NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 29

TREATMENT OF SOFT FOUNDATIONS FOR HIGHWAY EMBANKMENTS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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TREATMENT OF SOFT FOUNDATIONS FOR HIGHWAY EMBANKMENTS

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
- HIGHWAY DESIGN
- EXPLORATION-CLASSIFICATION (SOILS)
- FOUNDATIONS (SOILS)
- MECHANICS (EARTH MASS)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1975

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP Synthesis 29

Project 20-5 FY '72
ISBN 0-309-02334-3
L. C. Catalog Card No. 75-20631

Price: $3.20

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are available from:

Transportation Research Board
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

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Printed in the United States of America.

PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the various practices without in fact making specific recommendations as would be found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available concerning those measures found to be the most successful in resolving specific problems. The extent to which they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of special interest and usefulness to highway design, soils, and foundation engineers who are faced with the problems of highway construction in areas of soft foundation soils. Information is offered on advance planning and preliminary design considerations, subsurface investigation and testing, design techniques, and construction alternatives that have proven successful in practice. Detailed design procedures available in textbooks are not reported.

Administrators, engineers and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information often is fragmented, scattered, and unevaluated. As a consequence, full information on what has been learned about a problem frequently is not assembled in seeking a solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem. In an effort to resolve this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of synthesizing and reporting on common highway problems—a synthesis being identified as a composition or combination of separate parts or elements so as to form a whole greater than the sum of the separate parts. Reports from this endeavor constitute an NCHRP report series that collects and assembles the various forms of information into single concise documents pertaining to specific highway problems or sets of closely related problems.

A variety of foundation treatment alternatives, including removal and replacement, stabilization by consolidation, and pile-supported roadways, have been developed and used with an acceptable record of success in soft foundation areas to provide pavement support comparable with that more easily obtainable in areas of firm foundation soils. Uniformly acceptable riding quality, without discontinuities related to foundation support, is a valued safety feature in these times of high-speed, high-volume traffic. Initial costs of the foundation treatments are often high, but substantial reductions in maintenance and replacement costs are compensating features. Because of the complexities of the reaction of soft foundations to embankment loadings, thorough and careful study, treatment selection, and design by specially trained and competent personnel are needed to assure success.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from many highway departments and agencies responsible for highway planning, design, construction, operations, and maintenance. A topic advisory panel of experts in the subject area was established to guide the researchers in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. Meanwhile, the continuing process of search for better methods should go on undiminished.

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ACKNOWLEDGMENTS

This synthesis was completed by the Transportation Research Board under the supervision of Paul E. Irick, Assistant Director for Special Projects. The Principal Investigators responsible for conduct of the synthesis were Thomas L. Copas and Herbert A. Pennock, Special Projects Engineers.

Special appreciation is expressed to Stanley J. Johnson, Special Assistant, Soils and Pavement Laboratory, U.S. Army Waterways Experiment Station, who was responsible for the collection of data and preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Advisory Panel, consisting of Ara Arman, Professor of Civil Engineering and Assistant Director, Division of Engineering Research, Louisiana State University; Raymond A. Forsyth, Supervising Materials and Research Engineer, Transportation Laboratory, California Department of Transportation; David S. Gedney, Regional Engineer, Region 15, Federal Highway Administration; Lyndon H. Moore, Director, Soil Mechanics Bureau, New York State Department of Transportation.

John W. Guinnee, Engineer of Soils, Geology and Foundations, Transportation Research Board, assisted the Special Projects staff and the Topic Advisory Panel.

Information on current practice was provided by many highway agencies. Their cooperation and assistance were most helpful.

TREATMENT OF SOFT FOUNDATIONS FOR HIGHWAY EMBANKMENTS

SUMMARY

In many areas the earliest preliminary location planning should consider the possibility that some routes might involve soft foundation soils. The relatively long time required to evaluate the impact of soft foundation areas makes it advantageous to include special foundation investigations as part of preliminary planning studies. Right-of-way for some soft foundation construction alternatives may exceed usual requirements. In addition, construction alternatives involving subsoil stabilization by consolidation require surcharge loading periods. Additional right-of-way and time for surcharge loading may be available only if early planning studies recognize these special needs and consider their impact before final route selection and public hearings. If this is not done, an objective appraisal of all applicable construction alternatives may be precluded.

Construction over soft foundation areas requires extensive investigations and detailed comparative analyses to evaluate possible construction alternatives. Such additional investigations are expensive and the cost of preparing comparative designs should be considered separately from the cost of preparing designs, plans, and specifications for normal subsoil conditions. The added engineering costs are, however, but a small part of potential savings in construction costs. Embankment failures, poor-riding pavement, and high maintenance costs must be considered. Qualified specialized personnel are required in-house, even if plans and contract documents are prepared under contract.

Applicable construction alternatives include (a) elevated structure, (b) embankment fill supported by piles, (c) excavation of soft soils and replacement by suitable fill materials, (d) subsoil stabilization with or without sand drains, and (e) no treatment whatsoever, relying instead on especially detailed field investigations and careful design studies to achieve uniform settlements. Each alternative can be evaluated based on factors such as construction cost, maintenance, ecological and environmental effects, fill availability, and disposal area availability. No one method need be considered to have sufficient merit to warrant a significant cost premium over other alternatives. The time available for construction and subsoil stabilization often affects selection of a construction method. Although the Swedish method of supporting an embankment on piles is widely used in Norway and Sweden, it has not been used in the United States.

Where subsoil stabilization involves use of vertical sand drains, the type of drain influences the design procedures. If displacement drains are used, field results should be at least as good as predicted using results from conventional consolidation tests on good-quality, undisturbed soil samples. However, field consolidation will proceed at a faster rate in most cases, and especially where nondisplacement-type drains are installed. Where nondisplacement drains are used, field permeability tests are desirable because they result in a somewhat higher field coefficient of consolidation that will reduce the estimated consolidation time. Field permeability values should be reduced to account for effects of embankment loading. Extensive field instrumentation should be required where subsoil stabilization by consolidation is used.

Where subsoil consolidation techniques are used, field test sections are desirable

to achieve maximum economy. An additional benefit is obtained where consolidation techniques have not been attempted and where elevated structure or other techniques are preferred. In this case, a field test section will assure that consolidation techniques are technically reliable. Available field experiences indicate that this will be the case if consolidation designs are prepared properly. Field test sections are also useful for training construction personnel.

Quality and amount of field inspection are especially important and can be related to the postconstruction behavior of the types of construction discussed. Where the excavation and backfill technique is used, the quality of field control exercised affects the cost of the completed work, with the lowest costs associated with the best quality control.

CHAPTER ONE

INTRODUCTION

Highway construction in areas of soft foundation soils involves special problems that affect (a) design, (b) construction scheduling, (c) construction and postconstruction costs, (d) use of the completed highway, and (e) public attitudes toward the competency of local, state, and federal engineering activities. Problems involved (see Table 1) concern other factors in addition to construction and maintenance costs. Minimum construction cost is not necessarily a dominating factor. Embankment failures, poor-riding pavement, and high maintenance costs must be considered.

