PROGRESS REPORT NO. 1

ODOT STUDY NO. 84-12-2, Item 2140
ORA 155-857

EVALUATION OF CAUSES OF EXCESSIVE SETTLEMENTS OF PAVEMENT BEHIND BRIDGE ABUTMENTS AND THEIR REMEDIES - PHASE I

Prepared by

Joakim G. Laguros, David Ross Boyd Professor
M. M. Zaman, Assistant Professor
I.U. Mahmood, Research Assistant

School of Civil Engineering and Environmental Science

Submitted to

Research Division
OKLAHOMA DEPARTMENT OF TRANSPORTATION

From the

OFFICE OF RESEARCH ADMINISTRATION
UNIVERSITY OF OKLAHOMA
NORMAN, OKLAHOMA

January 1986

TABLE OF CONTENTS

LIST OF TABLES

SUMMARY

Bridge approach settlement problem is quite extensive in the U.S.A. This problem has been investigated since early 1960s, but no satisfactory solution has been achieved. A comprehensive literature search has been carried out with the aim of understanding the problem and the approaches of many investigators. The pertinent works have been reviewed thoroughly and the highlights of these previous studies are presented in this report. It was felt that the experience of various agencies involved in construction of roads and highways would be immensely helpful in deciding the course of this research. Hence, a survey was conducted by sending a questionnaire to various agencies involved in construction and maintenance of roads and highways. The responses have been carefully analyzed and presented in the report. At the end, a discussion of the findings and recommendations for further research have been made.

CHAPTER 1

INTRODUCTION

..1 Background and Objective

Differential settlement between the approach pavement and :he bridge deck or, as some engineers define it as settlement at :he end of the bridge, has been a recognized problem for a long :ime. It has manifold influence on the function and maintenance ›f the state's roads and highways. Differential settlement ıffects the riding characteristics of the road; it creates liscomfort and an unsafe riding condition. The bridge structure .s also subjected to undesirable impact loads by the passing ·ehicles. The maintenance work is costly and impedes the flow of :raffic, and in most cases, the solution is only temporary.

Cognizant of the extensiveness of this problem in Oklahoma, :he Department of Transportation (ODOT) commissioned the Univer;ity of Oklahoma*, to study the problem with the main objectives ›eing:

.. To undertake a systematic research effort so as to identify the various causes which contribute to the excessive settlement of approach pavement and assess their relative contribution.

!. To develop guidelines for the design, material selection, construction and maintenance of approach pavement and embankment and to substantially reduce this settlement

* under contract 84-12-2, Item 2140

problem without causing any adverse effect on the structural performance of the bridge.

To accomplish its intended goals, the study was proposed to be conducted in several phases. Phase I was concerned with the literature survey and collection of pertinent information on the experience of other states with the referenced settlement problem and solutions which were found satisfactory. This progress report is intended to present the findings of this Phase.

The following tasks were identified to achieve the objectives of Phase I:

1. Comprehensive search of available literature to establish the state-of-the-art of approach pavement settlement and related areas.
2. Survey various state, federal and private agencies involved in construction and/or maintenance of pavements and bridges to gather pertinent information on settlement of approach pavements.
3. Analyze survey response and synthesize existing literature so as to initiate the development of an in-depth understanding of the referenced settlement problem.

1.2 Overview of Study Tasks

The computer search facilities of the Highway Research Information Service (HRIS) as well as the search facilities at the University of Oklahoma (OU) were used to accomplish the intended goals of Task 1. The three computer search systems at OU included DIALOG, ORBIT and BRS. All of these systems have broad data bases which are updated at two weeks to two months intervals. In ddition to computer search, manual searches were conducted to ocate pertinent literature. Detail review of related publica- ions are presented in Chapter 2.

Based on the knowledge gained through the literature review questionnaire for the survey was designed, as discussed subse- uently. With the exception of a recent study by Hopkins et al. 1985), it appeared from the literature review that most of the revious investigations focused on some particular aspect of the eferenced settlement problem, as such no satisfactory solution as attained.

For Task 2, a questionnaire was prepared, in consultation ith ODOT, and was sent to various agencies associated with onstruction, operation and maintenance of roads and highways. he questionnaire focused basically on three aspects, (i) status f the referenced settlement problem in various states, (ii) ossible causes of such settlement, and (iii) solutions which ere found satisfactory.

The outcome of this survey was very encouraging and en- lightening. The authors of this report sincerely appreciate the efforts of all responding agencies. A synthesis of the survey responses is included in Chapter 3. Many responding agencies viewed the referenced settlement problem as a serious problem in approach pavement maintenance and indicated the need for system- atic indepth research efforts.

CHAPTER 2

REVIEW OF PERTINENT LITERATURE

2.1 Introduction

To accomplish the stated objectives of Phase I, a comprehensive search of pertinent literature was made using the computer search facilities of the Highway Research Information Service (HRIS) as well as other facilities available at the University of Oklahoma (OU). At the present time, the University has three computer search systems, namely, (i) DIALOG offered by the Lockheed Information System, Inc., (ii) ORBIT offered by the System Development Corporation, and (iii) BRS offered by the Bibliographic Systems, Inc. By assigning proper key words, all of these systems can produce citations and abstracts of papers/technical reports published in the United States and other countries of the world that are related to the fields requested. Hence, the most recent information can be obtained without much difficulty. In this chapter, a detail review of the literature pertinent to the long term settlement of approach pavement, embankment and foundation is presented. A summary of previous investigations concerning the referenced settlement problem and possible remedies is also presented at the end.

2.2 Detail Review of Previous Studies

One of the early investigations to minimize settlement of approach pavement was done by Margason and Cross (1966). Their work involved using fresh hopper ash as filling behind the bridge abutments and comparing its performance with that of a well raded sandy gravel. This study was part of a program of field nvestigations conducted by the Road Research Laboratory in ngland, in which the use of various materials as embankment-illing behind bridge abutments was examined. The primary bjective was to establish whether there was any need to place estrictions on the type of filling used behind bridge abutments hen the compaction work was carried out in accordance with the pecifications. The work was carried out at two bridge sites. oth bridges had closed type abutments with a nominal 12-inch hick drainage layer of hand-packed brick rubble at the back. he rear face of both abutments, at which Pulverized Fuel Ash PFA) was to be placed, was first treated with bituminous paint s a precaution against possible sulphate attack. Transition labs of structural concrete were provided at both bridges. efore embankment construction commenced, the existing soil clay) was excavated down to the gravel stratum and was replaced y granular material to the same specifications as the embankment illing. The gravel layer, which occurred at depths of up to bout 5 feet and was 15 to 20 feet thick, was underlain by reconsolidated London clay of considerable thickness. The fill aterial used at the two abutments was granular while PFA was sed at two other abutments. Rod-type gages were used to record ettlement of the sub-soil. The movements of the road surface ere recorded by high precision levels. Metal studs driven into he bituminous wearing course were used as measuring locations. he maximum differential settlement recorded was .40 inch. In iew of the fact that the control of moisture content of the PFA 'as difficult and relatively light compaction equipment was used, .he performance of these embankments was considered satisfactory. 'he embankments constructed of PFA performed better than those ›uilt of well graded sandy gravel. This investigation employed 'resh hopper ash having low moisture content. Thus, the findings ›f this investigation could not be applied to wet lagoon ashes.

McLaren (1967) evaluated the performance of a medium clay :ill, which formed the approach embankments of a bridge on the Motorway in Leicestershire, England. The state of compaction .nd moisture content of the medium-clay fill closely conformed to .he existing specifications. The underbridge was of precast con- :rete portal construction having solid abutments. The abutment 'alls were constructed of concrete and piled to a depth of .pproximately 35 feet below ground level. Floating transition labs of reinforced concrete, 16 feet long and 1.17 feet thick, 'ere cast in-situ after the embankment construction was complet- :d. The subsoil at the site consisted of a firm to hard red ;ilty clay which extended to a depth of at least 60 feet. ›verlying were deposits of silty and sand clays, sand and gravel, 'hich varied in thickness between 5 and 10 feet. Midland boulder :lay was used to fill the 20 to 22 feet high approach embankment. 'he boulder clay generally consisted of a medium-clay soil and :ontained a small proportion of stones.

Settlement gages were installed on the surface of the sub- ;oil, a few feet clear of the abutment walls. The movement of :he road surface was recorded by levelling on metal studs mounted ›n the asphalt wearing course. About 1/8 inch settlement was re-

:orded within the fill material, 2 years after the completion of ›aving. The settlement records obtained from the foundation ;ages, installed beneath the abutments, indicated that in the ›edge areas, the settlement of the subsoil was more or less uni- :orm. The compression of the subsoil resulting from the imposi- :ion of the embankment was approximately 2 inches and practically ıll of this movement had taken place before the road was opened :o traffic. The results further showed that the settlement of :he subsoil and the road surface was continuing at a rate of ıbout .10 inch per year and that the settlement within the fill ›as largely completed within the first 6 to 8 months after pav- .ng. Measurements on transverse rows of studs installed in the ·oad surface showed that settlement across the width of car- ·iage-way was practically uniform suggesting that the traffic .oading has had little influence on the settlement of the fill. 'his investigation concluded that a medium-clay soil could be :eadily employed as a satisfactory fill material for constructing ıpproach embankments behind bridge abutments. The likely costs, .ncluding extra costs of compaction involved when placing common :ill behind bridge abutments, were also examined and were shown :o be small in relation to the substantial expense which would be .ncurred by importing special fill materials for use in these ıreas.

Hopkins (1969) investigated the problem in Kentucky in ;omewhat more detail. The major objectives of his study were to .nvestigate the factors which might be responsible for settlement ›f the pavement at bridge abutments and to explore ways and means of eliminating, or minimizing such settlement. Secondary objectives were to develop a multi-point, mercury-filled, settlement gage for measuring settlement of approach embankment foundations, and to establish analysis procedures and design criteria for approach embankments. From the data obtained in a preliminary survey of existing bridge approaches, it was observed that there was a general relationship between development of the approach fault and such possible causative factors as the type of abutment, geological and soil conditions. The second phase of his study initiated in 1966 was to determine if the settlement at bridge abutments was primarily the result of settlement of the embankment and/or foundation, and to compare observed and predicted foundation settlement. To achieve these objectives mercury-filled settlement gages were installed on the original ground of the approach embankment foundation at four selected bridge sites and at an embankment site. Settlement plates were installed at one other bridge site. Undisturbed (shelby tube) soil samples were collected from the foundation at each of the six sites and consolidation tests were performed on these samples. Using these data and Terzaghi's theory of one-dimensional consolidation, the expected foundation settlements were calculated.

A survey conducted by Hopkins in the summer of 1964 of 782 bridge approaches revealed that 51% of these approaches required some form of maintenance. The approaches were classified according to one of the following settlement categories:

Group 1 settlement - no maintenance necessary and no approach fault noticeable.

Group 2 settlement - no maintenance performed; however, an approach fault was observed.

Group 3 settlement - maintenance performed on the approach.

. comparison of portland cement concrete and bituminous concrete .pproaches showed the use of a markedly higher percentage of mooth approaches for concrete pavements. The approach fault .ppeared to be confined within 100 feet of the end of the bridge.

