PERFORMANCE OF HIGHWAY BRIDGE ABUTMENTS ON SPREAD FOOTINGS

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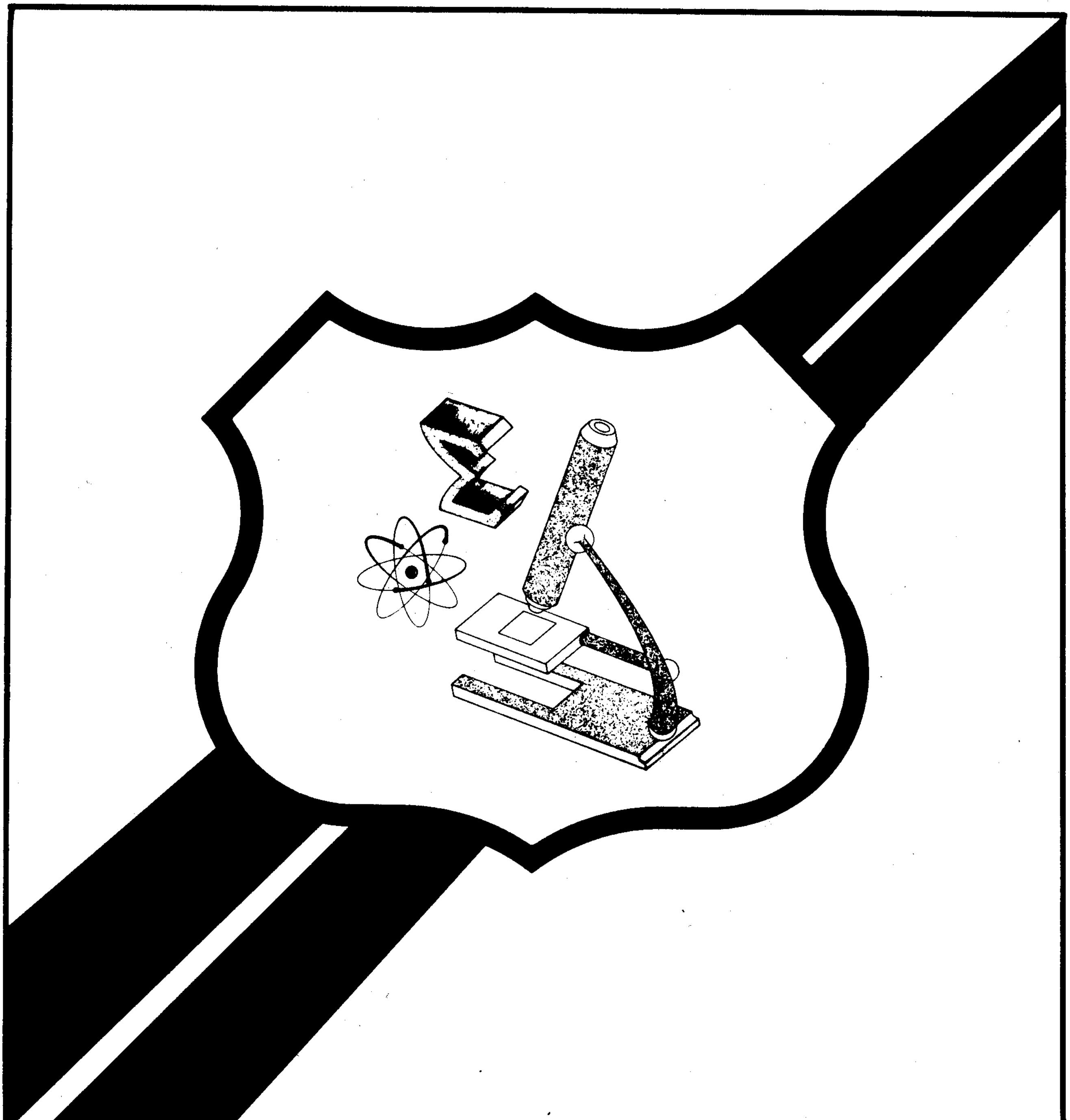

FOREWORD

This report presents the results of a performance evaluation of spread footings on compacted fill. These results demonstrate the potential for increased utilization of spread footings to support highway bridges which should result in significant cost savings from a corresponding reduction in the use of piles. This report will be of interest to bridge engineers and foundation specialists who are concerned with reducing the high cost of bridge foundations.

The performance evaluation was conducted by the Federal Highway Administration (FHWA) staff researchers in cooperation with the Washington State Department of Transportation (WSDOT). Appreciation is extended to the Bridge Division and Materials Laboratory of the WSDOT for their valuable support and guidance. A special thanks is given to Mr. Arthur J. Peters for his advice and guidance throughout the study.

Sufficient copies of the report are being distributed by FHWA Bulletin to provide a minimum of two copies to each FHWA regional office, two copies to each FHWA division office, and three copies to each State highway agency. Direct distribution is being made to the Division offices.

Richard E. Hay

Richard E. Hay, Director
Office of Engineering
and Highway Operations
Research and Development

NOTICE

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16. Abstract

A visual inspection was made of the structural condition of 148 highway bridges supported by spread footings on compacted fill throughout the State of Washington. The approach pavements and other bridge appurtenances were also inspected for damage or distress that could be attributed to the use of spread footings on compacted fill. This review, in conjunction with detailed investigations of the foundation movement of 28 selected bridges, was used to evaluate the performance of spread footings on compacted fills. It was concluded that spread footings can provide a satisfactory alternative to piles especially when high embankments of good quality borrow materials are constructed over satisfactory foundation soils. None of the bridges investigated displayed any safety problems or serious functional distress. All bridges were in good condition and many were found to be in very good condition. In addition to the performance evaluation, cost-effectiveness analyses and tolerable movement correlation studies were made to further substantiate the feasibility of using spread footings in lieu of expensive deep foundation systems. Cost analyses showed spread footings were 50-65 percent cheaper than the alternate choice of pile foundations. Foundation movement studies showed that these bridges have easily tolerated differential settlements of 1-3 inches (25-75 mm) without serious distress.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
Angstroms	0.0000001 (10^{-7})	millimetres
inches	2.54	centimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square inches	0.00064516	square metres
square feet	0.09290304	square metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
grams	0.001	kilograms
pounds (mass)	0.4535924	kilograms
tons (2000 pounds)	907.1847	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.59327631	kilograms per cubic metre
pounds (force)	4.448222	newtons
pounds (force) per square inch	6894.757	pascals
pounds (force) per square foot	4.882428	kilograms per square metre
miles per hour	1.609344	kilometres per hour
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

PREFACE

This is the final report of an in-house research study on "A Field Evaluation of Highway Bridge Abutments Supported by Spread Footings on Compacted Fill." It was conducted under the Federal Highway Administration's (FHWA's) Federally Coordinated Program (FCP) of Highway Research and Development, Project 4H, "Improved Foundations for Highway Bridges." The research was initiated and conducted by the Soils and Exploratory Techniques Group, Materials Division, of the Office of Research. This report presents the salient results of the performance evaluation study; complete coverage of the data collection and field inspection notes will not be made available in published form.

The performance study was carried out in cooperation with the Washington State Department of Transportation's (WSDOT) Materials Laboratory and Bridge Division. The author wishes to express his sincere appreciation to Messrs. Art Peters and Al Killian of the Materials Laboratory for their assistance in the conduct of this research. Special thanks are also extended to Mr. Stephen J. Seguirant, formerly with FHWA, for his assistance in data acquisition and field inspections.

During the early 1960's, the State of Washington concluded that significant savings in bridge costs could be achieved by supporting abutments on spread footings in the approach embankment. It was further decided that greater savings would occur if natural material could be used to build the embankment rather than special borrow material that had to be processed to meet rigid specifications. This practice, which is still in use today suggested the research study reported herein to determine the benefits or consequences of that milestone decision nearly 20 years ago.

A total of 148 bridges were inspected and found to be in very good condition. All of these bridges had at least one abutment supported on a spread footing in the compacted approach fill. Many bridges had both abutments and the intermediate piers founded on spread footings. Cost comparisons were included in this report that demonstrate significant cost savings in the range of 50-65 percent. Tolerable movement analyses also show that moderate differential settlements of 1-3 inches (25-75 mm) caused very little distress in any of the simple or continuous span structures.

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1. INTRODUCTION

1.1 Background

The use of spread footings to support highway bridge piers varies widely between the various highway agencies in the United States. A recent survey by the Federal Highway Administration's Office of Highway Operations determined that some States use spread footings to support most of their bridges, while some others use spread footings very little. Most States use pile foundations to support the majority of their bridges.

Of those States that do use spread footings, some use them only on rock or very hard gravels and glacial tills. Some use them on natural ground and compacted fill, and some only on natural ground but never on fill. Very few States use spread footings to support bridge abutments on compacted fill, and documented performance evaluations are very scarce. During recent years numerous indications of successful and economical use of spread footings on compacted fill have been identified suggesting the need to conduct a comprehensive performance evaluation of existing bridges supported in this manner.

The State of Washington has been designing and constructing spread footings to support bridge abutments and piers for many years with very favorable results. In the 15-year period from 1965 to 1980, WSDOT constructed over 500 bridges with one or more piers or abutments on spread footings. During this same period, 180 bridges were constructed with one or both abutments supported by spread footings in the approach fill. The apparent good results prompted WSDOT and FHWA engineers to conduct a systematic evaluation of spread footing performance on compacted fill.

The WSDOT Materials Laboratory is responsible for performing the soil survey and bridge foundation investigation for each new structure upon request from the Bridge Division. In addition to the soils and foundation data presented to the Bridge Division, the Materials Laboratory also provides specific recommendations for type, size and location of the appropriate foundation unit. Confirmation of the actual foundation type used can only be found in the Bridge Division files.

1.2 Objective and Scope of Work

The performance evaluation was designed to obtain basic information on the safety, reliability, and cost effectiveness of spread footings to support highway bridge abutments on compacted fills.

The study was divided into four major tasks: file search, field inspections, movement surveys, and data analysis. Personal interviews with design, construction, and maintenance personnel were also conducted during the file search and field inspection phases of the study. Cost comparisons between spread footings and piles for several bridges were also made to evaluate the cost effectiveness of spread footings.

2. WSDOT FILE SEARCH

2.1 General

Washington State requires that detailed records be maintained for 15 years and then microfilmed. The information search for this study was initially limited to active files, with the option to review the older files if enough bridges were not available in the active files.

The file data came from three sources. The review began in the Materials Laboratory where the "Bridge Foundation Investigation and Recommendation" files are located. Next was the Bridge Division, where the "as-built" plans were reviewed; and then the Bridge Condition Survey Branch, where the "Damage Survey Reports" were reviewed.

Project files for the newer bridges were very complete and informative, but many older files were incomplete. Lack of information concerning older bridges was unfortunate, because length of service was a key factor of the study. Although it was possible to correlate damage with service time, it was not possible to correlate the amount of movement with damage because as-built elevations were not available for many of the older bridges. Correlations with other parameters such as superstructure type, span configurations, abutment type, and soil profiles were also difficult to make due to a lack of information on the older bridges. Correlations with newer bridges are limited by the shorter performance periods.

2.2 Bridge Foundation Investigation and Recommendation Reports

The Soils Department of the Materials Laboratory investigates the soil and site conditions at each proposed bridge site and furnishes a report to the Bridge Division which documents the field and laboratory test data. The report often includes a soil profile and descriptions of pertinent soil and site conditions. Recommendations are also made for the type of foundation systems that should be considered and any special design or construction problems that might occur.

Many of these project files also contained the preliminary bridge plans which accompanied the request for a soils investigation. The main reason for beginning the file search at the Materials Laboratory was the section on "Foundation Type Recommended" which provided the first indication that a spread footing might have been used. A copy of the data collection sheet is shown in Appendix A along with a description and explanation of some of the terms used on the form. For the sake of brevity, the author has omitted many details reported on the data collection sheets. These data can be made available by the author upon request.

Of 942 bridge files reviewed in detail, only 252 bridges were suitable for this study, i.e., one or both abutments recommended to be supported by spread footings on compacted fills. There were also 340 bridges with one or more piers or abutments supported by spread footings on natural ground, plus 350 bridges that were recommended to be supported entirely on piles or drilled caissons.

2.3 As-built Construction Plans

The 252 bridges within the scope of this study were checked against "as-built" plans in the Bridge Division to determine which ones were supported by spread footings on fill. A total of 180 met this requirement, and each was checked for data on the final or "as-built" elevations of each abutment or pier.

2.4 Damage Survey Reports

Each bridge that qualified for further study was checked for damage reported in the files of the Bridge Condition Survey Branch. All existing bridges on State routes in Washington are inspected indepth every 2 years by a team of special investigators. These damage survey reports were used as a starting point for conducting the field inspections; however, there were no reports of any significant damage to any of the 180 bridges selected for further study. The list was further reduced to 148 bridges because some were either new or located in remote parts of the State.