It is now essential to consider the impact of ecological

TABLE 1

PROBLEMS INVOLVED IN CONSTRUCTING EMBANKMENT OVER SOFT FOUNDATIONS

DESCRIPTION OF PROBLEM	REMARKS
Additional construction costs	Substantial; may be as much as several hundred thousand or even several million dollars per mile.
Safety and public relations	Excessive postconstruction differential settlements may require taking part of roadway out of service for maintenance: Serious safety hazard for heavily traveled roads. Major inconvenience—causes poor public image and public relations problems.
Maintenance costs	May be large and burdensome: More expensive construction may minimize postconstruction maintenance. Maintenance costs may sometimes be regarded as deferred construction costs.
Ecological considerations	May determine type of highway construction and possible alternatives for foundation treatment.
Foundation stability during construction	Detailed borings, laboratory tests, and design studies required.
Tolerable postconstruction total and differential settlements	Appropriate criteria not well formulated; subjective and depends on engineering and public attitudes.
Structure vs. embankment	An important decision affecting both construction and maintenance costs.
Construction time available	Some alternatives may be eliminated by need for early completion date.

and aesthetic considerations and safety and public relations aspects. Public relation considerations are especially important when constructing embankments over soft foundations because of the long time period required when foundation stabilization is being accomplished by consolidation under surcharge fills. Under these circumstances, a news release explaining that the delay in completing the roadway will minimize construction costs and maximize postconstruction behavior of the roadway seems desirable. Such public relations efforts do not appear to have been adequately exploited.

The construction of highways in areas of soft soils involves many decisions and evaluation of possible alternatives. These decisions are greatly affected by the construction time available; hence, it is particularly important that the nature of problems involved in constructing over areas of soft subsoils be recognized at the inception of planning processes.

SCOPE

This synthesis is intended to be used in conjunction with *NCHRP Synthesis 8*, "Construction of Embankments," (*1*) and *NCHRP Synthesis 2*, "Bridge Approach Design and Construction Practices" (*2*). A synthesis on "Acquisition and Utilization of Geotechnical Information" is being prepared for publication later in 1975. A primary objective of this synthesis is to describe policy and selection aspects of various alternatives for constructing highways over soft foundation soils. Detailed design procedures are beyond the scope of this synthesis, but some design details are discussed.

CHAPTER TWO

DESIGN PROCESS PHILOSOPHY

PLANNING AND PRELIMINARY DESIGN

Adequate Transportation System

Providing an adequate transportation facility at lowest overall cost involves many elements besides initial construction. Each of the following essential elements of embankment foundation design must be weighed fully in selecting a procedure for constructing a highway across soft foundation areas:

- Construction cost.
- Maintenance cost.
- Safety—Pavement smoothness; hazards caused by maintenance.
- Inconvenience cost—A tangible factor for heavily traveled roadways.
- Aesthetic aspects—Appearance of completed work relative to surroundings.

Safety considerations are especially important for heavily traveled roadways, and it may be necessary to provide more expensive initial construction in such areas than is suitable for roads carrying moderate to low traffic volumes. Inconvenience costs to the using public caused by removing a roadway or traffic lane for maintenance can be large; in some cases it can be almost impossible to close traffic lanes for maintenance purposes, even during night hours. Obviously, definitions of an adequate transportation facility must be flexible.

Planning Studies

It is essential that the earliest planning studies recognize fully the impact of constructing highways in areas of soft soils. The manner in which soft subsoil areas influence final decisions is not obvious because the effect varies greatly according to local considerations. Areas where soft foundation soils exist should be investigated in the earliest planning studies because at that time it may be possible to avoid soft foundation soil areas. Public hearings held after completion of planning studies may freeze alignment, even though subsequent studies show that alignment changes could avoid problems from soft foundation areas. However, care should be exercised during the early investigations to avoid giving the impression that one alignment is favored over another.

A conceptual flow chart designed to introduce special requirements where roadways must cross soft foundation soils is shown in Figure 1. Typical soil deposits presenting potential embankment foundation problems in the Northeastern United States are listed in Table 2, on the basis of experience in New York State.

In rural areas, early consideration of the impact of soft foundation soils on highway construction may permit relocating the alignment. In urban areas, high real estate costs and public relations aspects may preclude constructing highways except in areas of soft foundations, such as swamps, where development has not taken place. In such areas, the highway must not upset the existing ecology, and this may become a controlling factor. Alternatively, where

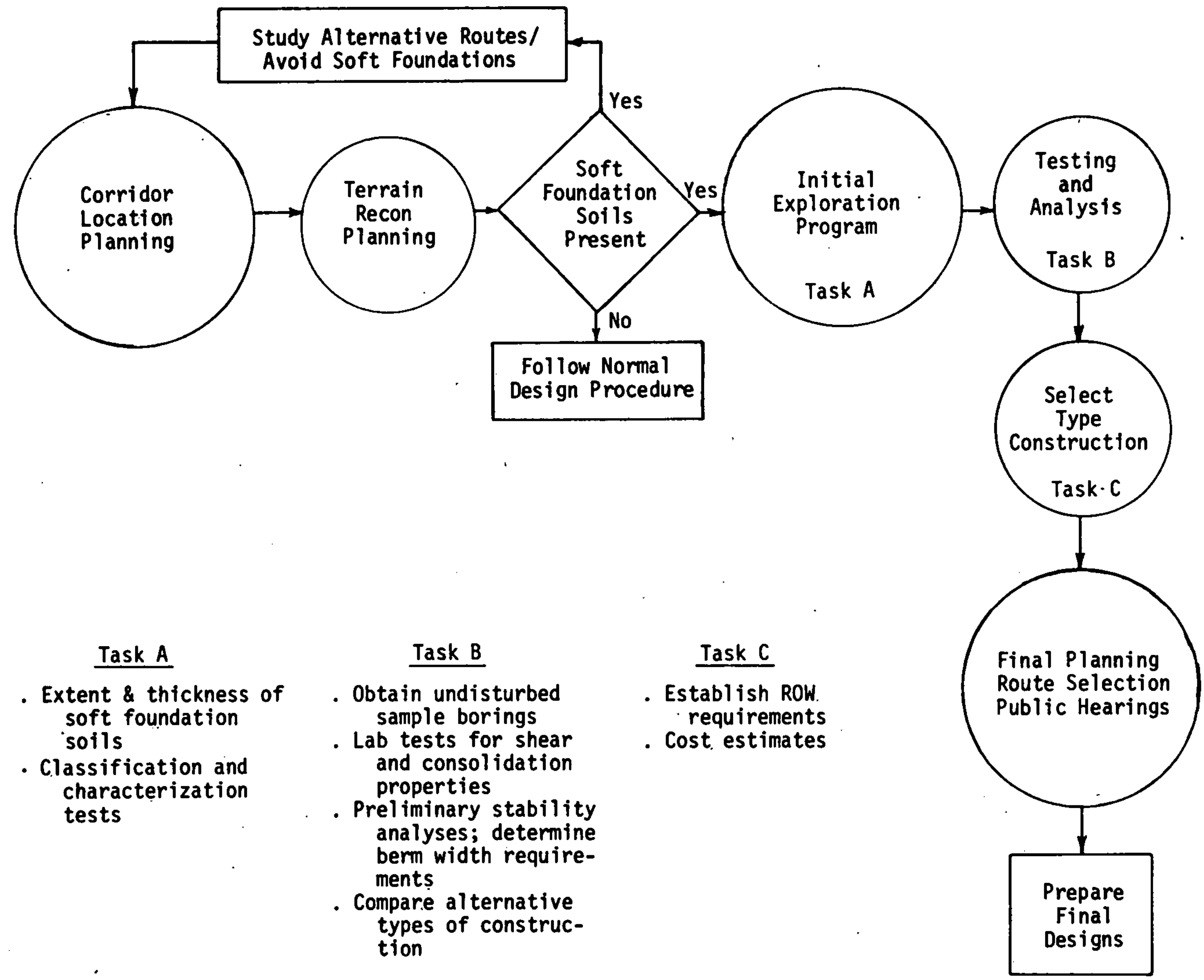


Figure 1. Flow chart—preliminary requirements for right-of-way design on soft foundations in corridor planning phase.

