number of degrees of freedom, d.f., is defined as the sample size minus one (n_r - 1).

Either Eq 3.1 or Eq 3.3 can provide an estimate of the required sample size for a given CRCP section if both the mean and the unbiased estimate of the standard deviation of DDI are provided for that section. However, these two expressions do not take into account section length. Hence, in general, for CRCP sections with similar unbiased standard deviations, allowable error, and Z_α (or t_α) values, basically the same required sample size is obtained for both a short section and a considerably longer section (Fig 3.1). This incongruity can be surmounted by considering the fact that there a finite number of elements for a given design section, which makes necessary the application of a finite multiplier, namely,

$$\frac{N - n_r}{N - 1} \tag{3.4}$$

where

N = population or universe size.

N can also be defined as the number of elements in a given CRCP section, that is,

$$N = \frac{L}{\bar{c}} \tag{3.5}$$

where

L = CRCP section length, feet, and

$\bar{c}$ = average crack spacing, feet.

Average crack spacing can be recorded when conducting a condition survey.

If the universe standard deviation of DDI is unknown, the estimated standard error of the mean of DDI for a finite universe is computed by

$$\hat{\sigma}_{\overline{DDI}} = \frac{\hat{\sigma}_{DDI}}{\sqrt{n_r}} \sqrt{\frac{N - n_r}{N - 1}} \tag{3.6}$$

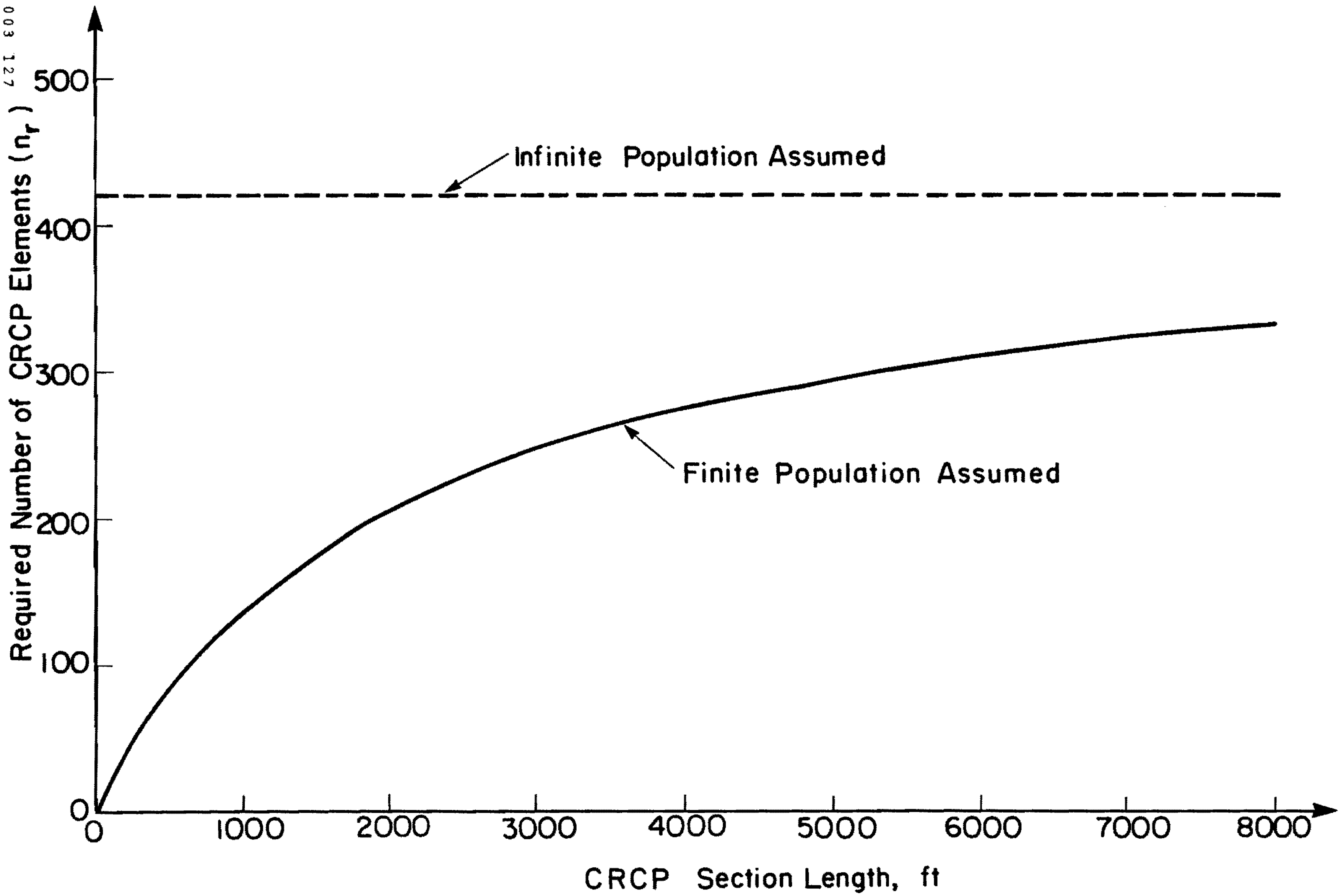


Fig 3.1. Comparison between sample size resulting from the approach that assumes an infinite universe and that estimated by applying the finite multiplier for a CRCP section of varying length and an average crack spacing of 5 ft, $\hat{\sigma}_{DDI}$ = 50%, e = 4%, and a 90-percent confidence level.

where

$\hat{\sigma}_{\overline{DDI}}$ = estimated standard error of the mean of DDI, percent, and

$\hat{\sigma}_{DDI}$ = unbiased estimate of the DDI universe standard deviation, percent.

Let the allowable error be equal to

$$e = \overline{DDI} - \mu \tag{3.7}$$

where

$\overline{DDI}$ = DDI sample mean, percent, and

μ = DDI universe mean, percent.

e can also be expressed as

$$e = t_\alpha \frac{\hat{\sigma}_{DDI}}{\sqrt{n_r}} \sqrt{\frac{N - n_r}{N - 1}} ,$$

or

$$e = t_\alpha \hat{\sigma}_{DDI} \sqrt{\frac{N}{n_r (N - 1)} - \frac{1}{N - 1}} \tag{3.8}$$

Solving for n_r, after some algebraic simplifications,

$$n_r = \frac{N t_\alpha^2 \hat{\sigma}_{DDI}^2}{(N - 1) e^2 + t_\alpha^2 \hat{\sigma}_{DDI}^2} \tag{3.9}$$

By dividing both the numerator and the denominator of the right-hand side of Eq 3.9 by $t_\alpha^2 \hat{\sigma}_{DDI}^2$, the following alternate equation is obtained:

$$n_r = \frac{N}{\dfrac{(N-1)\,e^2}{t_\alpha^2\,\hat{\sigma}^2_{DDI}} + 1} \tag{3.10}$$

In Refs 12 and 13, a normal distribution was considered in the estimation of n_r by assuming that the universe standard deviation was approximately equal to $\hat{\sigma}_{DDI}$. This simplified computations, since Z_α is solely dependent on the particular confidence level selected, whereas t_α is obtained for a given confidence level and number of degrees of freedom, which makes necessary an iterative process to compute n_r. Additionally, it was found that there was no significant difference in the sample sizes estimated with both approaches for a large number of combinations of values of the variables in Eq 3.10. Hence, for practical purposes, the sample will be large enough so as to use the following expression:

$$n_r = \frac{N}{\dfrac{(N-1)\,e^2}{Z_\alpha^2\,\hat{\sigma}^2_{DDI}} + 1} \tag{3.11}$$

Normally, the size of the population is sufficiently large so that the difference between N and N-1 is negligible. Hence, the finite multiplier can be modified:

$$\frac{N - n_r}{N - 1} \cong \frac{N - n_r}{N} \tag{3.12}$$

Finally, a less complicated version of Eq 3.11 is obtained:

$$n_r = \frac{1}{\left[\dfrac{e}{Z_\alpha\,\hat{\sigma}_{DDI}}\right]^2 + \dfrac{1}{N}} \tag{3.13}$$

It is recommended that e be selected as a percent of the mean DDI of a given CRCP section. If there is no previous DDI information available about a particular CRCP section, then a pilot sample could be taken so that the tentative number of CRCP elements required for the condition survey can be estimated.

DISCUSSION OF RESULTS

Expressions to estimate the number of elements required for CRCP condition surveys at the project level, in which a finite population is considered, have been derived. Figure 3.1 shows the estimated sample size for both an infinite and a finite deflection population at different section lengths for a CRC pavement with an average crack spacing of 5 feet and a particular combination of allowable error and DDI standard deviation. It can be observed that for short-length sections, the assumption of an infinite DDI population causes a significant overestimation of the number of elements required. This trend is also true for other combinations of values.

The findings from this chapter, as well as those from Chapter 2, have been incorporated into a computer program, DDI1. This program processes condition survey data of a CRCP section to estimate the values of its DDI mean and standard deviation. Since, in order to estimate the DDI of a given element, it is necessary to consider the distress condition of its adjoining elements, subsamples of at least 3 elements within a sample should be selected. It is suggested that these subsamples be taken at distance intervals approximately constant. This process is sometimes referred to as systematic sampling (Ref 15). If the first CRCP element of the sample is selected at random, then theoretically every element has the same likelihood of selection (Ref 14).

CHAPTER 4. DESCRIPTION OF COMPUTER PROGRAM DDI1

DDI1 is the first version of a computer program for estimating the deflection distress index of a CRC pavement from condition survey data. Field information is recorded as indicated in the manual for CRCP condition surveys at the project level (Appendix C) and analyzed by DDI1, which estimates the present DDI of every element surveyed. Additionally, this program attempts to predict the change in the mean and standard deviation of DDI for a given CRCP section resulting from the execution of up to four different rehabilitation strategies. Figure 4.1 is a general flow chart of computer program DDI1. The different subroutines and procedures shown in this figure will be subsequently explained in this chapter.

MAIN PROGRAM

First, DDI1 reads the user-specified options, which include the confidence level and allowable error for estimation of condition survey sample size, and the selected rehabilitation strategies. Then, the program reads and prints the information collected for every CRCP element included in the condition survey. A complete printout from program DDI1, corresponding to an example problem, is presented in Appendix F, whereas the form for recording condition survey data is included in Appendix C.

Asphalt and concrete patches in good condition are converted to their equivalent condition, according to the process described in Chapter 2. The next major step involves the estimation of the present distress index for every element surveyed, which is defined in Fig 4.2 as the minimum DDI value at both the left and right cracks of a CRCP element. The DDI value of every element at its right crack is estimated by means of subroutine EDI. The DDI value at the left crack of a given element is defined as

$$DDI_i\ (\ell) = DDI_{i-1}\ (r) \tag{4.1}$$

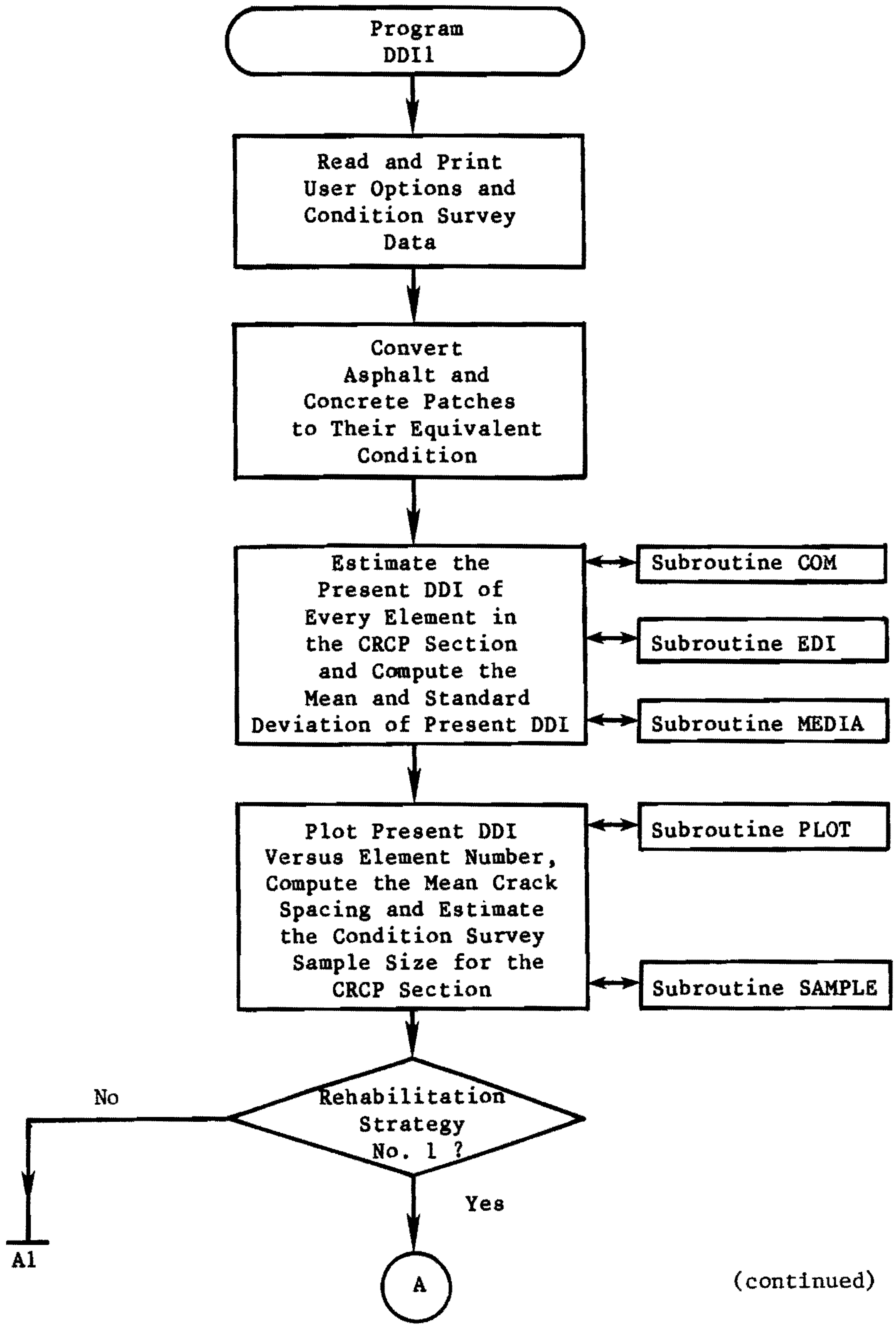


Fig 4.1. General flow diagram of computer program DDI1.

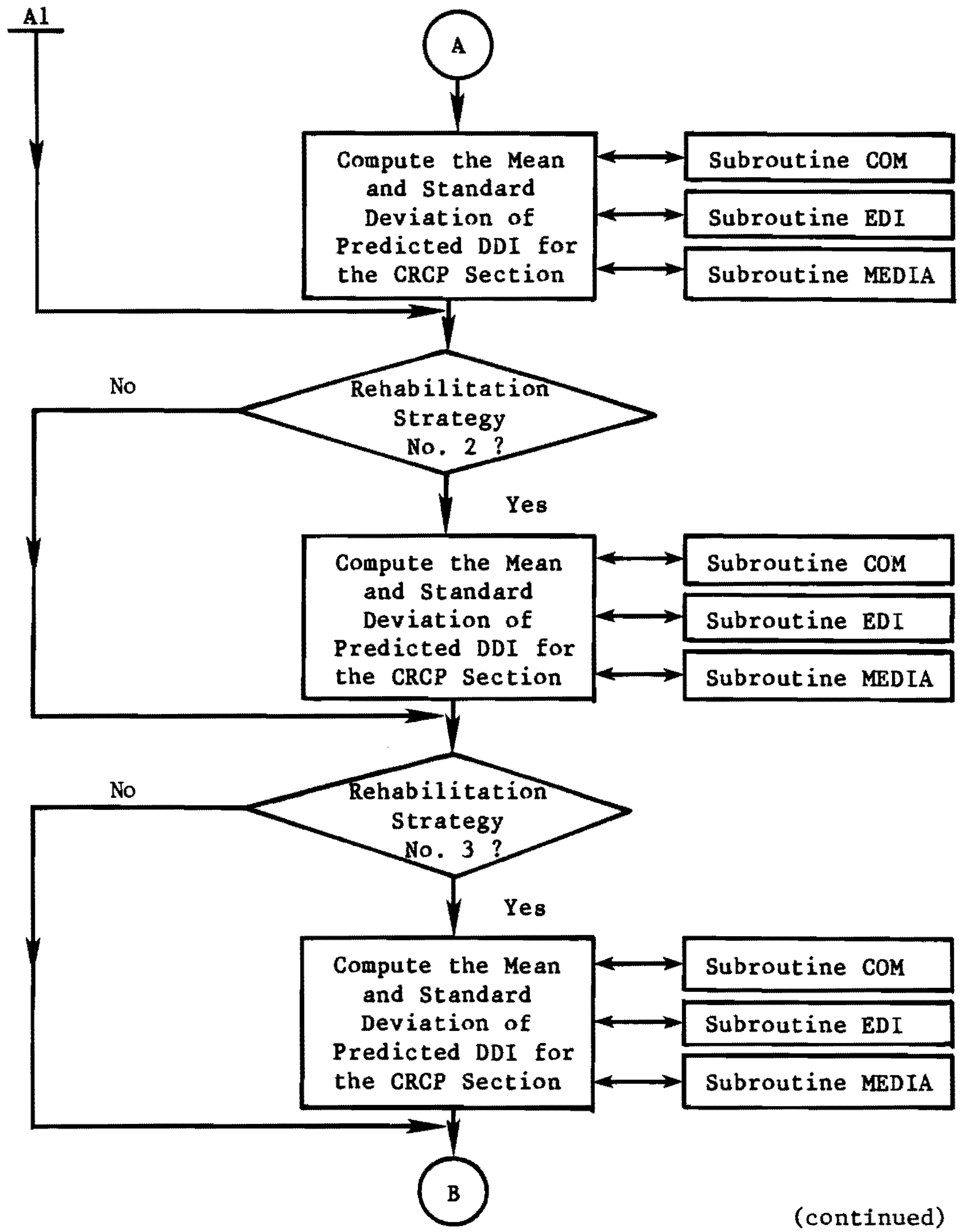


Fig 4.1. (continued)