2.5 Types of Bridges

Although there are six types of bridges represented in this study, Table 1 shows that 95 percent have concrete superstructures, and 75 percent are prestressed concrete girder bridges. These percentages, though not unusually high for the WSDOT, are significant because concrete structures are more susceptible to cracking from differential settlement than are steel bridges. It is also interesting to note that more than 70 percent have multiple, continuous spans. Differential settlement would damage these bridges more severely than ones having simple spans.

In addition to the wide range of structural types, there are wide ranges of size and site applications represented in the number of bridges inspected. Figures 1 and 2 illustrate the use of spread footings to support bridge abutments for stream crossing structures, and Figures 3 and 4 show two applications for interchange structures. A railroad overpass (Figure 5) and routine Interstate overcrossings and undercrossings (Figures 6 and 7) further illustrate the versatility of spread footings.

Table 1. Distribution of Bridges by Structure Type

Type of Structure	Number of Spans Simple 1	2	3	4	Continuous 2	3	4	5	6	7	8	9	Total
Prestressed Concrete Girder	14	1	12	11	15	40	6	10	-	1	-	-	110
Concrete Box Girder	-	-	-	-	-	6	6	-	1	1	2	-	16
Concrete Flat Slab	-	-	-	-	-	6	-	-	-	-	2	-	8
Concrete T-Beam	-	-	-	-	1	3	-	-	-	1	2	-	7
Steel Girder	1	1	-	-	-	1	2	-	-	-	-	-	5
Steel Girder and Tied Arch	-	-	-	-	-	-	-	-	-	1	-	1	2
Total	15	2	12	11	16	56	14	10	1	4	6	1	148

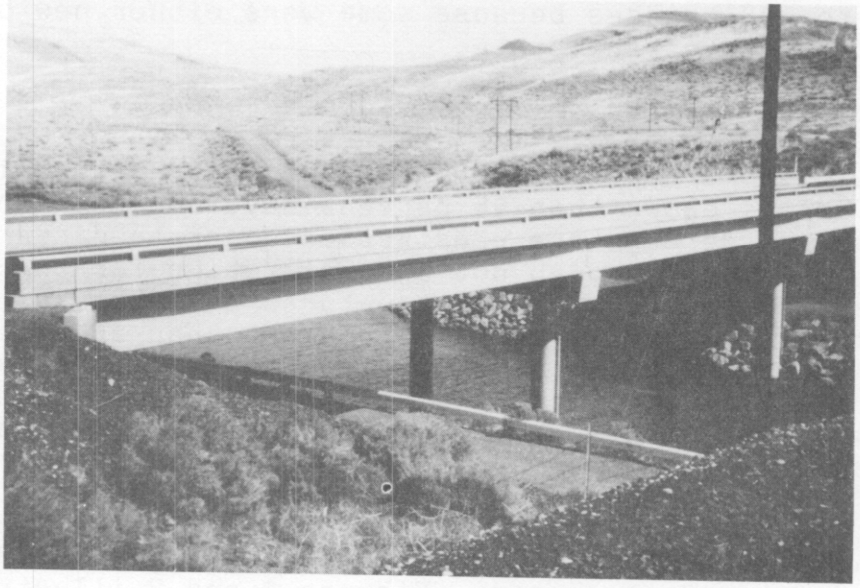

Figure 1. Alder Creek Bridge on SR 14 in Klickitat County

Figure 2. Carbon River Bridge on SR 162 in Pierce County

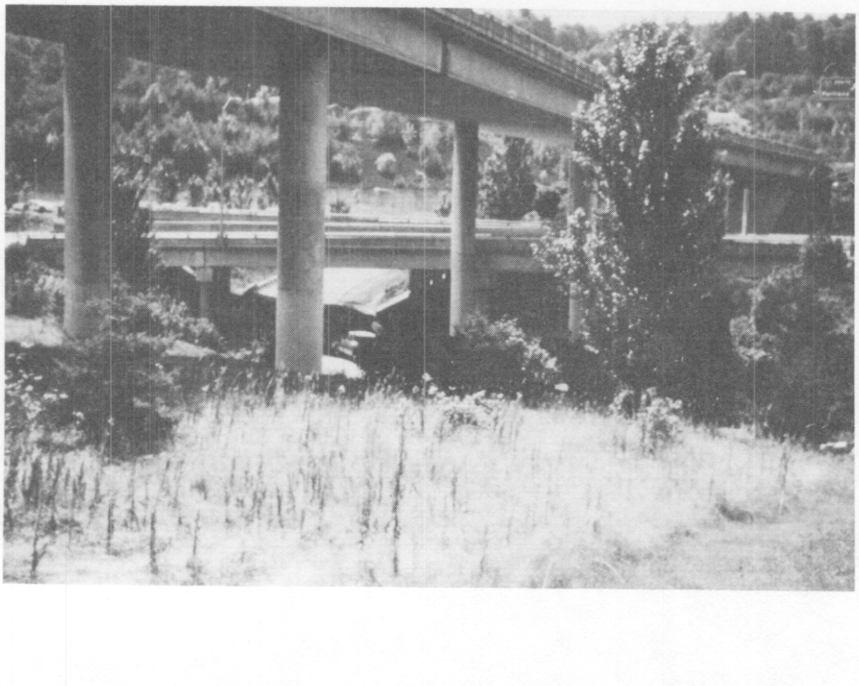

Figure 3. Tukwila Interchange Ramp E Bridge on I-5 in King County

Figure 4. SR 16 Interchange in Tacoma

Figure 5. Northern Pacific Railroad Overpass on I-90 in Adams County

Figure 6. Interstate 90 Twin Bridges Over SR 21 in Adams County

Figure 7. 236th Street Over Interstate 5 in Seattle

3. FIELD INSPECTIONS

3.1 General

Field inspections were conducted during the course of this research to determine if there were visible signs of damage attributed to using spread footings on compacted fill. The distribution of bridges according to structure type, number of spans, and span arrangement (simple or continuous) is shown in Table 1. Interviews with each District Maintenance Engineer were also conducted to get further maintenance history. No negative reports on the use of spread footings were received from any of the six District Maintenance Engineers. Two of them preferred spread footings to piles because they have much less trouble patching the bridge approaches to correct bumps at each end. The others had no special preference.

3.2 Types of Damage

An inspection report with photographs was developed for each bridge. The main types of damage investigated were bumps, cracks, misalignments, and damaged joints; however, the inspectors also looked for damage to utility lines, slope protection, and other bridge appurtenances.

Bumps, either at bridge ends or above intermediate piers, are sure signs of differential settlement. Pavement patches at approach fills (Figure 8) indicate corrective work was required to improve ride quality, and inspectors always took notes of rideability at posted speed limits whether or not pavement patches existed.

All concrete girders, abutments, piers, parapet walls, sidewalks, and bridge decks were inspected for cracks. The inspectors looked for excessive openings in vertical construction joints, especially those between wing-walls and abutments, and they looked for damage to deck joints.

The inspection team also looked for misaligned guardrail, handrails, or parapet walls (Figure 9) and jammed girders or tipped rocker arm assemblies (Figure 10). Excessive shimming beneath bearing devices (Figure 11) are also good indications of foundation problems. Three categories of damage were established: structural, architectural, and rideability.

3.3 Performance Evaluation Criteria

The spread footing and compacted fill for each abutment were evaluated as a combined system, and the performance of each was examined for "safety" and "effectiveness." The following sections define these criteria:

3.3.1 Safety

Preventing collapse is the main concern of any foundation system. The spread footing must be proportioned in accordance with the shear strength (bearing capacity) of the supporting soil to withstand a collapse. Such failures are most unusual for abutment footings and it was not expected that any would be found in either the field inspection or the maintenance records. Bearing capacity failures are rare because settlement criteria usually provide the limiting condition.

Spread footings are also susceptible to damage or collapse from scour, frost action, expansive soil pressures, and construction adjacent to the footing which reduces the confining pressure of the supporting soil. Such failures can occur gradually as well as suddenly.

Failure can also occur gradually from excessive, long-term settlement. Although collapse does not always occur, excessive settlement can severely crack the abutments, or it can overstress key superstructure elements such as girders and deck slabs. This type of failure results from design error or improper construction.

The frequency of these failures is one measure of the reliability of placing spread footings on compacted fill. A satisfactory spread footing must be dependable under a variety of situations to carry the imposed loading without jeopardizing the bridge's structural or architectural integrity. The engineer must have confidence in the ability of the foundation unit to perform well in almost all instances because a bridge is highly visible and sensitive to public reaction.

3.3.2 Effectiveness

A foundation system must be functional as well as safe. There is a wide spectrum of engineering performance between an unyielding support system and one that fails. Persistent maintenance problems and failures of subcritical elements are expensive to correct, and should be avoided if peculiar to certain systems, situations, or methodologies. To improve the design process, engineers should correlate functional distress (bumps, cracks, misalignments, etc.) with system characteristics (abutment type, soil type, superstructure type, amount and type of movement, etc.). Such correlations would establish the effectiveness of a spread footing to support heavy abutment loads on a compacted fill in certain situations, and point out those situations where spread footings are not appropriate.

Cost-effectiveness is also very important. The additional security of a deep foundation system is worth some additional cost; therefore, to compete successfully with deep foundations, a spread footing must be significantly cheaper to design and construct.