TABLE 2

SOIL DEPOSITS PRESENTING POTENTIAL EMBANKMENT FOUNDATION PROBLEMS, NORTHEASTERN UNITED STATES

DEPOSITIONAL UNIT	LAND FORM	SOIL TYPES	UNIFIED CLASSIFICATION
Alluvial deposits	Flood plain (first bottom)	Highly variable; natural levees to slack water deposits.	All (GW; GP are rare)
	Terrace (second bottom)	Highly variable.	All (GW; GP are rare)
Glacio-lacustrine	Delta	Typical structure of gravelly topset, sandy foreset, and fine-grained bottomset beds. Generally becomes finer with depth and distance from source.	All, depending on positions in land form
	Lake plain shore deposits	Thin veneer of sandy or silty soil over silt-clay soils.	SM; ML; ML-CL; ML-MH
	Lake plain bottom sediments	Laminated silt-clay soils with occasional fine sand laminae.	CH; CL; MH-CH; CL-CH; ML-CL
Glacio-marine	Marine plain bottom sediments	Massive silt-clay soils with laminations usually absent.	CH; MH-CH; CL-CH
Organic deposits	Swamp, bog, etc.	Plain; remains in various stages of decomposition with some mineral soil. May contain marl.	PT; OL; OH
	Tidal marsh	Highly variable but usually fine-grained. May have vegetative mat over organic silt or organic clay.	PT; OL; OH; MH; CH; MH-CH

a swamp or soft foundation area is already spoiled ecologically, the construction of an embankment may afford a means for obliterating an eyesore and for enhancing utilization of a problem area.

A major factor in constructing highways in areas of soft foundation soils is recognition of the importance of construction timing and planning so that all alternatives appropriate for a particular set of circumstances can be considered. To be more explicit, some methods for treating soft foundations require consolidation of soft subsoils. This is a time-consuming process requiring from several months to a year or two. The time required for such alternatives may not be available unless this need is recognized during the planning phase. Work on various sections of a road can often be scheduled to permit use of alternatives such as foundation consolidation for some portions. Failure to consider the time required for some foundation treatments may preclude consideration of their use during subsequent highway design, despite major cost savings.

Preliminary Design Studies

In those cases where early planning studies have shown that it is impracticable to avoid soft foundation soils, the influence of subsoil conditions should be considered early by preliminary design studies, when grade-line or alignment shifts to avoid or minimize problems can be accommodated. The thickness of soft foundation soils can often be reduced by minor changes in alignment or in grade. Although economic aspects of highway construction over soft foundations should not dominate final selection of grade-line or roadway alignment, neither should these factors be finalized without consideration of the benefits to be gained by considering the impact of soft foundations on highway construction.

Final Foundation Design

The time available for final design is becoming shorter and occasionally is only sufficient to prepare contract documents. Where this is expected, the general features of design must be determined in essentially a final manner during preliminary design, before final foundation design is initiated.

PHILOSOPHY OF DESIGN

Special Studies Required

Design concepts and attitudes for constructing highways over areas of soft foundation soils depend heavily on the experiences of individual highway departments and of consultants available to them. Best results are achieved where a separate study is made of alternative construction types before final design of a highway is commenced. Adequate lead time should be provided in the planning and design time schedules to plan and conduct soil engineering activities, including field exploration, laboratory testing, and design studies. This may be critical where foundation problems are of major importance. Construction of highways over soft foundation areas involves greatly increased construction costs. Also, substantial costs are incurred for additional subsoil investigation and testing and for adequate study and evaluation of possible alternatives.

Soft foundation areas vary greatly, and many alternative designs and variations must be prepared to accommodate differences in subsoil properties. Selection of the most suitable alternative generally involves an effort greater than normally inherent in designing for average subsoil conditions. When the highway design is to be made by consulting engineering firms, these additional evaluation studies should be provided and paid for separately to assure that appropriate alternatives are investigated. The evaluation of various alternatives requires specialized foundation engineering knowledge.

Elevated Structure or Embankment?

The nature of decisions involved in highway construction over soft foundations involves many questions, some of which are listed in Table 3. The first and most major decision is the choice between an elevated structure and embankment construction, with or without foundation treatment. For some highways, this question involves a choice between methods having cost differentials which may be several million dollars per mile (see Fig. 2).*

In areas where soft foundation soils have been troublesome, the question of using an elevated structure or an embankment is an important one, especially so in urban areas and for heavily traveled roads. Where soft foundations are thick, weak, and highly compressible, this decision involves, for some engineers, the feasibility of constructing an embankment without excessive postconstruction settlements. This question (see Table 3) is particularly troublesome where designers have not had satisfactory ex-

* Structure costs including foundations generally range from about $25 to $40 per sq ft of traffic lane but vary widely depending on local soil conditions, geographical area, and other local conditions.

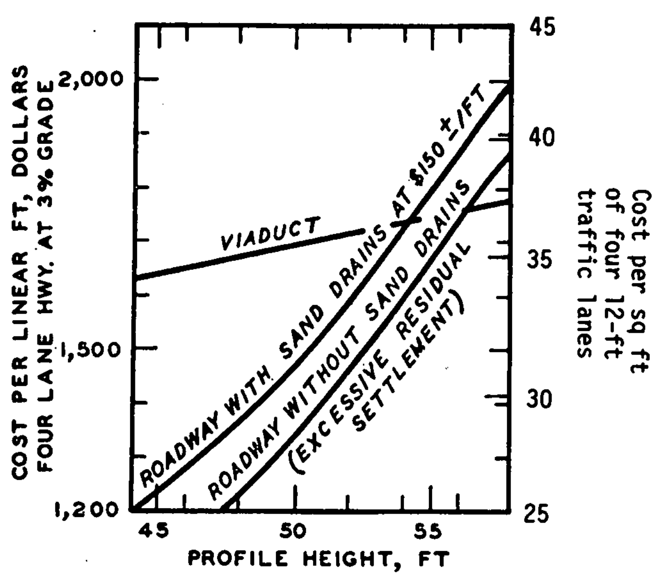


Figure 2. Cost of structure versus earth fill for highway construction (after Landau (3)).