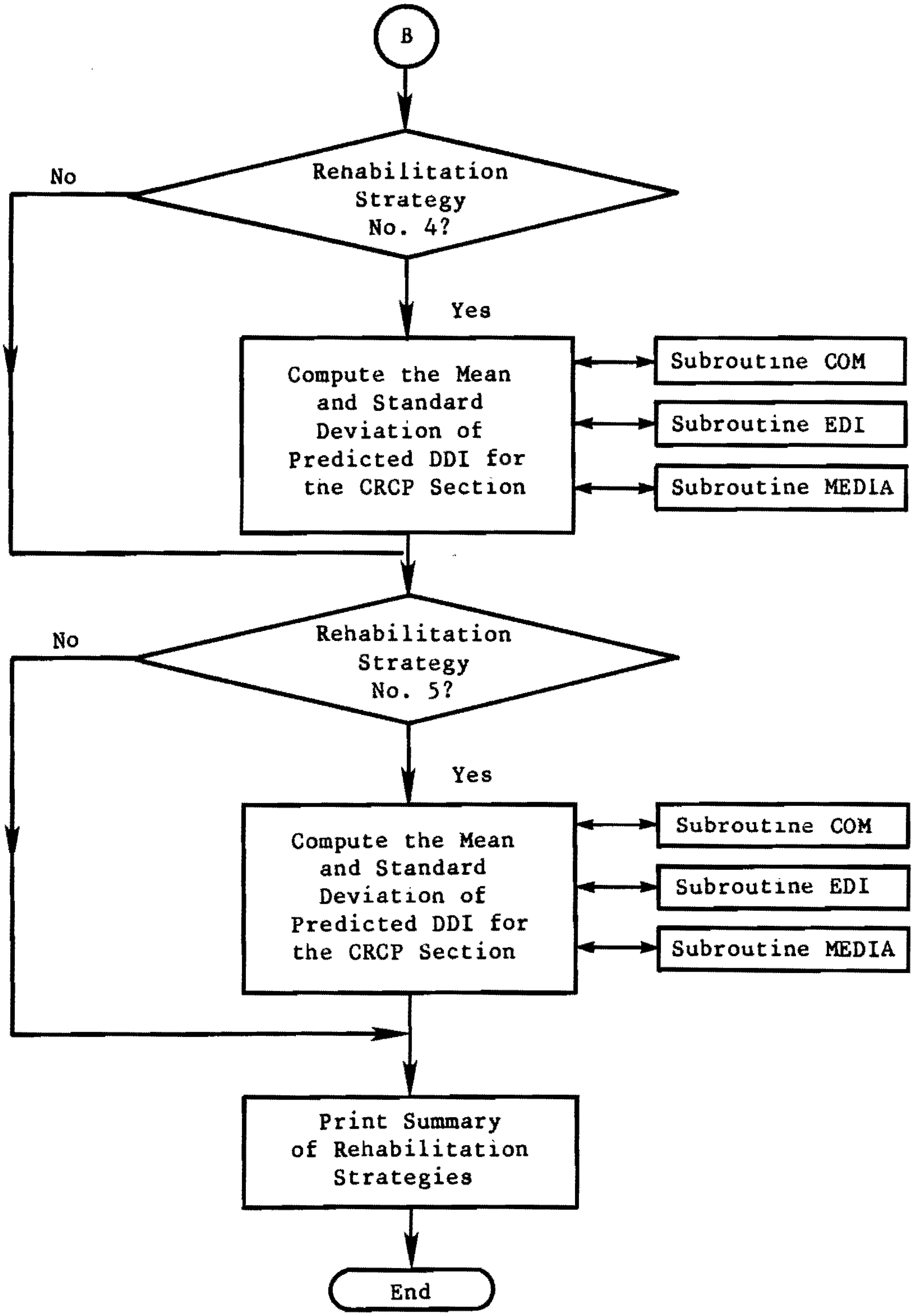
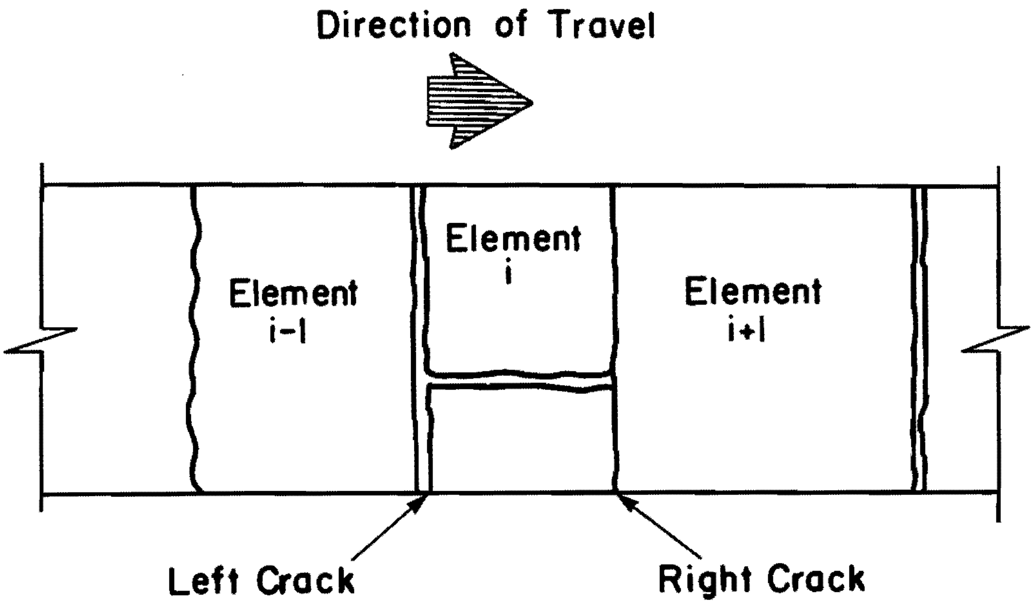


Fig 4.1. (continued).



$$DDI_i = \text{Min}\left[DDI_i\,(l),\ DDI_i\,(r)\right]$$

Where:

DDI_i = Deflection Distress Index of CRCP Element i, %

$DDI_i\,(l)$ = DDI at the Left Crack of Element i, %

$DDI_i\,(r)$ = DDI at the Right Crack of Element i, %

Fig 4.2. Estimation of the DDI of a CRCP element as the minimum DDI value at both the left and right cracks.

where

$DDI_i\ (\ell)$ = deflection distress index at the left crack of element i, percent, and

$DDI_{i-1}\ (r)$= deflection distress index at the right crack of element i-1, percent.

Once the deflection distress index for every element surveyed in a CRCP section has been estimated, the mean and the standard deviation of the present DDI are computed. The term "present" is used to indicate that the estimated DDI corresponds to the distress condition of a CRCP element at the time of the condition survey. The main program subsequently calls subroutine PLOT to generate a plot of present DDI versus element number and subroutine SAMPLE to estimate the required condition survey sample size for the confidence level and allowable error specified by the user. Information regarding the mean crack spacing is also provided by program DDI1. When every element within a given CRCP section is surveyed, mean crack spacing is computed as

$$\bar{x} = \frac{L}{N} \qquad (4.2)$$

where

$\bar{x}$ = average crack spacing, feet,

L = CRCP section length, feet, and

N = number of elements in the CRCP section (population size).

If a sample, not including every element, is taken within a CRCP section, the following expression is used:

$$\bar{x} = \sum_{i=1}^{n} \frac{x_i}{n} \qquad (4.3)$$

where

n = number of CRCP elements in the sample, and

x_i = surveyor's estimate of crack spacing for CRCP element i, feet.

Equation 4.3 involves the possibility of some human error, because the surveyor is asked to enter in the condition survey form (Appendix C) his best estimate of the crack spacing for every CRCP element. Otherwise a considerable amount of time would have to be spent to measure this spacing, especially in large samples. The program informs the user about the approach followed to estimate mean crack spacing, through a message included in the printout.

Computer program DDI-1 continues the analysis by attempting to predict the change in the mean and the standard deviation of the DDI for a given CRCP section due to the execution of the rehabilitation strategies requested by the user. At the end, a summary table is presented that permits an evaluation, in terms of the decrease in the distress of a CRCP section, of the selected rehabilitation strategies.

SUBROUTINE COM

Subroutine COM selects from the condition survey data the combinations of the various factorial arrangements described in Chapter 2 that correspond to every CRCP element analyzed. For a given element, subroutine COM also considers data for the next element (in the direction of travel) and chooses the corresponding combinations of crack spacing, crack load transfer, single punchouts, double punchouts, and punchout size.

The surveyor's estimate of crack spacing for every element is converted to three different levels of crack spacing, depending on its crack-spacing value, namely,

Lower Level: $0 < x_i \leq 3$ (4.4)

Intermediate Level: $3 < x_i \leq 6$ (4.5)

High Level: $6 < x_i$ (4.6)

where

x_i = surveyor's estimate of crack spacing for CRCP element i, feet.

Sometimes, certain single- and double-punchout combinations are the "mirror-image" combinations of equivalent combinations considered in the factorial arrangement. Those combinations are converted to their corresponding "mirror-image" combinations by following the process illustrated in Fig 4.3, in which a certain single-punchout combination is equivalent to combination No. 2 in the factorial arrangement for single-punchout combinations. Symmetrical combinations have the same DDI, basically because of the location at which the two 9,000-pound wheel loads were simulated by computer program SLAB49.

SUBROUTINE EDI

This subroutine contains the DDI value for every cell of the various factorial arrangements considered in the analysis described in Chapter 2. Based on the information provided by subroutine COM, a DDI value that corresponds to the various factorial-arrangement combinations for a given CRCP element is searched for . Additionally, data from the basic factorial arrangements have been expanded to include more cases. For example, the maximum deflections for the crack-spacing combinations in which the crack spacing of elements i+1 and i are 2 and 5 feet, respectively, have been estimated by averaging the maximum deflections corresponding to crack spacing combinations 1 and 2 (Fig 2.5). Then, a DDI value was computed for every case included in these intermediate crack-spacing combinations by following the procedure given in Chapter 2. This resulted in a significant reduction in the total computer cost of the simulation by means of SLAB49. Subroutine EDI was developed in a way that will facilitate its future expansion, if required.

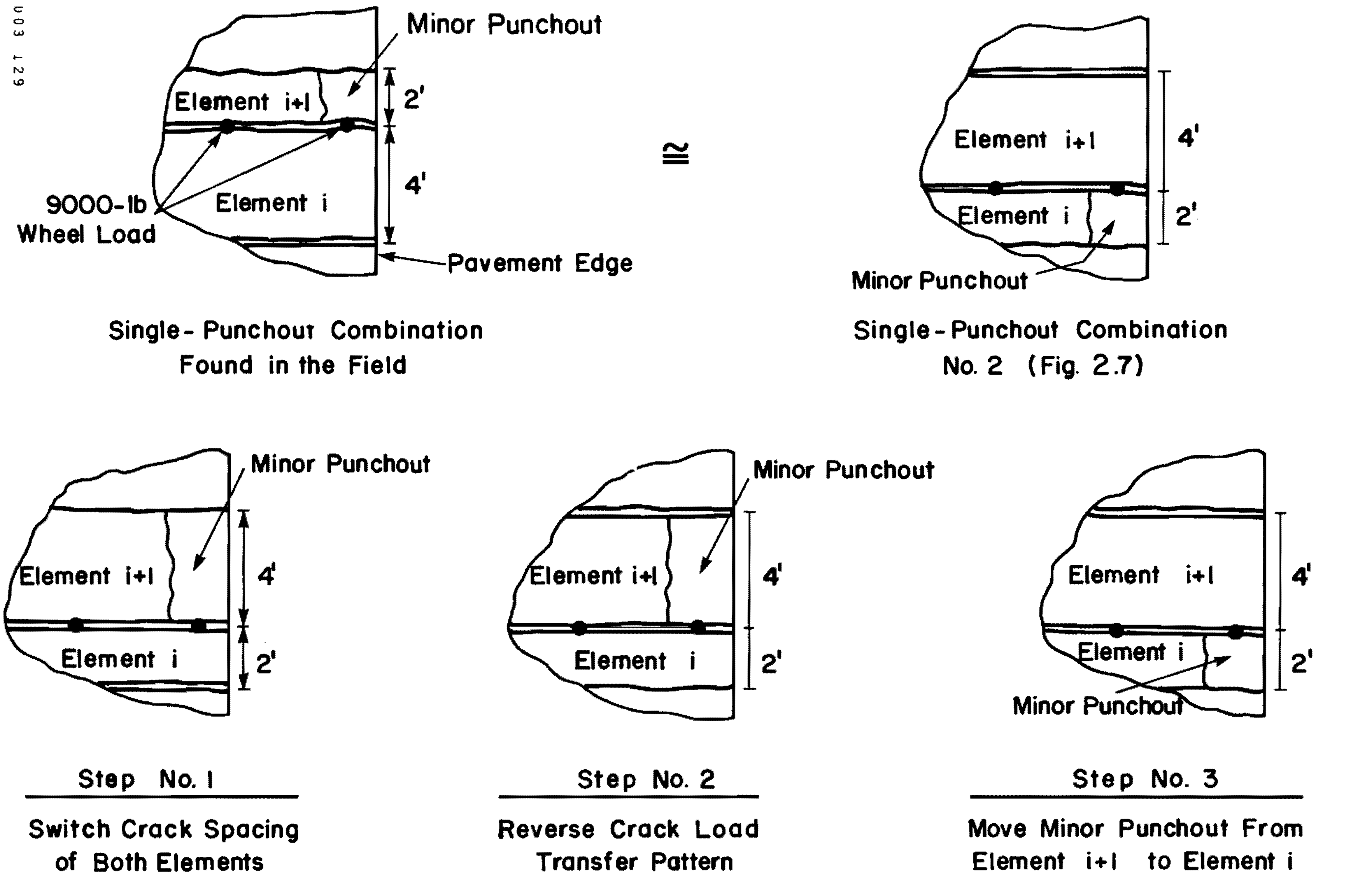


Fig 4.3. Exemplification of the process followed by subroutine COM to convert "mirror-image" combinations to their equivalent condition.

SUBROUTINE MEDIA

Subroutine MEDIA computes the mean and the standard deviation of an array. Equation 3.2 is used to compute the unbiased estimate of the universe standard deviation of the array. This subroutine is repeatedly called to estimate the mean and the standard deviation of DDI. Likewise, output from subroutine MEDIA is used in the estimation of the required condition survey sample size. Subroutine media also prints a cumulative frequency distribution table of the DDI data, thus allowing further analysis of within-project variation of distress. Appendix F includes several cumulative frequency distribution tables for an example CRCP section.

SUBROUTINE PLOT

A plot of present DDI versus element number is provided by this subroutine. Such a plot is particularly useful when studying the within-project variation of present distress index, since it allows the engineer to locate those segments within a given section that have the worst distress condition. Therefore, it provides a refinement in the process of selecting the most adequate rehabilitation strategies to be carried out.

Two different types of plots are possible, depending on whether every CRCP element within a section is surveyed. If every element in a certain CRCP section is analyzed, then a plot such as that presented in Fig 4.4 is produced. However, if a sampling plan is adopted, then DDI data are plotted as shown in Fig 4.5, in which the limits of a given sample are clearly delineated; the minimum number of elements in a sample is three. For both plot types, the DDI value for every CRCP element is printed, so that it does not have to be read directly from the top horizontal axis.