From the survey it was evident that the lowest percentage of .efective approaches were in an area which was a basin; it was a .issected plateau with rolling hills and moderately wide valleys. .n outstanding feature of this area was the broad alluvial ottoms of large rivers. A large number of approaches studied .ay within these recent alluvial deposits. Soils of this area .ave been formed by weathering of sandstones and shales and large uantities of silts were present. The highest number of .pproaches in settlement Group 3 was in areas where the subsoil onsisted primarily of shale and plastic clays. The shale which as comparatively impervious and easily eroded had produced a ough, hilly terrain. The next ranking group of approaches with igh percentages of settlement Group 3 was located in the area hich had a rough, hilly terrain with valleys that were narrow, inding and entered by numerous streams. The soil was highly lastic and was considered to provide poor pavement support at ormal moisture content. Hence, there appeared to be a elationship between the presence of approach fault and soil ypes, geological formations and topography.

A comparison of the most commonly used abutment types (Fig. 1)

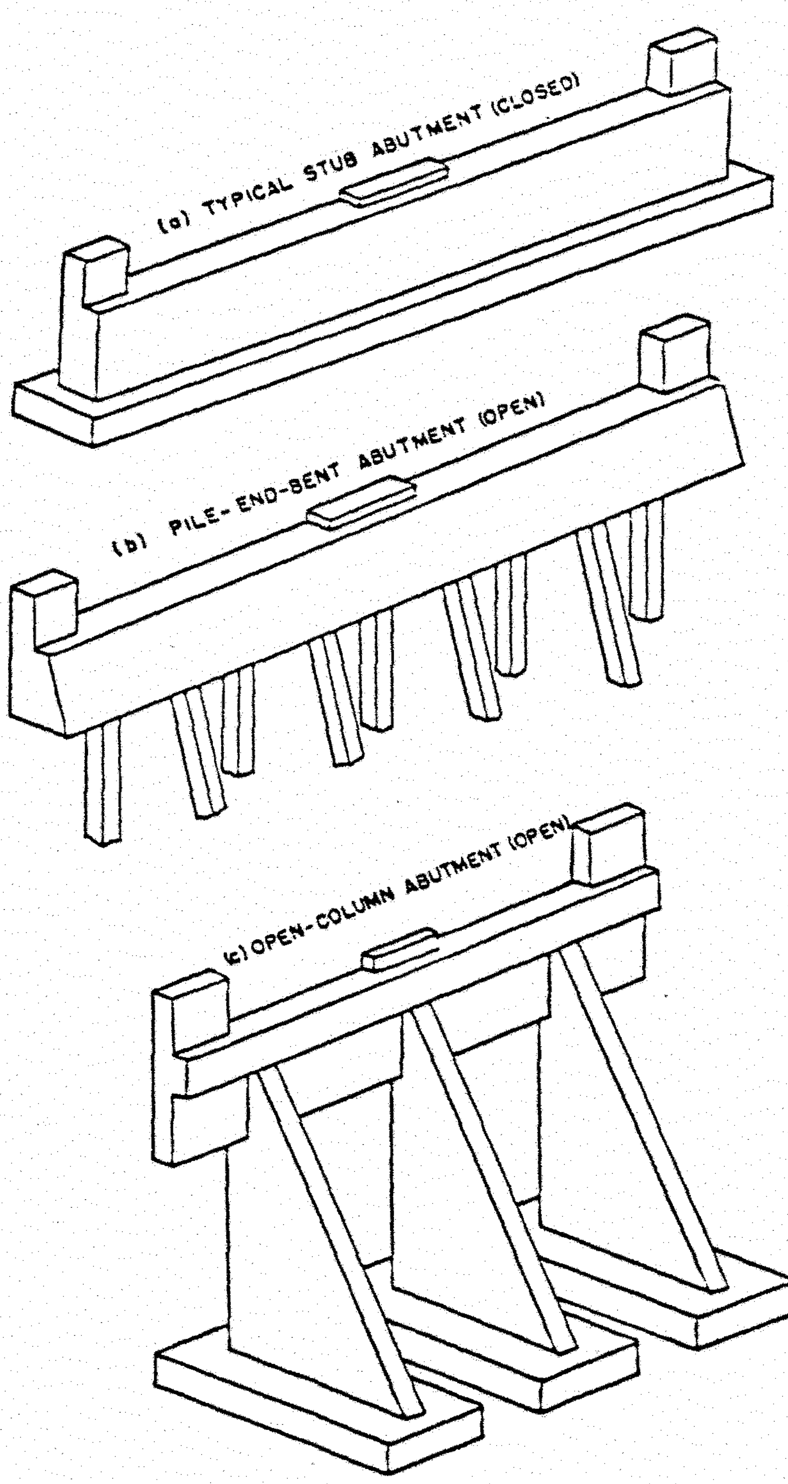


Fig. 1. Typical Types of Abutments Used in Kentucky (after Hopkins, 1969)

with respect to the three settlement groups revealed that the open-column type (open-end) was more commonly associated with settlement Group 3 than the pile-end-bent (open-end) type and the stub type (closed type). Stub abutments were associated with smoother bridge approaches, smaller average heights of embankment and a thinner layer of foundation soil. The pile-end-bent abutments had greater average heights of embankment and thickness of foundation soil than the open-column abutment but the pile-end-bent abutments had better bridge approaches. The better performance of approaches located behind stub abutments was attributed to smaller settlements associated with shallower embankments and thin foundation soil. The comparatively large time for consolidation before construction of the pavement and the need for less hand compaction near the abutment may account for better performance of approaches associated with pile-end-bent abutments than those approaches at open-column abutments.

Hopkins also indicated that the erosion of soil adjacent to the abutment contributed to development of the approach fault. Additionally, there was evidence that seepage was responsible in some cases for the development of approach fault. It was observed that approaches sloping towards the abutment had a higher percentage of Group 3 settlement.

There was suggestive evidence that progressive failure or creep of the approach embankment might have, in some cases, contributed to the development of approach fault. The survey also showed that embankments located in valleys of major streams had a much greater percentage of settlement Group 3 approaches than embankments at other locations. The study concluded that traffic was not a major factor for settlement of bridge approaches.

Hopkins recommended the following measures for preventing defective bridge approaches;

1. Where embankments were located on soft, compressible foundations, the post-construction settlement could be reduced by;
   (a) completely or partially removing the soft, compressible material and replacing with rock or a suitably compacted material wherever practical;
   (b) preconsolidating the soft foundation by use of a surcharge fill;
   (c) allowing sufficient time for consolidation of the foundation under the load of the planned embankment; and
   (d) using vertical sand drains, with or without a surcharge fill, to accelerate foundation settlement.
2. Adequate drainage should be provided at all abutments.
3. Longitudinal camber (parabolic curve) of the approaches should be provided.
4. The use of a reinforced concrete slab would be effective in minimizing the approach fault.

A NCHRP study conducted by Irick and Copas (1969) on bridge approach settlements summarized the existing information on the causes of settlement and possible solutions. The study indicated that embankment foundation was most often suspected to be the ause of settlement and that abutment backfill material, drainage nd construction methods were critical items in building and aintaining good bridge approaches. Though the synthesis ummarized the opinion of various agencies related to onstruction of approach abutments, it did not suggest any onclusive design, specification or new approach to rectify this roblem but recommended further research in this area.

Another investigation by Hopkins and Scott (1970) concluded hat settlement of the approach foundation contributed signifi-antly to the settlement of the bridge approaches, the amount f settlement being highly dependent on the time at which the pproach pavement was constructed. They conducted laboratory consolidation) tests on undisturbed soil specimens to predict he settlement and compared it with field measurements. Their tudy also revealed that settlement of the embankment contributed ignificantly to settlement of the approach pavement, especially f the embankment material was compressible. They suggested an arlier construction of embankment to allow consolidation before he construction of the pavement or alternatively a temporary avement could be constructed and periodically maintained until he embankment and foundation were stabilized, at which time a ermanent pavement could be constructed. They further ecommended the use of some means of bridging, such as extending he structure and/or providing heavily reinforced concrete pproach slabs as a means of reducing differential settlement.

Cross (1970) examined the use of a uniformly graded fine to edium sand and compared it with the performance of a well graded sandy gravel. The work was carried out at the site of an over-bridge which had 'open' abutments comprised of three vertical columns founded on bored piles. At each end of the bridge the transition from the bridge deck to the wedge filling was 'bridged' by a 3 m long slab of reinforced concrete. Underneath the whole site, at depths of between 4 and 5 m, there was a considerable thick layer of London clay. Overlaying the clay was sandy gravel between 2.5 and 4.5 m thick. The gravel was overlain by up to 1.2 m of sandy-silty clay. There was also up to .6 m of top soil which was removed prior to commencement of filling.

The south abutment wedge was filled with a uniformly-graded fine to medium sand. For comparative purposes, a well graded sandy gravel was used as fill in the wedge on the north side. Behind each abutment a three-point version of the mercury-filled settlement gage was installed at the subsoil level before construction was commenced. The points were located on the center line of the road; 3 m apart on the south side of the bridge and 5 m apart on the north side. The settlement of these points were measured relative to datum plates which, together with the gage indicator units, were housed in metal cabinets clear of the embankments. The levels of these datum plates were checked periodically relative to two permanent datum points located on each side of the motorway to the west of the bridge, well clear of any interference from the embankments. These permanent datum points consisted of 32mm diameter free-standing mild steel rods driven into gravel stratum and protected by 64 mm diameter steel casings ith screw caps.

The movement of the road surface was recorded by levelling ith an automatic precise level on metal studs which were driven nto the asphalt wearing course as it was being constructed and efore it hardened. These levels were related to temporary bench arks on the bridge which in turn were related to the permanent atum points. These studs were levelled periodically and these ata enabled determination of rate and distribution of settlement f the road surface. The settlement of the road surface was ompared with that of the subsoil and thus the settlement within he fill materials could be calculated. The settlement within he fill material was insignificant. Almost all of the settle-ent recorded was due to the compression of the subsoil. Mea-urement on the transverse rows of studs on the bridge deck and he embankment showed that there was no significant variation in ettlement with respect to transverse position across the road. his indicated that measurements were not affected by compression n the surfacing materials and that traffic loading had no ignificant influence on the settlement of the fill materials. he results showed that a uniformly-graded sand, when compacted o a standard specification, performed as well as a compacted ell-graded sandy gravel.

Hopkins and Deen (1970) investigated the settlement problem nd concluded that there existed a general relationship between he development of the approach fault and such possible causative actors as type of embankment, geological conditions and soil onditions. They noticed that for a short period of time portland cement concrete pavement performed better but in the long run equalled the performance of bituminous concrete pavement. They also observed that open-column (open-end) type of abutment was more commonly associated with hazardous settlement than pile-end-bent (open-end) or stub type (closed-end) in the initial period but over a long range of time, stub type abutments showed better performance and attributed it to the smaller average heights of embankment and thinner foundation soil associated with this type of abutment.

McLaren (1970) studied the performance of a silty clay fill in an approach embankment and compared its performance with that of a sandy gravel filling at the other abutment. The reinforced concrete bridge structure consisted of a single span portal with "V" frame open abutments on spread footings which were connected by prestressed concrete ties passing under the motor way. The approach embankment was constructed with gradient 1 in 30 and had a maximum height of 6.7 m at the abutment of the bridge. Transition slabs of reinforced concrete approximately 5 m long were provided at both ends of the bridge. The top soil was removed prior to the commencement of embankment construction. Records obtained from boreholes located near the bridge footings showed that the subsoil consisted of a 1.75 m thick layer of sandy clay on a stratum of gravel and sand between 4.4 and 5.5 m thick; this was underlain to a considerable depth by London clay. The main parts of the bridge approach embankments were constructed with domestic ash more than 30 years old but its use was not permitted in the areas immediately behind the bridge abutments. Behind the south abutment a sandy-gravel filling was used. For the purpose of investigation the filling behind the north abutment was specified to be a silty clay, with liquid limit of 37% and plastic limit of 19% (PI = 18). Types of filling were specified to be placed in accordance with the normal requirements for the compaction of earthwork specifications.