TABLE 3

QUESTIONS INVOLVED IN HIGHWAY CONSTRUCTION OVER SOFT FOUNDATIONS

QUESTION	REMARKS
Elevated structure or embankment?	Can an embankment provide a satisfactory riding surface? Can added cost of elevated structure be justified? Construction time required may be a factor.
Can, or should, postconstruction embankment settlements be accepted?	Will settlements be uniform or irregular? Should design remove all primary settlements and reduce secondary compression settlements? How much time is available for construction?

periences with embankment construction techniques they have used and where they have not attempted state-of-the-art designs. Under these circumstances the evaluation of experiences reported by others is difficult, especially because of differences on details among specialists.

In evaluating the merits of elevated structure versus an embankment with some type of foundation stabilization, it is satisfactory to assume that each can provide an equivalent roadway when current state-of-the-art technology is employed. Conversely, inferior design or construction can result in a rough pavement surface regardless of the method of construction employed. Designers with limited experience in constructing embankments on soft foundations often question the capability of state-of-the-art design procedures for constructing embankments over soft foundations. Although such designers would pay a premium to obtain an elevated structure, the consensus of experience is that a premium is not warranted. This does not mean that an elevated structure in certain areas is not economically attractive or desirable because of timing, high grade line, or other factors, but that alternatives should be evaluated on their merits without one method of construction being favored by an inherent cost premium regardless of results of comparative evaluations. Highway departments in New York, California, Delaware, New Hampshire, Maine, Illinois and others, have considerable experience with embankments and structures in soft foundation areas and generally have valuable unpublished information available.

Foundation Stabilization For Embankments

Even where designers consider an embankment to be a practicable means for constructing a highway, major questions still remain (see Table 3) regarding postconstruction settlements that can or should be tolerated. Some alternatives provide for minimal construction costs at the expense of postconstruction maintenance. Alternatively, designs can be prepared to minimize or, for practical purposes, avoid postconstruction maintenance because of soft foundations. A basic decision must be made as to which approach should be used for particular local conditions. The answer depends heavily on the acceptance by designers of the feasibility of designing and constructing embankments that will settle but not be subjected to excessive irregular settlements.

The attitude of a particular highway agency toward postconstruction settlements influences greatly the design criteria and the method of construction selected. Some agencies consider that construction of an embankment over soft foundations should not result in postconstruction maintenance more severe than in normal soil areas. This is possible but involves added construction costs. The position of these agencies is that design for anything less merely shifts construction costs to a maintenance category and subjects the using public to inconvenience costs and unnecessary safety hazards.

Alternatively, other highway agencies have the opinion that postconstruction settlements are not detrimental provided they are uniform, and they are willing to accept a certain risk. In these agencies the basic philosophy is that exceedingly detailed borings, testing, and analyses are warranted and feasible to achieve minimum construction cost with reasonable postconstruction maintenance and risk. This line of reasoning requires a willingness to spend a considerable added amount for investigation, testing, and design and a commitment to the concept that, if carried out, the results will be satisfactory. This approach is feasible for some experienced highway agencies having trained staffs but is not practicable everywhere.

Settlements Considered Tolerable

Postconstruction settlements during the economic life of a roadway of as much as 1 to 2 ft (0.3 to 0.6 m) are generally considered tolerable provided they (a) are reasonably uniform, (b) do not occur adjacent to a pile-supported structure, and (c) occur slowly over a long period of time. If the last condition occurs, any detrimental settlement can be corrected when the pavement is resurfaced, which is often done at intervals of 10 to 15 years.

An additional requirement, previously discussed, is that sufficient investigations be made to assure the designer that sharp differential settlements will not occur. Where a high fill crosses a valley, maximum settlement generally occurs near the center of the crossing. A vertical curve with the low point in the area of maximum settlement is often desirable for this condition.

Settlements of 1 to 2 ft (0.3 to 0.6 m) are considered tolerable even where rigid pavements are used, although in many areas flexible pavements are specified. Rigid pavements have undergone 1 to 2 ft of uniform settlement without distress or objectionable riding roughness. Where some doubt exists about the uniformity of postconstruction settlements, flexible pavement is usually selected. This is also done in some states when predicted settlements exceed six in. (150 mm).

CHAPTER THREE

FOUNDATION TREATMENT METHODS

DESCRIPTION

The various methods (*4, 5*) for treating soft foundation soil areas consist basically of (a) removal of soft foundation soils and replacement by suitable fill, (b) stabilization of soft foundation materials by consolidation, and (c) pile-supported roadways. These methods and variations of each are listed in Table 4. All have been used in the United States except for the Swedish method of supporting fill on piles driven into suitable bearing material.

The choice between the various methods of constructing over soft foundation soils can be extremely large, amounting to several million dollars per mile as illustrated, for example, in Figure 2 comparing elevated structure versus earth fill, with and without vertical sand drains. Comparable cost differentials apply for other methods. Where extremely high fills are required, an elevated structure is generally economical; but, as shown in Figure 2, this is not the case for most highway construction. It is evident that where soft foundation areas extend for long lengths, which may be miles or several tens of miles in some areas, the decision as to an appropriate construction procedure becomes a major factor worthy of detailed comparative cost and design evaluations. Field test sections are often desirable to establish the behavior of alternatives to elevated structures, and for other reasons also. All the variations of

TABLE 4

FOUNDATION TREATMENT ALTERNATIVES

METHOD	VARIATIONS OF METHOD
Removal of soft foundation soils and replacement by suitable fill	Complete excavation of soft material and replacement by suitable fill.
	Partial excavation (the upper part) of soft material and replacement by suitable fill. No treatment of soft material not removed.
	Displacement of soft material by embankment weight, assisted by controlled excavation.
	Displacement of soft material by blasting, augmented by controlled placement of replacement and embankment fill.
Stabilization of soft foundation materials by consolidation	Consolidation by surcharge fill only.
	Consolidation by surcharge fill combined with vertical sand drains to accelerate consolidation.
	Consolidation by surcharge fill combined with pressure relief wells or vertical sand drains along toe of fill. Mainly applicable in stratified soft materials and where pervious soils underlie soft materials.
Pile-supported roadway	Elevated structure supported by piles driven into suitable bearing stratum.
	Swedish method of supporting fill on piles driven into suitable bearing material. Piles have individual pile caps covering only a portion of base area of fill.
Reduced stress method	Lightweight fill (expanded shale, etc.; see Table 9).
Consolidation with paving delayed	Before paving, permit consolidation to occur under normal embankment loading without surcharge; accept postconstruction settlements.

the basic methods listed in Table 4 can be considered applicable, but not necessarily economical, for virtually any thickness of soft foundation soils.

The detailed design of methods for treating soft foundation soil areas is beyond the scope of this report. Selected representative references discussing the various design techniques are listed in Appendix A. Also, it is beyond the scope of this report to describe in detail results of using the various treatments. Typical references that describe case histories are listed in Appendix B.

REMOVAL AND REPLACEMENT METHODS

Complete Removal

The complete removal of soft foundation soils and replacement by suitable sand, sand and gravel, or blasted rock fill constitutes a positive construction procedure. Factors involved in using this method are listed in Table 5. This type of construction has been used for highways, dams built partially under water, and for creating land suitable for industrial construction purposes. This method has been used at a number of places where the maximum required dredging depth exceeded 100 ft (30 m) and has been used in water depths as great as 217 ft (66 m). Hence, consideration of the method for highway construction can be based largely on its cost relative to other alternatives. Shallow excavation can be made in the dry, especially in fibrous organic materials, but this causes slope stability and dewatering problems; excavation in the wet is economical and practicable. Where underwater excavation is used, the water level in the excavated area should be maintained at its normal elevation.