SUBROUTINE SAMPLE

The procedure for estimating sample size for condition survey of CRC pavements explained in Chapter 3 has been incorporated into subroutine SAMPLE. It is required that the user of computer program DD11 input both an allowable error and a confidence level. The allowable error is expressed in

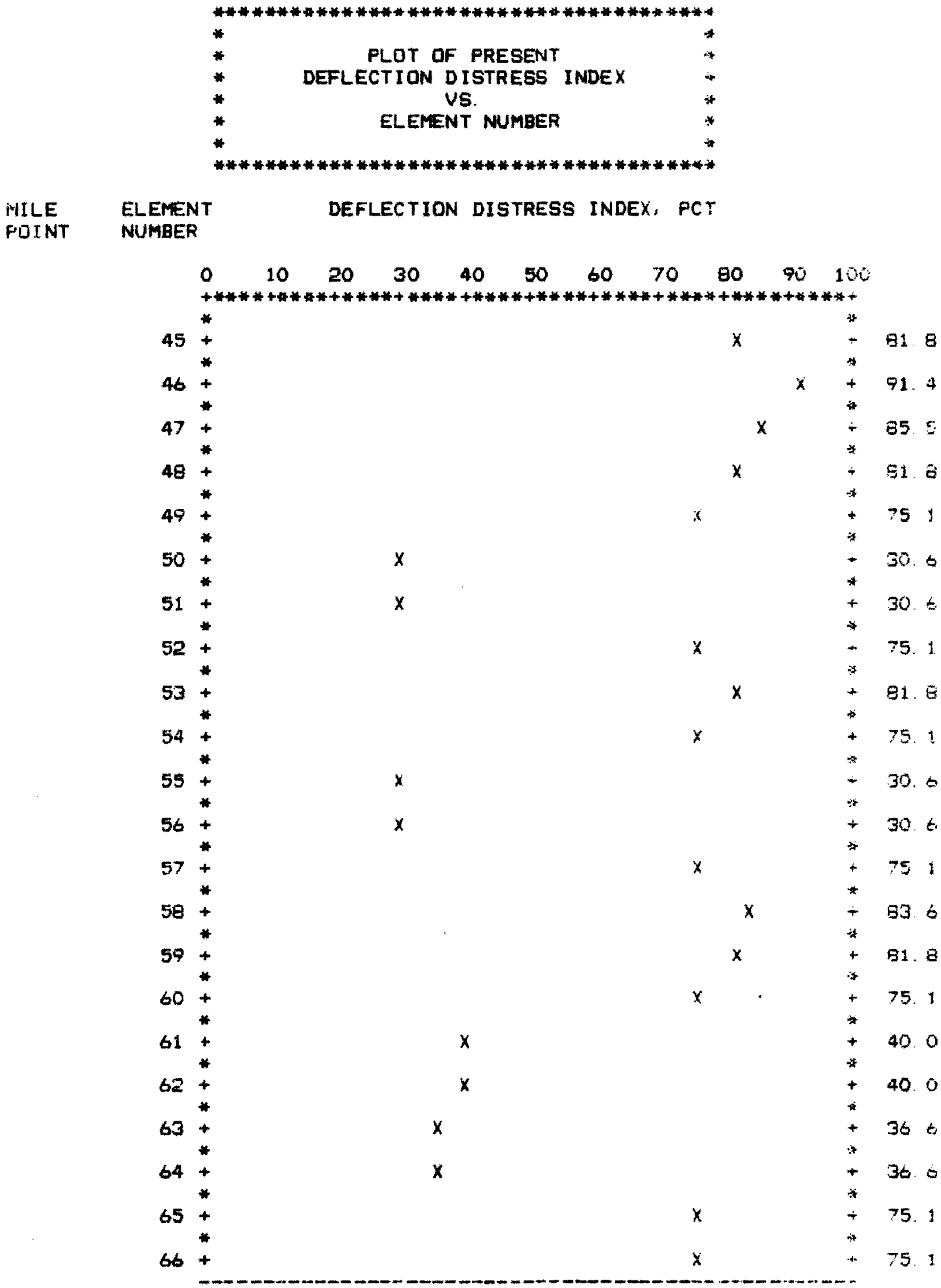


Fig 4.4. Example partial plot of present DDI versus element number when every element within a CRCP section is surveyed.

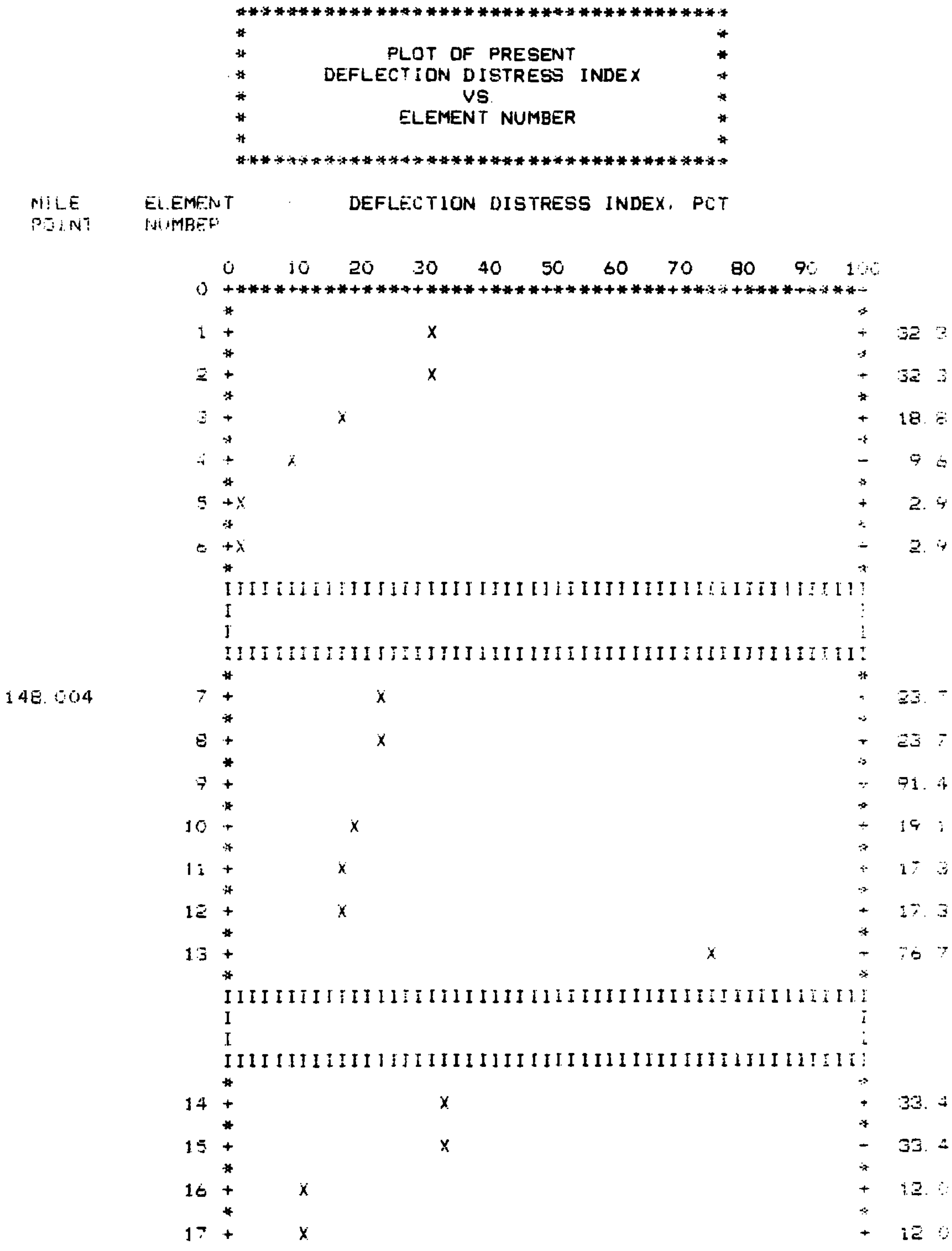


Fig 4.5. Example partial plot of present DDI versus element number when a sampling plan is adopted.

terms of the mean DDI, whereas the confidence level is that corresponding to a two-tail test of significance.

ANALYSIS OF REHABILITATION STRATEGIES

Computer program DDI1 contemplates the estimation of the change in the mean and the standard deviation of DDI of a CRCP section due to performing the rehabilitation strategies specified by the user. It is important to emphasize the fact that this analysis is based on the assumption that a CRCP element when rehabilitated has the same maximum deflection as that for the same element with no distress. For example, program DDI1 estimates the present DDI of a certain CRCP element that exhibits some pumping, as evidenced by the condition survey form. Then, given that the user requested the evaluation of an undersealing operation, the program predicts the DDI for this element after it is rehabilitated. This is done by assuming that its distress condition is equivalent to that of a similar element with no pumping, thereby considering that the grouting operation will be highly effective. In order to differentiate this DDI from that of a given CRCP element at the time of the condition survey, the term "predicted" is used in front of DDI.

The five different rehabilitation strategies that can be evaluated by computer program DDI1 are discussed below.

Rehabilitation Strategy No. 1: Undersealing

If a rigid pavement has been subjected to pumping action for an extended period, it may be necessary to fill the resulting void under the pavement by application of a mud jack. Undersealing material generally consists of a mixture of sand and cement mixed into a slurry, which is then pumped under the slab (Ref 20). The DDI values of only those CRCP elements that showed pumping during the condition survey are estimated again by assuming that after undersealing is applied to those elements, the voids underneath them will be completely filled in. Subroutines COM, EDI, and MEDIA are called to estimate the mean and the standard deviation of the predicted DDI for a CRCP section.

Rehabilitation Strategy No. 2: Repair of Severe Punchouts and Asphalt Patches

Severe punchouts and asphalt patches are "repaired" according to the procedure illustrated in Fig 2.23. Asphalt patches are, in general, just a temporary repair, and their use is not recommended for a CRC pavement. Normally, a low DDI value is computed for an element in which there is an asphalt patch or a severe punchout, as illustrated in Fig 2.22. This rehabilitation strategy is analyzed by program DDI1 in a way similar to that for strategy no. 1.

Rehabilitation Stragegy No. 3: Crack Fusion with Polymer and Repair of Severe Punchouts and Asphalt Patches

Load transfer across open cracks can be restored by using polymer. This relatively new rehabilitation method is considered by computer program DDI1 in conjunction with rehabilitation strategy no. 2 to define rehabilitation strategy no. 3.

Rehabilitation Strategy No. 4: Undersealing and Repair of Severe Punchouts and Asphalt Patches

This strategy is a combination of rehabilitation strategies 1 and 2, and the process for estimating the mean and the standard deviation of the predicted DDI does not differ from that for the first two strategies.

Rehabilitation Strategy No. 5: Undersealing, Repair of Severe Punchouts and Asphalt Patches and Rigid Shoulder Addition

Rehabilitation strategy no. 5 is applied only to flexible-shoulder CRC pavements, and it goes beyond what strategy no. 4 does; it also evaluates the reduction in distress attributable to the addition of a rigid shoulder. However, since in the development of the DDI concept two different criteria were considered for flexible- and rigid-shoulder CRC pavements, results from this rehabilitation strategy cannot be compared directly with those corresponding to the other three strategies. In order to avoid this comparison, a pertinent message is printed by computer program DDI1.

Finally, a summary of the mean and the standard deviation of the predicted DDI values for all the rehabilitation strategies is provided at the end of the printout. The mean and the standard deviation of the present DDI values are also included in the summary for the CRCP section analyzed.

SUMMARY

A description of the main features of computer program DDI1 has been presented in this chapter, and some of the assumptions made in the development of the scheme for estimating deflection distress index from condition survey data have been emphasized. The cost per run of the program depends on the number of elements analyzed and the rehabilitation strategies requested by the user. The input guide for computer program DDI1 is provided in Appendix D.

CHAPTER 5. APPLICATIONS OF COMPUTER PROGRAM DDI1

The purpose of this chapter is to discuss several of the possible applications of computer program DDI1. This is achieved by using condition survey data collected on highway US-59 near Victoria, Texas and highway US-71 near Columbus, Texas were processed by program DDI1. The discussion also presents data for an assumed CRCP section, which includes almost every distress manifestation considered in the analysis described in Chapter 2.

ANALYSIS OF DDI WITHIN-PROJECT VARIATION

Figure 5.1 shows the various distress manifestations and crack spacings considered for a hypothetical CRCP section, which contains 22 elements. A plot of present DDI versus element number for this section was produced by computer program DDI1 (Fig 5.2); the estimated DDI value for every CRCP element is printed at the right-hand vertical axis. It can be observed that present DDI values of 0.0 percent are estimated for elements 20 and 21, since the occurrence of two adjacent large severe punchouts is considered as a terminal condition in the scheme for estimating DDI values from condition survey data (Fig 2.4). An estimated DDI value of 100 percent corresponds to the "right" crack of element 9 (or "left" crack of element 10). However, the DDI value of an element was defined as the minimum DDI value at both the "left" and the"right" cracks of that element (Fig 4.2). Hence, the DDI value at the "left" crack (91.4 percent) was assigned to element 9 by computer program DDI1.

The estimated present DDI for the condition survey data from Victoria, Texas, was plotted for each of the 132 elements contained in the 500-foot CRCP section selected. Figure 5.3 shows the present DDI for the first 22 elements. Despite the fact that this section has been periodically rehabilitated, both pumping along the pavement edge and severe spalling were the most common distress manifestations observed, although pumping occurs only at the beginning of the CRCP section. Severe punchouts that were recorded by the CTR staff in previous surveys had been repaired with portland

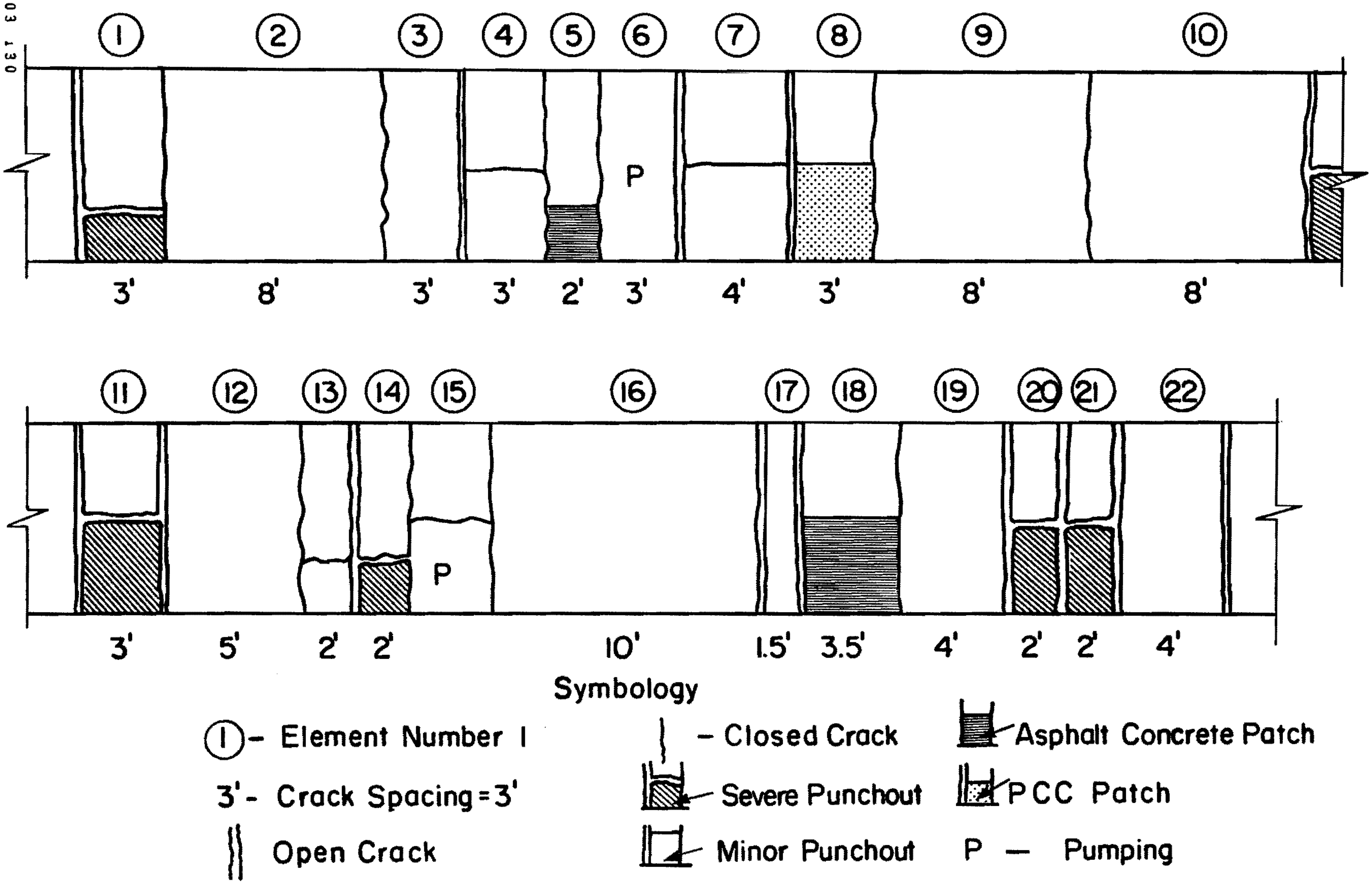


Fig 5.1. Hypothetical CRCP section analyzed by computer program DDI1.

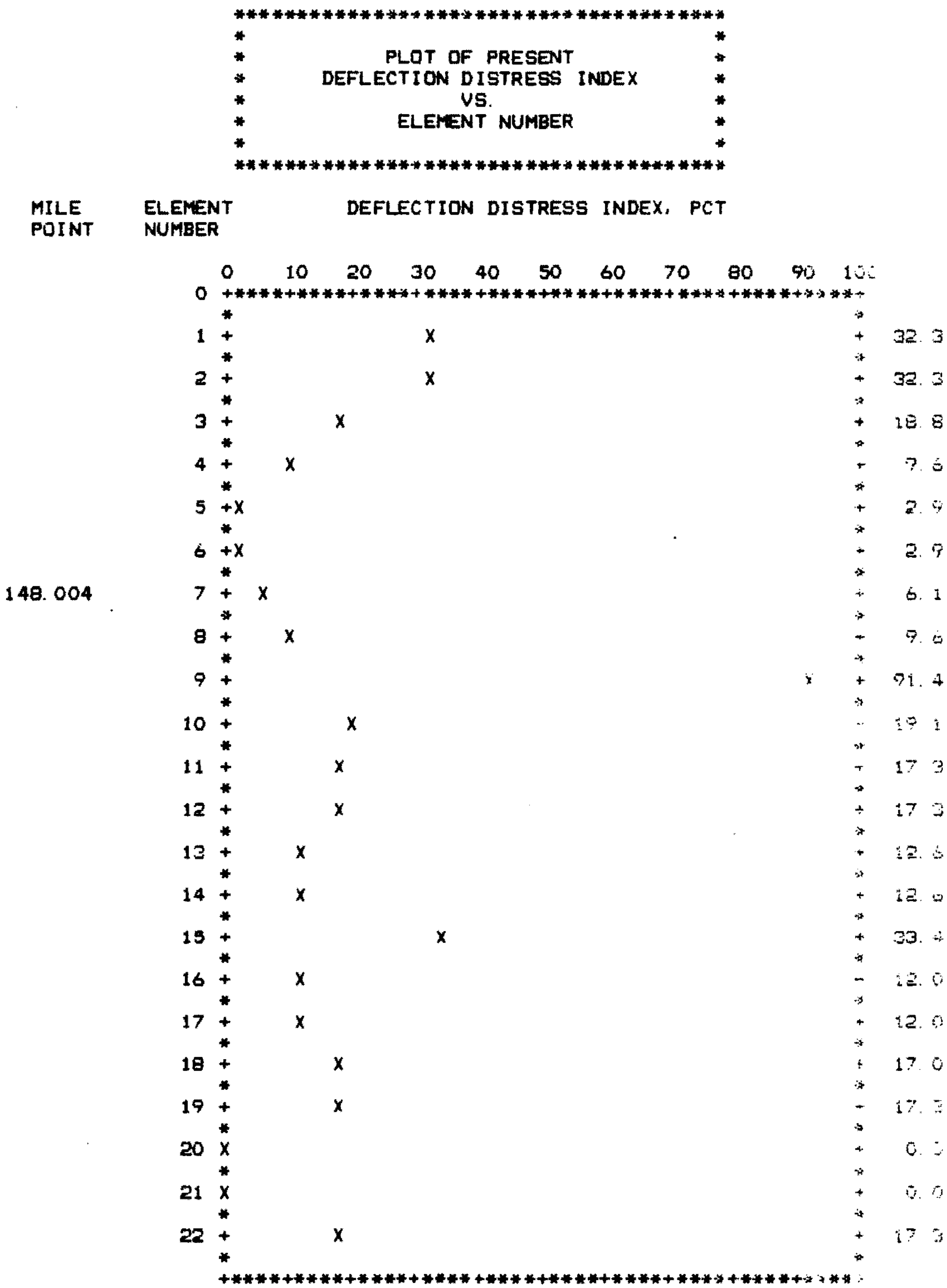


Fig 5.2. Plot of present DDI versus element number for the hypothetical CRCP section produced by computer program DDI1.

cement concrete, and these patches did not, at that time, exhibit any distress. It can be observed in Fig 5.3 that the mean present DDI for the first 22 elements of the CRCP section has a very low value (about 34 percent). However, if the whole section is considered, the value of the mean present DDI increases significantly (Table 5.1).