Figure 8. Pavement Patch at Bridge End

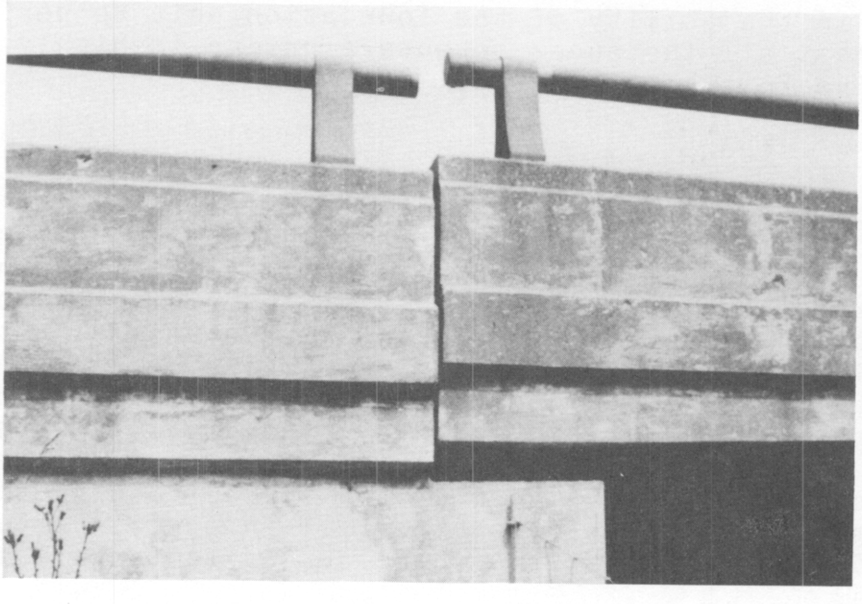

Figure 9. Misaligned Parapet Wall and Handrail

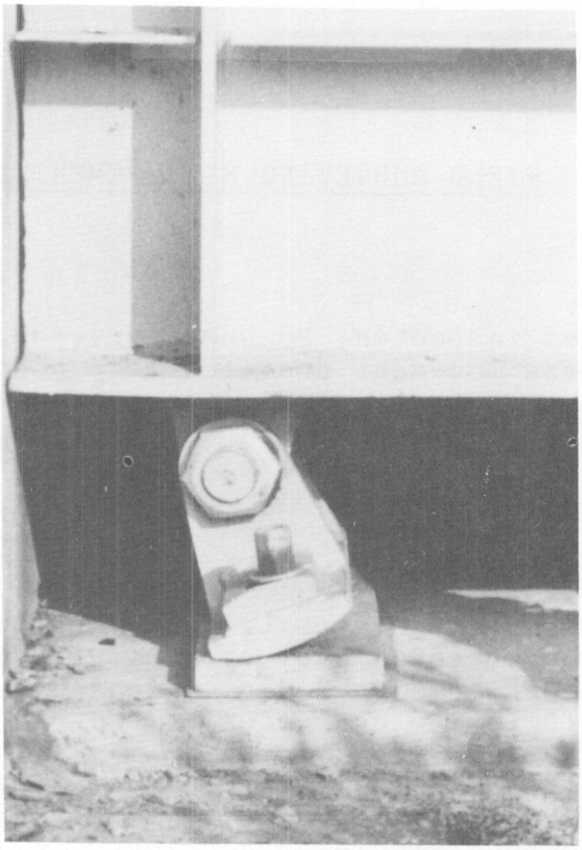

Figure 10. Bridge Girder Jammed Against Abutment and Excessive Rocker Tilt

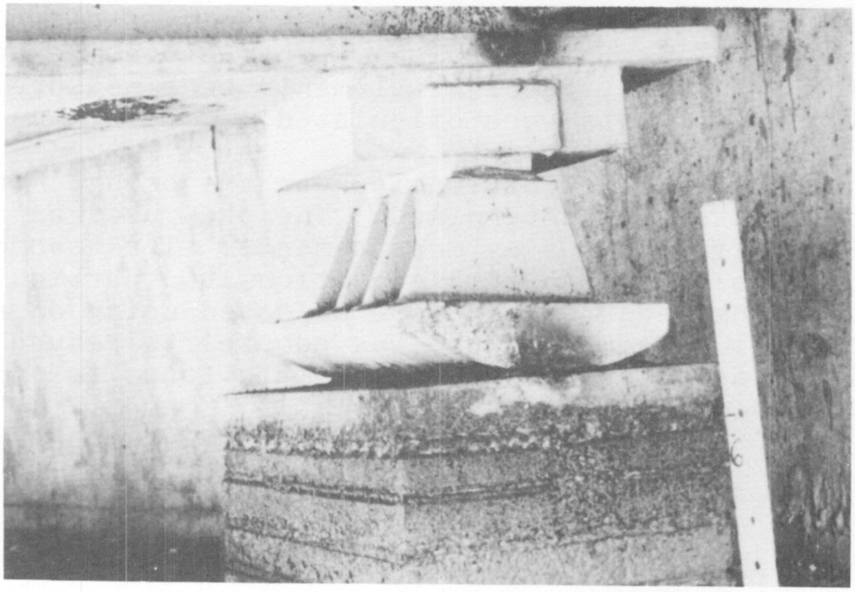

Figure 11. Significant Shimming Beneath Bearing Device

4. FIELD SURVEYING MEASUREMENTS

4.1 General

Of the 148 bridges inspected, 28 were surveyed for differential settlements. These movement profiles were compared with their "as-built" plans to determine the amount of differential settlement. These settlements were then compared to corresponding damage reports to evaluate current guidelines for tolerable movements of bridge foundations.

4.2 Basis for Selection

The bridges included in this portion of the study were selected on the basis of observed damage, age, type of structure, and the amount of settlement predicted during design. The bridges chosen have the following characteristics:

The ages vary between 5 and 17 years; nearly half of which were built before 1970. The bridges built since 1970 are of continuous design, except for one single span bridge. Nearly half of the bridges built before 1970 are of continuous design. Two are steel structures; 22 are prestressed concrete girders; three are concrete box girder bridges; and one is a concrete T-beam bridge.

4.3 Assumed Elevations and Equations

The current bridge elevations were measured by field survey crews from several WSDOT district offices. When elevation bench marks were available on site, total settlements were measured and differential settlements were calculated.

When bench marks were not available near the bridge, only differential settlements were determined. The crew used an assumed elevation to begin the survey measurements. The assumed elevation was set equal to the "as-built" elevation at a particular point, and the remaining measurements were adjusted using an equation (see Appendix E). The procedure was adopted to reduce surveying costs; this is acceptable because the main focus is on differential settlement, not on total settlement.

5. PERFORMANCE EVALUATION RESULTS

5.1 General

The data analysis had two main purposes. The first was to evaluate the performance of spread footings as a safe and functional foundation unit for highway bridge abutments. The second was to correlate foundation movement with functional distress. The demonstration of spread footing reliability was very successful; however, the correlation efforts were only partially successful because the foundation movements did not cause much distress. The absence of distress data proved the reliability of spread footings, but it did not help analyze the structural consequences of the foundation movements.

Because none of the bridges had any safety problems, the reliability was excellent. Their functional ratings were high as well; none had low ratings for rideability or maintenance. All of the bridges received a "good" rating, while many received a "very good" rating for functional reliablity.

For cost effectiveness, there is no comparison between spread footings and piles. Spread footings are almost always cheaper, and quite often they are significantly cheaper. The attractiveness of spread footings also increases when considering the benefits of reduced energy requirements and conservation of natural resources. The consumption of energy to fabricate and install piles plus the indiscreet use of timber, concrete and steel resources are becoming important factors in a comparative analysis. For this study and its specific parameters, it was clearly demonstrated that spread footings were extremely cost effective in lieu of piles. (See Appendix C).

5.2 Safety

As previously noted, the safety performance record of the bridges investigated is perfect. The safety record of all WSDOT bridges supported by spread footings on natural ground or fill is very good as well. The WSDOT records of the past 20 years show one failure of a spread footing on fill and one of a spread footing on natural ground. Both of these failures occurred on bridges that were not part of this study, but are briefly described below.

Improper construction procedures caused the failure on fill, not a deficiency in the spread footing design. The clay fill was placed during the wet season without proper control of moisture and density. Settlement caused excessive cracking of the abutment walls which had to be replaced before building the superstructure.

The spread footing failure on natural ground was caused by scour. The problem could have been avoided by using a scour protection system such as rip rap or gabion walls. This abutment had to be completely rebuilt.

5.3 Effectiveness

Besides being safe, a foundation system must not cause undue maintenance and serviceability problems, i.e., the engineer must feel comfortable that functional reliability is very high. Engineers for the WSDOT do not hesitate to use spread footings (under appropriate engineering conditions) to support large river crossing or major interchange structures as well as routine overpass structures. Spread footings are also routinely used in Washington to support either simple span or continuous bridges of all sizes and types; i.e., spread footings are not restricted to small bridges on minor roadways. The results of this study have reinforced their confidence in using spread footings to support bridge abutments on compacted fill.

5.3.1 Functional Reliability

None of the 148 bridges evaluated have shown signs of serious functional distress. No record of maintenance or repair activities (other than routine maintenance) was uncovered and each District Maintenance Engineer cited favorable performance records for each bridge.

Although no main structural members of any bridges showed signs of serious distress, two bridges had moderate amounts of hairline cracks. The cracks indicated that some distress had occurred, possibly from settlement, but there was no concern for structural failure.

Little architectural or cosmetic damage was observed. The most serious problems were aesthetic ones. There were minor cracks in the deck, abutment walls, curbs, or parapet walls, and slight misalignments in adjacent sections of curbing and parapet walls.

Rideability was evaluated on each of the 148 bridges, and none had a low rating. The amount of patchwork at the bridge ends was small, and many WSDOT personnel believe that the patching problem is far less severe for bridges supported by spread footings than for those with pile supported abutments. A comparison of patch lengths was made at bridge approaches of some of the bridges evaluated and a number of pile supported abutments. The pile supported footings were compared with spread footings on both fill and natural ground. (2)*

It was found that spread footings on natural ground had the shortest mean patch lengths, 1.9 feet (0.6 m): while spread footings on fill had 3.7 feet (1.1 m). Pile supported footings had the greatest lengths 24.8 feet (7.6 m). It was also noted that only 35 percent of the bridge approaches where a spread footing was used required patching, while 91 percent of the approaches using pile supported abutments required patching. (2)

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*References are listed alphabetically at the end of the report.

It was also noted that pile supported abutments required more frequent and longer patches. The length of a given patch was assumed to be directly proportional to the size of the bump at the transition point between the deck and approach pavement. If the bump is large and it develops gradually, intermittent patching may be needed. Spread footings on compacted fill have the advantage of settling evenly with the fill, whereas a pile foundation and its approach fill settle independently. (2)

None of the bridges had damaged bearing devices, misseated girders, damaged joints or broken utility lines. The most serious damage caused by settlement involved a bridge abutment that tipped away from the fill causing the main girders to be pressed against the abutment wall. Although there were no signs of distress to the girder or abutment wall, the bridge will eventually require corrective action such as horizontal trimming of the girders. In addition, there were several bridges having slightly tipped bearing rockers.

5.3.2 Cost Effectiveness

A spread footing foundation is usually much cheaper than a pile foundation. The actual savings can often be equated to the cost of the piles because the size of the pile cap is roughly equal to the size of the spread footing needed to support the abutment. On one bridge near Ft. Lewis, Washington, the need for piles was questioned after noting that piling had been driven through a gravel approach fill. The engineers deleted the piles under the opposite abutment and both abutments of an adjacent structure in the same interchange. The size of the pile cap was larger than that required for a spread footing, thus eliminating a redesign of the footing, (see Appendix C). The cost savings on three bridges described in Appendix C averaged approximately 60 percent less than pile foundations.

In a competitive cost-analysis, spread footings become more attractive when considering their reduced energy requirements for construction and better conservation of natural resources such as timber, concrete and steel. These factors are difficult to quantify in monetary terms; however, they have recently become important considerations in selecting the type of foundation system to be used.

Designing the structure to accommodate differential settlement involves additional costs that should be considered in a cost comparison. For example, the use of simple instead of continuous spans or larger girders to withstand the increased stresses are two commonly used methods. Some States utilize special hinges in their girder design and others design jacking pads to facilitate maintenance operations to correct accumulated settlements. The latter method is frequently used by the WSDOT to correct post-construction settlements. The added cost of a small concrete pad under each girder is small, and the cost of jacking and shimming each girder is reasonable. (See Appendix D for technical details and approximate cost of jackable abutments.)

5.4 Tolerable Movement Correlation

As previously shown, the efforts to demonstrate spread footing reliability and cost effectiveness were successful; however, the tolerable movement correlation efforts were only partly successful because the foundation movements of the WSDOT bridges were small and they did not cause significant distress. The lack of distress data supported the reliability findings of this study, but it did not provide meaningful correlations in the tolerable movement analysis. These data helped prove that small amounts of differential settlement are tolerable for certain span lengths. When combined with many other case studies, these data will help to establish improved guidelines for tolerable movement of bridge foundations.

Differential settlement data were classified according to ranges of settlement, and a cumulative frequency table was developed (Table 2). Only 46 abutments of the 28 bridges are represented because the other 10 abutments were not supported by spread footings on compacted fill. When the differential settlement values for these 10 abutments were included in the distribution table, the frequency values did not change significantly.

Table 2: Cumulative Frequency of Differential Settlement Data

CLASS NO.	CLASS LIMITS*	CLASS FREQUENCY**	CUMULATIVE FREQUENCY	CUMULATIVE RELATIVE FREQUENCY
1	0.0- 0.5 In (13mm)	8	8	17.4%
2	0.5- 1.0 In (25mm)	13	21	45.8%
3	1.0- 2.0 In (50mm)	16	37	80.5%
4	2.0- 3.0 In (75mm)	3	40	87.0%
5	3.0- 4.0 In (100mm)	4	44	96.0%
6	4.0- 5.0 In (125mm)	1	45	98.0%
7	5.0-15.0 In (375mm)	1	46	100.0%
	Total	46		

* Differential settlement.
** Number of abutments.

At least 80 percent of the abutments have experienced over 0.5 inches (13 mm) of differential settlement without distress. Table 2 shows that more than half of the abutments have undergone more than 1 inch (25 mm) of differential settlement without distress and 9 abutments, 20 percent, have undergone more than 2 inches (50 mm) of differential settlement without showing distress. The figures suggest that highway bridges can withstand a small amount of differential settlement, undermining the "zero settlement" design philosophy. If a blanket criterion must be assigned to bridges of any length, stiffness, and material type, the maximum allowable differential settlement should be at least 1 inch (25 mm) and maybe greater.

The data also show that a spread footing can support heavy bridge loads without causing excessive deformations. The large majority of the abutments, 80 percent, had settled less than 2 inches (50mm) differentially. Many highway engineers have wrongly believed that heavily-loaded spread footings would cause large settlements in even the most densely compacted granular soil masses. WSDOT standard design practice for spread footings on granular soils is 3 tons per square foot (.287 MPa).

The data in Table 3 shows the distribution of these bridges by structure type, continuous or simple span. The distribution agrees with the 70 percent figure cited in Section 2.5, Types of Bridges, and indicates that bridge designers need not shy away from using continuous structures which have spread footings as their foundation support. This figure is much higher, at least 90 percent, when single span bridges and those built before 1970 are excluded from the analysis.

Table 3: Distribution of Movement Data by Structure Type

CLASS NO.	CLASS LIMITS*	CONTINUOUS	SIMPLE
1	0.0 - 0.5-Inch	4	0
2	0.5 - 1.0-Inch	5	1
3	1.0 - 2.0-Inch	6	4
4	2.0 - 3.0-Inch	1	1
5	3.0 - 4.0-Inch	1	3
6	4.0 - 5.0-Inch	1	0
7	5.0 -15.0-Inch	0	1
	TOTAL	18	10

* Differential Settlement.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 General

Although spread footings have been used extensively for many years in a few States, their acceptance has not been quick or widespread among the majority of States. The lack of well documented performance studies is one reason for the slow acceptance rate. This need for additional performance data was recognized long ago by Karl Terzaghi in his Presidential Address to the First International Conference on Soil Mechanics and Foundation Engineering in 1936:

> "Successful work in soil mechanics and foundation engineering requires not only a thorough grounding in theory, combined with an open eye for possible sources of error, but also an amount of observation and measurement in the field far in excess of anything attempted by the preceding generation of engineers. Hence, the center of gravity of research has shifted from the office and the laboratory into the construction camp where it will remain." (3)

Terzaghi's words are still valid today, especially for bridges supported by spread footings. Further studies of this type are encouraged to increase the statistical data base to permit more valid conclusions about the safety and reliability of spread footings, and their appropriate limits of tolerable movement.