The excavation of soft foundation soils and replacement by suitable fill materials is often considered to be a relatively simple operation. Practically, however, this is not the case and stringent inspection and control must be provided to assure satisfactory and economical results, especially when all work is submerged. Unless careful inspection is exercised, soft materials may not be removed or, alternatively, may be removed to excessive depths, increasing both excavation and backfill costs. The process of excavating soft soils underwater almost invariably, and regardless of the method of excavation, results in quantities of soft materials going into suspension and settling out along the bottom. Unexcavated soft material or accumulations of soft material ahead of the advancing fill may become entrapped by the fill. This can be detected and prevented by adequate inspection control and testing (*6*) (Table 6). Entrapped pockets of soft material can become so thick that large sections of fill must be excavated and the bottom thoroughly cleaned; alternatively, the entrapped materials can be stabilized by consolidation through use of a temporary surcharge fill with or without vertical sand drains. On rare occasions sand drains are installed in entrapped materials to accelerate consolidation.

It is not generally possible to excavate underwater in one continuous cut to final grade. Almost invariably it is essential to make several passes and to do cleanup excavation as fill is placed. Details involved are discussed by Johnson et al. (*6*). A small hydraulic dredge (see Fig. 3) is frequently used to remove fines that result from placement of the fill or that accumulate from the dredging process. A small dredge frees the main excavating equipment for removing the bulk of material to be excavated.

The excavation of soft foundation materials (see Fig. 4)

TABLE 5

EXCAVATION OF SOFT FOUNDATION SOILS

FACTOR	REMARKS
Excavation methods	Dragline or clamshell. Hydraulic suction dredging. Dipper dredge.
Disposal of excavated materials	A major consideration: Availability of disposal areas. Cost of disposal may control feasibility. Permits required time consuming.
Ecological environmental considerations	Ecological considerations must be fully evaluated during preliminary design. Disposal of excavated materials may affect disposal area adversely or beneficially. Aesthetic enhancement and other benefits of controlled disposal operations may be significant; investigate fully in preliminary design.

TABLE 6

CONSTRUCTION INSPECTION AND CONTROL PROCEDURES

METHOD	CHARACTERISTICS
Probings, sampling and borings	Probings Grab sampling Clamshell Other Exploration and undisturbed borings Single-entry sampling Bottom samples Borings with casing (reentry sampling) Wire-line sampling through casing
In situ testing	Vane shear Penetration tests Cone Split spoon Borehole shear tests Plate bearing tests Geophysical borehole logging methods (resistivity, density, etc.) Nuclear density meters
Laboratory testing	Classification Compaction Permeability Strength Consolidation
Instrumentation	Piezometers Settlement plates (surface and at various depths) Slope indicators

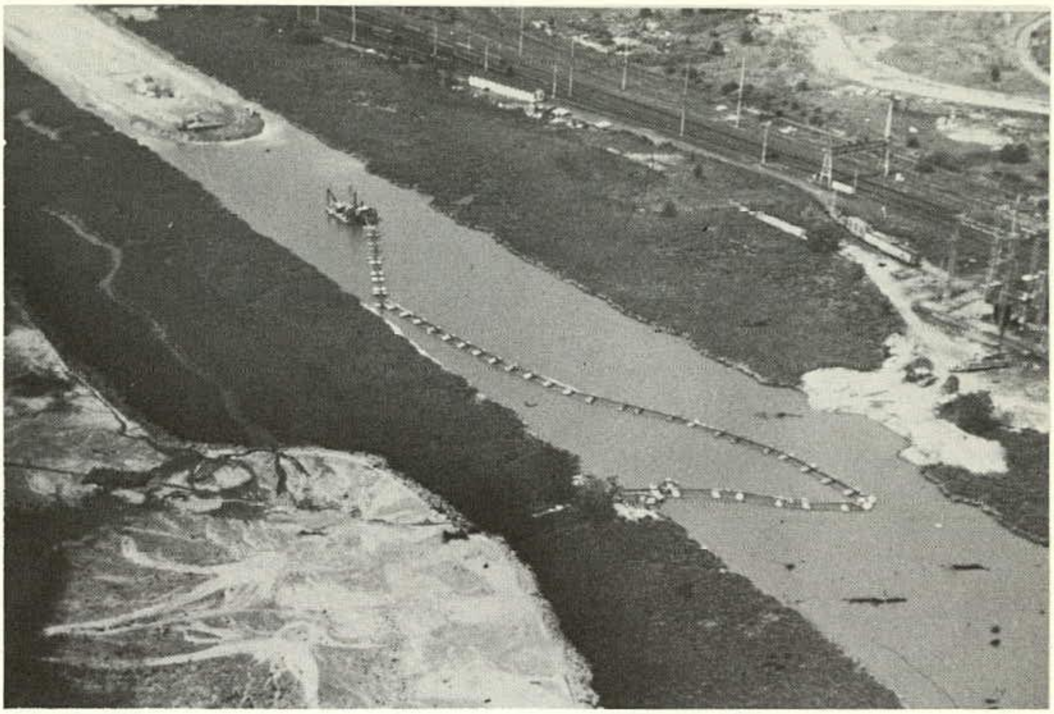


Figure 3. Small hydraulic dredge removing fines from fill placement.

must, as a minimum, remove soft materials, the consolidation of which could affect the pavement or shoulders of the roadway. In addition, the extent of removal of soft materials depends on their thickness and requires stability analyses, but some engineers contend lesser width of excavation than indicated by stability analyses is adequate (*4*).

Clean sand or sand and gravel with less than 8 to 12 percent finer than a No. 200 sieve is well suited for underwater placement, since these materials are not sensitive to placement water content. Materials containing more fines can be upgraded, as described by Sinacori et al. (*5*).

Partial Excavation

In some locations the upper portions of soft materials have been excavated and replaced by suitable fill, with no treatment of remaining soft materials. Where this has been done, the upper material has generally been of a fibrous organic nature capable of causing large settlements. The unexcavated soft material often causes significant nonuniform postconstruction settlements, and this alternative does not appear desirable for high-quality roads except in those cases where considerable attention is devoted to determining the uniformity of postconstruction settlements. This alternative thus appears generally undesirable but may have application under particular conditions.

In addition to settlement problems discussed previously, this method frequently involves stability problems. Unexcavated soft materials may be too weak to support the embankment without berms. Furthermore, the excavation process may leave accumulations of soft suspended material on the bottom and may disturb the underlying soft soil. Embankment stability analyses with failure surfaces extending to the unexcavated soft material should be performed for the end-of-construction condition.

Underwater Fill Placement

A variety of methods may be used for placing underwater fill, as listed in Table 7. Construction inspection and control procedures suitable for excavation and fill placement are listed in Table 6. Effective construction control for dredging and fill placement has an identifiable economic value because it affects directly the amount of material excavated and hence the volume of backfill that must be placed. Differences in quality of control as related to the volume of required excavation, and hence to fill, are listed in Table 8 for highway construction (*6*). The quality of construction control provided affects the cost of the work to a degree far greater than differences in cost of the various degrees of inspection. In addition, poor construction control may result in a rough-riding pavement because of postconstruction settlements from consolidation of soft materials that would have been avoided by better construction supervision.