Figure 5.4 is a plot of present DDI versus element number generated from the condition survey information for the first 22 elements of a 500-foot CRCP section at Columbus, Texas. This section of rigid-shoulder CRCP was constructed about three years ago and showed very little distress at the time of the survey. Severe spalling was the distress manifestation observed within that section, in only eight different CRCP elements (out of a total of 116 elements). The mean present DDI for the first 22 elements of this CRCP section has a relatively high value (about 84 percent).

Table 5.1 provides a comparison of the values of selected statistical parameters for the three CRCP sections analyzed by computer program DDI1. It can be observed that the lowest value for the mean of the present DDI was estimated for the hypothetical CRCP section. Likewise, due to the variety of distress manifestations exhibited by this section, a standard deviation of the present DDI higher than the mean value for that index was computed.

The CRCP section at Victoria, Texas, can be divided in two subsections since pumping was observed only in the first 36 elements. These two segments can be considered to be completely different from each other. Subsection A has a mean of the present distress index of 36.6 percent (Table 5.1), due to the occurrence of pumping. Subsection B has much less distress than subsection A. Hence, two different rehabilitation strategies would be needed for the whole section. It can also be observed that the standard deviations of DDI for both subsections are lower than that for the whole CRCP section. This indicates, that by dividing this section, two segments more homogeneous than the whole section have been identified.

The CRCP section at Columbus, Texas, has the highest mean of the present DDI and the lowest standard deviation of the present DDI, among the three sections analyzed. This CRCP section can be considered to have a good distress condition. Subsection A, at Victoria, Texas, and the hypothetical

```
                  ****************************************
                  *                                      *
                  *           PLOT OF PRESENT            *
                  *      DEFLECTION DISTRESS INDEX       *
                  *                 VS.                  *
                  *            ELEMENT NUMBER            *
                  *                                      *
                  ****************************************

MILE     ELEMENT          DEFLECTION DISTRESS INDEX, PCT
POINT    NUMBER

           0    10   20   30   40   50   60   70   80   90   100
         0 +****+****+****+****+****+****+****+****+****+****+
           *                                                 *
         1 +                  X                              +   37.9
           *                                                 *
         2 +                  X                              +   37.9
           *                                                 *
         3 +                  X                              +   37.9
           *                                                 *
         4 +                 X                               +   35.3
           *                                                 *
         5 +        X                                        +   18.5
           *                                                 *
         6 +        X                                        +   18.5
           *                                                 *
         7 +                 X                               +   35.9
           *                                                 *
         8 +                 X                               +   35.9
           *                                                 *
         9 +                 X                               +   35.9
           *                                                 *
        10 +                 X                               +   35.9
           *                                                 *
        11 +                 X                               +   35.9
           *                                                 *
        12 +                 X                               +   36.6
           *                                                 *
        13 +                 X                               +   36.6
           *                                                 *
        14 +                 X                               +   36.6
           *                                                 *
        15 +                 X                               +   35.9
           *                                                 *
        16 +                 X                               +   35.9
           *                                                 *
        17 +                 X                               +   36.6
           *                                                 *
        18 +                 X                               +   36.6
           *                                                 *
        19 +                                        X        +   81.8
           *                                                 *
        20 +        X                                        +   18.8
           *                                                 *
        21 +        X                                        +   18.8
           *                                                 *
        22 +        X                                        +   18.8
           ---------------------------------------------------
```

Fig 5.3. Partial plot of present DDI versus element number for the CRCP section at Victoria, Texas, produced by computer program DDI1.

```
                  ****************************************
                  *                                      *
                  *             PLOT OF PRESENT          *
                  *       DEFLECTION DISTRESS INDEX      *
                  *                  VS.                 *
                  *             ELEMENT NUMBER           *
                  *                                      *
                  ****************************************

MILE     ELEMENT          DEFLECTION DISTRESS INDEX, PCT
POINT    NUMBER

                  0    10   20   30   40   50   60   70   80   90   100
                0 +****+****+****+****+****+****+****+****+****+****+
                  *                                                 *
                1 +                                           X     +   88.1
                  *                                                 *
                2 +                                           X     +   88.1
                  *                                                 *
                3 +                                         X       +   84.5
                  *                                                 *
                4 +                                        X        +   81.1
                  *                                                 *
                5 +                                        X        +   81.1
                  *                                                 *
                6 +                                         X       +   84.5
                  *                                                 *
                7 +                                        X        +   81.1
                  *                                                 *
                8 +                                        X        +   81.1
                  *                                                 *
                9 +                                        X        +   81.1
                  *                                                 *
               10 +                                        X        +   81.1
                  *                                                 *
               11 +                                             X   +   91.8
                  *                                                 *
               12 +                                         X       +   84.5
                  *                                                 *
               13 +                                        X        +   81.1
                  *                                                 *
               14 +                                        X        +   81.1
                  *                                                 *
               15 +                                         X       +   84.5
                  *                                                 *
               16 +                                        X        +   81.1
                  *                                                 *
               17 +                                        X        +   81.1
                  *                                                 *
               18 +                                         X       +   84.5
                  *                                                 *
               19 +                                         X       +   84.5
                  *                                                 *
               20 +                                         X       +   84.5
                  *                                                 *
               21 +                                         X       +   84.5
                  *                                                 *
               22 +                                         X       +   84.5
                  ---------------------------------------------------
```

Fig 5.4. Partial plot of present DDI versus element number for the CRCP section at Columbus, Texas, produced by computer program DDI1.

TABLE 5.1. COMPARISON OF THE VALUES OF THREE DIFFERENT STATISTICAL PARAMETERS ESTIMATED BY COMPUTER PROGRAM DDI1 FOR THE THREE CRCP SECTIONS ANALYZED

CRCP Section	Total Number of Elements	Mean of Present DDI, %	Standard Deviation of Present DDI, %	Mean Crack Spacing, ft
Hypothetical	22	17.9	19.0	2.7
at Victoria, Texas				
Whole Section	132	61.0	23.7	3.8
Subsection A	36	36.6	12 2	4.0
Subsection B	96	70.6	19.3	3.7
at Columbus, Texas	116	78.1	13.6	4.3

section are examples of CRCP sections in poor distress condition. Additionally, it must be remembered that the criterion used for deriving the present DDI in rigid-shoulder CRC pavements is different from that for flexible-shoulder CRC pavements. Therefore, for the same mean present DDI value, a rigid-shoulder CRCP can be expected to carry significantly more axle-load applications than a flexible-shoulder CRCP. As explained in Chapter 2, the existence or the addition of a rigid shoulder results in reduced deflections and stresses in the CRC pavement.

EVALUATION OF POSSIBLE REHABILITATION STRATEGIES

Computer program DDI1 predicts the deflection distress index for those elements showing some type of distress after they are rehabilitated. As explained in Chapter 5, this prediction is based on the assumption that a CRCP element after being rehabilitated has a DDI value that would correspond to that element with no distress.

Table 5.2 is a summary of the predicted mean and the standard deviation of the DDI after several rehabilitation strategies are carried out, and it presents data for three different CRCP section. In the section at Victoria, Texas, it is possible to predict the mean and the standard deviation of the DDI corresponding to undersealing, undersealing and rigid-shoulder addition, and crack fusion with polymer. Neither severe punchouts nor asphalt patches were recorded in that section. Open cracks were the only distress manifestion observed in the CRCP section at Columbus, Texas.

Undersealing has a small effect on the mean of the deflection distress index for the hypothetical section, since only two elements exhibit pumping. This rehabilitation strategy performed on the CRCP section at Victoria, Texas, however, would result in a significant increase in the mean of the deflection distress index. Such an increment is due to the fact that pumping along the pavement edge was the most common type of distress encountered in that section.

If severe punchouts and asphalt patches were repaired, an important increase in the mean of DDI would be obtained for the hypothetical section, since those distress manifestations occur in many CRCP elements within that

TABLE 5.2. SUMMARY OF REHABILITATION STRATEGIES FOR THREE DIFFERENT CRCP SECTIONS.

CRCP Section	Rehabilitation Strategy No. *	Mean of DDI, %	Standard Deviation of DDI, %
Hypothetical	None	17.9	19.0
	1	19.3	19.3
	2	54.3	33.3
	3	72.2	20.5
	4	60.4	32.2
	5	64.7	27.1
At Victoria, Texas	None	61.0	23.7
	1	69.9	21.5
	3	73.0	20.0
	5	70.6	21.3
At Columbus, Texas	None	78.1	13.6
	3	83.5	3.0

*Rehabilitation Strategy No.
1. Undersealing
2. Repair of severe punchouts and asphalt patches
3. Crack fusion with polymer and repair of severe punchouts and asphalt patches
4. Undersealing and repair of severe punchouts and asphalt patches
5. Undersealing, repair of severe punchouts and asphalt patches and rigid-shoulder addition.

section. Rehabilitation strategy no. 3 produces the most significant increase in predicted DDI in all three CRCP sections. These results stress the importance of maintaining a good load transfer across transverse cracks in CRC pavements.

There is an increment in the mean of the DDI when rehabilitation strategy no. 5 is carried out on the CRCP sections with a flexible shoulder (hypothetical and that at Victoria, Texas). Nevertheless, results for this rehabilitation strategy should not be compared directly with those corresponding to the other rehabilitation strategies. This comparison should be avoided because flexible- and rigid-shoulder CRC pavements were considered separately in the development of the DDI concept.

ESTIMATION OF CONDITION SURVEY SAMPLE SIZE

Computer program DDI1 can be used to attempt to solve one of the most common problems associated with CRCP condition surveys at the project level, i.e., the estimation of the number of elements required for obtaining an adequate estimate of the mean of the deflection distress index of a CRCP section. As an example of this convenient feature of program DDI1, data for the three sections analyzed are used in Table 5.3 to estimate the condition survey sample size for various combinations of confidence level and allowable error. It can be observed that the required number of CRCP elements increases with the confidence level desired but decreases with allowable error. Furthermore, the condition survey sample size, in relation to the total number of elements, is very high in the hypothetical CRCP section This is the result of to the significant within-project variation of the present DDI. As explained above, the value of the standard deviation of the present DDI is higher than the value of the mean of the present DDI for that section. The CRCP section at Columbus, Texas, on the contrary, shows an insignificant within-project variation. This results in a small condition survey sample size for every combination of confidence level and allowable error analyzed for that section.

In order to select the most adequate sample size for a given CRCP section, provided there are condition survey data available, consideration

TABLE 5.3. CONDITION SURVEY SAMPLE SIZE FOR VARIOUS COMBINATIONS OF CONFIDENCE LEVEL AND ALLOWABLE ERROR CORRESPONDING TO THE THREE CRCP SECTIONS ANALYZED

CRCP Section	Total Number of Elements	Confidence Level, %	Allowable Error, * %	Required Number of Elements
			5	22
		80	10	20
			20	15
			5	22
Hypothetical	22	90	10	21
			20	18
			5	22
		96	10	22
			20	19
			5	57
		80	10	21
			20	6
			5	73
at Victoria, Texas	132	90	10	31
			20	10
			5	87
		96	10	43
			20	15
			5	17
		80	10	5
			20	2**
			5	26
at Columbus, Texas	116	90	10	8
			20	3
			5	36
		96	10	12
			20	4

*Allowable error is expressed as a percent of the mean of present DDI for each section. The values of both the mean and the standard deviation of present DDI for the three CRCP sections are given in Table 5.1.

**Minimum sample size should always be three elements.

should also be given to the different costs associated with the collection of field information at the project level.

EVALUATION OF EFFECTIVENESS OF REHABILITATION STRATEGIES

If a CRCP section that has been rehabilitated is periodically monitored, then computer program DDI1 could be used to estimate its present distress index every time a condition survey is conducted. For example, undersealing was performed about three years ago in the CRCP section at Victoria, Texas; however, pumping along the edge has occurred again in several segments of that section. Hence, the mean of the present DDI for the section gradually decreased as the number of CRCP elements exhibiting pumping increased. This can be interpreted as a relatively low effectiveness of the undersealing operation in those segments of that CRCP section. This analysis could be extended to the evaluation of other rehabilitation strategies, such as repair of severe punchouts and rigid-shoulder addition.

ESTABLISHMENT OF REHABILITATION PRIORITIES FOR CRCP SECTIONS

The network-level prioritization process for rigid pavements (Ref 10) currently used in Texas is based on the value of a distress index that is estimated from condition survey information for every rigid section analyzed. However, a single number is used to denote the distress condition of a given pavement section, without accounting, in any way, for the variation of distress within that section. A significant refinement could be introduced to that process if information corresponding to the cumulative frequency distribution of DDI, which is provided by computer program DDI1, were used to establish critical values of DDI, as follows:

$$DDI_c = DDI_{nth} \tag{5.1}$$

where

DDI_c = critical value of DDI, percent; and

DDI_{nth} = the n^{th} percentile DDI on the DDI cumulative frequency distribution, percent.

The n^{th} percentile DDI value is that selected so as to include a certain percent (n) of all the DDI values of the CRCP elements in a section.

Since detailed information is required for estimating DDI for a CRCP section, it is recommended that the critical value of DDI be computed for only those sections that had a high priority at the network level. This process could result in a new assignment of priorities among the CRCP sections analyzed. The same n value should be used to compare several CRCP sections so that consistency in the prioritization process is insured.

RELATIONSHIP BETWEEN REMAINING LIFE AND DDI IN CRC PAVEMENTS

Since both the ideal and the terminal conditions of a CRCP element have been clearly defined in the development of the DDI scheme, it is possible to suggest a relationship between remaining life and DDI in CRC pavements. Unfortunately, remaining life would have to be expressed as a percent, instead f using the conventional units of time or axle load applications. However, this new approach offers a new rational view of the relationship between distress and remaining life in CRC pavements. Strictly speaking, a CRCP section has no remaining fatigue life when all its elements have a DDI value of zero percent, i.e., every element in that section exhibits a large severe punchout and has a crack spacing of less than 3 feet. On the other hand, a CRCP section has a 100 percent remaining life when all its elements show crack spacings greater than 6 feet, have an excellent load transfer acrosstransverse cracks and do not exhibit any type of distress, i.e., an ideal condition.

If the present DDI of a CRCP section is monitored with time or load applications, as recommended in Chapter 6, the relationship between DDI and remaining life of a CRC pavement could be studied in much greater detail. It will be necessary, however, to confine in the meantime such relationship to that expressed by Eq 5.2.

$$RL = DDI \tag{5.2}$$

where

RL = remaining life of a given CRCP section, percent; and

DDI = deflection distress index of the same CRCP section, percent.

This interim approach also permits the analysis of the variation of remainng life within a CRCP section, since the present DDI value of every CRCP element surveyed can be computed. The proposed approach represents a significant improvement over existing methods for estimating the remaining life of a CRCP section, which infer the value of this parameter from a very limited number of observations.

SUMMARY

This chapter has described several applications of computer program DDI1. Since the DDI can be estimated for every CRCP element surveyed, it is possible to study the variation of distress along a given CRCP section. This allows the maintenance engineer to select the best rehabilitation strategies to be carried out on that section. Depending on the within-project variation of distress, he can opt to rehabilitate the most deteriorated section segments or to adopt a single rehabilitation strategy for the whole section. It is also possible to predict the change in the mean DDI due to the execution of various rehabilitation strategies and to estimate the required sample size for future monitoring of a certain CRCP section. Computer program DDI1 can also be used to assign rehabilitation priorities to a group of CRCP sections, if a critical value of DDI is selected for every section analyzed.

Appendix B presents the input data for the hypothetical CRCP section, and the complete output from computer program DDI1 for the same section is included in Appendix F.

CHAPTER 6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter presents a summary of the analyses carried out to derive the scheme for estimating the DDI of CRC pavements from project-level condition survey data and briefly describes the main features of computer program DDI1. The principal conclusions from this study are provided in the second section of this chapter, and recommendations for further research and possible extensions of the concept of the present distress index are made.