6.2 Safety and Functional Reliability

Properly engineered embankments can provide good foundation support for bridge abutments on spread footings. It is standard practice in Washington to use compacted granular soil to support a spread footing in the bridge approach fill. An allowable bearing pressure of 3 tons per square foot (.287 MPa) is used to design the spread footing. Over 200 abutments of 148 bridges were inspected and found to be performing safely and efficiently. The key to a safe design is a proper engineering analysis of the foundation soils and site conditions, an adequately designed and constructed approach fill, and, in the case of stream crossings, a properly designed scour protection system.

None of the bridges evaluated under this study have shown any signs of serious functional distress and none had expensive maintenance or repair histories. Maintenance and construction engineers in each WSDOT district office reported that they have experienced favorable performance records for spread footings on compacted fill. No structural distress, architectural damage, or rideability problems were detected in any of the field inspections. Based on the visual examinations it was concluded that spread footings are functionally reliable foundation units for highway bridge abutments.

6.3 Cost-Effectiveness

When soil conditions permit the use of spread footings, the cost savings between piles and spread footings is usually significant. A comparative analysis should be made on a case-by-case basis. A series of three cost comparisons were made on actual WSDOT bridges (see Appendix C) which showed significant cost savings resulted from using spread footings instead of piles. In the first cost comparison example, the spread footing alternate was 67 percent cheaper than the pile foundation alternate. In the second example, spread footings were 46 percent cheaper than piles. The third example demonstrated a 65 percent cost savings.

6.4 Tolerable Movement Criteria

In view of the limited distress data available, the correlation efforts of this study were limited. The lack of significant distress data and the generally small magnitude of movement substantiated the functional reliability of spread footings on compacted fill, but it was not possible to precisely define the limits of tolerable movement. The data obtained from the 28 bridges surveyed clearly indicate that bridges can tolerate moderate (1-3 inches or 25-75 mm) amounts of vertical differential settlement. The specific amount of tolerable settlement depends on the span length between bridge piers and the degree of continuity over the spans. If a blanket criterion is used instead of designing on a case-by-case basis, it is recommended that 1 inch (25 mm) be used as the allowable differential settlement value.

6.5 Summary

The selection of the right type of foundation system to use for bridge abutments and piers is governed by both economic and performance considerations. These are in turn influenced by the engineering requirements of adequate bearing capacity and minimal settlement. The case studies reported herein are intended to demonstrate that spread footings are very reliable as well as inexpensive, and also that bridge superstructures can withstand moderate settlement without distress.

The prevailing use of piles in highway bridge foundations suggests the need to evaluate the potential for increasing the use of spread footings, especially on properly prepared fills. The conservative use of piles prompted the noted foundation expert, O. J. Porter to observe:

> "While we have had many mistakes due to inadequate foundations, we have also had many buried treasures of money due to using an expensive pile foundation where spread footings could be safely used." (1)

REFERENCES

1. Porter, O. J. "Discussion of: The use of Soil Mechanics in the Design and Construction of Bridge Foundations," Proceedings, Annual Convention, Association of Highway Officials of North Atlantic States, 1953.

2. Sequirant, S. J., "An Evaluation of the Performance and Cost Effectiveness of the Use of Spread Footings in Fill Embankments for the Support of Highway Bridge Abutments in the State of Washington," M.S. Thesis, University of Washington, Seattle, Washington, 1979.

3. Terzaghi, K., Presidential Address: First International Conference on Soil Mechanics and Foundation Engineering, Volume 3, Cambridge, Massachusetts, 1936.

APPENDIX A

DATA COLLECTION PROCEDURE

Processing the data from the large number of bridges in the study required an efficient data collection procedure. The bulk of the data from the file search and field inspections were put on a form, Figure 12. The back side of the form held notes of the field inspections and salient points of any previous inspections by WSDOT personnel. Any additional comments under the "Remarks" section were also placed on the back side of this form.

Most of the data came from the bridge foundation recommendation files of the Materials Laboratory. They were later verified against the "as-built" plans from the Bridge Division. The identification numbers and the names of structures and locations allowed access to other data files, and that helped find the bridges in the field.

The format of the data sheet is simple and most of it is self-explanatory. The year recorded represents the year that construction of the bridge was completed. The superstructure type represents the material (concrete or steel) and the configuration (girder, flat slab, T-beam, arch, box girder, etc.) of the superstructure. The span lengths were measured from center-to-center of the beam seats and the continuity arrangement was noted by the manner in which the span lengths were separated. For example, a hyphen separates span lengths of continuous bridges, and a semicolon designates simple span bridges. The width of the bridge was measured between curb lines, and girder depths were usually recorded for the end girders only.

The allowable bearing values are normally based on good quality granular fill material compacted to 95 percent of the maximum target density. This material varies from glacial till to sand and gravel or shot rock. WSDOT standard design practice for spread footings on engineered fills of granular soil is 3 tons per square foot (.287 MPa).

Jackable abutments are described in Appendix D. Stub fills are constructed in areas where good quality granular fill materials are scarce. The stub fill is built only large enough to provide adequate abutment support. It may be constructed full height or just slightly above footing elevation. It is normally constructed 3 footing widths wide with 1:1 side and end slopes.

The general soil profile was recorded on the data sheet in terms of a written soil description and the actual soil profile was copied and attached to the data sheet. Many of the bridge approach fills were expected to settle significant amounts prior to construction of the abutments and superstructure. Measurements were made to determine when the settlement was nearly completed before starting bridge construction. If settlement was progressing slowly or there was uncertainty regarding additional settlement, the construction engineer could use a system of "jackable" abutments. Jackable abutments are often specified during design when soil conditions indicate potential settlement problems.

Recommended foundation treatments were also included for the foundation soils below the approach fills, abutments, and intermediate piers. Removal limits or in situ stabilization requirements were specified to treat inadequate foundation soils and, in some cases, delay periods between fill and bridge construction and/or surcharge loads were also recommended.

The elevation of each abutment and intermediate pier at both gutter lines were taken from the "as-built" plans. Twenty-eight bridges were later surveyed for current elevations to determine their differential settlement values. Cost data were only accumulated on a few bridges, and detailed cost-effectiveness examples are presented in Appendix C.

DATA COLLECTION FORM

State Route Number ______ Control Section ______ Contract __________

Location Number _______ Federal Aid Number ________

Structure Name ____________________________ Bridge Number __________

Year ______ Project Location ____

Superstructure Type _________________________ Number of Spans ______

Span Lengths ________________________________ Width ________________

End Piers: Allowable Bearing ________________ Design Bearing _______

Girder Depth: Center of Span ________________ Ends _________________

Interior Piers: Allowable Bearing____________ Design Bearing _______

Piles _______ Shaft _________

Jackable Abutment ___________Stub Fill _______Approach Slab ________

Fill Height __________________

General Soil Profile ____

____

Fill Settlement: Estimated ______ Measured ______How Measured _____

Recommended Foundation Treatment ___________________________________

____

Elevations: Pier #______ Pier # ______ Pier # ______ Pier # ______

Plan

As built

Total Cost ______________________________Foundation Cost __________

Remarks: ____

____

Figure 12. Sample Data Collection Form Used During File Search

APPENDIX B

CASE HISTORY EXAMPLES

1. Evergreen Parkway U-xing:

This bridge (Figures 13-15) is an ACI award winning bridge over SR-101 (Evergreen Parkway) near Olympia, Washington. It is a six-span concrete box girder on rollers at all piers except the middle one, which is fixed. The bridge was built in 1975 with one abutment on spread footings in the fill, and the other abutment on a spread footing in natural ground. Of the five intermediate piers, four are on piles and one is on a spread footing in natural ground. The span lengths are 100 feet (30.4 m) - 2 at 145 feet (44 m) - 2 at 114 feet (34.7 m) - 87 feet (26.5 m).

The approach fill is 23 feet (7 m) high and is supported on medium compact to compact silty sand and gravel. Removal of some highly compressible peat was required under several pier locations. Basalt bedrock is within 50 feet (15.2 m) of the ground surface in this area. Gravel extends to the surface in two pier locations. An allowable bearing pressure of 3 tons per square foot (.287 MPa) was used to design the spread footings.

The abutment on fill has settled almost 2 inches (50 mm) differentially from the adjacent pier on piles. There are no signs of distress anywhere. The structure is in excellent condition.

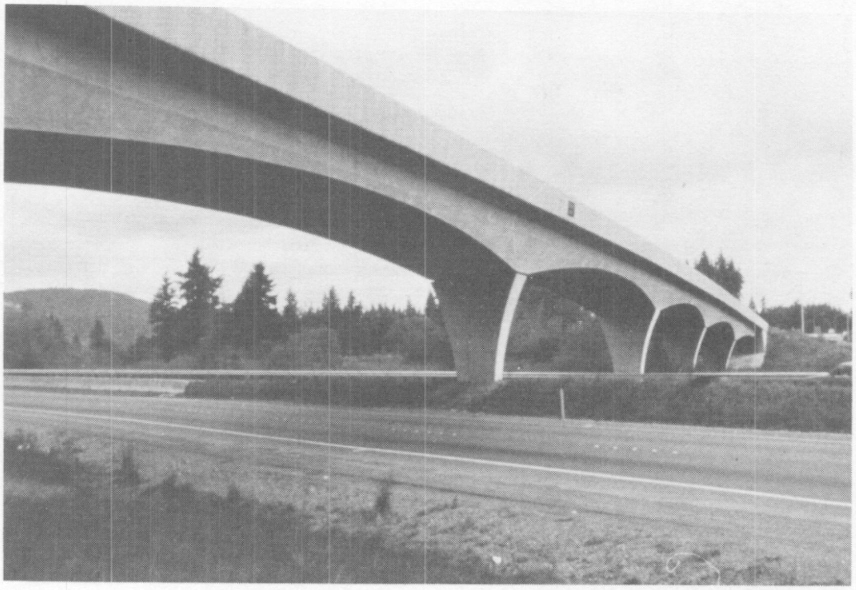


Figure 13. Evergreen Parkway Under-crossing

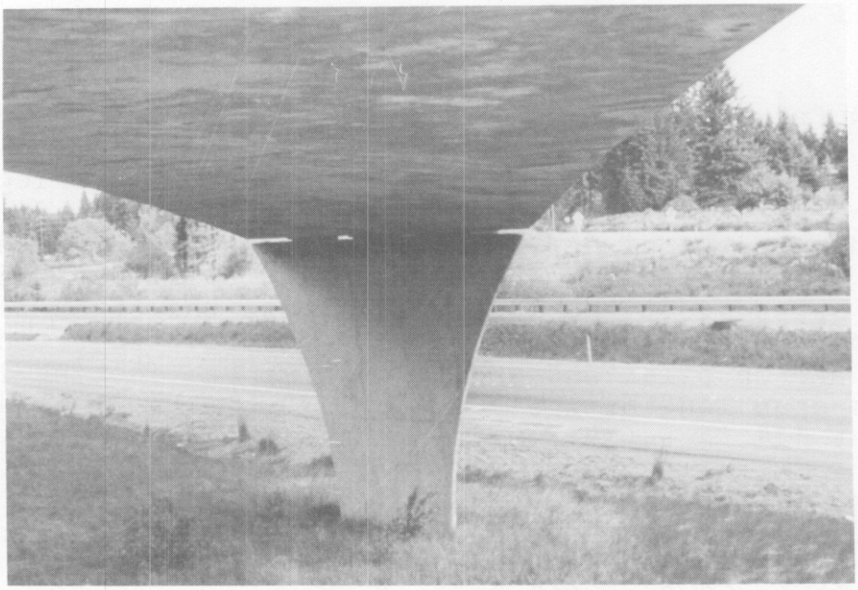


Figure 14. Evergreen Parkway Pier #2 and Underside of Box Girder

Figure 15. Abutment No. 1 of Evergreen Parkway Structure

2. Anderson Road U-xing:

This bridge (Figures 16-18) carries Anderson Road across Interstate 5 north of Seattle, Washington. It is a two-span continuous, prestressed concrete girder bridge that is typical of a grade separation structure over a major highway in Washington. The bridge was built in 1975. Both abutments are on spread footings in the fill, and the center pier is on piles. The span lengths are each 104 feet (31.7 m) long.

Each abutment was designed as a "jackable" abutment (see Appendix D) because the soils report contained a recommendation that provisions should be made to adjust the beam seat elevations in case the settlement predictions were inaccurate. The uncertainty involved in the settlement prediction was due to an erratic soil profile. Thus far, the abutments have settled less than 1 inch (25 mm) differentially from the center pier.