Displacement of Soft Subsoils by Weight of Embankment

As an alternative to excavation, displacement of soft materials by deliberately overstressing them by the weight of embankment combined with a temporary surcharge, as illustrated in Figures 5 and 6, is sometimes employed. If this is done, upheaved marsh material that accumulates at

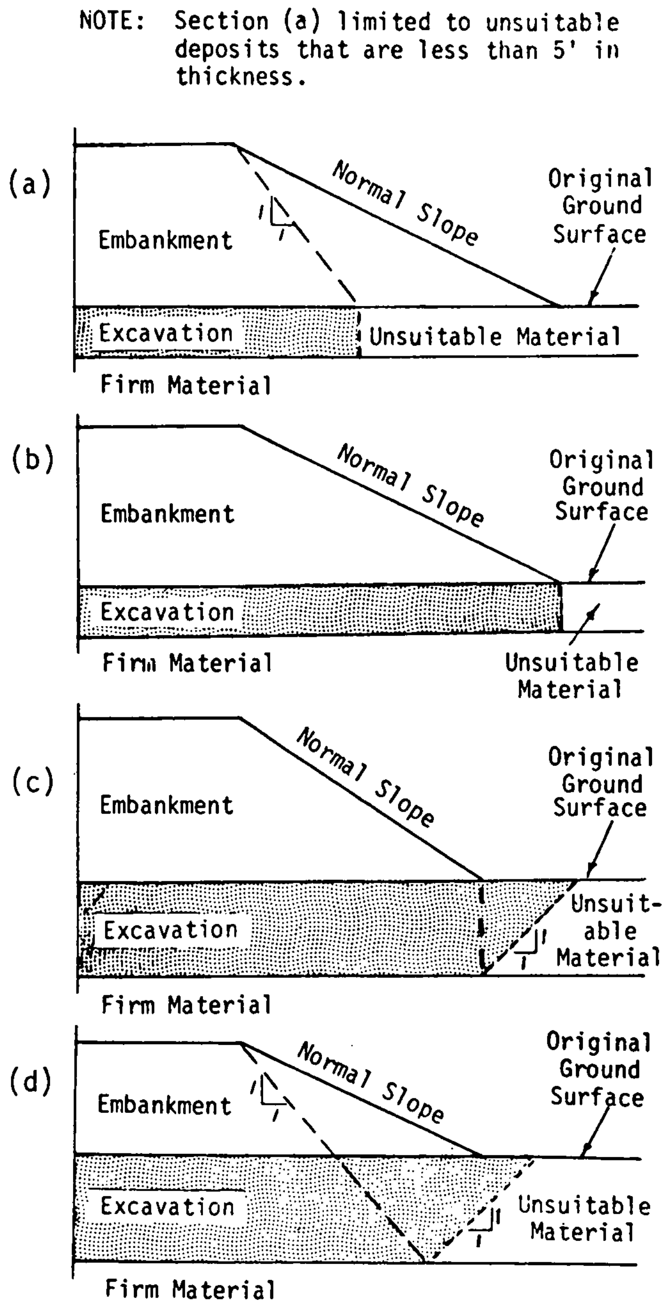


Figure 4. Examples of excavation of unsuitable material.

the leading edge of the fill should be removed to avoid entrapping pockets of displaced soft soil within the embankment.

The displacement of soft subsoils by the weight of the embankment may result in the intrusion of fill into the area outside the limits of the roadway, thus adding to the cost of the work. In addition, in some cases excellent removal of the soft soil may be achieved, but elsewhere pockets of soft soil may remain, resulting in differential settlements.

An argument against use of the displacement procedure is that the cost of fill lying beyond the limits of the embankment section may be so large as to make this method cost more than alternatives that are more positive in their action and do not incur the possibility of excessive postconstruction differential settlements. An opposite view is taken by Moore (*7*) in New York, who maintains that ". . . if the mudwave and possible surface organic mat is removed from in front of the fill for a distance of 50 ft (15 m) then all displacements will go in this direction and there will be very little sideways displacement. A good rule is to excavate all mudwave appearing above the water surface. We have had several projects with displacements for 30 to 50 ft (9 to 15 m) in depth and have not found any sideways displacement when the mudwave is properly controlled."

California has had two mud displacement projects. The first (*8*) was experimental and was considered to have developed construction procedures for obtaining essentially complete mud displacement.

The mud displacement method should be designed just like any other alternative. Its success may depend on the sensitivity of the soft soils to remolding. Selection of this method should follow evaluation of other alternatives and should consider inspection control available and consequences of delays and of postconstruction settlements. It seems best suited for roads with low traffic densities.

Displacement of Soft Materials by Blasting

The displacement of soft materials by blasting has been attempted on numerous occasions. Its use is augmented by controlled placement of foundation and embankment fill. The blasting technique requires expert and constant field supervision to assure that variations in blasting procedures are made as conditions warrant. Unless this is done, soft material may not be removed properly. This method is considered to be sufficiently sensitive and difficult to use so that it should not normally be considered as an appropriate alternative. Blasting procedures are discussed extensively by Casagrande (*9*).

FOUNDATION STABILIZATION BY CONSOLIDATION

Consolidation Concepts

The basic concept of stabilizing soft foundation soils by consolidation (*10*) involves the empirical observation that loading soils causes water to be squeezed from them until the water content and the volume of the soil are in equilibrium under the loading stresses imposed. The reduction in water content is accompanied by a gain in shear strength. These processes occur even where soils are located below the groundwater level. The larger the final stresses caused by the embankment, the more volume of water that must be squeezed from the voids, and hence the greater the reduction in volume that occurs. By preloading soft foundation soils, the required reduction in volume that occurs under final loading conditions can be achieved before the roadway is paved and hence postconstruction settlements are reduced. The squeezing out of water from the voids and the accompanying reduction in volume is termed primary consolidation and is reasonably well described both as regards magnitude and time rate of settlement by the familiar Terzaghi theory of consolidation and subsequent

TABLE 7

UNDERWATER FILL PLACEMENT METHODS

METHOD	CHARACTERISTICS
Bottom-dump scows	Fill assumes flat slopes unless retained. Limited to minimum depths of about 15 ft because of scow and tug drafts. Rapid; quick discharge entraps air and minimizes segregation.
Deck scows	Usable in shallow water. Unloading is slow, by dozer, clamshell, or hydraulic jets. Steep side slopes of fill can be achieved.
Hydraulic	Coarse materials drop out first; may cause shear failures in soft foundations. Fines may collect in low areas and have to be removed. Inspection of material being placed may be difficult.
Dumping at land edge of fill and pushing material into water by bulldozer.	Fines in material placed below water tend to advance and accumulate in front of advancing fill. Work arrangement should result in central portion being in advance of side portions to displace sideways any soft bottom materials. In shallow water, bulldozer blade can shove materials downward to assist displacement of soft materials that accumulate at toe of fill. (Not suitable for displacing unexcavated soft materials).

advancements. Highly organic soils may have large but rapid primary consolidation settlements; secondary compression settlements are large and should be evaluated in design.