SUMMARY

The primary objective of this research was to develop a deflection distress index for project-level evaluation of CRC pavements. The discrete-element computer program SLAB49 was used to predict the immediate response, in terms of maximum deflection, of the most common types of distress manifestations found in CRCP sections in the state of Texas. The computer simulation was divided into two basic groups, flexible- and rigid-shoulder CRC pavements, after the terminal and ideal conditions of a CRCP lane were designated. The terminal condition of a CRCP lane corresponds to the occurrence of two adjacent large severe punchouts. The ideal condition exists when a CRCP lane exhibits crack spacings of about 8 feet, good load transfer across transverse cracks, and no distress manifestations. The highest and the lowest maximum deflections of all the factorial arrangements analyzed were predicted by SLAB49 for the terminal and the ideal conditions, respectively.

Once the maximum deflection for every cell in the various factorial arrangements considered was known, an expression from the AASHO Road Test was used to estimate the number of unweighted axle load applications to reach a present serviceability index (PSI) of 2.5. A DDI value of 0 percent was assigned to the terminal condition of a CRCP lane. A value of 100 percent was established for the ideal condition. The DDI value of a given cell of the factorial arrangements was estimated by computing its corresponding number of unweighted axle load applications to reach a PSI of 2.5 and comparing this value with those for the ideal and terminal conditions. In order to accomplish this, it was necessary to assume a certain variation of DDI with number of axle load applications.

Since an element-by-element approach was followed in the scheme for estimating deflection distress index from condition survey data, it is possible to compute the DDI for every element surveyed. Consequently, both the mean and the standard deviation of DDI can be estimated for a given CRCP section, which represents a major improvement over previous methods used for processing CRCP condition survey data. Statistical expressions are presented for computing the number of CRCP elements required to obtain an adequate estimate of the section mean of the DDI for the selected combination of allowable error and confidence level. These expressions take into account section length and average crack spacing.

A description of computer program DDI1 is also presented. Essentially, this program reads condition survey data, process them and estimates the DDI of every element input. The DDI value for every cell of the various factorial arrangements analyzed was incorporated into the program. Condition survey sample size can be estimated by DDI1 if an allowable error and confidence level are specified by the user. The program can also predict the change in the mean and the standard deviation of the DDI due to carrying out each of five different rehabilitation strategies. Computer program DDI1 was written in FORTRAN 77 so that it can be easily loaded in any computer system. Its cost per run depends on the number of CRCP elements analyzed and the rehabilitation strategies requested by the user. An input guide for DDI1 is included in Appendix D. Several possible applications of this computer program are also presented.

A project-level condition survey manual (Appendix C) has been prepared to present definitions and descriptions of the various distress manifestations considered in the scheme for estimating the DDI value of CRCP sections. This manual also presents the condition survey forms that should be used for recording field information. The data collected on these forms can be easily input to computer program DDI1, since the format of every variable is the same as that required in the DDI1 input guide.

It is important to point out that program DDI1 can be used for only those sections that have a uniform pavement structure along their full lengths. For example, if there are two subbase thicknesses in a given CRCP section, and the section segment with the smaller subbase thickness consistently shows more distress than the other segment, then the difference in distress for the two segments could be attributed to the variation of subbase thickness. A similar example would be that of a CRCP section in which there are two different types of outside shoulder along its length. In these two cases, both CRCP sections would have to be divided into subsections with uniform structures, or characteristics, before computer program DDI1 is used, and these subsections should be analyzed independently.

CONCLUSIONS

The primary conclusions stemming from this study are the following:

(1) Both crack spacing and crack load-transfer have a significant influence on maximum deflection at a given crack. In general, deflection becomes larger as crack spacing is decreased and it decreases as crack load transfer is improved.

(2) CRC pavements constructed with a rigid-shoulder experience lower deflections than similar flexible-shoulder CRC pavements under the same loading conditions.

(3) It is concluded from the study described herein that maximum deflection increases as the size of a severe punchout increases. The reverse trend was observed for minor punchouts, i.e., large minor punchouts exhibit smaller deflections than small minor punchouts, although the size effect is not as important in minor punchouts as in severe punchouts.

(4) The occurrence of two adjacent severe punchouts is by far one of the most serious distress conditions found in CRC pavements. Predicted deflections corresponding to these double-punchout combinations ranked among the highest of the various factorial arrangements analyzed.

(5) A common observation, that pumping beneath the PCC layer results in higher deflections, was supported in this study.

(6) It is possible to estimate the required sample size for condition surveys at the project level by using the mean and the standard deviation of the present DDI and selecting a confidence level and allowable error. CRCP section length and average crack spacing are also required to account for the fact that the number of CRCP elements in a section is always a finite number.

(7) In general, the required condition survey sample size increases with increasing standard deviation of the present DDI, CRCP section length, and confidence level but decreases with increasing allowable error.

(8) The assumption of an infinite population of CRCP elements results in overestimation of the required condition survey sample size in short-length sections; however, estimates based on the assumption of a finite population of CRCP elements approximate those for an infinite population as section length increases.

(9) A scheme for estimating the deflection distress index of a CRC pavement from project-level condition survey data has been derived, and that scheme has been incorporated in computer program DDI1. This program estimates the DDI of every element surveyed, thereby providing information about the variation of distress within a given CRCP section. Computer program DDI1 is very useful in the selection of the most adequate rehabilitation strategy to be carried out on a given CRCP section, since it generates a plot of present DDI versus distance. The program also attempts to predict the change in the mean and standard deviation of DDI due to performing each of five different rehabilitation plans.

(10) Computer program DDI1 can be used to evaluate the effectiveness of rehabilitation strategies at the experimental stage, provided that the rehabilitated CRCP sections are periodically monitored and the resulting data are input to the program.

(11) A significant refinement could be introduced to the network-level prioritization process of CRC pavements if more detailed condition

survey data are collected for those sections that had a high priority at that level. Then, critical values of DDI for every CRCP section considered could be established by using the cumulative frequency distribution of DDI provided by computer program DDI1. Priorities could be subsequently reassigned based on the critical value of the DDI for every section analyzed.

RECOMMENDATIONS

Several recommendations for further research along with possible extensions of the concept of deflection distress index are presented below.

(1) By monitoring the present DDI of a CRCP section with time, the relationship between the deflection distress index and the fatigue life of a CRC pavement could be investigated in greater detail. It is suggested that this long-term monitoring be done on the experimental sections that CTR personnel routinely survey. Adequate traffic data, such as number and lane distribution of axle loads, should be available so that data can be plotted as in Fig 6.1.

(2) More effort should be directed toward research involving the study of the relationship between distress and performance of CRC pavements. This could be accomplished by estimating simultaneously both the PSI and the mean and the standard deviation of the present DDI of selected CRCP sections. Statistical analysis could then be performed with the collected data to try to arrive at a expression that relates these two indices.

(3) An additional advantage of periodically surveying the experimental CRCP sections in the state of Texas would be that of allowing researchers to improve the current procedures for design of CRC pavements. This would permit to study in more detail the effect on the DDI of variables, such as temperature drop and moisture in the pavement, percent of steel reinforcement, concrete tensile strength, etc.

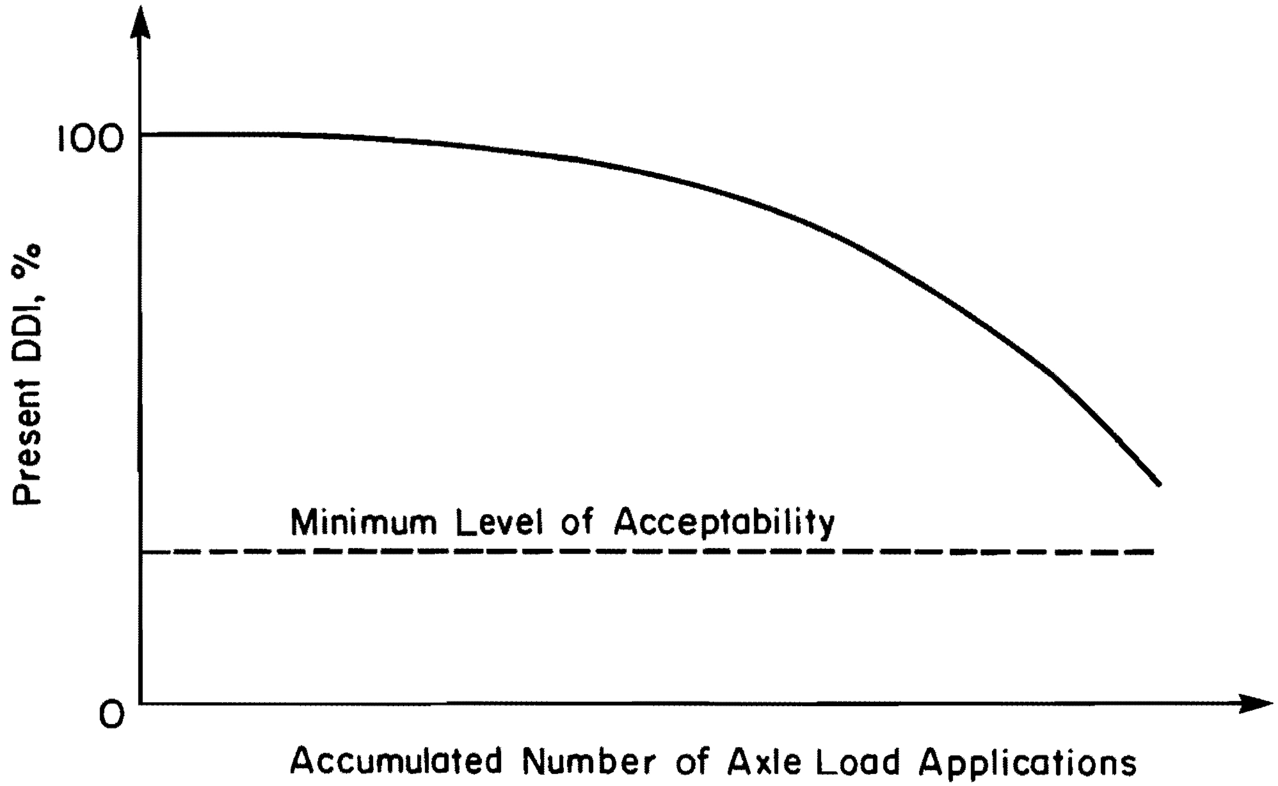


Fig 6.1. Conceptual trend of present DDI with accumulated number of axle load applications for a CRCP section with no rehabilitation.

(4) Inasmuch as maximum deflection at transverse cracks was the immediate response of a CRC pavement predicted by computer program SLAB49, which was used in the derivation of the scheme for estimating DDI, it would be appropriate to select, in the field, distress manifestations that approximate some of those included in the various factorial arrangements analyzed. The maximum deflection due to the application of a certain load could then be measured for each of those distress manifestations selected. These deflections should be normalized so that a comparison can be made with those deflections predicted by SLAB49. These field measurements could be used to validate or to modify the approach followed in the development of the DDI scheme.

(5) It is recommended that deflections from NDT (nondestructive testing) devices and the present DDI be jointly used in the evaluation of CRCP sections that have been selected as candidates for rehabilitation.

(6) The concept of deflection distress index could be extended to other rigid-pavement types, such as jointed and prestressed concrete pavements, and thin-bonded concrete overlays. The first step in the derivation of a DDI for these pavements would involve the identification of the terminal and ideal conditions of an "element". This would be followed by an extensive computer simulation of the behavior of typical distress manifestations when subjected to a given load.

The research described herein represents a significant contribution to the collection and analysis of network-level condition survey data of CRC pavements. The rational procedure developed in this study permits analysis of the CRCP within-project variation of distress. The scheme for project-level evaluation of CRC pavements from distress data constitutes a major improvement over previous methods of analysis of condition survey data. Those methods lump distress manifestations into per mile or 0.2-mile summaries and do not provide any other useful information. An element-by-element approach is followed in the proposed scheme. This resulted in new objective definitions of the ideal and terminal conditions of a CRCP element. Furthermore, an innovative procedure is presented for estimating sample size for project-level condition surveys of CRC pavements.

The scheme for project-level evaluation of CRC pavements from condition survey data will be a very valuable tool in the selection of the rehabilitation strategies for the extensive CRCP network in Texas. This procedure will also be extremely useful in research studies of behavior and performance of CRC pavements.

The concept of deflection distress index, as developed in this study, is applicable only to CRC pavements. The detailed condition survey information required for the scheme for distress evaluation of CRCP sections limits its scope to the project level. This scheme may not be adequate for CRC pavements in which the most common or severe distress manifestations are substantially different from those considered in this study. An important requirement of the proposed procedure is that the CRCP sections analyzed should have reasonably uniform structures or characteristics along their full lengths. This distress evaluation procedure assumes that the severity of every distress manifestation simulated can be assessed by means of the performance equation from static edge deflection developed at the AASHO Road Test. Computer program SLAB49 predicted the maximum deflection for every distress manifestation included in the analysis. However, deflection per se could not be used to establish the DDI value for those distress manifestations, because the relationship between deflection and pavement damage is a nonlinear one.

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APPENDIX A

MAXIMUM DEFLECTIONS FROM COMPUTER PROGRAM SLAB49 USED IN THE DEVELOPMENT OF THE SCHEME FOR ESTIMATING THE DEFLECTION DISTRESS INDEX FROM CONDITION SURVEY DATA

APPENDIX A. MAXIMUM DEFLECTIONS FROM COMPUTER PROGRAM SLAB49 USED IN THE DEVELOPMENT OF THE SCHEME FOR ESTIMATING THE DEFLECTION DISTRESS INDEX FROM CONDITION SURVEY DATA

This appendix is devoted to presenting maximum deflections from computer program SLAB49 corresponding to the factorial arrangements described in Chapter 2. Terms used in Tables A.1 to A.12, such as crack load-transfer combination, crack spacing combination, single-punchout combination, punchout size, double-punchout combination, and punchout-size combination, are defined in Figs 2.5 to 2.11.

TABLE A.1. MAXIMUM DEFLECTIONS, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR NO-PUNCHOUT COMBINATIONS, LEVEL 1: NO PUMPING, FLEXIBLE SHOULDER.

Crack Load Transfer Combination	Crack-Spacing Combination					
	1	2	3	4	5	6
1	2.73	2.03	2.17	1.74	2.03	1.65
2	1.60	1.52	1.59	1.49	1.52	1.43
3	1.56	1.52	1.54	1.49	1.48	1.43
4	2.32	1.82	2.11	1.70	2.02	1.65
5	1.56	1.48	1.56	1.47	1.52	1.43
6	1.52	1.47	1.51	1.46	1.47	1.43
7	2.03	1.82	1.88	1.70	1.82	1.65
8	2.32	2.02	1.93	1.74	1.82	1.65

TABLE A.2. MAXIMUM DEFLECTION, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR NO-PUNCHOUT COMBINATIONS, LEVEL 2: PUMPING, FLEXIBLE SHOULDER

Crack Load Transfer Combination	Crack-Spacing Combination					
	1	2	3	4	5	6
1	3.40	2.60	2.80	2.31	2.60	2.18
2	1.94	1.93	1.94	1.98	1.93	1.90
3	1.89	1.93	1.95	1.98	1.98	1.90
4	2.86	2.32	2.71	2.25	2.60	2.18
5	1.89	1.98	1.89	1.94	1.93	1.90
6	1.93	1.94	1.93	1.94	1.94	1.90
7	2.60	2.32	2.40	2.25	2.32	2.18
8	2.86	2.60	2.47	2.31	2.32	2.18

TABLE A.3. MAXIMUM DEFLECTIONS, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR NO-PUNCHOUT COMBINATIONS, LEVEL 3: NO PUMPING, RIGID SHOULDER.

Crack Load Transfer Combination	Crack-Spacing Combination					
	1	2	3	4	5	6
1	1.51	1.13	1.20	0.97	1.13	0.93
2	0.87	0.84	0.87	0.82	0.84	0.79
3	0.85	0.83	0.85	0.82	0.82	0.79
4	1.28	1.02	1.17	0.95	1.12	0.93
5	0.85	0.82	0.85	0.81	0.83	0.79
6	0.84	0.81	0.83	0.81	0.84	0.79
7	1.13	1.02	1.05	0.95	1.02	0.93
8	1.28	1.12	1.07	0.97	1.02	0.93

TABLE A.4. MAXIMUM DEFLECTIONS, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR NO-PUNCHOUT COMBINATIONS, LEVEL 4: PUMPING, RIGID SHOULDER.

Crack Load Transfer Combination	Crack-Spacing Combination					
	1	2	3	4	5	6
1	1.67	1.25	1.34	1.09	1.25	1.04
2	0.95	0.92	0.95	0.92	0.92	0.89
3	0.92	0.92	0.92	0.92	0.92	0.89
4	1.41	1.13	1.30	1.07	1.25	1.04
5	0.92	0.92	0.92	0.91	0.92	0.89
6	0.92	0.91	0.92	0.91	0.92	0.89
7	1.25	1.13	1.17	1.07	1.13	1.04
8	1.41	1.21	1.19	1.09	1.13	1.04

TABLE A.5. MAXIMUM DEFLECTIONS, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR SINGLE-PUNCHOUT COMBINATIONS, LEVEL 1: NO PUMPING, FLEXIBLE SHOULDER.

Punchout Size	Single-Punchout Combination	Crack-Spacing Combination					
		1	2	3	4	5	6
1	1	1.57	1.54	1.55	1.51	1.48	1.45
	2	2.32	2.03	1.94	1.77	1.83	1.68
	3	2.74	2.06	2.18	1.76	2.03	1.68
	4	3.04	2.42	2.39	2.05	2.22	1.94
	5	1.53	1.50	1.52	1.49	1.48	1.45
	6	2.59	2.41	2.13	2.04	2.00	1.93
2	1	1.56	1.52	1.54	1.49	1.48	1.43
	2	2.32	2.03	1.93	1.74	1.82	1.65
	3	2.73	2.03	2.17	1.74	2.03	1.65
	4	3.27	2.62	2.37	2.16	2.31	2.03
	5	1.52	1.47	1.51	1.46	1.47	1.43
	6	2.77	2.61	2.11	2.15	2.09	2.02

TABLE A.6. MAXIMUM DEFLECTIONS, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR SINGLE-PUNCHOUT COMBINATIONS, LEVEL 2: PUMPING, FLEXIBLE SHOULDER.