Each abutment footing was placed on 24 feet (7.3 m) of compacted granular fill overlying compact to very compact sand and gravel. Beneath the sand and gravel at various depths are loose sands and silts with scattered pockets of clay and organic matter. An allowable bearing pressure of 3 tons per square foot (.287 MPa) was used to design the spread footings.

This bridge is in very good condition. There were no bumps at the bridge ends; but there were 15-20 foot (4.6-6.1 m) pavement patches at both ends. The bridge deck, curbing and barrier walls had minor cracks; however, the reason for the cracks was unknown.

Figure 16. Anderson Road over Interstate 5

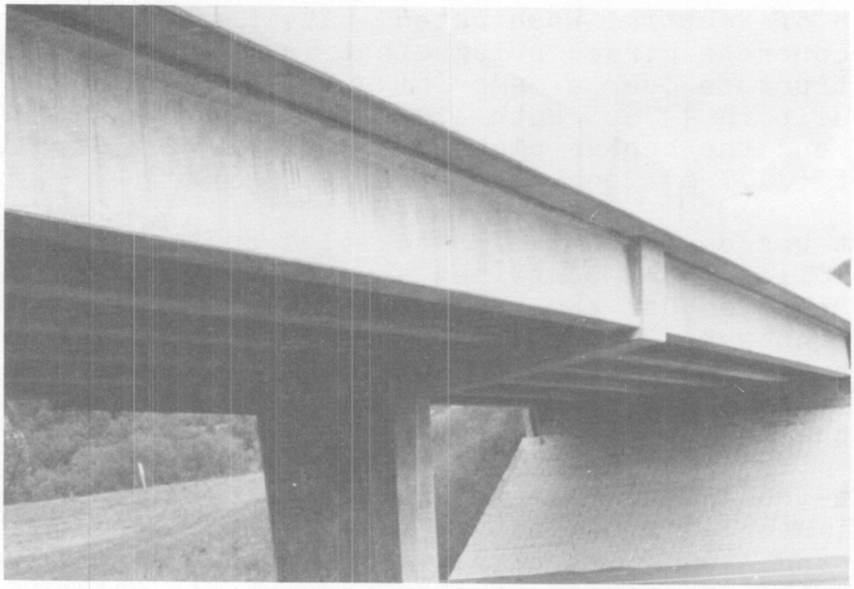


Figure 17. Pier No. 2 and Concrete Girders of Anderson Road Overpass

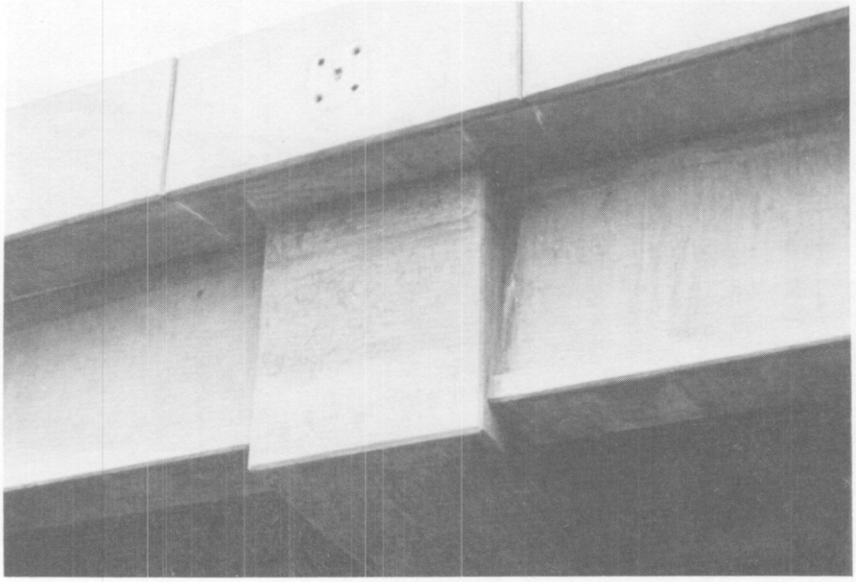


Figure 18. Closeup View of Pier No. 2 of Anderson Road Overpass

3. AR 19 Ramp in Pacific Avenue Interchange

This bridge (Figures 19-21) is a ramp in a major interchange in Tacoma, Washington. It is a four-span continuous concrete box girder bridge, built in 1964. It is a curved girder bridge supported entirely on spread footings. One abutment is on a spread footing in a 34 foot (10.4 m) high fill, and its two adjacent piers are also supported on high fills. The other piers are on natural ground. Differential settlements between piers were less than 1 inch (25 mm). The span lengths are 50 feet (15.2 m) - 85 feet (26 m) - 85 feet (26 m) - 50 feet (15.2 m).

The general soil profile at the pier locations consisted of dense sand and gravels overlain by 4 feet (1.2 m) of loose sands and gravels. An allowable bearing pressure of 3 tons per square foot (.287 MPa) was used to design the spread footings.

This bridge is also in good condition. There is a slight bump at pier 5 (abutment on fill), but no patching has yet been done. Minor spalling and cracking has occurred in the deck and in some girders, and there is a 1 inch (25 mm) displacement between the bridge deck and fill curbs near pier 5.

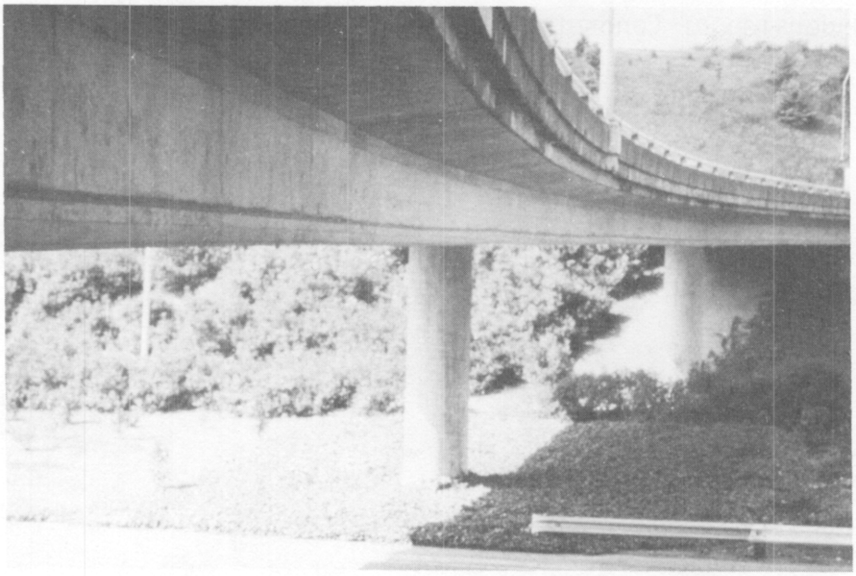


Figure 19. AR 19 Ramp in Pacific Avenue Interchange

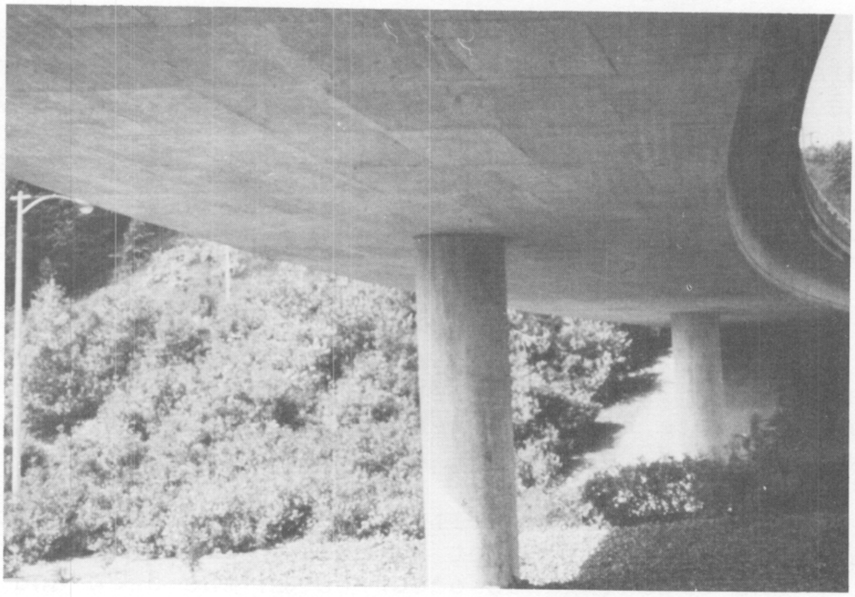


Figure 20. Underside of Concrete Box Girder Bridge (AR 19 Ramp)

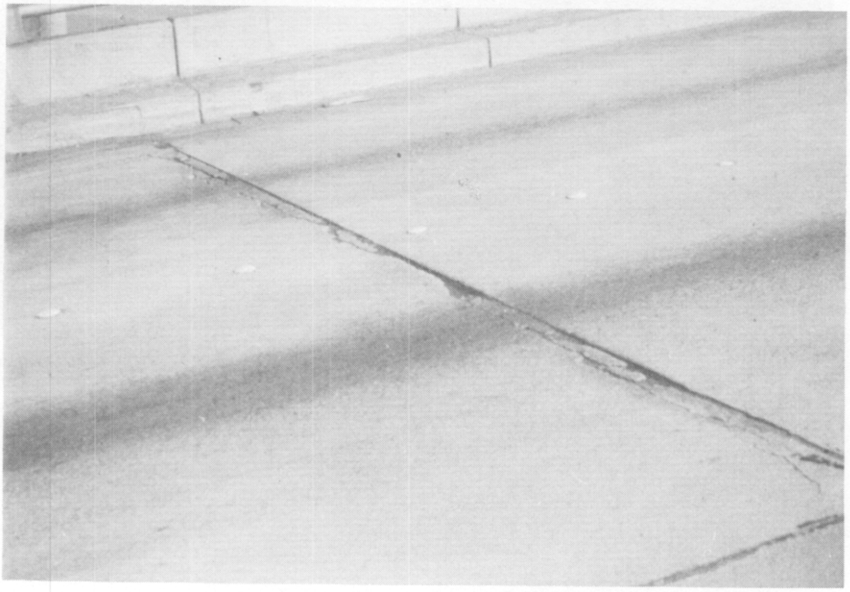


Figure 21. Bridge Approach Pavement for AR 19 Ramp

4. BL Line U-xing in Nalley Valley Interchange

This bridge (Figures 22-24) is also a curved structure in Tacoma, built in 1971. It is a seven-span continuous, concrete T-beam structure supported entirely on spread footings. Five piers, including both abutments, are supported on fill. The largest differential settlement has been 1.25 inches (31 mm).

The span lengths are 73 feet (22.2 m) - 5 at 91 feet (27.8 m) - 25 feet (7.6 m). One approach fill is 47 feet (14.3 m) high and the other is 50 feet (15.2 m). Very compact gravelly silty sand underlies most pier locations and medium compact sand deposits are under the remaining piers. An allowable bearing pressure of 3 tons per square foot (.287 MPa) was used to design the spread footings.

The bridge is in good condition. There are neither bumps, patches, nor signs of distress. There is some deck cracking, but it does not seem to come from differential settlement.