To record the settlement of the subsoil, a multi-point mercury-filled settlement gage was installed in the surface of the area behind each abutment before the filling was placed. The movement of the road surface was recorded by optical levelling on metal studs which were driven into the asphalt wearing course immediately after laying. The levels were initially related to temporary bench marks established on the bridge and these bench marks were then referred to a permanent datum installed well clear of any influence from the earthworks. The total settlement of the road surface behind the north abutment, where silty clay was used to complete the approach embankments, had amounted to a maximum of about 85 mm in the 4.5 year period since surfacing was completed. During this period the bridge abutment had settled by 20 mm and the main embankment by 15 mm which resulted in a maximum differential settlement of about 70 mm. Traffic loading was found to have made a considerable contribution to the settlement of the silty clay fill. The influence of traffic became apparent in the third year after the road was opened and was manifested by an increase in the rate of settlement of the road surface. Prior to this time the settlement had proceeded at a uniform rate in the areas behind the abutment where there was a similar depth of filling. The settlement during this first period occurred mainly from the consolidation of the fill and the subsoil under the weight of the embankment and it was clearly demonstrated that the presence of the transition slab had prevented an abrupt step being formed at the run-on to the bridge. A possible explanation for the subsequent increase in the rate of settlement in the third year after the road was completed could be due to the occurrence of increased dynamic stress induced by traffic as a result of the changes in the level profile of the road. The effect of this increase in dynamic loading appears to have been related to the direction of traffic. Invariably, more settlement was found to occur on the west side of the road where traffic travelled in a direction from the bridge towards the approach embankment. The performance of the silty clay filling at this site was very different from that obtained from a previous investigation wherein a medium clay fill was used and only very small movements within the filling had been recorded. A major difference between the two sites was in the type of abutment employed. At the previous site the bridge was designed with closed abutments while at the present site open abutments were constructed. It is possible, therefore, that the restraint offered by closed abutments might have some effect in reducing the settlement of a road surface carried by a fairly plastic clay fill. At the south abutment, where a sandy gravel fill was used for completing the approach embankment, settlement of the road after 4.5 years varied from 25 mm on the main embankment to about 50 mm on the gravel filled area behind the ɔutment. As the abutment also settled by 30 mm, the maximum ifferential movement over a length of about 20 m from the end of he bridge had only amounted to about 25 mm. There had been egligible settlement within the gravel filling.

Although the silty clay was particularly well compacted, ettlement of up to 45 mm occurred, after the road was completed, s a result of compression of the abutment filling under self-eight of the embankment and the dynamic effects of traffic. The ompression of the silty clay filling together with subsoil move-ents produced differential settlements of about 70 mm on the oad surface behind the abutment. After 4.5 years the movement ithin the fill had practically ceased but settlement of the ubsoil were still occurring at a rate of about 5 mm per year due o the consolidation in the underlying London clay.

As part of the Road Research Laboratory (England) studies, stony-clay filling vs. a sandy-gravel was evaluated by Margason 1970). The approach embankments were well compacted. Seven ears after the completion of the road, a settlement of 26 mm was bserved in stony-clay fill. The bridge settled by 23 mm and the ubsoil beneath the approach embankment settled by 48 mm. The lifferential settlement was not very significant to require emedial work; hence, it was concluded that stony-clay material as satisfactory as a fill material.

Kemahli (1971) of the Louisiana Department of Highways nvestigated the problem of differential settlement of approach avements in that state. Studying this problem from a view point of living with it, he concluded that in order to keep the settlement within control, it would be necessary to have a structural transition from one medium into another along with a geometric transition in the roadway profile. Using a 150 feet approach slab supported on piles of diminishing penetration, instead of the usual 20 feet approach slab, appeared to be a very promising method of accomplishing the necessary transition from a soil embankment to a bridge deck. It was believed that the new approach slab would behave just as a bridge deck sitting on long piles at the structure end. By gradually shortening the pile penetration towards the embankment end, the load would gradually shift from the piles to the embankment under the slab. At the embankment end, the approach slab would behave just like a concrete roadway slab following any displacement or settlement of the embankment. Timber piles were used for economy. Longest piles used at the structure end were 75 feet in length while only 15 feet piles were used at the embankment end. The approach slab was designed to be continuous and self supporting for a length of 150 feet resting on pile caps spaced at 10 feet on centers. At each pile cap there were four or six timber piles (depending on the roadway width) spaced at 7-feet intervals. The Department had four pile supported approach slabs under construction on I-10 west of New Orleans at the U.S. 51 interchange at the time of their report publication. No comments about their performance were available at that time. It was mentioned that pile supported approach slabs cost about half as much as a bridge deck.

Yee (1974) undertook an investigation in California to evaluate the use of lime treatment as a means to reduce differential settlement between bridges and approach embankments. The study compared the compressional characteristics of lime treated versus untreated approach embankments consisting of silty clay. The approaches were constructed with gradients of about 6.5% and reached a maximum height of 35 feet at the bridge abutments. Transition slabs of unreinforced concrete were poured at both ends of the bridges. From each end of the abutments a longitudinal distance of 100 feet for the right bridge approaches was lime treated. Logs of test boring revealed that the north end of the embankment subsoil consisted of soft to very stiff brown silty clay and soft to stiff brown silty clay at the south end. Ground water was encountered during the subsurface exploration at 2.5 feet below the ground surface. R values of the untreated material ranged from 5 to 10. The addition of 2% lime, by dry weight, increased the R value range of the untreated soil from 40 to 54. The addition of 5% lime increased the R values to 60 or higher. Vented fluid type settlement platforms were installed near ground elevation to record settlement of the subsoil. After completion of the embankments, surface hubs were installed and routinely used to monitor the compression within the embankment. This study, however, could not claim any effectiveness of lime treated approach embankment because the compressions actually measured were small (.04 feet for the control section and .05 feet for the experimental section) and the difference between the two measurements was insignificant.

Murray and Symons (1974) investigated the settlement and stability of a road embankment constructed on compressible alluvium. A soil survey over the route of a by-pass in Yorkshire, UK showed the presence of extensive deposits of compressible alluvium. The thickness of the compressible subsoil extended to a depth of 7.3 m adjacent to the point where the maximum height of the embankment was to be constructed. The alluvium comprised a layer of top soil and firm brown clay extending to a depth of about 1.4 m. Beneath this layer was a deposit of soft blue-grey clay of about 1.4 m thickness. The remaining 4.5 m of the compressible material was composed of a dark grey silty clay, changing to a more sandy brown-grey clay towards the base of the layer. A total of five settlement gages of the rod type were installed to measure the settlement occurring beneath the embankment. The gages were arranged in two horizontal profiles, one profile comprising two gages to measure the settlement of the ground surface beneath the center and beneath the shoulder 8.2 m south of center. The three gages in the remaining profile were established at a depth of 1.5 m below ground surface to monitor the deformation of the more compressible layers beneath the relatively stiff crust. The investigation showed that the construction of embankments over the areas of poor subsoil would provide a satisfactory engineering solution although close control over settlement and stability was essential. It also concluded that settlement prediction, based on coefficients of consolidation, determined from laboratory testing, seriously underestimated the rate of movement at the site and might well have led to the adoption of a more expensive design for the road structure. The researchers obtained satisfactory estimates of both the rate and magnitude of settlement from a multi-layer method of analysis using coefficients of consolidation determined from in-situ measurements of permeability.

Holmberg (1979) concluded that embankment piles beneath bridge approaches on soft ground was a suitable means to eliminate the traditional problem of differential settlements. Anticipating large differential settlements at sites underlain by compressible subsoil material, along a highway north of Bangkok, Thailand, the approaches were designed to be partly supported by embankment piles. In addition to the embankment piles, the bridges were constructed with approach slabs that were supported at one end by a footing resting in the embankment fill.

The length and spacing of the piles were determined so that the piles close to the bridges would theoretically be able to support the full weight of the embankment. With increasing distance from the bridges, pile lengths were gradually reduced and the spacing increased so that the weight of the embankment was gradually transferred from the piles to the ground surface. Piles 16 m long or less were timber piles with a diameter of 20 cm, while piles larger than 16 m were 22x22 cm prestressed concrete piles. Concrete cappings, 80 cm in diameter, were cast on top of the piles. The embankment fill at the bridge approaches was sand with a built-in bulk density of 1.9 t/m^3.

The inspection of the bridge approaches, after it had been in use for more than 6 years, showed that despite large settlements, the pile supported bridge approaches still provided a smooth transition between the bridge structure and the pavement. It had not been necessary to carry out any repair work on the surface of the approaches. In contrast, such maintenance was carried out on other highways in the vicinity once a year. Holmberg concluded that the use of embankment piles confirmed that their use beneath bridge approaches on soft ground was a suitable means of eliminating the problem of differential settlement. In his opinion the "floating" approach slabs were important in connection with the use of embankment piles.

Hughes (1981) discussed the use of different types of vertical drains to accelerate consolidation settlement under bridge approach settlements.

Ferry and Burrell (1981) suggested the use of a transition slab or techniques, such as preloading, to reduce differential settlement.

Selim, Walsh and Hannon (1981) used wick drains to accelerate the settlement of embankment. Adoption of a similar technique is reported by Nicholson and Jardine (1981).

Wicke (1982) suggested the inadequate compaction behind abutments as a possible reason for settlement of approach embankment. He mentioned that expansion of concrete pavements with temperature exert forces on the abutment creating a gap in the filling areas. This was another reason for settlement of the embankment. The third reason according to Wicke (1982) was the movement of the ground at the foundation level. He suggested the use of sleeper slabs, cement stabilization of fill material and pplication of drainage system behind the abutment as possible olutions.

Holroyd, Dawson and Jones (1982) reported the use of narrow rains for accelerating primary settlement and used pulverized uel ash as embankment material.

Hannon and Walsh (1982) reported the construction of approach embankments with special features such as reinforcing fabric to distribute embankment loading and prevent differential ettlement and failure of soft foundation soil during contruction. They also suggested the use of light weight fill, uch as saw dust, to reduce total embankment loading and vertical ick drains to accelerate the consolidation process.

Cheney and Chassie (1982) addressed the approach embankment ettlement problem in a soil and foundation workshop organized by he Federal Highway Administration in November, 1982. The pinion was advanced that the approach embankment settlement was he most prevalent foundation problem in highway construction. he clear definition of responsibility for designing the approach mbankment was stressed and it was pointed out that the approach mbankment needed special material and placement criteria to revent internal consolidation and moderate external onsolidation. A possible solution that was discussed in the eliberations of the workshop was construction of soil mbankments using quality control with regard to material and ompaction. It was emphasized that specific standard pecifications and drawings should be prepared for the approach mbankment. The need for the special attention in the interface rea between the structure and the approach embankment was mphasized. It was felt that poor compaction behind the butments, due to the restricted access of equipment, contributed ignificantly to the settlement problem. It was suggested that roper gradation of soil could help in attaining desired densifi-ation with minimum compaction effort. Other solutions con-idered were the reduction of the grade line, excavation and eplacement of soft soil, use of lightweight fill, reduction of onsolidation time by using surcharge or sand drains.