Punchout Size	Single-Punchout Combination	Crack-Spacing Combination					
		1	2	3	4	5	6
	1	1.90	1.97	1.96	2.02	1.91	1.94
	2	2.87	2.60	2.48	2.34	2.33	2.22
1	3	3.41	2.64	2.81	2.35	2.60	2.22
	4	3.41	2.67	2.81	2.38	2.61	2.25
	5	1.85	1.91	1.93	1.98	1.91	1.93
	6	2.87	2.66	2.48	2.37	2.33	2.25
	1	1.90	1.93	1.96	1.98	1.91	1.90
	2	2.87	2.60	2.48	2.31	2.33	2.19
2	3	3.41	2.60	2.81	2.32	2.60	2.19
	4	3.69	2.92	2.79	2.53	2.74	2.38
	5	1.85	1.91	1.93	1.94	1.91	1.90
	6	3.09	2.91	2.46	2.52	2.45	2.38

TABLE A.7. MAXIMUM DEFLECTIONS, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR SINGLE-PUNCHOUT COMBINATIONS, LEVEL 3: NO PUMPING, RIGID SHOULDER.

Punchout Size	Single-Punchout Combination	Crack-Spacing Combination					
		1	2	3	4	5	6
1	1	0.86	0.84	0.85	0.82	0.82	0.79
	2	1.28	1.13	1.07	0.97	1.02	0.93
	3	1.51	1.13	1.20	0.97	1.13	0.93
	4	1.59	1.20	1.25	1.03	1.17	0.98
	5	0.84	0.82	0.83	0.81	0.82	0.79
	6	1.35	1.20	1.12	1.03	1.06	0.98
2	1	0.86	0.83	0.85	0.82	0.82	0.79
	2	1.28	1.13	1.07	0.97	1.02	0.93
	3	1.51	1.13	1.20	0.97	1.13	0.93
	4	1.69	1.31	1.31	1.10	1.22	1.05
	5	0.84	0.82	0.83	0.81	0.82	0.79
	6	1.43	1.30	1.18	1.10	1.11	1.05

TABLE A.8. MAXIMUM DEFLECTIONS, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR SINGLE-PUNCHOUT COMBINATIONS, LEVEL 4: PUMPING, RIGID SHOULDER.

Punchout Size	Single-Punchout Combination	Crack-Spacing Combination					
		1	2	3	4	5	6
1	1	0.93	0.91	0.91	0.90	0.90	0.89
	2	1.41	1.25	1.20	1.09	1.13	0.93
	3	1.68	1.25	1.35	1.09	1.25	0.93
	4	1.68	1.26	1.35	1.10	1.26	1.05
	5	0.91	0.90	0.90	0.90	0.90	0.89
	6	1.41	1.26	1.20	1.09	1.13	0.93
2	1	0.93	0.90	0.91	0.90	0.90	0.89
	2	1.41	1.25	1.20	1.09	1.13	0.93
	3	1.68	1.25	1.35	1.09	1.25	0.93
	4	1.78	1.37	1.37	1.17	1.31	1.11
	5	0.91	0.90	0.90	0.90	0.90	0.89
	6	1.50	1.37	1.26	1.17	1.17	1.11

TABLE A.9. MAXIMUM DEFLECTIONS, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR DOUBLE-PUNCHOUT COMBINATIONS, LEVEL 1: NO PUMPING, FLEXIBLE SHOULDER.

Punchout-Size Combination	Double-Punchout Combination	Crack-Spacing Combination 1	2	3	4	5	6
	1	1.73	1.71	1.82	1.80	1.79	1.78
	2	2.57	2.27	2.29	2.10	2.20	2.04
1	3	3.06	2.27	2.60	2.10	2.47	2.04
	4	3.44	2.74	2.90	2.57	2.74	2.52
	5	1.54	1.52	1.55	1.53	1.52	1.51
	1	1.71	1.66	1.79	1.73	1.75	1.69
	2	2.55	2.22	2.25	2.01	2.15	1.94
2	3	3.04	2.22	2.56	2.02	2.42	1.94
	4	3.70	2.93	2.83	2.57	2.81	2.45
	5	1.53	1.48	1.53	1.48	1.50	1.45
	1	1.78	1.74	1.89	1.83	1.84	1.78
	2	2.70	2.34	2.42	2.15	2.29	2.05
3	3	3.27	2.34	2.81	2.15	2.63	2.06
	4	3.70	2.81	3.12	2.57	2.93	2.45
	5	1.53	1.50	1.52	1.49	1.48	1.45
	1	1.77	1.71	1.88	1.80	1.83	1.75
	2	2.69	2.31	2.41	2.13	2.29	2.03
4	3	3.27	2.32	2.81	2.13	2.62	2.04
	4	4.08	3.13	3.39	2.81	3.13	2.65
	5	1.52	1.47	1.51	1.46	1.47	1.43

TABLE A.10. MAXIMUM DEFLECTIONS, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR DOUBLE-PUNCHOUT COMBINATIONS, LEVEL 2: PUMPING, FLEXIBLE SHOULDER.

Punchout-Size Combination	Double-Punchout Combination	Crack-Spacing Combination 1	2	3	4	5	6
	1	1.92	2.01	2.03	2.12	1.99	2.10
	2	2.89	2.68	2.55	2.46	2.44	2.39
1	3	3.43	2.68	2.89	2.57	2.73	2.52
	4	3.44	2.74	2.90	2.57	2.74	2.52
	5	1.87	1.94	1.97	2.05	1.94	2.03
	1	1.90	1.95	1.99	2.02	1.94	1.97
	2	2.87	2.62	2.51	2.35	2.39	2.26
2	3	3.41	2.62	2.84	2.35	2.67	2.26
	4	3.70	2.93	2.83	2.57	2.81	2.45
	5	1.85	1.89	1.94	1.97	1.91	1.94
	1	1.98	2.04	2.11	2.16	2.05	2.09
	2	3.06	2.75	2.72	2.54	2.57	2.41
3	3	3.70	2.75	3.15	2.54	2.93	2.41
	4	3.70	2.81	3.12	2.57	2.93	2.45
	5	1.85	1.91	1.93	1.98	1.91	1.93
	1	1.97	2.01	2.10	2.13	2.04	2.07
	2	3.05	2.75	2.72	2.52	2.57	2.40
4	3	3.69	2.75	3.15	2.52	2.93	2.40
	4	4.08	3.13	3.39	2.81	3.13	2.65
	5	1.85	1.91	1.93	1.94	1.91	1.90

TABLE A.11. MAXIMUM DEFLECTIONS, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR DOUBLE-PUNCHOUT COMBINATIONS, LEVEL 3: NO PUMPING, RIGID SHOULDER.

Punchout-Size Combination	Double-Punchout Combination	Crack-Spacing Combination					
		1	2	3	4	5	6
	1	0.90	0.87	0.91	0.88	0.87	0.85
	2	1.35	1.18	1.15	1.03	1.09	0.99
1	3	1.60	1.18	1.29	1.03	1.21	0.99
	4	1.66	1.27	1.36	1.11	1.27	1.05
	5	0.84	0.82	0.84	0.81	0.82	0.80
	1	0.89	0.87	0.90	0.87	0.87	0.84
	2	1.34	1.17	1.14	1.03	1.08	0.98
2	3	1.59	1.17	1.29	1.03	1.20	0.98
	4	1.79	1.37	1.42	1.18	1.32	1.12
	5	0.84	0.81	0.83	0.81	0.81	0.79
	1	0.93	0.90	0.95	0.92	0.92	0.89
	2	1.41	1.22	1.23	1.10	1.16	1.05
3	3	1.69	1.22	1.40	1.10	1.31	1.05
	4	1.79	1.32	1.47	1.17	1.37	1.12
	5	0.84	0.82	0.83	0.81	0.82	0.79
	1	0.92	0.89	0.91	0.91	0.92	0.88
	2	1.41	1.22	1.09	1.09	1.16	1.04
4	3	1.69	1.22	1.09	1.09	1.30	1.04
	4	1.83	1.44	1.26	1.26	1.44	1.20
	5	0.84	0.82	0.81	0.81	0.82	0.79

TABLE A.12. MAXIMUM DEFLECTIONS, IN. x 10^{-2}, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR DOUBLE-PUNCHOUT COMBINATIONS, LEVEL 4: PUMPING, RIGID SHOULDER.

Punchout-Size Combination	Double-Punchout Combination	Crack-Spacing Combination 1	2	3	4	5	6
	1	0.91	0.93	0.95	0.93	0.91	0.90
	2	1.37	1.26	1.21	1.10	1.14	1.05
1	3	1.01	1.26	1.35	1.10	1.26	1.05
	4	1.66	1.27	1.36	1.11	1.27	1.05
	5	0.89	0.91	0.93	0.92	0.91	0.90
	1	0.90	0.92	0.94	0.92	0.90	0.89
	2	1.36	1.25	1.20	1.09	1.13	1.04
2	3	1.60	1.25	1.35	1.09	1.26	1.04
	4	1.79	1.37	1.42	1.18	1.32	1.12
	5	0.88	0.90	0.92	0.91	0.90	0.89
	1	0.99	0.96	1.00	0.98	0.97	0.95
	2	1.54	1.31	1.29	1.17	1.22	1.12
3	3	1.83	1.31	1.47	1.17	1.37	1.12
	4	1.79	1.32	1.47	1.17	1.37	1.12
	5	0.91	0.90	0.90	0.90	0.90	0.89
	1	0.99	0.95	0.99	0.97	0.96	0.94
	2	1.50	1.31	1.28	1.16	1.21	1.11
4	3	1.83	1.31	1.46	1.16	1.36	1.11
	4	1.83	1.44	1.55	1.26	1.44	1.20
	5	0.91	0.90	0.90	0.90	0.90	0.89

APPENDIX B

DEFLECTION DISTRESS INDEX FOR THE VARIOUS FACTORIAL ARRANGEMENTS CONSIDERED IN THE ANALYSIS

APPENDIX B. DEFLECTION DISTRESS INDEX FOR THE VARIOUS FACTORIAL ARRANGEMENTS CONSIDERED IN THE ANALYSIS

This appendix presents the computed deflection distress index corresponding to the factorial arrangements described in Chapter 2. Terms used in Tables B.1 to B.12, such as crack load-transfer combination, crack spacing combination, single-punchout combination, punchout size, double-punchout combination, and punchout-size combination, are defined in Figs 2.5 to 2.11.

TABLE B.1. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR NO-PUNCHOUT COMBINATIONS, LEVEL 1: NO PUMPING, FLEXIBLE SHOULDER.

Crack Load Transfer Combination	Crack-Spacing Combination					
	1	2	3	4	5	6
1	9.7	30.6	24.1	52.1	30.6	62.3
2	69.1	81.8	70.5	87.4	81.8	100.0
3	75.1	81.8	78.4	87.4	89.3	100.0
4	18.8	44.7	26.7	56.4	31.2	62.3
5	75.1	89.3	75.1	91.4	81.8	100.0
6	81.8	91.4	83.6	93.4	91.4	100.0
7	30.6	44.7	40.0	56.4	40.0	62.3
8	18.8	31.2	36.6	52.1	44.7	100.0

TABLE B.2. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR NO-PUNCHOUT COMBINATIONS, LEVEL 2: PUMPING, FLEXIBLE SHOUDER.

Crack Load Transfer Combination	Crack-Spacing Combination					
	1	2	3	4	5	6
1	3.0	12.0	8.7	19.1	12.0	23.7
2	35.9	36.6	35.9	33.4	36.6	38.6
3	39.3	36.6	35.3	33.4	33.4	38.6
4	7.9	18.8	10.0	21.1	12.0	23.7
5	39.3	33.4	39.3	35.9	36.6	38.6
6	36.6	35.9	36.6	35.9	35.9	38.6
7	12.0	18.8	16.5	21.1	18.8	23.7
8	7.9	12.0	14.7	19.1	18.8	23.7

TABLE B.3. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR NO-PUNCHOUT COMBINATIONS, LEVEL 3: NO PUMPING, RIGID SHOULDER.

Crack Load Transfer Combination	Crack-Spacing Combination					
	1	2	3	4	5	6
1	6.4	27.2	21.2	48.7	27.2	56.7
2	71.8	81.1	71.8	88.1	81.1	100.0
3	77.8	84.5	77.8	88.1	88.1	100.0
4	15.9	40.5	23.6	52.6	28.2	56.7
5	77.8	88.1	77.8	91.8	84.5	100.0
6	81.1	91.1	84.5	91.8	81.1	100.0
7	27.2	40.5	36.3	52.6	40.5	56.7
8	15.9	28.2	33.8	48.7	40.5	56.7

TABLE B.4. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR NO-PUNCHOUT COMBINATIONS, LEVEL 4: PUMPING, RIGID SHOULDER.

Crack Load Transfer Combination	Crack-Spacing Combination					
	1	2	3	4	5	6
1	2.5	17.7	12.7	31.4	17.7	37.6
2	52.6	59.0	52.6	59.0	59.0	66.3
3	59.0	59.0	59.0	59.0	59.0	66.3
4	9.7	27.2	14.8	33.8	17.7	37.6
5	59.0	59.0	59.0	61.3	59.0	66.3
6	59.0	61.3	59.0	61.3	59.0	66.3
7	17.7	27.2	23.6	33.8	27.2	37.6
8	9.7	20.5	22.0	31.4	27.2	37.6

TABLE B.5. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR SINGLE-PUNCHOUT COMBINATIONS, LEVEL 1: NO PUMPING, FLEXIBLE SHOULDER.

Punchout Size	Single-Punchout Combination	Crack-Spacing Combination					
		1	2	3	4	5	6
1	1	73.5	78.4	76.7	83.6	89.3	95.6
	2	18.8	30.6	35.9	49.2	43.9	58.7
	3	9.6	29.1	23.7	50.2	30.6	58.7
	4	5.8	16.0	16.8	29.6	22.2	35.9
	5	80.1	85.5	81.8	87.4	89.3	95.6
	6	12.2	16.2	25.8	30.1	32.3	36.6
2	1	75.1	81.8	78.4	87.4	89.3	100.0
	2	18.8	30.6	36.6	52.1	44.7	62.3
	3	9.7	30.6	24.1	52.1	30.6	62.3
	4	3.8	11.6	17.3	24.5	19.1	30.6
	5	81.8	91.4	83.6	93.4	91.4	100.0
	6	9.1	11.8	26.7	24.9	27.6	31.2

TABLE B.6. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR SINGLE-PUNCHOUT COMBINATIONS, LEVEL 2: PUMPING, FLEXIBLE SHOULDER.

Punchout Size	Single-Punchout Combination	Crack-Spacing Combination 1	2	3	4	5	6
1	1	38.6	34.0	34.6	31.2	37.9	35.9
	2	7.7	12.0	14.5	18.2	18.5	22.2
	3	2.9	11.2	8.5	17.9	12.0	22.2
	4	2.9	10.7	8.5	17.0	11.8	21.1
	5	42.3	37.9	36.6	33.4	37.9	36.6
	6	7.7	10.9	14.5	17.3	18.5	21.1
2	1	38.6	36.6	34.6	33.4	37.9	38.6
	2	7.7	12.0	14.5	19.1	18.5	23.3
	3	2.9	12.0	8.5	18.8	12.0	23.3
	4	1.4	7.1	8.8	13.4	9.6	17.0
	5	42.3	37.9	36.6	35.9	37.9	38.6
	6	5.3	7.3	15.0	13.6	15.2	17.0

TABLE B.7. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR SINGLE-PUNCHOUT COMBINATIONS, LEVEL 3: NO PUMPING, RIGID SHOULDER.

Punchout Size	Single-Punchout Combination	Crack-Spacing Combination 1	2	3	4	5	6
1	1	74.7	81.1	77.8	88.1	88.1	100.0
	2	15.9	27.2	33.8	48.7	40.5	56.7
	3	6.4	27.2	21.2	48.7	27.2	56.7
	4	4.3	21.2	17.7	39.0	23.6	47.0
	5	81.1	88.1	84.5	91.8	88.1	100.0
	6	12.3	21.2	28.2	39.0	35.0	47.0
2	1	74.7	84.5	77.8	88.1	88.1	100.0
	2	15.9	27.2	33.8	48.7	40.5	56.7
	3	6.4	27.2	21.2	48.7	27.2	56.7
	4	2.2	14.2	14.2	30.3	19.7	36.3
	5	81.1	88.1	84.5	91.8	88.1	100.0
	6	9.0	14.8	22.8	30.3	29.2	36.3

TABLE B.8. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR SINGLE-PUNCHOUT COMBINATIONS, LEVEL 4: PUMPING, RIGID SHOULDER.

Punchout Size	Single-Punchout Combination	Crack-Spacing Combination					
		1	2	3	4	5	6
1	1	56.7	61,3	61.3	63.8	63.8	66.3
	2	9.7	17.7	21.2	31.4	27.2	37.6
	3	2.4	17.7	12.3	31.4	17.7	37.6
	4	2.4	17.1	12.3	30.3	17.1	36.3
	5	61.3	63.8	63.8	63.8	63.8	66.3
	6	9.7	17.1	21.2	31.4	27.2	37.6
2	1	56.7	63.8	61.3	63.8	63.8	66.3
	2	9.7	17.7	21.2	31.4	27.2	37.6
	3	2.4	17.7	12.3	31.4	17.7	37.6
	4	0.7	11.4	11.4	23.6	14.2	29.2
	5	61.3	63.8	63.8	63.8	63.8	66.3
	6	6.3	11.4	17.1	23.6	23.6	29.2

TABLE B.9. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR DOUBLE-PUNCHOUT COMBINATIONS, LEVEL 1: NO PUMPING, FLEXIBLE SHOULDER.