Secondary Compression Settlements

Primary consolidation settlements vary from a few inches in moderately soft soils with low embankment heights to as much as 10 or 15 ft (3.0 or 4.6 m) or even more where compressible soils are thick, have high water contents, and embankment loadings are high. Such settlements comprise the major portion of the soil volume reduction that occurs under the weight of embankment fill. There is an additional secondary compression settlement, however, that occurs essentially as a plastic readjustment of soil grains. The magnitude of such settlements depends mainly on the natural water content of the soil; because this reflects soil type, it depends also on whether the soils are lean clays, highly plastic clays, or contain much organic material. The coefficient of secondary compression, C_α, (*10*) measures the amount of secondary compression that occurs for various soil types. The value of C_α, plotted in Figure 7, is high for organic soils and is reduced by disturbance or remolding, as shown.

Because primary consolidation settlements are large, foundation stabilization is often, but not always, designed to eliminate all primary consolidation settlements before roadways are paved. Secondary compression settlements are small and states do not generally design to decrease postconstruction settlements from this cause except in highly organic soils, in which they are large. Nevertheless, a number of important highways having soft foundation soils have been designed to reduce postconstruction secondary compression settlements to insignificant amounts (*10*).

TABLE 8

EFFECT OF CONSTRUCTION CONTROL ON DREDGING OF UNSUITABLE MATERIALS

QUALITY OF CONTROL	EXCESS EXCAVATION VOLUME [a] (%)
Excellent (probably best available)	+5 to +8
Good to better than average	+16
Fair to poor	+25 to +30

[a] Excess of actual excavation to estimated minimum excavation.

The practicality of reducing postconstruction secondary compression settlements by an increased thickness of preloading fill has been demonstrated by both laboratory and field observations, as shown in Figures 8 and 9. Theories for secondary compression settlements are complex and the mechanism involved is imperfectly understood and still being studied. Nevertheless, simplified design procedures (*10*) to reduce secondary compression settlements to desired values are adequate for practical purposes, even where soils are highly organic.

The magnitude of secondary compression settlements for soils having water contents less than about 100 percent is adequately described by results from laboratory tests. With increasing water contents, secondary compression settlements may be somewhat larger than computed values. When initial water contents become as large as, say, 400 percent, secondary compression settlements may exceed predicted values, possibly by 25 percent, but this introduces no major difficulty in practical designs. Designs to

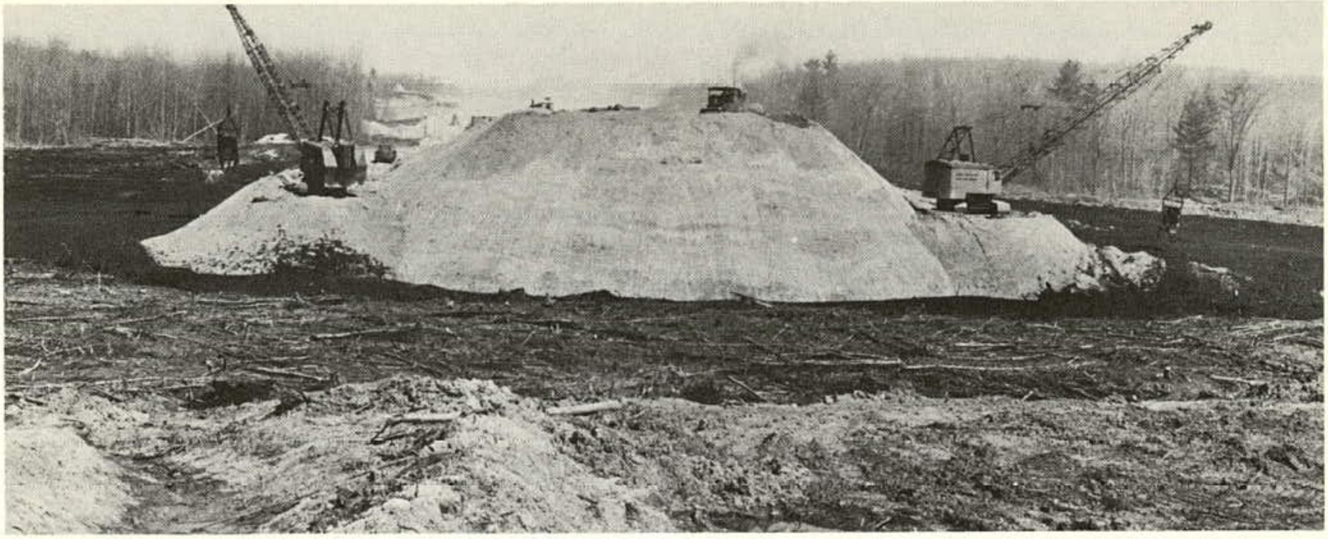


Figure 5. Marsh displacement (45 ft deep) and embankment construction to surcharge grade (Michigan).

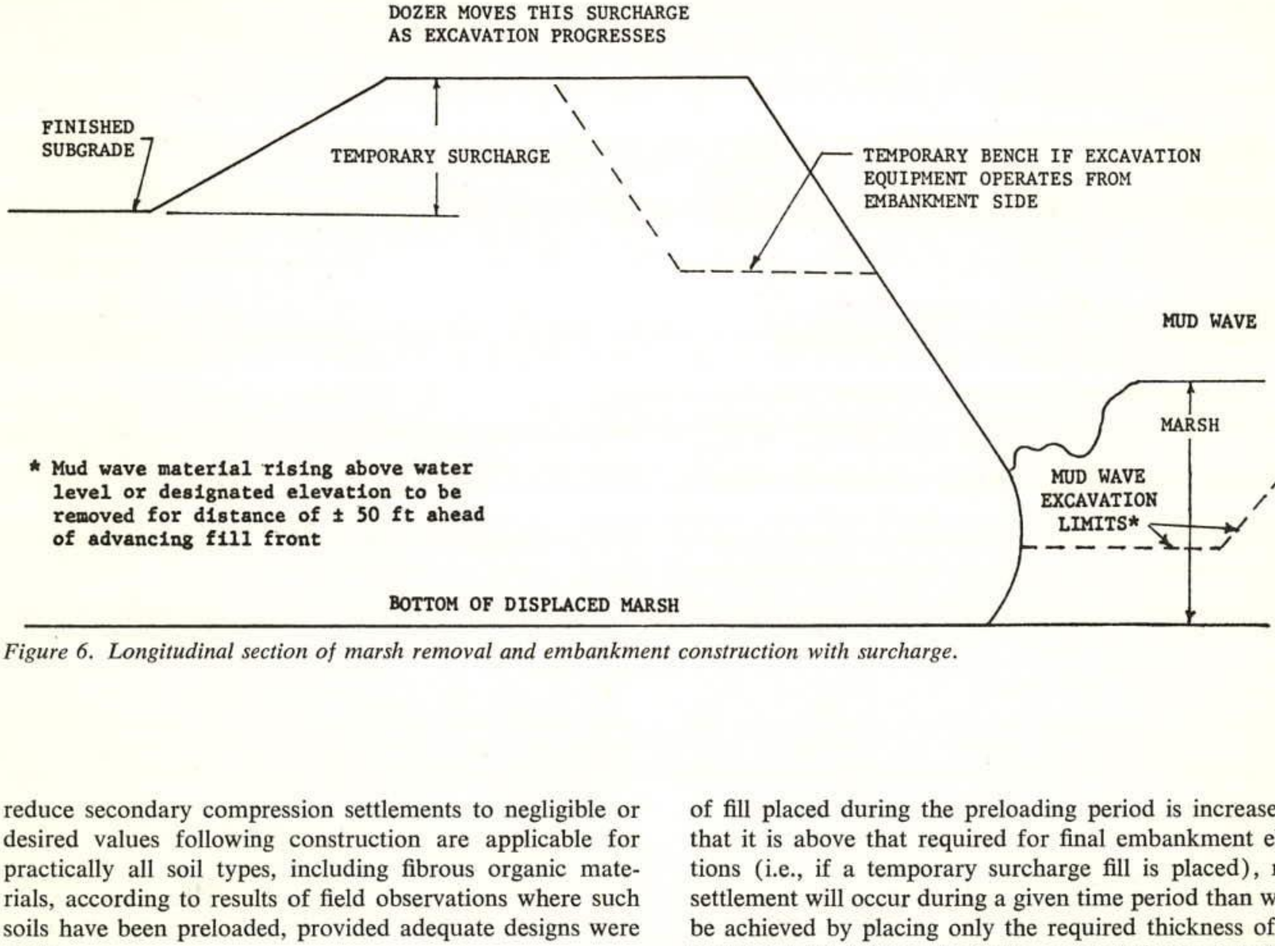
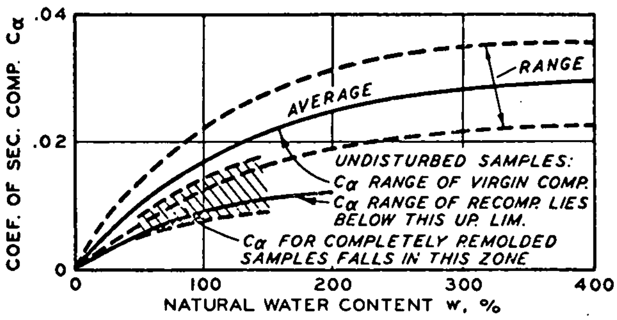