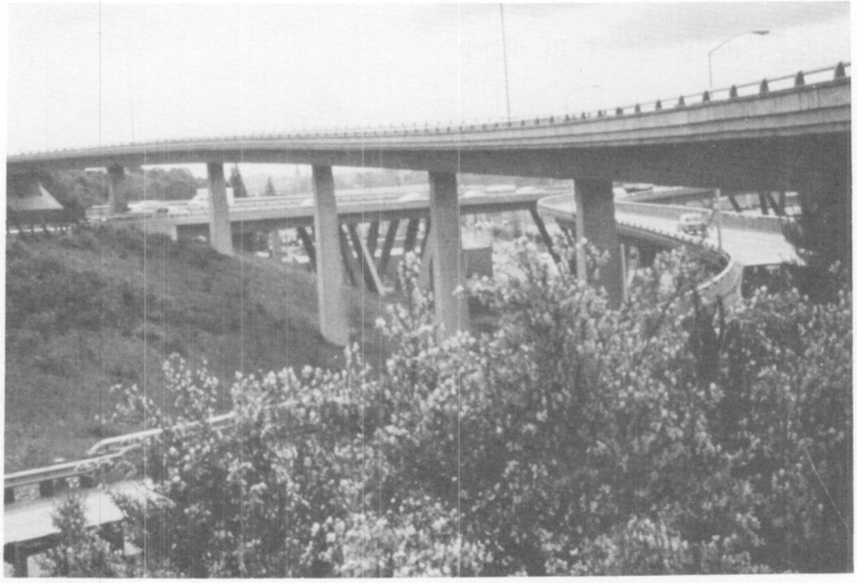


Figure 22. BL Ramp in Nalley Valley Interchange

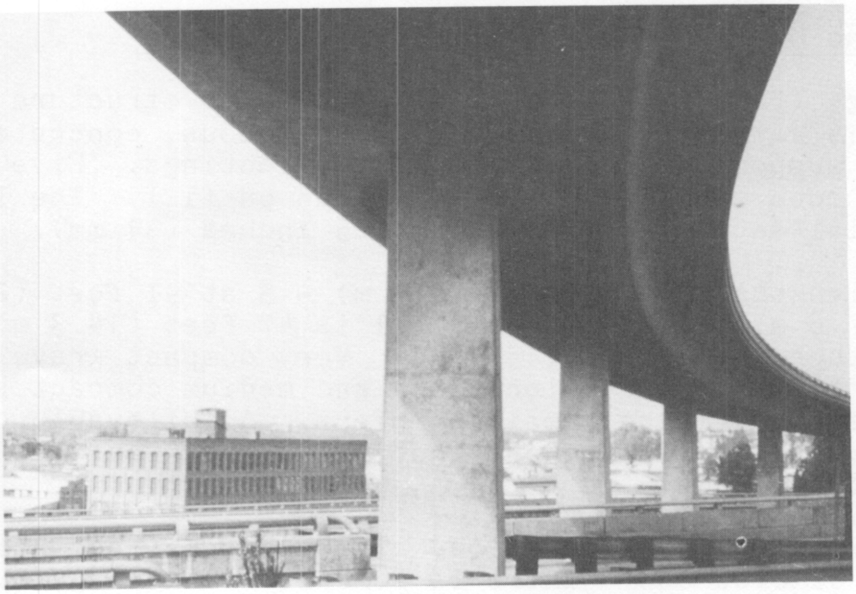


Figure 23. Underside View of BL Ramp

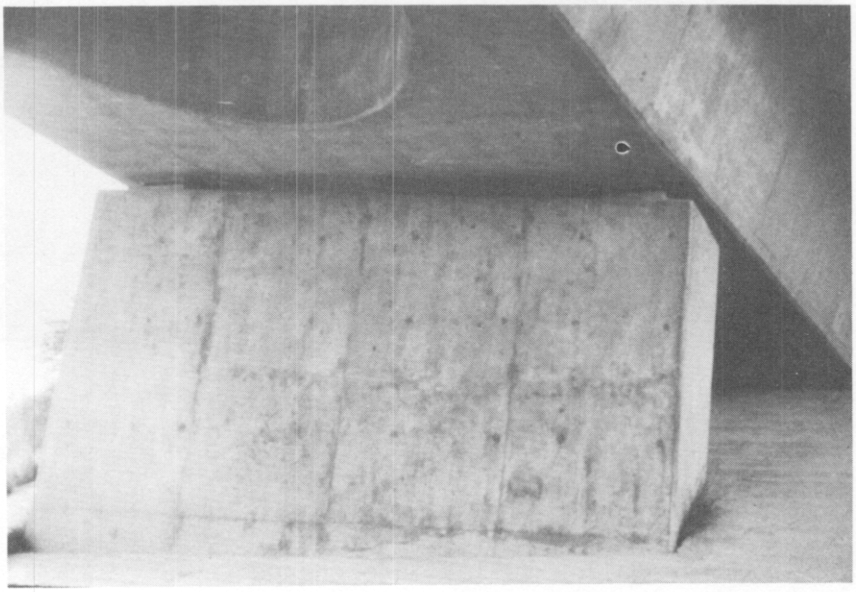


Figure 24. Abutment of BL Ramp

5. Mill Creek Bridge

This bridge (Figures 25-27) is a single span steel structure carrying SR4 over the mouth of Mill Creek, where it flows into the Columbia River. It was built in 1963 with one abutment on rock and the other on fill. The span length is 165 feet (50.3 m) and the girders are 10 feet (3 m) in depth.

The approach fill is 28 feet (8.5 m) high and is supported on loose to dense layers of organic silty sands with occasional zones of fibrous peat, clay, and silt. The fill was constructed of broken basalt rock and a 6-months waiting period was used to allow settlement to occur prior to construction of the abutment. An allowable bearing pressure of 3 tons per square foot (.287 MPa) was used to design the spread footings.

The abutment on fill continued to settle after construction and has settled 15 inches (0.4 m); but the bridge is in very good condition. There are no bumps at either end, and deck cracking is minimal. Each corner of the bridge has very slight vertical and lateral displacements. The most significant sign of distress is that bearing rockers at the fill abutment are tipped slightly inward.

Figure 25. Mill Creek Bridge on SR 4

Figure 26. East Abutment on Rock

Figure 27. West Abutment on Fill

6. Columbia River Bridge at Olds, Washington

This bridge (Figures 28 and 29) is a seven-span concrete box girder bridge, carrying SR2 over the Columbia River near Wenatchee, Washington. It has simply supported end spans and continuous intermediate spans. It was built in 1975 with both abutments on spread footings in the fill, and the intermediate piers are on drilled shafts. The span lengths are three at 190 feet (58 m), one center span at 260 feet (80 m) and three at 190 feet (58 m).

The abutments had been designed for pile support; however, a detailed design analysis revealed that pile lengths of nearly 200 feet (61 m) would be required to reach firm bearing. In addition, drag loads (from negative skin friction) of 50-100 tons (45.4-90.7 tonnes) would be exerted on each pile due to the consolidation of a thick clay layer beneath both bridge approach fills.

Overloads and delay periods for the embankment construction were used to handle part of the settlement prior to bridge construction. Simple spans and jackable abutments were specified at each end of the bridge to handle post-construction settlements.

Settlements of 0.8 feet (0.24 m) were predicted at pier 1 (west abutment) and 0.3 feet (90 mm) at pier 8 (east abutment). Approximately 6 to 9 months were predicted for 90 percent settlement to occur. Although pier 1 was expected to be more troublesome than pier 8, it has not yet required jacking. Pier 8 has been jacked twice for a total of 0.34 feet (102 mm) and it may require additional jacking.

It has been far more economical to reduce the effects of settlement (overload, delay period, simple span arrangement, jackable abutments) than using long piles. The cooperation among design, construction, and maintenance personnel has made this solution possible.

The bridge is in very good condition. There are neither bumps, patches, nor signs of serious distress. The inspection report shows only one hairline crack in the bottom flange of one girder.

Figure 28. Columbia River Bridge at Olds, Washington

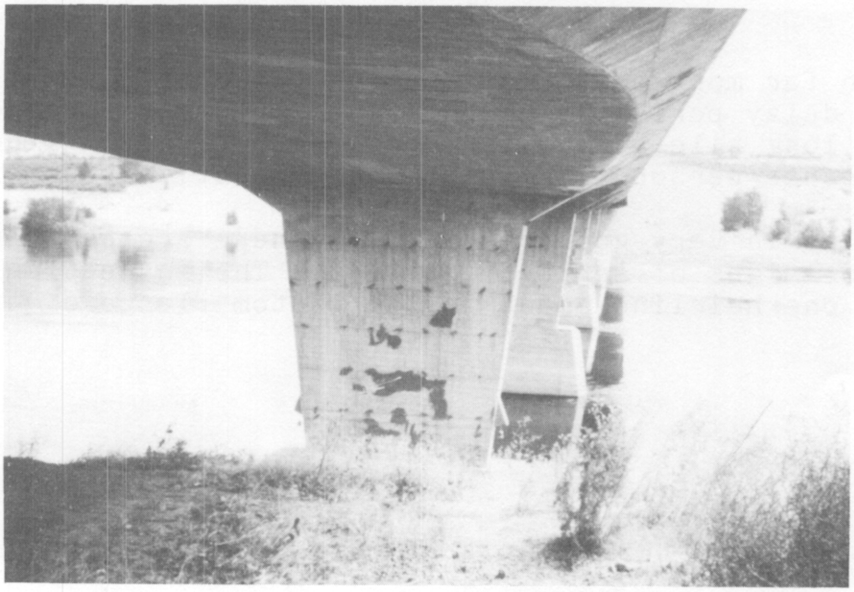


Figure 29. Underside of Concrete Box Girder and Piers of Columbia River Bridge

7. Nalley Valley Viaduct

This bridge (Figures 30-32) is a very long, high viaduct in Tacoma, Washington. It is supported entirely on spread footings in either fill or natural ground. This structure was evaluated as part of the original 148 bridges, but it was not surveyed for vertical movements because its foundation conditions were favorable. It was selected as a case history example to demonstrate the confidence of WSDOT engineers in supporting large structures on spread footings.

This bridge is a continuous concrete T-beam structure with one 70 foot (21.3 m) span and 6 spans at 92 feet (28 m). One abutment is on a 25 foot (7.6 m) approach fill and the other abutment is on natural ground.

The foundation soils consist generally of compact to very compact silty sand and gravel overlain by variable depths of loose to medium compact silt, sand and gravel. In general the loose zones are due to site regrading and in several instances the loose fill becomes rather extensive. An allowable bearing pressure of 3 tons per square foot (.287 MPa) was used to design the spread footings.

Figure 30. Nalley Valley Viaduct

Figure 31. Closeup View of Nalley Valley Viaduct

Figure 32. Substructure of Nalley Valley Viaduct

APPENDIX C

COST-EFFECTIVENESS EXAMPLES

1. Ellingston Road O'xing

This bridge was designed and constructed in 1976 with the abutments (piers 1 and 4) on spread footings in the approach fill, and the intermediate piers (2 and 3) on 55-ton (50 tonnes) cast-in-place concrete piles. It is a prestressed concrete girder bridge with three continuous spans of 48.5 feet (14.8m), 63 feet (19.2m) and 51.5 feet (15.7 m).

The spread footing design was selected because a long settlement period was available between the time the approach fills and bridge were to be constructed. The load on each abutment is 820 tons (745 tonnes) including the weight of the abutment itself. The allowable footing load was established as 3 tons per square foot (.287 MPa) which resulted in a footing 46 feet (14 m) long and 6 feet (1.8 m) wide. If piles had been used, each abutment would have required 15 piles.

The length and cost of the abutment piles can be estimated from the cost of the interior piers. The piles under the interior piers developed bearing in a hard layer (Figure 33) 45 to 60 feet (13.7-18.3 m) below the original ground surface. Assuming an average footing elevation of 85 and an average pile tip elevation of 20, the pile length estimate is 65 feet (19.8 m).

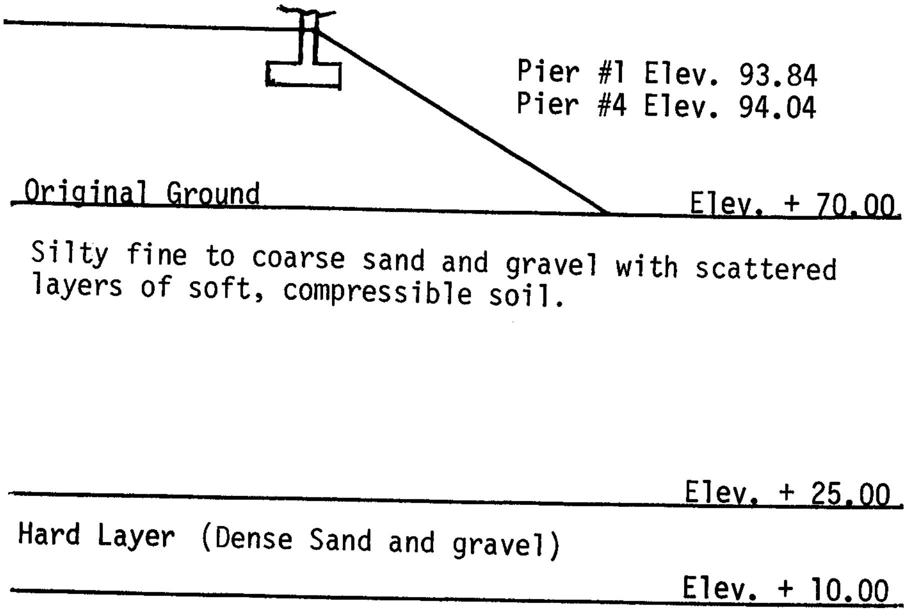


Figure 33. Profile of Ellingston Road Bridge Approach Embankment

The contract price for piles was $200 for driving each pile, and $5.80 per foot of pile furnished. The average of five bid prices on this project was $194 for driving each pile and $6.42 per foot of pile furnished. Thus the total cost of furnishing and installing the piles would have been $17,310 (15 x 2 x $200 + 15 x 2 x 65 x $5.80 = $6,000 + $11,310 = $17,310). This figure would have to be adjusted to represent increased costs due to inflation.

Those figures represent the cost of piling which is usually a close estimate of the potential savings involved. Other costs to consider are excavation, reinforcing steel, delay periods, surcharges, special quality fill material, extra compaction, and different sizes of spread footing and pile cap.