Hopkins (1985) reported the results of a study of long-term ovements at six bridge approach embankment sites in Kentucky. A ariety of means and instruments, including optical surveys, isual inspections and photo documentation, slope inclinometers, ercury-filled settlement gages, settlement platforms, and iezometers were utilized to monitor movement. Based on nformation compiled from observations at six selected bridge ites, Hopkins presented the following conclusions:

. Settlement of bridge approach foundations contributed significantly to settlements of approach pavements. The settlement was dependent on the time at which the approach pavements were placed during the construction process. Though primary consolidation was complete before the placement of approach pavement, secondary compression of the foundation was a significant factor causing settlement of approach pavements.

. Improper compaction of approach embankments contributed to settlement of approach pavements. At two sites where approaches were constructed of a mixture of durable rocks and non-durable shales and in 2 to 3 feet lifts, large approach pavement settlements occurred.

3. Lateral movements of approach embankments contributed to the settlement of approach pavements. Such movements occurred over a period of several years and were most prominent where approach embankments were resting on foundations having slope towards the ends of a bridge. Sites having relatively soft alluvium deposits as foundation of approach embankments were more susceptible to lateral movements. At the Bull Fork Creek site located in Rowan County, Kentucky, monitored by Hopkins, the largest lateral movements (approximately 0.2 to 0.5 inch per year) occurred in the top 40 feet of the embankment.
4. Erosion of materials from around the abutment and internal erosion aggrevated the settlement of approach pavements.
5. Generally, if the embankment had a large factor of safety (FS > 1.5), settlement of the approach pavement was smaller than at those sites where the FS was relatively low.
6. Effects of secondary compression and shear strain appear years after construction and were major contributors to the approach pavement settlement.
7. Seldom was there agreement between predicted settlement rate based on laboratory consolidation test and observed rates. Hopkins (1985) proposed an empirical method which he claimed lead to better agreement. However total settlement predicted generally agreed with observed total settlement.

- Use of reinforced concrete bridge approach pavements provided a smoother transition but it was uneconomical and did not eliminate differential settlement.

opkins (1985) suggested that to minimize or prevent differential ettlement, detailed attention must be given to such contributing actors as primary and secondary compression, shear strains, ompaction, lateral movements and erosion.

He further recommended the following measures:

(A) Elimination of post-construction settlement of compressible foundations by:

(i) Preconsolidation with a surcharge fill. This is feasible where sufficient time is available under surcharge load. A detailed settlement analysis of foundation and stability analyses of surcharged embankment was essential. He suggested a surcharge length, $S_L = 5\ (H_e + d_f)$ where H_e is the height of embankment and d_f is the depth of foundation.

(ii) Using drains. If settlement analyses show that the rate of settlement under surcharge would be slow, sand or wick drains may be required to increase the rate of settlement.

(iii) Removal of soft or compressible soil. Completely or partially removing the soft compressible material in the foundation and replacing it with rock or a suitable well-compacted material may be effective but impractical at depths greater than

10 or 15 feet. Analysis of benefits and costs of total or partial removal of foundations should be conducted.

(iv) Consolidation. Allowing sufficient time for consolidation under the load of the planned embankment may be a feasible means of reduction in approach pavement settlement in many cases.

(v) Lightweight fill. Foundation settlement may be reduced by use of lightweight fill such as furnace slag, lightweight concrete, expanded shale, coal waste refuse, coal, or other materials having relatively low unit weights.

(vi) Small secondary compression. Approach embankments should be constructed of materials that exhibit small secondary compression and shear strain settlement. Well compacted granular materials generally exhibit these properties.

(B) Special compaction provisions, such as follows:

(i) The maximum length, L_c, of the approach embankment where special compaction provisions would be applicable is:

$L_c = 5\ (H_e + d_f)$ where H_e is the height of approach embankment and d_f is the depth of foundation.

(ii) The approach embankment should be compacted to 98% of maximum dry density and the recommended tolerable range of moisture content about optimum moisture content is ± 2%.

(iii) Compaction equipment and methods applicable to fine and coarse-grained soils should be as recommended by the Design Manual, Soil Mechanics, Dept. of Navy. (NAVFAC DM-72, May 1982), Table 5, p. 7.2 - 48 and 7.2 - 49.) However, when durable rock is used, the compacted lift thickness is recommended to be 2 feet instead of 3 feet.

(iv) For shales with a slake-durability index greater than 95%, the compacted lift thickness should not exceed 1.5 ft.

(v) When non-durable shales having a slake-durability less than 95% but greater than 60% or when mixtures of non-durable shales and durable rocks are used to construct the approach embankment, the loose lift thickness should not be greater than 12 inches. For non-durable shales having a slake-durability index less than 60%, the lift thickness should not exceed 8 inches.

(vi) To compact shales having a slake-durability index less than 95%, the following items are recommended:

(a) Oversized material - any rock material measuring 6 inches in thickness and 1.5 feet in any other direction should not exceed 20% of the compacted mass; that is, not more than seven 6-inch or larger pieces in a square yard. Blasting techniques should be employed to crush rocks.

(b) Loose lift thickness as described in item (v) above.

(c) Since the natural water contents of most non-durable shales are below optimum, the addition of water to the shale will be necessary for proper compaction. Water should be added using only a spray bar attachment. The moisture content range should be +2% above optimum water content. Loose shale and water should be mixed using a heavy-duty 24-inch disk.

(d) Shales should be compacted using static and vibratory compactors. A static front roller having a minimum weight of 53,000 lbs should be used to break down the shales after mixing with a 24-inch disk. The static tamping roller should measure a minimum of 6 inches in length. Each foot should have a small area. Recommended number of passes is two to four. When a vibratory pad drum roller is used, the minimum weight should be 55,000 lbs. When a pneumatic tire, vibratory roller is used, the minimum weight should 100,000 lbs. Recommended number of passes using the vibratory roller is four to six. If 98% of dry density is not achieved in six passes, then the number of passes should be increased until such result is obtained.

(e) Use of nuclear density equipment is permissible only if it is checked against the sand cone technique.

(f) Laboratory maximum dry density and optimum moisture content should be adjusted for oversize particles before comparing to field values.

Hopkins' study showed that secondary compression and shear strain may occur even for well compacted fills and for embankments constructed of fine-grained plastic soils (CL, OL, MN, CH). It becomes significant for embankment heights greater than about 30 feet. However, for other materials (GW, GP, GM, GC, SW, SP, SM, SC AND ML), settlements become significant for embankment heights greater than about 55 feet. Hopkins recommended that priority be given to selecting materials that exhibit little secondary compression.

Consolidation tests on compacted specimen were recommended to estimate secondary compression and stressed on the design method to limit the amount of secondary compression. In case it is uneconomical to use such materials or if such materials are not available and the approach embankment must be constructed to a height greater than about 30 feet of plastic soils, Hopkins suggested the use of temporary asphaltic concrete approaches. Hopkins suggested an empirical method to calculate the settlement due to shear strain and secondary compression.

Drainage measures were suggested around bridge abutments and under approach embankments. The specific proposals are as follows:

1. Select granular backfill should be used behind, under and in front of the abutment. The select material should have less than 5% passing the No. 200 sieve.
2. The select backfill should be completely encapsulated with a geotextile filter fabric. Protective filter criteria should be satisfied.
3. Perforated pipe, or PVC, should be installed in the backfill. The pipes should run to collection points outside the confines of the abutment. Water from these pipes should not be allowed to drain onto unprotected slopes of the approach embankment.
4. Some type of permanent slope protection should be installed on the face of the slope that lies directly under the bridge. The face of the slope should be covered with a geotextile drainage fabric or sand layer. A thin layer of select rock is placed on top of the fabric or sand. Concrete revetments placed on top of geotextile drainage filter, or sand layer would probably perform properly.
5. When drainage pipes of the bridge deck are placed directly over the face of the approach embankment, splash blocks should be placed directly under the drainage pipes to dissipate the energy of the falling water and to prevent erosion of the fill.

Based on observations, Hopkins concluded that generally in ases where embankment is a side-hill fill and original roundline slope towards the bridge ends, lateral movement of the pproach embankment occurs. The approach embankment generally is ocated on relatively thin overburden soils and the bedrock is omposed of clayey shales. The overburden soils often contain a one of highly weathered shale. Hopkins recommended the ollowing for situations of this type.

. If the overburden soils are relatively thin, consideration should be given to removal of the overburden soils and weathered clayey shale zone. Benches should be constructed in the shale.
. Select granular drainage material should be placed on the benches to prevent encroachment of ground water into the approach fill at a later date. Perforated pipe should be placed in the drainage layer.
. Consideration should be given to using small rock berms, or rock shear keys, at the toe of the approach embankment so the factor of safety can be maintained at a high level.

Hopkins also suggested longitudinal camber of the bridge approach embankment, the amount to be used at any given site would epend on the thickness and compressibility of the embankment and oundation.

Hopkins concluded that the study on the bridge approaches as brought about several benefits. Subsurface investigations re presently being conducted at all bridge approach embankments reater than 20 feet in height.

2.3 A Summary of the Previous Studies

In the preceding section, the major studies related to bridge approach settlement ~~has~~ have been discussed in some detail. This section presents a summary of these studies.

Two significant studies are identified. The one undertaken by the Road Research Laboratory in U.K. investigated the performance of various fill materials for the approach embankment. The performance of fresh hopper ash, medium clay, silty clay, stony clay, uniformly graded fine to medium sand was evaluated. It was concluded that all these materials except silty clay performed satisfactorily.

Another major series of investigation were undertaken by the Kentucky Department of Transportation and spanned the period from 1964 to 1985. The first phase of the study involved surveying 782 bridge approaches in an attempt to relate bridge approach settlement problems with various causative factors. This survey led to the following conclusions:

(i) In the initial stage the portland cement concrete approaches performed better than bituminous concrete approaches but in the long run, the performance was similar.

(ii) Geological features of the area had a relation with approach pavement settlement. The lowest percentage of defective bridge approaches were in areas with unique topographic features such as broad alluvium bottoms of large rivers.

(iii) The settlement problem was most severe in areas where subsoil consisted primarily of shale and plastic clays.

(iv) Stub abutments were associated with smoother bridge approaches compared to open-column or pile-end-bent abutments.

(v) Erosion of soil adjacent to abutment was also in some cases responsible for approach problems.

(vi) Progressive failure or creep of the approach embankment was also a significant causative factor.

(vii) Traffic condition had no apparent contribution to the problem.

This study was followed by an in-depth investigation of well instrumented, well monitored bridge sites. The research conducted by Hopkins (1985) on behalf of the Kentucky Department of Transportation showed that the most significant contribution to approach pavement settlement came from the following: (a) settlement of embankment foundation, (b) improper compaction of embankment, (c) lateral movement of embankment, (d) erosion of materials from around the abutment and (e) secondary compression and shear strain of embankment. Hopkins (1985) suggested a number of measures and compaction requirements to prevent or minimize the approach pavement settlement. He recommended the elimination of post construction settlement of compressible foundation by surcharge fill, drains, allowing sufficient time for consolidation of subsoil, and the use of lightweight fill. He suggested the use of material that does not exhibit significant secondary compression for embankment fill. Hopkins also suggested some compaction measures and drainage requirements.

Besides the above mentioned two major series of studies, isolated studies have also been reported in the literature. Two of these studies investigated the use of piles to support the approach embankments. In one case (Kemahli, 1971), the adequacy of the approach was not reported. In the other case (Holmberg 1978), it was observed that the pile foundation of the approach embankment provided a smooth transition from bridge structure to pavement though it could not stop the settlement of approach embankment.