Punchout-Size Combination	Double-Punchout Combination	Crack-Spacing Combination					
		1	2	3	4	5	6
1	1	53.2	55.3	44.7	46.5	47.4	48.3
	2	12.6	20.4	19.7	27.1	22.9	30.1
	3	5.6	20.4	12.0	27.1	14.7	30.1
	4	2.7	9.6	7.4	12.6	9.6	13.6
	5	78.4	81.8	76.7	80.1	81.8	83.6
2	1	55.3	61.1	47.4	53.2	51.1	57.5
	2	13.0	22.2	21.1	31.7	24.9	35.9
	3	5.8	22.2	12.8	31.2	16.0	35.9
	4	1.4	7.0	8.3	12.6	8.5	15.2
	5	80.1	89.3	80.1	89.3	85.5	95.6
3	1	48.3	52.1	39.3	43.9	43.1	48.3
	2	10.2	18.2	16.0	24.9	19.7	29.6
	3	3.8	18.2	8.5	24.9	11.4	29.1
	4	1.4	8.5	5.1	12.6	7.0	15.2
	5	80.1	85.5	81.8	87.4	89.3	95.6
4	1	49.2	55.3	40.0	46.5	43.9	51.1
	2	10.4	19.1	16.2	25.8	19.7	30.6
	3	3.8	18.8	8.5	25.8	11.6	30.1
	4	0.0	5.0	3.0	8.5	5.0	11.1
	5	81.8	91.4	83.6	93.4	91.4	100.0

TABLE B.10. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR DOUBLE-PUNCHOUT COMBINATIONS, LEVEL 2: PUMPING, FLEXIBLE SHOULDER.

Punchout-Size Combination	Double-Punchout Combination	Crack-Spacing Combination 1	2	3	4	5	6
	1	37.2	31.7	30.6	26.2	32.8	27.1
	2	7.5	10.5	13.0	15.0	15.5	16.8
1	3	2.8	10.5	7.5	12.6	9.7	13.6
	4	2.7	9.6	7.4	12.6	9.6	13.6
	5	40.8	35.9	34.0	29.6	35.9	30.6
	1	38.6	35.3	32.8	31.2	35.9	34.0
	2	7.7	11.6	13.8	17.9	16.8	20.7
2	3	2.9	11.6	8.1	17.9	10.7	20.7
	4	1.4	7.0	8.3	12.6	8.5	15.2
	5	42.3	39.3	35.9	34.0	37.9	35.9
	1	33.4	30.1	26.7	24.5	29.6	27.6
	2	5.6	9.4	9.9	13.2	12.6	16.2
3	3	1.4	9.4	4.8	13.2	7.0	16.2
	4	1.4	8.5	5.1	12.6	7.0	15.2
	5	42.3	37.9	36.6	33.4	37.9	36.6
	1	34.0	31.7	27.1	25.8	30.1	28.6
	2	5.7	9.4	9.9	13.6	12.6	16.5
4	3	1.4	9.4	4.8	13.6	7.0	16.5
	4	0.0	5.0	3.0	8.5	5.0	11.1
	5	42.3	37.9	36.6	35.9	37.9	38.6

TABLE B.11. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR DOUBLE-PUNCHOUT COMBINATIONS, LEVEL 3: NO PUMPING, RIGID SHOULDER.

Punchout-Size Combination	Double-Punchout Combination	Crack-Spacing Combination					
		1	2	3	4	5	6
	1	63.8	71.8	61.3	69.0	71.8	77.8
	2	12.3	22.8	25.3	39.0	31.4	45.2
1	3	4.0	22.8	15.3	39.0	20.5	45.2
	4	2.7	16.5	11.8	29.2	16.5	36.3
	5	81.1	88.1	81.1	91.8	88.1	95.8
	1	66.3	71.8	63.8	71.8	71.8	81.1
	2	12.7	23.6	26.3	39.0	32.6	47.0
2	3	4.3	23.6	15.3	39.9	21.2	47.0
	4	0.6	11.4	9.3	22.8	13.7	28.2
	5	81.1	91.8	84.5	91.8	91.8	100.0
	1	56.7	63.8	52.6	59.0	59.0	66.3
	2	9.7	19.7	19.1	30.3	24.5	36.3
3	3	2.2	19.7	10.1	30.3	14.2	36.3
	4	0.6	13.7	7.6	23.6	11.4	28.2
	5	81.1	88.1	84.5	91.8	88.1	100.0
	1	59.0	66.3	52.6	61.3	59.0	69.0
	2	9.7	19.7	19.7	31.4	24.5	37.6
4	3	2.2	19.7	10.5	31.4	14.8	37.6
	4	0.0	8.6	5.2	17.1	8.6	21.2
	5	81.1	88.1	84.5	91.8	88.1	100.0

TABLE B.12. DEFLECTION DISTRESS INDEX (DDI), %, CORRESPONDING TO FACTORIAL ARRANGEMENT FOR DOUBLE-PUNCHOUT COMBINATIONS, LEVEL 4: PUMPING, RIGID SHOULDER.

Punchout-Size Combination	Double-Punchout Combination	Crack-Spacing Combination					
		1	2	3	4	5	6
	1	61.3	56.7	52.6	56.7	61.3	63.8
	2	11.4	17.1	20.5	30.3	26.3	36.3
1	3	3.8	17.1	12.3	30.3	17.1	36.3
	4	2.7	16.5	11.8	29.2	16.5	36.3
	5	66.3	61.3	56.7	59.0	61.3	63.8
	1	63.8	59.0	54.6	59.0	63.8	66.3
	2	11.8	17.7	21.2	31.4	27.2	37.6
2	3	4.0	17.7	12.3	31.4	17.1	37.6
	4	0.6	11.4	9.3	22.8	13.7	28.2
	5	69.0	63.8	59.0	61.3	63.8	66.3
	1	45.2	50.6	43.6	47.0	48.7	52.6
	2	5.5	14.2	15.3	23.6	19.7	28.2
3	3	0.0	14.2	7.6	23.6	11.4	28.2
	4	0.6	13.7	7.6	23.6	11.4	28.2
	5	61.3	63.8	63.8	63.8	63.8	66.3
	1	45.2	52.6	45.2	48.7	50.6	54.6
	2	6.6	14.2	15.9	24.5	20.5	29.2
4	3	0.0	14.2	7.9	24.5	11.8	29.2
	4	0.0	8.6	5.2	17.1	8.6	21.2
	5	61.3	63.8	63.8	63.8	63.8	66.3

APPENDIX C

MANUAL FOR CRCP CONDITION SURVEYS AT THE PROJECT LEVEL

APPENDIX C. MANUAL FOR CRCP CONDITION SURVEYS AT THE PROJECT LEVEL

The collection of condition survey data at the project level according to the guidelines presented herein represents the first step in the estimation of the deflection distress index (DDI) of a CRCP section by means of computer program DDI1.

DESCRIPTION OF CRCP DISTRESS MANIFESTATIONS

Several of the following descriptions are based, to some extent, on Refs 16 and 17.

Open Crack

A transverse crack is said to be open when it exhibits severe spalling or when there is a tensile failure of the reinforcement steel that crosses that crack. Spalling is generally defined as the widening of existing cracks by secondary cracking or breaking of the crack edges, and severe spalling is considered as that condition in which the spall is wider than half an inch.

Punchout

When two successive transverse cracks are linked by a longitudinal crack and the pavement edge to form a block, the block is called a punchout. When the average distance between the longitudinal crack and the pavement edge is less than 2 feet, the punchout is said to be of small size; when the average distance between these two discontinuities is of 2 or more feet, the punchout is said to be of large size.

Severe Punchout. This occurs when a punchout deflects significantly under traffic loads, the cracks surrounding this block are wide, and there are signs of pumping along its edges.

Minor Punchout. This distress manifestation is defined as a condition where, although a block has formed, no sign of movement under traffic loads is apparent.

Repair Patch

This definition includes only those repair patches in good condition made with either portland cement concrete or asphalt concrete. The repair work must be done over the full depth of the concrete. A patch in poor condition is considered to be equivalent to a severe punchout. The size of a repair patch depends on the average distance between its two longitudinal boundaries; this distance is less than 2 feet for a small patch and 2 or more feet for a large patch. Portland cement concrete and asphalt concrete patches are recorded separately on the condition survey form.

Pumping

Pumping is said to occur if water penetrates through cracks and openings in the pavement and then, when a load, such as a heavy vehicle passing over a crack, is applied, water is ejected through discontinuities, taking fine material of the sublayers with it.

For the purpose of this manual, only pumping at the pavement edge should be recorded; it is usually evidenced by the presence of streaks of fines on the surface of the shoulder or pavement.

CONDITION-SURVEY FORM

The proposed form for collection of CRCP condition survey data at the project level is presented in Fig C.1. Distress information corresponding to the most deteriorated lane of a CRCP section is recorded on this form. The selected CRCP lane is divided into a finite number of "elements." An "element" is defined as that portion of a full-depth CRCP lane bounded by two successive transverse cracks, as shown in Fig C.2. The "left" crack of an element is that transverse crack the surveyor crosses first as he moves from the beginning to the end of a CRCP section; the other transverse crack of that CRCP element is designated as the "right" crack.

Information About the Location of the CRCP Section

The top two lines of the condition survey form are provided for recording information about the location of the CRCP section surveyed. The top line should be used for the district, control, and section numbers as

PROJECT-LEVEL CRCP CONDITION SURVEY

DIST	CONTROL	SECTION	HIGHWAY AND DIRECTION	COUNTY	JOB No.	MO	DAY	YR

RIG. SHOULDER	LOCATION FROM MILEPOST	TO MILEPOST	RATERS
	•	•	

MILE POINT	APPROX. CRACK SPACING	OPEN CRACK	MINOR PUNCHOUT		SEVERE PUNCHOUT		CONCRETE PATCH		ASPHALT PATCH		PUMPING	COMMENTS
			SMALL	LARGE	SMALL	LARGE	SMALL	LARGE	SMALL	LARGE		
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											
	•											

Fig C.1. Proposed form for CRCP condition surveys at the project level.

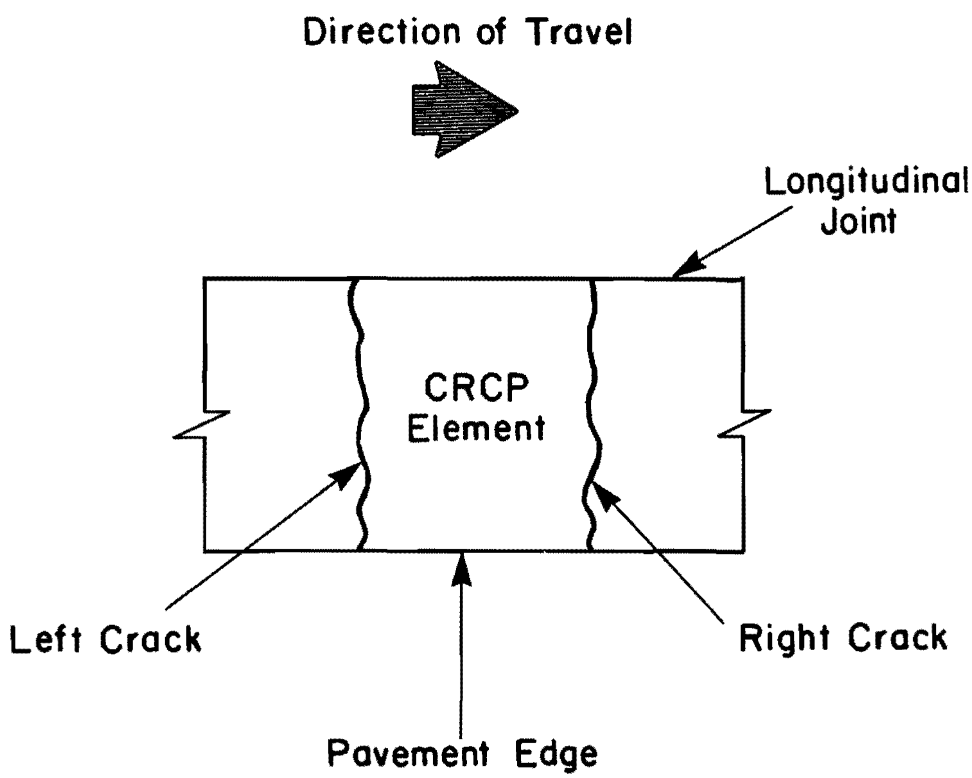


Fig C.2. Illustration of the definition of a CRCP element and associated terms.

003 132

well as for the highway number and direction, the county, and the job number of the CRCP section considered. Enough space has also been provided for recording the date of the survey. A number 1 is entered on the appropriate space in the second line when the CRCP section has a rigid shoulder; otherwise, a zero is entered or the space is left blank. The name of the raters should also be recorded on the second line of the form. It is very important that the exact location of the CRCP section surveyed be accurately recorded. These data should be entered according to the format MMMM.FFFF, where M is in miles, and F is in feet, and it should be right-justified, with unused spaces filled out with zeros. For example, 40.0065 corresponds to that location at 40 miles and 65 feet of a given highway. The locations of both the beginning and the end of the CRCP section are recorded in this way.

Information for Every Element Surveyed

Data for every CRCP element surveyed should be recorded in the second series of lines. The information corresponding to the first and last columnsis optional, but may be very useful if the exact location of each element is wanted. Comments are appropriate, for example, to report the occurrence of a repair patch in poor condition, since it is equivalent to a severe punchout. They can also be used to indicate if a distress manifestation not accounted for in this procedure has been observed and an equivalent condition has been assumed.

The approximate crack spacing, in feet, for every element is entered in the second column. It was originally thought that measuring this distance would significantly increase the overall time required for conducting the condition survey of a CRCP section. However, when the procedure presented herein was tested in the field, it was concluded that crack spacing to the nearest tenth of a foot could be rapidly recorded. The decision as to whether to measure or to estimate the element crack spacing is left to the surveyor.

The distress manifestations in columns 3 to 12 are entered as binary values, i.e., a value of 1 is recorded when a given condition exists; otherwise the column is either left blank or a zero is entered. Even though four spaces are provided for each one of these distress manifestations, only the right-most space should be used. Moreover, only one of the variables in columns 4 to 11 can be assigned a value of 1 for a given element. This variable should correspond to the worst distress manifestation found in that CRCP element, usually in that portion of the element adjacent to the pavement edge. A number 1 is entered in the third column when the "right" crack (see Fig C.2) is open and in column 12 when pumping is observed in a given CRCP element.

Two lines are always required for the first element in a sample. In the first line, data for only two columns are recorded. A value of 0.0 is entered for the crack spacing, and a number 1 is recorded in the third column when the left crack of this first element is open. Data for the second line are filled as explained above.

In general, it is not necessary to survey every element in a given CRCP section. The required number of elements for a condition survey can be estimated by computer program DD11 if there is previous distress information available for a CRCP section, or if a pilot sample is taken. Given that the number of CRCP elements has been estimated for a given section, samples of at least three elements should be taken at distance intervals approximately equal. Figure C.3 is an example of how the condition survey form should be filled out when not surveying every element in a CRCP section is surveyed.

Even though three is the minimum number of CRCP elements in a given sample, it is recommended that this lower limit be seldom used. It is very important to keep an approximately constant distance between successive samples within a CRCP section.

PROJECT-LEVEL CRCP CONDITION SURVEY

DIST	CONTROL	SECTION	HIGHWAY AND DIRECTION	COUNTY	JOB No.	MO.	DAY	YR
15	529	8	US-281 NB	BEXAR	10	AUG	22	84

RIG. SHOULDER	LOCATION FROM MILEPOST	TO MILEPOST	RATERS
	148.0040	148.0100	LONG AND TORRES_VERDIN

MILE POINT	APPROX CRACK SPACING	OPEN CRACK	MINOR PUNCHOUT SMALL	MINOR PUNCHOUT LARGE	SEVERE PUNCHOUT SMALL	SEVERE PUNCHOUT LARGE	CONCRETE PATCH SMALL	CONCRETE PATCH LARGE	ASPHALT PATCH SMALL	ASPHALT PATCH LARGE	PUMPING	COMMENTS
	0.0	1										
	5.5					1						
	3.0		1								1	
	8.0	1										
	6.5											
	2.0											
	3.									1		
	0.0											
	2.0						1					
	7.0	1					1				1	

Fig C.3. Example on how to record data for a CRCP section in which not every element was surveyed. The zero crack-spacing value entered in both the top line and the third line from the bottom indicates the beginning of a sample.

APPENDIX D

INPUT GUIDE FOR COMPUTER PROGRAM DDI1

APPENDIX D. INPUT GUIDE FOR COMPUTER PROGRAM DDI1

DESCRIPTION OF PROGRAM

Computer program DDI1 estimates the deflection distress index (DDI) of a CRCP section from project-level condition survey data. Essentially, a CRCP section is divided into small elements, for each of which a DDI value is estimated by using the condition survey information input to the program. Then, a plot of the present DDI versus element number is provided along with the estimated mean and standard deviation of the DDI for a given CRCP section. Computer program DDI1 also estimates the required condition survey sample size (given in terms of number of CRCP elements) and predicts the mean and standard deviation of the DDI for the rehabilitation strategies selected by the user.

LIMITATIONS

This program can be used for only CRC pavements, and it is capable of handling up to 500 elements.

INPUT DATA

The input data required for each card are described below. Each variable (except for the alphanumeric) should be entered as either a real or an integer value. If a variable is real, it should be entered with a decimal point anywhere in its column range. If a variable is specified as an integer, it must be entered without a decimal point and must also be right-justified in its column range.