In this case, there was no extra cost due to a delay period, but there were extra costs to make each abutment jackable. The cost of six jacking pads was approximately $100 because the total volume of concrete was approximately two-thirds of a cubic yard and the bid price for concrete per cubic yard in-place was $150.

There were no extra costs involved in furnishing special quality fill material beneath the spread footing for this project because the same material would have been used in each case. Extra compaction costs to satisfy the spread footing requirements for 95 percent maximum density were probably insignificant on this project.

The cost of excavation and concrete are important. Excavation costs would make a difference if the spread footing were larger than the pile cap, or if the footing were placed at a lower elevation. These factors should be considered on a case-by-case basis. The cost of forming and placing concrete would also be substantially different if the size of the footing and pile cap were different. For the Ellingston Road Bridge, the cost of concrete for a spread footing was approximately $2,300 for each abutment. The estimated cost of a pile cap was approximately $1,500 for each abutment. Excavation costs favored the pile cap ($1,300 vs $800). Reinforcing steel costs were nearly the same. Miscellaneous costs, such as design modifications to the superstructure to resist the effects of settlement or preboring through the fill to aid penetration of the piles, were not applicable in this analysis. A cost comparison shows spread footings cost only one-third (33 percent) of the amount estimated for a pile foundation.

COST COMPARISON SUMMARY

Foundation Type	Concrete	Excavation	Piles	Pile Driving	Total
Spread Footings	$4,600	$2,600	-	-	$7,200
Piles	$3,000	$1,600	$11,310	$6,000	$21,910

The actual savings will vary with the length of piles furnished. The size of the spread footing and pile cap, and the number of piles will remain unchanged for this project, but the pile lengths will vary with driving resistance. Figure 34 shows the effect that pile lengths have on the cost comparison of spread footings and piles.

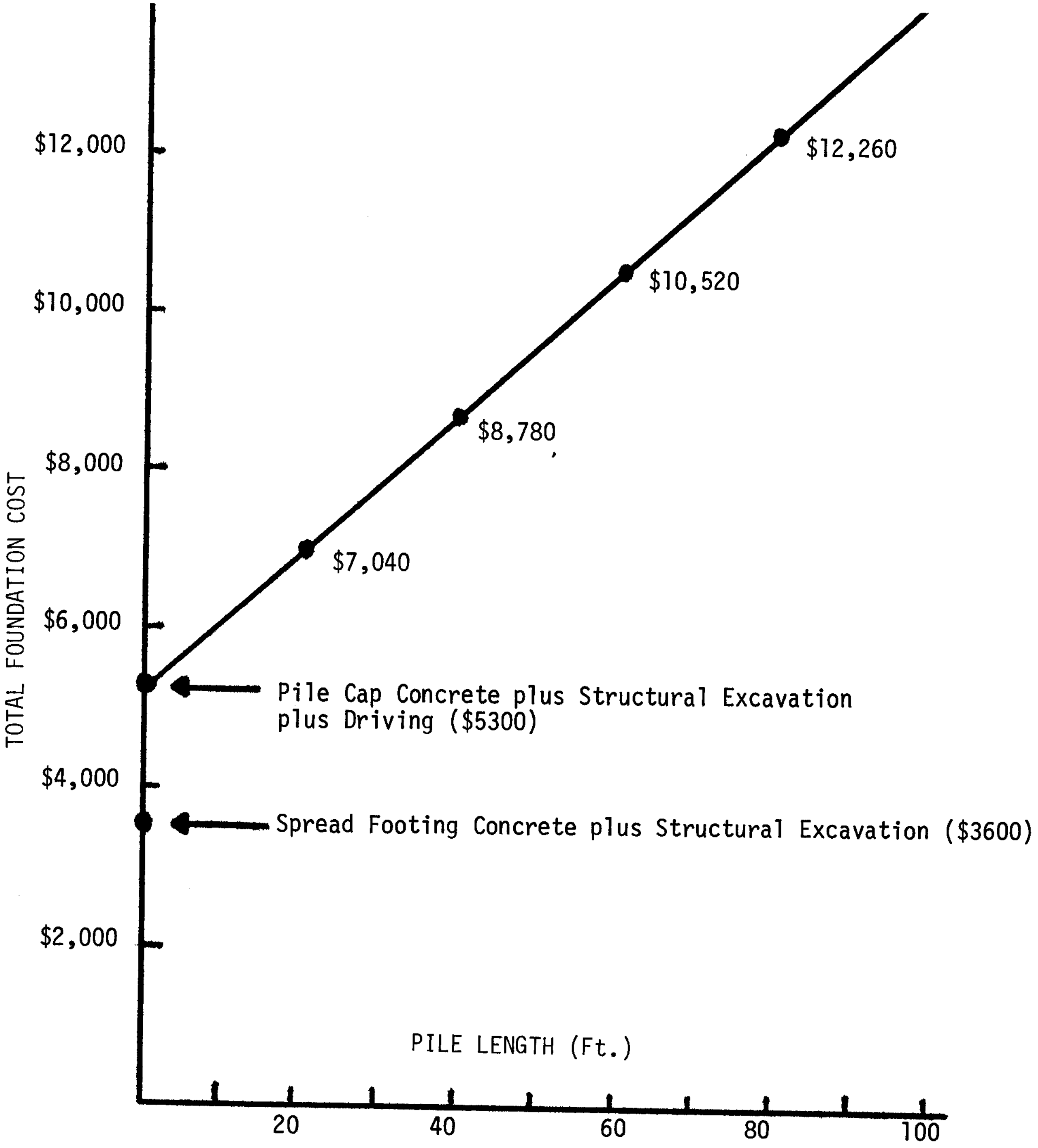


Figure 34. Pile Lengths versus Total Foundation Cost for one abutment

2. Pilchuck River Bridge

This bridge is an eight-span continuous prestressed concrete girder structure that was constructed in 1979 to carry SR2 over the Pilchuck River. The piling costs were obtained from the WSDOT's 1978 Bid Book because actual costs were only available for spread footings on this contract. The span lengths ranged from 73 feet (22.2 m) to 150 feet (45.8 m) at the main channel. The abutments were designed both as pile supported footings and as spread footings in fill. The spread footings were selected because they were far cheaper than piles; spread footings were estimated to cost only 54 percent of the required pile foundations for both abutments.

In order to use spread footings, it was necessary to build each embankment to full height and allow the embankment to settle for 30 days before footing excavation could be started. One abutment also required removal of 7 feet (2.1 m) of poor surface materials and replacement with granular material, compacted to 95 percent maximum density.

The pile supported footing for abutment 1 was designed as a pile group of 22 steel "H" piles (12HP53) with a pile batter of 3:12. The average elevation of the top of the piles was estimated at 81.09, and the estimated pile-tip elevation was 35. An average length of pile then became 46.09 feet (14 m). The average length was later increased to 47.5 feet (14.5 m) to account for pile batter.

The average 1978 Bid Book price for driving each pile was $230 resulting in an estimated driving cost of $5,060 for abutment 1. The estimate for furnishing the steel piles was $10,450 based on a price of $10 per foot of pile (22 x 47.5 x $10). The total piling cost for abutment 1 would have been $15,510, plus the cost of structural concrete ($7,055) and structural excavation ($9,802) for the pile cap.

The spread footing and pile cap were designed the same size (8 feet by 74 feet) (2.4 m by 22.6 m). However, the pile cap was 6 inches (150 mm) thicker than the spread footing. The estimated cost of strucural concrete was $117 per cubic yard, and the extra volume of concrete for the pile cap resulted in an additional cost of $1,283. The cost of reinforcing steel for both foundation systems was about equal, but the cost of structural excavation was slightly higher ($429) for the pile cap. The structural concrete cost for the spread footing was $5,772 and the structural excavation was $9,373.

The only extra cost in constructing the spread footing for abutment 1 was the excavation and replacement of unsuitable material from the foundation layer (Figure 35). At an estimated cost of $2.74 per cubic yard and a volume of 1,377 cubic yards, the cost came to $3,774. The total spread footing cost was $18,919, which was 58 percent of the cost of the required pile foundation for abutment 1.

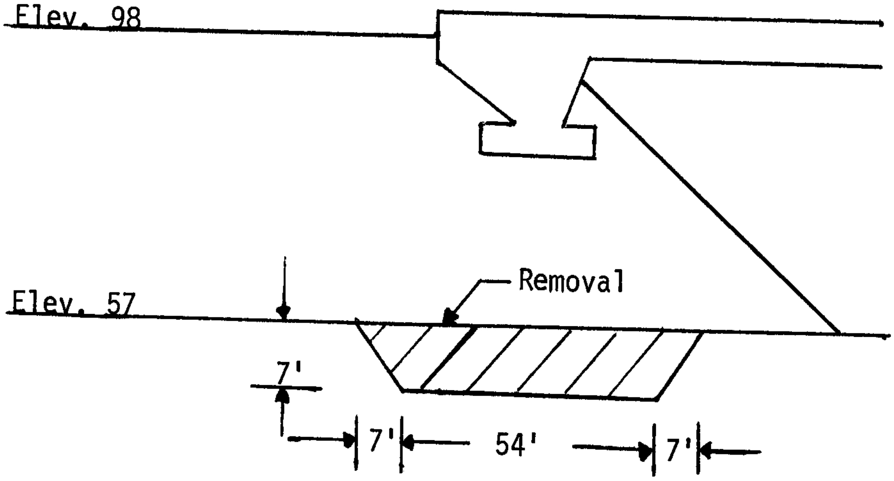
The pile supported footing for abutment 2 was a group of 18 steel "H" piles (12HP53) having a batter of 3:12. The average elevation of the top was estimated at 65.31, and the estimated pile tip elevation was 25.00 resulting in an average length of 41.6 feet (12.7 m), including batter.

The cost of driving was equal to 18 x \$230 = \$4,140, and the cost of furnishing was \$7,488 (18 x 41.6 x \$10). The total cost of piling for abutment 2 was \$11,628. The extra cost of concrete for the thicker pile cap was \$947. The extra cost of excavation was \$354. The structural concrete cost for the spread footing was \$4,737 and the structural excavation was \$7,692. There were no extra costs for constructing the footing due to removal of unsuitable materials, and the delay periods for each abutment did not cause appreciable extra costs. The total cost of the spread footing for abutment 2 was 49 percent of the alternate pile foundation.

COST COMPARISON SUMMARY

Foundation Type	Concrete	Excavation	Piles	Driving	Total
Spread Footings(#1)	\$5,772	\$13,147*	-	-	\$18,919
Piles (#1)	\$7,055	\$9,802	\$10,450	\$5,060	\$32,367
Spread Footings(#2)	\$4,737	\$7,692	-	-	\$12,429
Piles (#2)	\$5,684	\$8,046	\$7,488	\$4,140	\$25,358

* Includes removal and replacement of unsuitable foundation soils.



NOTE: Transverse length of removal area = 84'

Figure 35. Profile for Approach Embankment of Pilchuck River Bridge

3. North Fort Lewis Interchange

This comparison concerns two parallel structures in the same interchange; Interstate 5 was being widened in 1969 to four lanes divided, with new ramp facilities. The main structure would carry the northbound lanes of I-5, and the other structure would be the northbound collector-distributor ramp (Figure 36). The southbound lanes would run on the existing bridge, west of the new structures. The mainline structure is a continuous, prestressed concrete girder bridge with 45-foot (13.7m) end spans and an 86-foot (26.2m) center span.

Both the mainline and ramp structures were designed with pile supported footings at all abutments and with spread footings on natural ground at the interior piers. After construction of abutment #1, piles were eliminated at the three remaining abutments because the 24-foot (7.3m) high approach fills were constructed of good sand and gravel. These soils were similar to the natural ground which supported the interior piers. An allowable bearing pressure of 3TSF (.287 MPa) was used to design the spread footings.

The pile caps proposed for the other three abutments were considered large enough to be spread footings. A change order was issued to delete the piles for these abutments. The following cost comparison represents an accurate savings because none of the unit prices had to be estimated. The lengths of the remaining piles were closely estimated from the results of driving piles for the completed abutment.

Abutment #1 was built on 12 steel "H" piles (21BP53) at an average pile length of 25 feet (7.6m). The contract price for furnishing them was $5.88 per foot, and the cost of driving each pile was $71. The savings in pile costs for the opposite abutment of the mainline bridge amounted to $2,616 (12 x 25 x $5.88 + 12 x $71).

The abutments for the ramp structure were to be supported by eight piles which amounted to a savings of $3,488 (16 x 25 x $5.88 + 16 x $71). The total savings came to $6,104 in 1969. That figure would be at least three times greater in 1981 dollars. The savings from using spread footings to support the intermediate piers was not estimated; but they would also be substantial. In terms of percentages, the spread footing for abutment #2 cost 35 percent of the cost of piles to support abutment #1.