Another direction of study investigated the use of sand drains, wick drains to accelerate the settlement of foundation (Nicholson and Jardine, 1981; Wicke, 1982). There were, however, not much mentioned about the effectiveness of these measures.

Another study made by Yee (1974) investigated the performance of a lime-treated approach embankment. His study, however, could not offer any conclusive results.

2.4 Fly Ash Embankments

While no comprehensive literature search was conducted in regards to the utilization of non-soil or stabilized soil embankments, a cursory review of fills (HRIS, 1985) behind bridge abutments and embankments, in general, points to the fact that fly ash is finding wider and more viable use in such projects. The possibility, therefore, exists that the settlement problem, as in this study, may partly find its answer in the use of fly ash.

CHAPTER 3

SUMMARY OF RESPONSE TO QUESTIONNAIRE

3.1 Introduction

A comprehensive understanding of various causative factors is essential for the development of appropriate design guidelines and specifications to eliminate or substantially reduce detrimental settlements of approach pavements. To this end, a survey of various agencies involved in construction and maintenance of highways and roads, was conducted to obtain first hand information pertinent to the problem under consideration.

A questionnaire was prepared in cooperation with the Oklahoma Department of Transportation (ODOT) with the aim of obtaining the views of the aforementioned agencies on various aspects of approach pavement settlements and their remedies. The questionnaire was sent to 52 state DOTs and 36 Corps of Engineers Districts as well as to some other agencies and professionals involved in design, construction and/or maintentance of parvements and bridges. A summary of the responses received thus far is presented in this chapter.

3.2 Overview of the Questionnaire

A copy of the questionnaire is presented in Appendix I. It consisted of eight questions related to the following areas:

(i) Significance of the approach pavement settlement problem.

(ii) Research studies undertaken to investigate this problem.

(iii) Probable causes of differential settlement between bridge abutments and approach pavements.

(iv) Possible remedies to minimize this problem.

In some questions (1, 3, 4, 6 and 7) multiple choices were provided and the respondent was asked to select the appropriate choice based on the experience of the responding agency, while for the other questions the respondent was requested to state his/her views pertinent to the question. The multiple choices provided was selected carefully, based on the information available in the literature. A number of the Oklahoma DOT officials contributed to the preparation of the questionnaire by suggesting their views and experience concerning the problem. In some questions (namely 6 and 7) related to the causes and remedies of approach pavement settlement, the responding agency was requested to rank various choices in order of importance or effectiveness.

3.3 Evaluation of Responses Received

A list of the responding surveyees is included in Appendix II.

The overall outcome of the survey was very encouraging and enlightening. Forty-three state DOTs and eighteen Corps of Engineers districts responded prior to writing this report. In most cases the questionnaire was completed by personnel directly associated with the construction and maintenance of bridges and pavements. As the responses were received, they were analyzed carefully. A summary of this analysis is presented in what follows.

Question 1 addressed the significance of approach pavement ettlement problem in various states. Of the 61 respondents, 42 onsidered the problem to be significant or very significant in neir states (Table 3.1). Only 2 respondents regarded the ifferential approach pavement settlement as a severe problem. tates in this category include Idaho and Maryland. Eight rganizations, Illinois, Mississippi, New Jersey, Pennsylvania, ermont and Corps of Engineers districts of Little Rock, Los ngeles and Norfolk, considered the problem to be insignificant. ne topographical and geological features probably contributed to etter approach pavement performance, rather than adoption of dvanced design and construction techniques and specifications.

Question 2 was related to research efforts of various rganizations pertinent to the problem. It was interesting to ote that of the 42 responding organizations who considered the ifferential approach pavement settlement as significant or very ignificant, only about 5 of them have undertaken some research ork to investigate this problem. Included in this category are ich states as California, Iowa, Kentucky, Ohio, and Texas. This irvey as well as the literature reviews indicates the need for ibstantial research on causes and remedies of approach pavement ettlement.

A significant number of bridge approaches require costly aintenance to rectify this problem. The response to question 3 nquiring about the extent of maintenance work performed is shown n Table 3.2

It is important to be able to predict the time required, after the paving is completed, for the start of the significant differential settlement. From the summary responses presented in Table 3.3, this is seen to vary in different states and for different bridge approaches. Therefore, it cannot be generalized that after a certain period of time, a particular site will start developing significant differential settlement.

The majority of the responding organizations (43) mentioned that they used approach slabs, generally of reinforced concrete in their construction. However, only a few claimed that it had any effectiveness in reducing the differential settlement.

Different causative factors have been ranked (1 being the most significant), according to the significance of their contribution to bridge approach settlement problem by the responding organizations. However, it has to be emphasized that the factors ranked were listed in the questionnaire based on the existing knowledge. As may be seen from Table 3.4, the most significant factors contributing to the settlement process is the condition or type of embankment foundation. Construction technique is ranked the 2nd while material of embankment is ranked the 3rd most significant factor.

Table 3.4 shows the ranking of each causative factor. For example, 22 responding organizations considered "foundation of the embankment" to be the most significant cause of settlement (by assigning rank 1), while 8 considered it the 2nd most significant cause and so on.

The responses overwhelmingly considered the above mentioned three factors to be the most significant. However, some of the responding organizations considered some other factors, besides those listed in the questionnaire, as contributing factors. Frost action and heave, horizontal movement of approach embankment toward the structure, use of piles to support abutments, abutment movement and freeze-thaw cycle were mentioned as other possible causes of bridge approach settlement.

In Table 3.5 the ranking of various causative factors assigned by each responding organization is shown. Also added in the Table are some of the causative factors which were not included in the questionnaire but were assumed as significant by any of the respondent.

The causative factors have been designated by letters, a to r, and are shown in Appendix III. For instance, Idaho considers causative factor a (i.e., material of the embankment) to be the most significant by asssigning a number 1. The blank spaces represent a "no comment" reply from the respondents. Although respondents from only a few states have attached great importance to a particualr causative factor, any or some of the factors may be very significant in a particular state. This suggests that although there are some well recognized factors which are thought to be responsible for settlements behind bridge abutments, there may be some other less common, yet very significant factors typical of certain topography, geologic, and climatic conditions. An in-depth study to investigate this problem has been conducted by Kentucky DOT and in its opinion, the secondary compression of the foundation is the most significant cause of settlement.

Also, it was pointed out that in high embankments, secondary compression and shear strain of the approach embankment also play significant roles.

Table 3.6 shows the rank of various preventive measures. For example, 42 respondents consider imposition of strict restriction on compaction specification to be an effective method to reduce approach pavement settlement while only 6 respondents consider it ineffective.

From the responses it is evident that the majority of the organizations feel the need of a "follow-up" of specification. Well graded, sandy gravel and coarse sand are often accepted as good fill material from the viewpoint of minimization of the settlement problem. The respondents also consider preloading with surcharge fill or allowing sufficient time for consolidation before pavement construction to be effective measures. However most of these measures present some type of disadvantages, either from a economic point of view or time limitation for the project.

Use of flowable mortar as fill material has been suggested by a responding organization [14]. Use of light weight fill, e.g., "bloated" shale or flat abutment slopes have also been suggested by some organizations. The effectiveness of bridge approach slabs is not very conclusive. Some of the organizations [32,33,37] claimed it to be effective while others maintained that these approach slabs only shifted the location of differential settlement without minimizing or eliminating it.

The Kentucky DOT suggested a long term factor of safety of ot less than 1.4 to minimize secondary compression and shear train of the embankment. Placement of a large drainage system nd the use of dynamic compaction of embankment have also been uggested.

Other suggestions include limiting the number of abutments upported on piles, using drive lapped guard-rail sections at nds to contain embankment, placement of rock layer (4 ft ± epth) at the bottom of embankment, extension of bridge structure o reduce embankment height, construction of embankment before xcavation for abutment.

The South Dakota DOT mentions that use of the following pecification for backfill alleviated the bridge approach ettlement and swelling problem.

Percent passing 1½ inch sieve - 100

Percent passing 1 inch sieve - 95 to 100

Percent passing ½ inch sieve - 25 to 60

Percent passing #4 sieve - 0 to 10

The California Transportation Department suggests the use of elect material for fill as sand equivalent value of not less han 20 and the following grading:

Percent passing 3 inch sieve - 100

Percent passing # 4 sieve - 35 to 100

Percent passing # 30 sieve - 20 to 100

Some other organizations suggested to live with the problem nd perform periodic maintenance to patch up the settlement until t is stabilized.

It is apparent from the survey that no solution is unique.

For any effective solution it is mandatory to consider the site, topographic, climatic and construction conditions typical to a particular state.

TABLE 3.1 Severity of Bridge Approach Settlement Problem in Different States

Degree of Severity	Number of Responding Agencies	% of Responding Agencies	List of Agencies (Ref. Appendix II)
Severe	2	3.3	9, 17
Very Significant	9	14.8	4, 5, 10, 14, 16, 28, 33, 38, 57
Significant	33	54.1	1, 2, 3, 6, 7, 8, 11, 13, 15, 18, 20, 21, 22, 23, 24, 26, 27, 29, 30, 32, 34, 35, 36, 39, 40, 41, 44, 45, 47, 48, 59, 60, 61
Insignificant	8	13.1	12, 18, 25, 31, 37, 50, 51, 53
No comment	9	14.8	42, 43, 46, 49, 52, 54, 55, 56, 58

TABLE 3.2 Extent of Maintenance Work Performed to Rectify Bridge Approach Settlement Problem

ercentage of ridge Approaches equiring Maintenance	Number and Percentage of Responding Organizations	List of the Organizations
0 - 20	16 (26.2)*	5, 7, 11, 12, 18, 20, 25, 31, 32, 36, 37, 44, 50, 51, 53, 60
21 - 40	17 (27.9)	3, 6, 8, 9, 22, 23, 24, 26, 27, 28, 34, 38, 39, 40, 41, 45, 47
41 - 60	7 (11.5)	1, 2, 4, 17, 29, 33, 35
61 - 80	9 (14.8)	10, 13, 14, 15, 16, 21, 30, 59, 61
81 - 100	1 (1.6)	57
o Comment	11 (18.0)	19, 42, 43, 46, 48, 49, 52, 54, 55, 56, 58

Numbers in parenthesis indicate percentages.

TABLE 3.3 Average Time for Significant Settlement to Start

Time in Years	Number and Percentage of Responding Organization
0 - 1	4 (6.6)*
1 - 2	8 (13.1)
2 - 3	10 (16.4)
over 3	12 (19.7)
varies	17 (27.9)
No comment	10 (16.4)

* Numbers in parenthesis indicate percentages.