<u>Card Type 1: Location of CRCP Section</u>

1 5	6 15	16 28	29 45	46 58	59 63	64 80

1.1 District number, alphanumeric, columns 1 - 5.

1.2 Control number, alphanumeric, columns 6 - 15.

1.3 Section number, alphanumeric, columns 16 - 28.

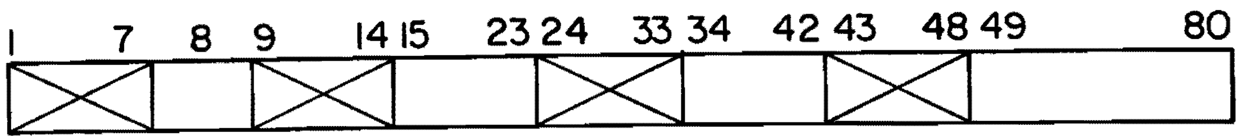
1.4 Highway and direction, alphanumeric, columns 29 - 45.

1.5 County, alphanumeric, columns 46 - 58.

1.6 Job number, alphanumeric, columns 59 - 63.

1.7 Survey date, alphanumeric, columns 64 - 80.

Card Type 2: Location of CRCP Section



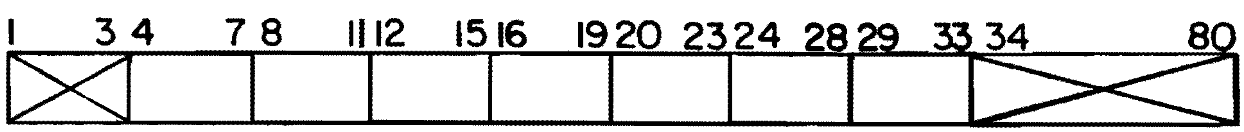
2.1 Rigid shoulder, integer, column 8 (1 = yes; 0 = no).

2.2 Initial milepost of CRCP section, real, columns 15 - 23. (The value for this variable should be entered as follows: MMMM.FFFF, where M is in miles, and F is in feet; it should be right-justified, with unused columns filled out with zeros. For example, 40.0065 is interpreted by the program as 40 miles and 65 feet.)

2.3 Final milepost of CRCP section, real, columns 34 - 42. (Entered in the same way as variable 2.2)

2.4 Name or initials of raters, alphanumeric, columns 49 - 80.

Card Type 3: User - Selected Options



3.1 Rehabilitation strategy No. 1, integer, columns 4 -7. (1 = yes; 0 = no)

3.2 Rehabilitation strategy No. 2, integer, columns 8 - 11. (1 = yes; 0 = no)

3.3 Rehabilitation strategy No.3, integer, columns 12 - 15. (1 = yes; 0 = no)

3.4 Rehabilitation strategy No. 4, integer, columns 16 - 19. (1 = yes; 0 = no)

3.5 Rehabilitation strategy no. 5, integer, columns 20-23. (1 = yes; 0 = no).

3.6 Confidence level for estimation of condition survey sample size (percent), real, columns 24 - 28. (Any of these values: 80.0, 85.0, 90.0, 93.0, 96.0, or 99.0)

3.6 Allowable error for estimation of condition survey sample size (percent), real, columns 29 - 33. (The value of this variable is entered as a percent of the mean DD1, which is to be estimated by the computer program.)

The following rehabilitation strategies are evaluated by computer program DDI1:

<u>Rehabilitation Strategy No. 1</u>. Undersealing.

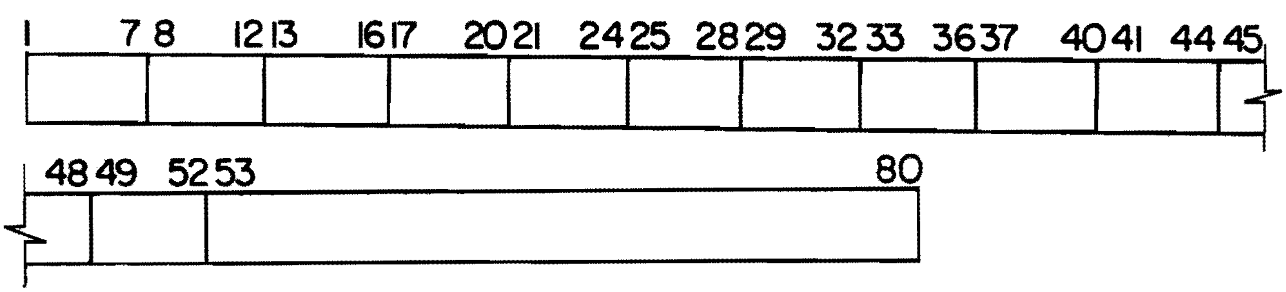
<u>Rehabilitation Strategy No. 2</u>. Repair of severe punchouts and asphalt patches.

<u>Rehabilitation Strategy No. 3.</u> Crack fusion with polymer and repair of severe punchouts and asphalt patches.

<u>Rehabilitation Strategy No. 4</u>. Undersealing and repair of severe punchouts and asphalt patches.

<u>Rehabilitation Strategy No. 5</u>. Undersealing, repair of severe punchouts and asphalt patches and rigid-shoulder addition. This strategy should be considered only for flexible-shoulder CRC pavements.

<u>Card Type 4: Condition Survey Information for Every CRCP Element to be Analyzed</u>



4.1 Milepost corresponding to element, alphanumeric, columns 1 - 7. (This variable is optional)

4.2 Approximate crack spacing of element, real, columns 8 - 12.

4.3 Open crack, integer, columns 13 - 16 (1 = yes; 0 = no)

4.4 Small minor punchout, integer, columns 17 - 20. (1 = yes; 0 = no)

4.5 Large minor punchout, integer, columns 21 - 24. (1 = yes; 0 = no)

4.6 Small severe punchout, integer, columns 25 - 28. (1 = yes; 0 = no)

4.7 Large severe punchout, integer, columns 29 - 32. (1 = yes; 0 = no)

4.8 Small concrete patch, integer, columns 33 - 36. (1 = yes; 0 = no)

4.9 Large concrete patch, integer, columns 37 - 40. (1 = yes; 0 = no)

4.10 Small asphalt patch, integer, columns 41 - 44. (1 = yes; 0 = no)

4.11 Large asphalt patch, integer, columns 45 - 48. (1 = yes; 0 = no)

4.12 Pumping, integer, columns 49 - 52. (1 = yes; 0 = no)

4.13 Comments, alphanumeric, columns 53 - 80. (Comments are optional).

The beginning of a sample is indicated to computer program DDI1 by using two cards for the first CRCP element in that sample. In the first card, a value of zero is entered for the crack spacing and the value of variable 4.3 corresponds to the "left" crack of the first element (the left crack of an element is that transverse crack the surveyor crosses first as he moves from the beginning to the end of a CRCP section). The data for the second card of the first element in a sample are entered in the same way as those data for the rest of the elements in that sample. That is, crack spacing must have a non-zero positive value, the value of variable 4.3 corresponds to the "right" crack of a given CRCP element. The value of the other variables depends on the condition survey information gathered for that element.

The total number of cards of Type No. 4 for a CRCP section is given by the following expression:

$$N_4 = n + s \tag{D.1}$$

where

N_4	=	total number of cards of Type No. 4,
n	=	number of CRCP elements surveyed, and
s	=	number of samples in the CRCP section.

APPENDIX E

INPUT DATA FOR THE HYPOTHETICAL CRCP SECTION USED IN CHAPTER 5

```
  15   529       8           US-281 NB         BEXAR        10    AUG 22 84
        0      148.0015           148.0100           LONG AND TORRES-VERDIN
      1   1   1   190.0 10.0
               1
         3.0               1
         8.0
         3.0   1
         3.0           1
         2.0                                1
         3.0   1                                    1
148 004  4.0   1       1
         3.0                            1
         8.0
         8.0   1
         3.0   1               1
         5.0
         2.0   1   1
         2.0               1
         3.0           1                            1
        10.0   1
         1.5   1
         3.5                                    1
         4.0   1
         2.0   1               1
         2.0   1               1
         4.0   1
```

APPENDIX F

OUTPUT FROM COMPUTER PROGRAM DDI1 FOR THE HYPOTHETICAL CRCP SECTION USED IN CHAPTER 5

```
DDDDDD     DDDDDD     IIIIIIII      11
DDDDDDD    DDDDDDD    IIIIIIII     111
DD     DD  DD     DD     II       1111
DD     DD  DD     DD     II         11
DD     DD  DD     DD     II         11
DD     DD  DD     DD     II         11
DDDDDDD    DDDDDDD    IIIIIIII  11111111
DDDDDD     DDDDDD     IIIIIIII  11111111
```

```
**********************************************
*                                            *
*         PROJECT-LEVEL ESTIMATION OF        *
*        DEFLECTION DISTRESS INDEX OF        *
*             CRC PAVEMENTS FROM             *
*            CONDITION SURVEY DATA           *
*                                            *
*      CENTER FOR TRANSPORTATION RESEARCH    *
*       THE UNIVERSITY OF TEXAS AT AUSTIN    *
*                                            *
**********************************************
```

```
PROGRAM DDI1, VERSION 1, SEPTEMBER 1984
CENTER FOR TRANSPORTATION RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN
```

```
*********************************
*                               *
*      PROJECT INFORMATION      *
*                               *
*                               *
*********************************

DISTRICT NUMBER:    15
CONTROL NUMBER:    529
SECTION NUMBER:    8
JOB NUMBER :  10
HIGHWAY AND DIRECTION:  US-281 NB
COUNTY:   BEXAR
SURVEY DATE:     AUG 22 84
RIGID SHOULDER:  NO
LOCATION
FROM MILE 148.0015
TO MILEPOST:  148.0100
RATERS:       LONG AND TORRES-VERDIN
```

```
**********************************
*                                *
*      USER-SELECTED OPTIONS     *
*                                *
**********************************

REHABILITATION STRATEGIES CONSIDERED:
1. UNDERSEALING
2. REPAIR OF SEVERE PUNCHOUTS AND
   ASPHALT PATCHES
3. UNDERSEALING AND REPAIR OF SEVERE
   PUNCHOUTS AND ASPHALT PATCHES
4. UNDERSEALING, REPAIR OF SEVERE
   PUNCHOUTS AND ASPHALT PATCHES AND
   RIGID-SHOULDER ADDITION

CONFIDENCE LEVEL:  90.0 PERCENT
ALLOWABLE ERROR:  10.0 PERCENT
```

INPUT DATA

ELE. NO.	MILE POINT	CRACK SPA.	OP CR	M S	P/O L	S S	P/O L	C S	PAT L	A S	PAT L	PU	COMMENTS
1			1										
1		3.0	0	0	0	1	0	0	0	0	0	0	
2		8.0	0	0	0	0	0	0	0	0	0	0	
3		3.0	1	0	0	0	0	0	0	0	0	0	
4		3.0	0	0	1	0	0	0	0	0	0	0	
5		2.0	0	0	0	0	0	0	0	1	0	0	
6		3.0	1	0	0	0	0	0	0	0	0	1	
7	148.004	4.0	1	0	1	0	0	0	0	0	0	0	
8		3.0	0	0	0	0	0	0	1	0	0	0	
9		8 0	0	0	0	0	0	0	0	0	0	0	
10		8.0	1	0	0	0	0	0	0	0	0	0	
11		3.0	1	0	0	0	1	0	0	0	0	0	
12		5.0	0	0	0	0	0	0	0	0	0	0	
13		2.0	1	1	0	0	0	0	0	0	0	0	
14		2.0	0	0	0	1	0	0	0	0	0	0	
15		3.0	0	0	1	0	0	0	0	0	0	1	
16		10.0	1	0	0	0	0	0	0	0	0	0	
17		1.5	1	0	0	0	0	0	0	0	0	0	
18		3.5	0	0	0	0	0	0	0	0	1	0	
19		4.0	1	0	0	0	0	0	0	0	0	0	
20		2.0	1	0	0	0	1	0	0	0	0	0	
21		2.0	1	0	0	0	1	0	0	0	0	0	
22		4.0	1	0	0	0	0	0	0	0	0	0	

```
                        ***************************************
                        *                                     *
                        *           PLOT OF PRESENT           *
                        *      DEFLECTION DISTRESS INDEX      *
                        *                 VS.                 *
                        *            ELEMENT NUMBER           *
                        *                                     *
                        ***************************************

 MILE      ELEMENT           DEFLECTION DISTRESS INDEX, PCT
 POINT     NUMBER

                 0    10   20   30   40   50   60   70   80   90   100
               0 +****+****+****+****+****+****+****+****+****+****+
                 *                                                 *
               1 +               X                                 +   32.3
                 *                                                 *
               2 +               X                                 +   32.3
                 *                                                 *
               3 +        X                                        +   18.8
                 *                                                 *
               4 +    X                                            +    9.6
                 *                                                 *
               5 +X                                                +    2.9
                 *                                                 *
               6 +X                                                +    2.9
                 *                                                 *
148.004        7 +  X                                              +    6.1
                 *                                                 *
               8 +    X                                            +    9.6
                 *                                                 *
               9 +                                             X   +   91.4
                 *                                                 *
              10 +         X                                       +   19.1
                 *                                                 *
              11 +        X                                        +   17.3
                 *                                                 *
              12 +        X                                        +   17.3
                 *                                                 *
              13 +     X                                           +   12.6
                 *                                                 *
              14 +     X                                           +   12.6
                 *                                                 *
              15 +                X                                +   33.4
                 *                                                 *
              16 +     X                                           +   12.0
                 *                                                 *
              17 +     X                                           +   12.0
                 *                                                 *
              18 +        X                                        +   17.0
                 *                                                 *
              19 +        X                                        +   17.3
                 *                                                 *
              20 X                                                 +    0.0
                 *                                                 *
              21 X                                                 +    0.0
                 *                                                 *
              22 +        X                                        +   17.3
                 *                                                 *
                 +****+****+****+****+****+****+****+****+****+****+
```

```
********************************
*                              *
*      PRESENT DEFLECTION      *
*        DISTRESS INDEX        *
*          INFORMATION         *
*                              *
********************************

      ** DDI MEAN =  17.9 PERCENT **
** DDI STANDARD DEVIATION =  19.0 PERCENT **

   ** AVERAGE CRACK SPACING COMPUTED **
   ** FROM TOTAL NUMBER OF ELEMENTS **
         ** AND PROJECT LENGTH **

 ** AVERAGE CRACK SPACING =  3.9 FEET **

 ******************************
 *                            *
 *      CONDITION SURVEY      *
 *        SAMPLE SIZE         *
 *                            *
 ******************************

   ** CONFIDENCE LEVEL = 90. PERCENT **
   ** ALLOWABLE ERROR = 10. PERCENT **
** REQUIRED SAMPLE SIZE =   21 ELEMENTS **
```

```
*************************************
*                                   *
*     REHABILITATION STRATEGY       *
*            NUMBER 1               *
*           UNDERSEALING            *
*                                   *
*************************************

  **********************************
  *                                *
  *     PREDICTED DEFLECTION       *
  *        DISTRESS INDEX          *
  *          INFORMATION           *
  *                                *
  **********************************

    ** DDI MEAN =  19.3 PERCENT **
** DDI STANDARD DEVIATION =  19.3 PERCENT **
```

```
************************************
*                                  *
*     REHABILITATION STRATEGY      *
*            NUMBER 2              *
*           REPAIR OF              *
*        SEVERE PUNCHOUTS          *
*      AND ASPHALT PATCHES         *
*                                  *
************************************

  *********************************
  *                               *
  *     PREDICTED DEFLECTION      *
  *        DISTRESS INDEX         *
  *         INFORMATION           *
  *                               *
  *********************************

       ** DDI MEAN =  54.3 PERCENT **
** DDI STANDARD DEVIATION =  33.3 PERCENT **
```

```
*************************************
*                                   *
*      REHABILITATION STRATEGY      *
*             NUMBER 3              *
*           UNDERSEALING            *
*               AND                 *
*            REPAIR OF              *
*         SEVERE PUNCHOUTS          *
*       AND ASPHALT PATCHES         *
*                                   *
*************************************

  **********************************
  *                                *
  *      PREDICTED DEFLECTION      *
  *         DISTRESS INDEX         *
  *           INFORMATION          *
  *                                *
  **********************************

     ** DDI MEAN =   60.4 PERCENT **
** DDI STANDARD DEVIATION =  32.2 PERCENT **
```

```
*************************************
*                                   *
*     REHABILITATION STRATEGY       *
*            NUMBER 4               *
*          UNDERSEALING,            *
*            REPAIR OF              *
*         SEVERE PUNCHOUTS          *
*       AND ASPHALT PATCHES         *
*               AND                 *
*     RIGID-SHOULDER ADDITION       *
*                                   *
*************************************

         ******************
         *                *
         *      NOTE      *
         *                *
         ******************

   ** RESULTS FOR THIS REHABILITATION STRATEGY **
  ** SHOULD NOT BE COMPARED DIRECTLY WITH THOSE **
     ** CORRESPONDING TO FLEXIBLE-SHOULDER **
               ** CRC PAVEMENTS **

  **********************************
  *                                *
  *     PREDICTED DEFLECTION       *
  *        DISTRESS INDEX          *
  *          INFORMATION           *
  *                                *
  **********************************

     ** DDI MEAN =  64.7 PERCENT **
** DDI STANDARD DEVIATION =  27.1 PERCENT **
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SUMMARY OF REHABILITATION STRATEGIES

REHABILITATION STRATEGY	DEFLECTION DISTRESS INDEX MEAN	DEFLECTION DISTRESS INDEX STANDARD DEVIATION
NO REHABILITATION (ORIGINAL PAVEMENT)	17.9	19.0
1. UNDERSEALING	19.3	19.3
2. REPAIR OF SEVERE PUNCHOUTS AND ASPHALT PATCHES	54.3	33.3
3. UNDERSEALING AND REPAIR OF SEVERE PUNCHOUTS AND ASPHALT PATCHES	60.4	32.2
4. UNDERSEALING, REPAIR OF SEVERE PUNCHOUTS AND ASPHALT PATCHES AND RIGID-SHOULDER ADDITION	64.7	27.1