Figure 36. North Fort Lewis Interchange Structure

APPENDIX D

JACKABLE ABUTMENTS

Concern for settlement does not rule out spread footings: they can work in very unfavorable conditions with the proper cost incentives. The basic approach is to design the size and location of the footing in accordance with the imposed loads, existing soil conditions, and the allowable settlement constraints. If the expected settlements are larger than what can be reasonably tolerated by the superstructure, the engineer must decide whether to improve the soil, make the structure more tolerant (flexible) to settlement, or use a deep foundation system.

The basis for this decision is usually one of economy. If a deep foundation system is too expensive, the number of spread footing options that are available increases significantly in both the soil improvement and structural modification alternatives. The final choice depends on a number of factors that are site and case specific. Proper treatment of the decision making process for this type of analysis is beyond the scope of this report.

If the engineer decides to use a spread footing where settlements could become a long-term problem, a relatively simple and inexpensive precautionary measure called "jackable" abutments can be incorporated in the abutment design to preclude extensive damage to the superstructure. This technique involves the design and construction of jacking pads on the abutments and the periodic jacking of the girders by maintenance personnel.

The periodic jacking process uses hydraulic jacks under each girder that can be synchronized by running a series of jacks from a central manifold system. The synchronization allows all the girders to be raised and shimmed simultaneously. Individual jacking may be required if there has been differential settlement across (transverse) the abutments as well as between the piers. The number of jacking operations required depends on the amount and rate of settlement and on the flexibility of the structure. Under normal circumstances a work crew of 3 or 4 people can jack one abutment in 2 or 3 days. The cost of materials, equipment and labor for jacking one abutment would be approximately $2,000.

The Columbia River Bridge at Olds, Washington, has been jacked twice for a total of 0.34 feet (102 mm). The first jacking was 0.2 feet (61 mm) and the second was 0.14 feet (43 mm). Additional jacking may be required if the abutments continue to settle at the current rate.

Figures 37, 38 and 39 illustrate three types of jackable abutments. Figure 37 shows a small concrete pad built on the abutment wall under each girder to support the jacks. Figure 38 shows a jacking shelf and Figure 39 shows a series of jacking nooks.

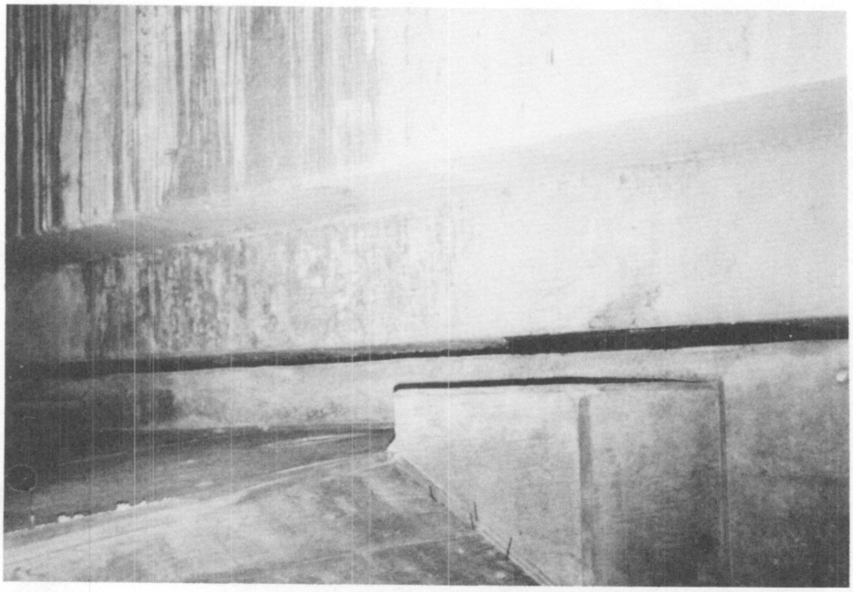


Figure 37. Jacking Pad for Jackable Abutment on Columbia River Bridge

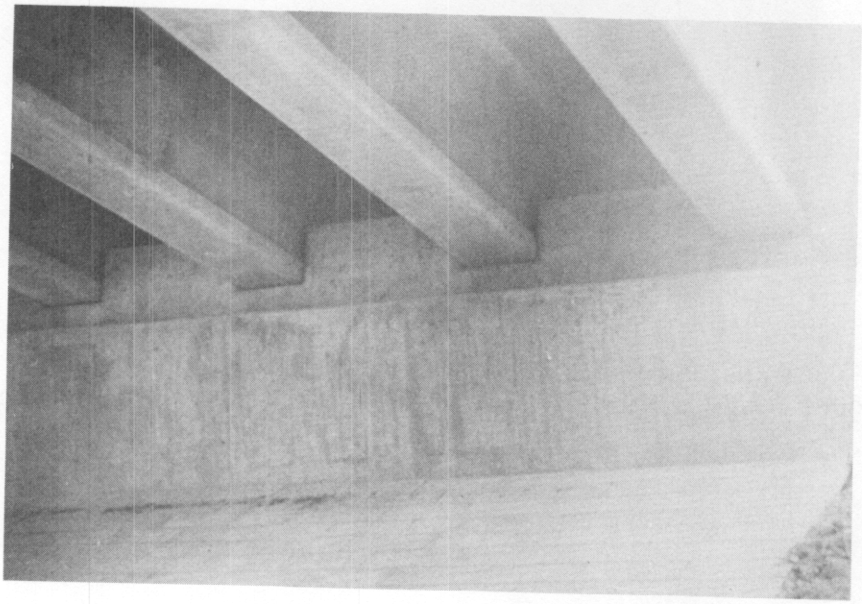


Figure 38. Jacking Shelf for Jackable Abutment on South 277 Street Bridge

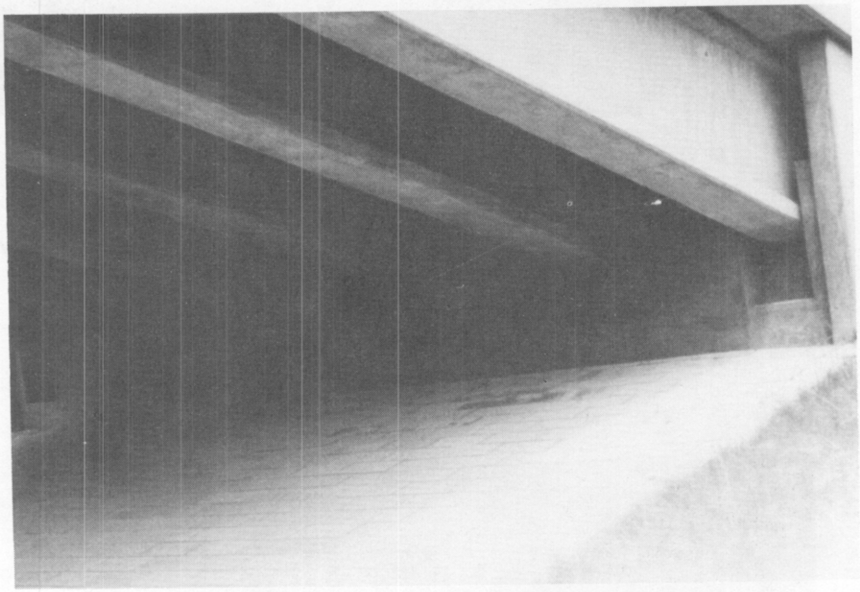


Figure 39. Jacking Nooks for Jackable Abutment on Anderson Road Bridge

APPENDIX E

FIELD MEASUREMENT OF SETTLEMENT

During this study, it became necessary to determine current elevations of some bridges that had been investigated. A total of 28 bridges were surveyed, and their results determined the amount of foundation settlement that occurred since the bridge was completed. The survey was performed by WSDOT crews.

When elevation bench marks were available, both total and differential settlements were determined. When bench marks were not available within a reasonable distance from the bridge, differential settlements were determined by a two-step procedure. First, an assumed elevation was used to initiate the survey measurements. That assumed elevation was set equal to an "as-built" elevation at one end of a pier. The remaining measurements were then adjusted by an equation.

To find the differential settlement between the base point (where the elevation was assumed) and other points on the bridge deck, the crews did three things. First, they subtracted the as-built elevation from the base point. Then they added that difference to the measured elevations of the other points on the bridge deck. Finally they subtracted the adjusted elevations from the corresponding as-built elevation.

Figure 40 illustrates this procedure. The survey crew assumed a base elevation of 5.00 feet at Pier 1's south end. They set that figure equal to the as-built elevation of 48.50 feet. Then they subtracted these values to get the adjustment factor of 43.50 that was needed to determine the differential settlement at the other points. The crew added the adjustment factor, 43.50, to the observed elevations to get an adjusted elevation. The differential settlement at the south end of Pier 2 is calculated by subtracting the adjusted elevation, 50.14 feet, from the as-built elevation, 50.18 feet. The difference, 0.04 feet, is the differential settlement between the south end of Pier 1 and the south end of Pier 2.

This procedure reduced the surveying costs significantly. It is considered acceptable because the main objective was to determine the amount of differential settlement which does not require actual elevation data.

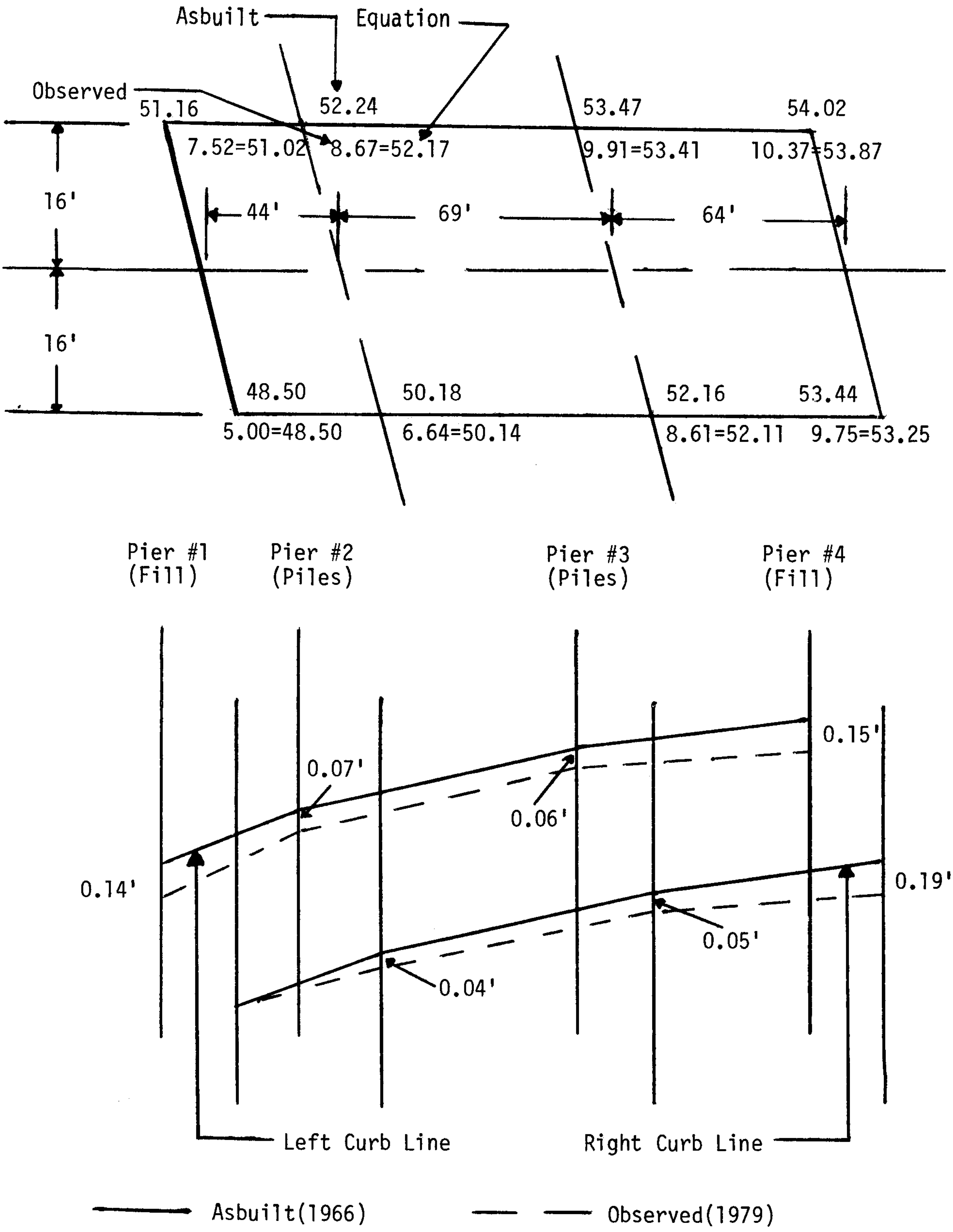


Figure 40. Profile of Differential Settlement for Tukwila Interchange Ramp E Bridge

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

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* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.