Causative Factor	Rank of Different Causative Factors								
	1	2	3	4	5	6	7	8	No Comment
Material of embankment	12(19.7)*	8(13.1)	15(24.6)	8(13.1)	2(3.3)	1(1.6)	1(1.6)	0(0)	14(23.0)
Type of pavement	1(1.6)	1(1.7)	1(1.6)	6(9.8)	4(6.6)	5(8.2)	6(9.8)	7(11.5)	30(49.2)
Foundation of embankment	22(36.1)	8(13.1)	8(13.1)	4(6.6)	1(1.6)	1(1.6)	0(0)	0(0)	17(27.9)
Type of abutment	2(3.3)	2(3.3)	4(6.6)	5(8.2)	6(9.8)	6(9.8)	2(3.3)	3(4.9)	31(50.8)
Progressive failure or creep of the approach embankment	1(1.6)	6(9.8)	4(6.6)	7(11.5)	4(6.6)	6(9.8)	4(6.6)	3(4.9)	26(42.6)
Erosion of soil from abutment	1(1.6)	3(4.9)	2(3.3)	7(11.5)	15(24.6)	3(4.9)	3(4.9)	3(4.9)	24(39.3)
Traffic direction	0(0)	1(1.6)	0(0)	0(0)	1(1.6)	7(11.5)	4(6.6)	13(21.3)	35(57.4)
Construction technique of embankment	15(24.6)	11(18.0)	9(14.8)	4(6.6)	3(4.9)	0(0)	1(1.6)	0(0)	18(29.5)

* Numbers in parenthesis indicate percentages.

Table 3.5 Rank of Various Causative Factors Assigned by Responding Organizations

Responding Organizations	Causative Factors																	
Dept. of Transportation	a+	b*	c+	d*	e+	f*	g*	h+	i*	j*	k*	l*	m*	n*	o*	p*	q*	r*
Alaska	6	7	1	8	4	5	8	3	2									
Arkansas	5		3		2			4							1			
Arizona	2	6	4	3	6	5	7	1										
California	1	5	1	8		8	8	1										
Colorado	1				3	5		2			4							
Delaware	4	7	2	3	6	5	8	1										
Georgia	4	8	2	5	7	3	6	1										
Hawaii	3		1	5	2			4										
Idaho	1	8	3	6	5	4	7	2										
Illinois (Material Div.)	1		4		2			3										
Illinois (Bridge Div.)	4	7	1	2	6	5	8	3										
Indiana	2		3			4		1										
Iowa	2	8	3	8	8	4	8	1										
Kansas	3	6	1	7	5	4	8	2				3						
Kentucky	2	6	1	7	3	5	8	4					1					
Maryland	3		5	4		2		1										
Massachussetts	4		1		2		5	3										
Mississippi																		
Missouri (Mat. & Res.)	4		1		3	5								2				
Missouri (Maint. & Traffic)	1		3		4	5		2										

* See Appendix III

a+ = Material of the embankment, c+ = Foundation of embankment
e+ = Progressive failure or creep of the approach,
h + = Construction technique of embankment

(continued)

Table 3.5 (continued)

Responding Organizations	Causative Factors a+	b*	c+	d*	e+	f*	g*	h+	i*	j*	k*	l*	m*	n*	o*	p*	q*	r*
Nebraska	4	7	1	5	2	6	8	3										
Nebraska	3	4	1	6	7	5	8	2										
Nebraska	3	4	1	6	7	5	8	2										
New Jersey	1	2						3										
New Mexico	1	4	2	3	6	6	6	5										
New York	4	3	2		5										1			
Ohio	3	7	4	1	6	5	8	2			1					1		
Oklahoma	3	5	2	5	6	7	8	1										
Oregon																	1	
Pennsylvania	2	8	1	4	7	5	6	3										
Rhode Island	2	4	3	5	8	7	6	1										
South Carolina	1		2			4		3										
South Dakota	3	4		5					2									1
Texas	1	6	3		5	4		2										
Utah	3		1					4										
Vermont	4	5	1	3	8	8	7	2		6								
West Virginia	3	8	1	2	4	7	6	5										
Washington, D.C.	1		4		3	2												
Wisconsin	3	7	1	6	4	5	8	2										
Wyoming	2	6	3	6	4	5	6	1										

* See Appendix III

a+ = Material of the embankment, c+ = Foundation of embankment
e+ = Progressive failure or creep of the approach,
h + = Construction technique of embankment

(continued)

Table 3.5 (continued)

Responding Organizations	Causative Factors a+	b*	c+	d*	e+	f*	g*	h+	i*	j*	k*	l*	m*	n*	o*	p*	q*	r*
Corps of Engineers																		
Alaska																		
Albuquerque																		
Buffalo	3	4	6	5	1	8	2	7										
Charleston	5	8	2	6	4	3	7	1										
Huntington	1		1	1				1										
Kansas City																		
Jacksonville																		
Little Rock	3					2		1										
Los Angeles	3		2	4				1										
New Orleans																		
Norfolk			1															
Sacramento																		
St. Louis																		
St. Paul																		
Nashville																		
Vicksburg																		
Walla Walla	1		1					1										
Chicago																		
Minnesota D.O.T.	2		1		4	5		3										
Nebraska D.O.T. (Roadway Div.)	7	8	1	4	2	6	8	5										

* See Appendix III

a+ = Material of the embankment, c+ = Foundation of embankment
e+ = Progressive failure or creep of the approach,
h + = Construction technique of embankment

TABLE 3.6 Effectiveness of Various Measures to Minimize the Settlement Problem

Measures	Number (Percentage) of Responding Organization			
	Effective	Not Effective	No Experience	No Comment
I. Imposing strict restriction on compaction specification	42(68.8)	6(9.8)	3(4.9)	10(16.4)
II. Replacing any compressive material with:				
(i) Pulverized fuel ash	3(4.9)	0(0)	44(72.1)	14(23)
(ii) Silty clay	10(16.4)	16(26.2)	22(36.1)	13(21.2)
(iii) Well graded sandy gravel	26(42.6)	8(13.1)	13(21.3)	14(23)
(iv) Fine to medium sand	18(29.5)	8(13.1)	20(32.2)	15(24.6)
(v) Coarse sand	24(39.3)	8(13.1)	17(27.9)	12(19.7)
III. Accelerating consolidation settlement of the approach embankment & foundation soil by:				
(i) Preloading with surcharge fill	41(67.2)	4(6.6)	7(11.5)	9(14.8)
(ii) Construction of sand drains	23(37.7)	3(4.9)	23(37.7)	22(36.1)
(iii) Placing of wick drains	16(26.2)	3(4.9)	28(45.9)	14(23.0)
IV. Employing techniques such as:				
(i) Pile foundation for embankment	6(9.8)	5(8.2)	36(59.0)	14(23.0)
(ii) Stabilizing the soil material	22(37.3)	2(3.4)	26(40.7)	11(18.6)
(iii) Allowing sufficient time for consolidation before permanent construction	41(67.2)	5(8.2)	5(8.2)	10(16.4)
(iv) Use of reinforcing fabric in embankment	3(4.9)	4(6.6)	38(62.3)	16(26.2)
(v) Use of lightweight fill	5(8.2)	3(4.9)	38(62.3)	15(24.6)
(vi) Grout injection	9(14.8)	6(9.8)	21(34.4)	15(24.6)
(vii) Providing stone columns	6(9.8)	1(1.6)	42(68.9)	12(19.7)

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Discussions and Conclusions

This study was primarily concerned with determining the causes of excessive settlement of pavements behind bridge abutments. To accomplish this objective, a comprehensive search of pertinent literature was made using the computer search facilities of the Highway Research Information Service (HRIS) as well as other facilities available at the University of Oklahoma. In addition, a survey of various agencies involved in construction and maintenance of highways and roads , was conducted to obtain first hand information pertinent to the problem under consideration.

Based on information compiled from the responses of the survey it is evident that the bridge approach settlement problem is quite extensive in Oklahoma and in many other states in the Country. The review of related published works leads to the observation that studies have been undertaken as early as in 1964, but most of these were concerned with specific aspects of the problem, such as effects of drainage condition, pavement types and backfill material. As a result, the findings of most of these studies have been either incomplete or inconclusive. Also, relatively few agencies have been involved with research to prevent or minimize this settlement problem. From the survey response it was found that of the 52 agencies having experience with this problem, only 5 had undertaken any studies to prevent r minimize this problem. Year after year costly maintenance and nterruption of traffic flow have been experienced.

From the review of related works and the survey response, it s evident that the causes of the settlement cannot be generalzed. They may be unique for a particular site. For example, econdary compression and shear strain of embankment was cited to e a very significant causative factor by one of the respondent, hile, it was not at all emphasized by most others. Some studies laimed that traffic did not have any influence on the settlement rocess while another study emphasized its significant contribuion. There are also some causative factors typical of a partiular region which may be insignificant in other regions. As far s the remedial measures are concerned, there is also diversity f opinion. Some measures could undoubtedly be effective but hey may not be practical in a particular situation. For exmple, removal of the compressible sub-soil would surely signifiantly reduce the settlement process, but this may not be feasile in most cases where the depth of compressible material is ignificant.

Imposition of strict restrictions on compaction specificaions may reduce the settlement of embankment but cannot reduce he settlement due to secondary compression and shear strain of he embankment or settlement of the foundation.

Use of granular materials for embankment may be effective in ome cases, but there will be an economic limitation if they are ot locally available.

Some other techniques like preloading with surcharge fill, llowing sufficient time for consolidation before the pavement is onstructed may not be practical in cases where time is limited.

Measures like the use of pile foundation for embankment may e effective but may not be justified from an economic point of iew.

Although some studies have claimed that transition slabs liminated the differential settlement problem, most of the pre-ious works as well as the survey responses termed them ineffec-ive.

The following conclusions are made based on the review of ertinent literature and compilation of response of survey uestionnaire:

. The bridge approach settlement problem is quite extensive in Oklahoma and many other states in the U.S.A.

. Most of the research efforts undertaken in the past to study this problem have focused on some specific aspects, such as drainage condition, pavement type and backfill material.

. Cost-benefit analysis has been either not considered or not reported in previous studies.

. The causes of approach pavement settlement cannot be generalized for all sites and/or all states in the country.

. Usually, settlement of embankment foundation, type of embankment material, and technique and quality of embankment construction are the most significant causes of approach pavement settlement.

. Pavement type usually does not have a significant effect on the magnitude of long term settlement. However, it may significantly influence the short term as well as the rate of settlement.

7. Abutment type seems to have some contribution in the settlement. Generally, stub type abutments provide smoother bridge approaches.
8. Erosion of soil from abutment sides and embankment contribute to the settlement problem.
9. Traffic direction relative to location of settlement has insignificant contribution to the settlement process.
10. Approach slabs do not prevent the problem but only shifts the location of settlement.
11. Stabilization of embankment material has not been evaluated by most investigators.
12. Use of pile supported approach embankment may provide a smooth transition between the bridge deck and approach pavement but cannot eliminate the differential settlement. Also the cost may be prohibitive in its use.
13. Use of select material for embankment may alleviate the problem in some areas.
14. Measures to allow completion of primary consolidation before pavement construction may not be effective for many sites where secondary consolidation is significant.

4.2 Recommendations for Further Study

Detail review of existing literature and synthesis of the survey responses indicate a need for more in-depth investigations of approach pavement settlement problem. The following recommendations are made for a further study:

1. For design and maintenance of approach pavements and embankments, it is important to estimate the total and the rate of settlements at the site. Appropriate prediction equations and methods should be developed for this purpose. Recently, Hopkins et al. (1985) have proposed empirical equations to predict the rate of primary settlement of embankment foundations. The predicted settlements were compared with the observed values obtained from a number of sites in Kentucky. Generally, the predicted rate of settlement was lower than the actual rate.

   From the information presented in Chapters 3 and 4, it is evident that the settlement of approach foundation may be influenced by the following factors, among others:

   a) Subsoil properties
      (i) coefficient of permeability
      (ii) coefficient of consolidation
      (iii) plasticity index
      (iv) compression index
   b) Depth of drainage layer
   c) Height of embankment
   d) Time and history (loading rate) of embankment construction.

   Although Hopkins' (1985) study was a pioneering work in the subject concerned, it neglected some of the aforementioned factors in the empirical equations. It is envisioned that better prediction equations could be obtained by incorporating the essential factors.

2. It is evident from previous studies that secondary compression or creep of embankment and foundation soils can contribute significantly towards the approach pavement settlement, especially long term settlement. Creeping of soil is sometimes responsible for tilting of abutments, too. It is believed that these phenomenona are particularly important for a site having highly plastic soil. An empirical procedure could be developed to predict creep and/or secondary compression related settlements of approach embankments and foundations.

3. In addition to the empirical methods mentioned above, a mathematical model, based on numerical analysis techniques such as the finite element, can be developed to predict consolidation and secondary compression or creep related settlements of approach foundation soil. This mathematical model would incorporate flow and strength properties of soil as well as such parameters as embankment height, construction history and drainage related boundary conditions.

   Development of accurate settlement prediction methods will immensely help in scheduling construction and maintenance programs.

4. Many other aspects of approach pavement settlement problem are important in terms of scheduling maintenance measures. One such aspect is to quantify or establish tolerable limts for such settlements. The word "bump", often used to characterize excessive differential settlements of approach pavement, is very subjective. An in-depth study should be able to assign numerical significance to it.

REFERENCES

Chaney, R.S.; Chassie, R.G. Soils and foundation workshop. U.S. Department of Transportation, FHWA, Washington, D.C., November 1982.

Cross, J.E. (1970). Settlement behind bridge abutments; The performance of a uniformly-graded sand fill in an approach embankment on the M4 Motorway. Road Res. Lab/UK/; 1970, RRL Dept. Lr 310, 7 pp.

Department of the Navy, Design Manual, Soil Mechanics, Foundation, and Earth Structures, NAVFAC DM-7, March 1971.

Ferry, A.G.; Burrell, R.W. (1981). A manual of pavement repairs. National Roads Board, New Zealand, P.O. Box 12-041, Wellington, New Zealand 0110-442x, 1981, Monograph.

Hannon, J.B.; Walsh, T.J. (1982). Wick drains, membrane reinforcement and lightweight fill for embankment construction at Dumbarton. Transportation Research Board, California Dept. of Transportation, Transportation Research Record N897, 1982, pp. 37-42.

Holmberg, S. (1979). Bridge approaches on soft clay supported by embankment piles. Southeast Asian Society of Soil Engineering, Geotechnical Engineering Vol. 10, No. 1, June 1979, pp. 77-89.

Holroyd, J.J.; Dawson, G.M.; Jones K.R. (1981). Design and construction of the approach embankments to the River Trent Bridge on the M180 South Humberside Motorway. Institution of Civil Engineers, Proceedings, Pt. 1, Vol. 70, No. PT1, Aug. 1981, pp. 481-499.

Hopkins, T. C. (1969). Settlement of highway bridge approaches and embankment foundations. Interim Report, KYHPR-64-17; HPR-1(4), Part II, Division of Research, Dept. of Highways, Commonwealth of Kentucky.

Hopkins, T.C. (1973). Settlement of highway bridge approaches and embankment foundations, Bluegrass Parkway Bridges over Chaplin River. Kentucky Dept. of Highway, N 356, Feb. 1973, Interim 39, pp 35.

Hopkins, T.C. (1985). Long-term movements of highway bridge approach embankments and pavements. A draft report, UKTRP-85-12, Kentucky Transportation Research program, Lexington, Kentucky.

Hopkins, T.C.; Deen, R.C. (1970). The bump at the end of the bridge. Highway Research Record, Hwy. Res. Board, 1970, No. 302, pp. 72-75.

opkins, T.C.; Scott, G.D. (1970) Estimated and observed settlements of bridge approaches. Highway Research Record, Highway Research Board, 1970, No. 302, pp. 76-86.

RIS (1985) Selections pertaining to: Fly ash in embankments.

ughes, F.H. (1981). Vertical drains accelerate consolidation settlement under bridge approach embankments. Highways and Public Works, Vol. 49, No. 1858, Oct. 1981, p. 8.

rick, P.E.; Copas, T.L. (1969) Bridge approach design and construction practices. NCHRP Synthesis of Highway Practice 2, Highway Research Board, 1969.

emahli, A.S. (1971). A different approach to bridge approach slabs. Highway Focus, Vol. 3, No. 3, August 1971, pp. 23-80.

argason, G. (1970). Settlements behind bridge abutments. The performance of a stony clay fill in an approach embankment to an overbridge on the M4 Motorway. Ministry of Transport, London/UK/; RRL Rept. Lr 311.

argason, G.; Cross, J.E. (1966). Settlement behind bridge abutments - the use of pulverized fuel ash in constructing the approach embankments to the bridges on the Staines By-pass. England Road Res. Lab., Report No. HS-002 948.

cLaren, D. (1967). Settlement behind bridge abutments. The performance of a medium-clay fill used to form the approach embankments to a bridge on the M1 Motorway. RRL Reports, Road Res. Lab/ UK/No. Lr 76.

cLaren, D. (1970). Settlement behind bridge abutments. The performance of silty clay fill in an approach embankment on the M4 Motorway. RRL Reports, Road Res. Lab/UK/RRL Dept., Lr 309.

cNulty, E.G. (1979). Corrective measures for unstable bridge-approach embankment US 68, Licking River, Blue Licks. Kentucky Bureau of Highways, Lexington. Div. of Research; Federal Highway Admin., Washington, D.C. Nov. 1979.

urray, R.T.; Symons, I.F. (1974). Embankments on soft foundations: Settlement and stability study at Tickton in Yorkshire. Transport and Road Res. Lab., Crowthorne, Berkshire, RG 11 6 AU England. 1974.

ational Cooperative Highway Research Program Synthesis of Highway Practice 2, (1969). Bridge approach design and construction practices. Highway Research Board, Div. of Engineering National Res. Council.

Nicholson, D.P.; Jardine, R.J. (1981). Performance of vertical drains at Queenborough by-pass. Geotechnique, Vol. 31, No. 1, Mar. 1981, pp. 67-90.

Selim, C.; Walsh, T.J.; Hannon, J.B. (1981). Wicks, fabrics and sawdust overcome thick mud. ASCE Civil Engineering, Vol. 51, No. 7, July 1981, pp. 53-56.

Wicke, M.; Stoelhorst, D. (1982). Problems associated with the design and construction of concrete pavements on approach embankments. Concrete Society Terminal House, Grosvenor Gardens, London, England, 1982.

Yee, W.S. (1974). Long term settlement study at bridge approaches (North Maxwell). California Dept. of Transportation. Transportation Laboratory, 5900 Folsom Boulevard; Sacramento, CA, 95819, Dec. 1974, Final Report.

APPENDIX I: SURVEY QUESTIONNAIRE

.gency:

.ddress:

'hone:

'erson Completing Survey:

QUESTIONNAIRE

. Is differential settlement between the approach pavement and the bridge deck a significant problem in your state? Please circle the answer that most closely describes the severity of the problem in your state.

(a) severe (b) very significant (c) significant

(d) insignificant

. Has any research work been performed by your organization to investigate this problem? If so, please specify.

. In your state, what percentage of the bridge approaches need maintenance to rectify this problem?

(a) 0-20 (b) 21-40 (c) 41-60 (d) 61-80 (e) 81-100

. What is the average time gap (years) between completion of construction and the beginning of significant differential settlement described in paragraph 1?

(a) 0-1 (b) 1-2 (c) 2-3 (d) over 3 (e) varies

5. Do you use structural approach slabs in your state and if so, which designs are most successful?

6. Several factors may be responsible for the differential settlement between bridge decks and approach pavements. Some of them are listed below. If your experience indicates that some of these factors are significantly contributing to this problem, please indicate by ranking the following factors in order of their significance, starting with 1 for the most significant.

______ a) Material of the embankment.
______ b) Type of pavement.
______ c) Foundation of the embankment.
______ d) Type of abutment.
______ e) Progressive failure or creep of the approach.
______ f) Erosion of soil from abutment.
______ g) Traffic direction relative to location of settlement.
______ h) Construction technique of embankment
______ i) Others (please specify)

7. Some known measures to reduce this problem are listed below. Please rate them according to their effectiveness
(a) effective (b) not effective (c) have no experience
(d) no comment

______ I) Imposing strict restriction on compaction specification.
II) Replacing any compressible embankment backfill soil with
______ (i) pulverized fuel ash
______ (ii) silty clay
______ (iii) well graded sandy gravel

_____ (iv) fine to medium sand
_____ (v) coarse sand
_____ (vi) others (please specify)

III) Accelerating consolidation settlement of the approach embankment and foundation soil by

_____ (i) preloading with surcharge fill
_____ (ii) construction of vertical sand drains
_____ (iii) placing of wick drains

IV) Employing techniques such as:

_____ (i) pile foundations for the embankments
_____ (ii) stabilizing the soil-material
_____ (iii) allowing sufficient time for the approach embankment and foundation to consolidate before the pavement is constructed.
_____ (iv) using reinforcing fabric in the embankment
_____ (v) using light weight fill such as saw dust for the embankment
_____ (vi) grout injection
_____ (vii) providing stone columns
_____ (viii) others (please specify)

V) Other (please specify)

What other approaches may be undertaken to address this problem?

APPENDIX II: LIST OF THE AGENCIES RESPONDING TO THE QUESTIONNAIRE

Serial No.	Responding Agency
1.	Alaska D.O.T.
2.	Arkansas D.O.T.
3.	Arizona D.O.T.
4.	California D.O.T.
5.	Colorado D.O.T.
6.	Delaware D.O.T.
7.	Georgia D.O.T.
8.	Hawaii D.O.T.
9.	Idaho D.O.T.
10.	Illinois D.O.T. (Bur. of Mat. & Res.)
11.	Illinois D.O.T. (Bur. of Bridge & Structure)
12.	Illinois D.O.T. (Bur. of Bridge & Structure)
13.	Indiana D.O.T.
14.	Iowa D.O.T.
15.	Kansas D.O.T.
16.	Kentucky D.O.T.
17.	Maryland D.O.T.
18.	Massachusetts D.O.T.
19.	Mississippi D.O.T.
20.	Missouri D.O.T. (Material & Research)
21.	Missouri D.O.T. (Maintenance & Traffic)
22.	Nebraska D.O.T.
23.	Nebraska D.O.T. (Transportation Planning)
24.	Nebraska D.O.T (Maintenance)
25.	New Jersey D.O.T.
26.	New Mexico D.O.T.
27.	New York D.O.T.
28.	Ohio D.O.T.
29.	Oklahoma D.O.T.
30.	Oregon D.O.T.
31.	Pennsylvania D.O.T.
32.	Rhode Island D.O.T.
33.	South Carolina D.O.T.

age 2

4. South Dakota D.O.T.
5. Texas D.O.T.
6. Utah D.O.T.
7. Vermont D.O.T.
8. West Virginia D.O.T.
9. Washington D.C. D.O.T.
0. Wisconsin D.O.T.
1. Wyoming D.O.T.
2. Corps of Engineers Alaska District
3. Corps of Engineers Albuquerque District
4. Corps of Engineers Buffalo District
5. Corps of Engineers Charleston District
6. Corps of Engineers Chicago District
7. Corps of Engineers Huntington District
8. Corps of Engineers Kansas City District
9. Corps of Engineers Jacksonville District
0. Corps of Engineers Little Rock District
1. Corps of Engineers Los Angeles District
2. Corps of Engineers New Orleans District
3. Corps of Engineers Norfolk District
4. Corps of Engineers Sacramento District
5. Corps of Engineers St. Louis District
6. Corps of Engineers St. Paul District
7. Corps of Engineers Nashville District
8. Corps of Engineers Vicksburg District
9. Corps of Engineers Walla Walla District
0. Minnesota D.O.T.
1. Nebraska D.O.T. (Roadway Design Div.)

APPENDIX III: VARIOUS CAUSATIVE FACTORS

(a) Material of the embankment.
(b) Type of pavement.
(c) Foundation of embankment.
(d) Type of abutment.
(e) Progressive failure or creep of the approach.
(f) Erosion of soil from abutment.
(g) Traffic direction relative to location of settlement.
(h) Construction technique of embankment.
(i) Frost action and heave.
(j) Freeze-thaw cycles.
(k) Poor drainage.
(l) Water at expansion joint and gutter.
(m) Secondary compression.
(n) Inadequate compaction or compaction at inappropriate moisture content.
(o) Use of piles to support abutment.
(p) Borrowing animals.
(q) Embankment spilling under end bent at top of slope.
(r) Abutment movement.

APPENDIX IV: PICTURES DEPICTING THE TYPE OF DISTRESS EXPERINCED BEHIND ABUTMENTS IN OKLAHOMA

The pictures provided herein were taken on November 5, 1985 and they depict the type of distress experienced behind abutments in Oklahoma.

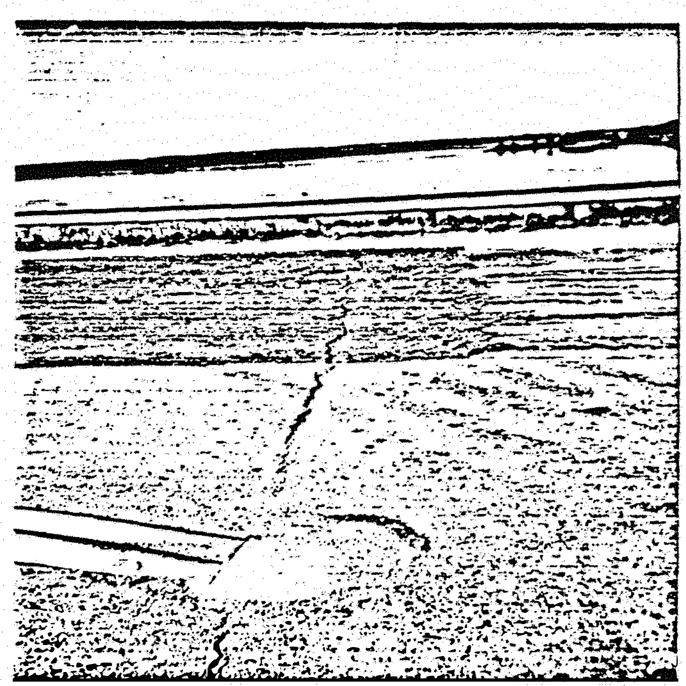


Fig. IV.1 Crack on the pavement above the abutment and bridge approach.

Fig. IV.2 Crack on the pavement above the abutment and bridge approach on another bridge.

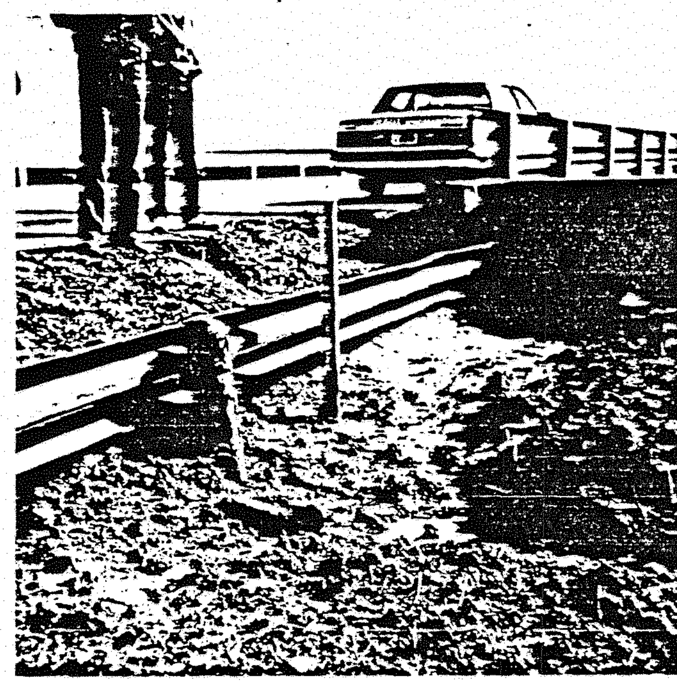


Fig. IV.3 Failure due to settlement of fill.

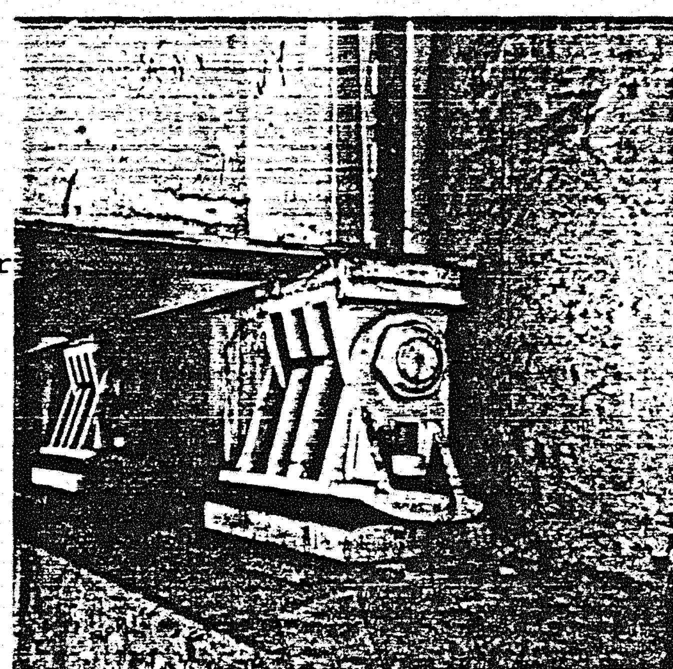
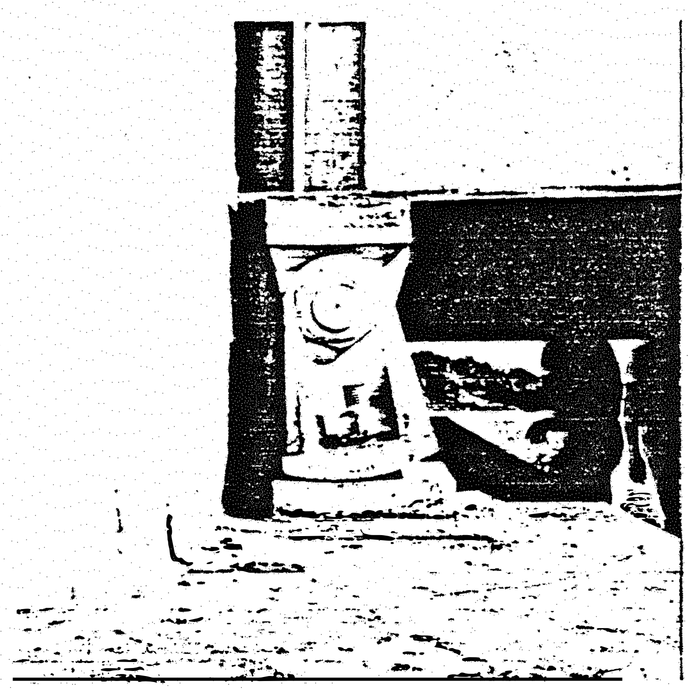


Fig. IV.4 Distress results in disorientation of roller from vertical.

ig. IV.5 Distress results in disorientation of roller from vertical. Bridge girder is dangerously approaching concrete abutment.



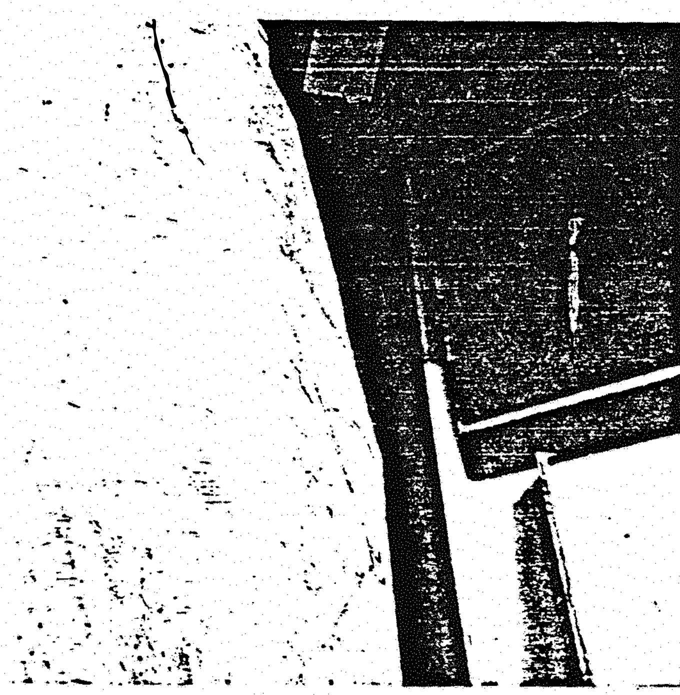


Fig. IV. 6 Bridge girder has been corrected (cut) to avoid pressing against abutment.

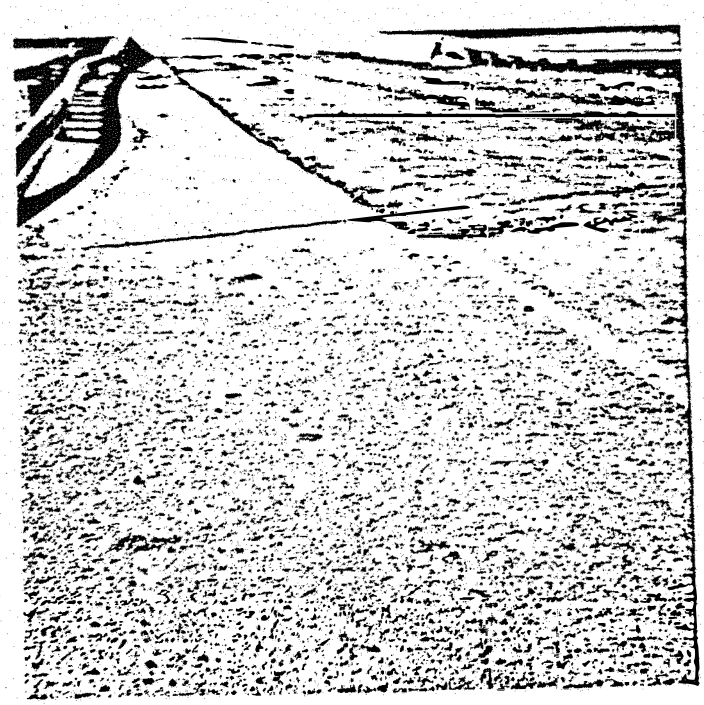


Fig. IV.7 Corrective patching at bridge approach after embankment settled.

The Oklahoma Highway and
Transportation
Engineering
Center

(405) 325-5911
202 West Boyd Street, Norman, OK 73019