Figure 6. Longitudinal section of marsh removal and embankment construction with surcharge.

reduce secondary compression settlements to negligible or desired values following construction are applicable for practically all soil types, including fibrous organic materials, according to results of field observations where such soils have been preloaded, provided adequate designs were made.

Preloading Surcharge Fills

If the embankment is placed long before roadways are paved (i.e., if soft foundation soils are preloaded), postconstruction settlements are reduced. Also, if the elevation of fill placed during the preloading period is increased so that it is above that required for final embankment elevations (i.e., if a temporary surcharge fill is placed), more settlement will occur during a given time period than would be achieved by placing only the required thickness of embankment fill. This is the basic concept of using surcharge loading fills, as indicated in Figure 10. Although this figure illustrates only the use of a surcharge load to obtain the ultimate primary consolidation during the surcharge loading period, the same concepts (*10*) are applicable to reduce postconstruction secondary compression settlements to predetermined values.



a. Cα VS w

Figure 7. Consolidation characteristics of fine-grained soils (Navy Design Manual DM-7).

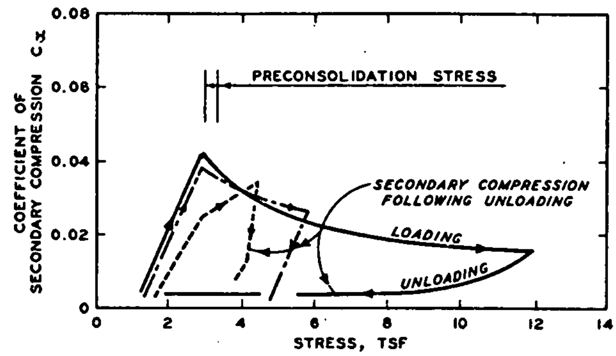


Figure 8. Secondary compression—variation in C_α during loading and unloading.

Preloading and Vertical Sand Drains

The amount of settlement that can be achieved during any given surcharge loading period is increased by increasing the thickness of surcharge load. This benefit is partially offset by the increased cost of handling and placing the fill and subsequently removing the unneeded portion and by berms that may be required because the danger of foundation instability is increased when a higher surcharge is used. This is especially true when the thickness of soft foundation soils is large and consolidation occurs slowly. Although the many combinations of soft soil thickness and type make generalizations almost meaningless, thicknesses of soft foundation soils of 10 to possibly 15 ft, and sometimes more, can often be stabilized by consolidation under surcharge fills only. For thick deposits of soft soils, it is often economically advantageous to install vertical sand drains (*11*) in the soft foundation soil (see Figs. 11 and 12). The vertical sand drains, which are often 10 to 16 in. (250 to 410 mm) in diameter, are installed at spacings of 6 to 15 ft (1.8 to 4.6 m) and sometimes more. As illustrated in Figures 11 and 12, vertical sand drains decrease the length of drainage path for water that is squeezed from the voids of the soil. Because the rate of consolidation is roughly inversely proportional to the square of the length of drainage path, the benefits of reducing the flow distance are to reduce (a) the thickness of surcharge fill, (b) the required time of surcharge loading, and (c) the size of berms, if required. These benefits are offset by the cost of the drains, which generally range from \$1 to \$2 per linear foot (\$3.30 to \$6.60 per meter or somewhat more). In addition, a sand drainage blanket on the surface of the ground is required to conduct water squeezed into the drains to beyond the perimeter of the loaded area, as illustrated in Figure 11. Furthermore, collector drains may also be required beneath wide fills. This further increases the cost. The cost of the sand blanket is sometimes reduced by substituting sand-filled trenches (with or without collector pipes) over the lines of sand drains. Drainage blankets sometimes consist of shell or crushed gravel.

Technical discussion and controversy about the effects of drain installation methods have caused some engineers to question the reliability of consolidation concepts. This is unfortunate because it is possible to design an installation of drains with surcharge fill that will provide satisfactory postconstruction performance for any type of drain installation procedure, but the displacement installation method is not recommended in sensitive soils. Equally important, the availability of various types of installation techniques and types of vertical drains permits the designer to select a procedure or drain type in which he has confidence.

Vertical sand or other drains generally serve no purpose in fibrous organic materials because of their high perme-

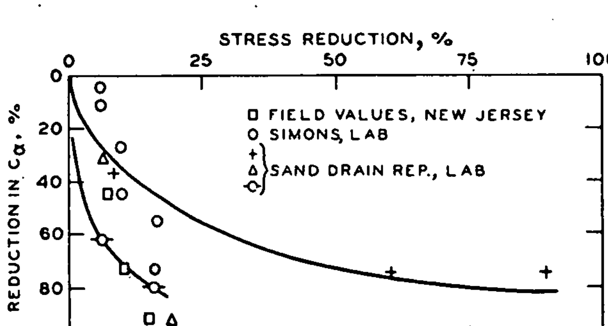


Figure 9. Secondary compression—reduction in C_α versus reduction in stress.

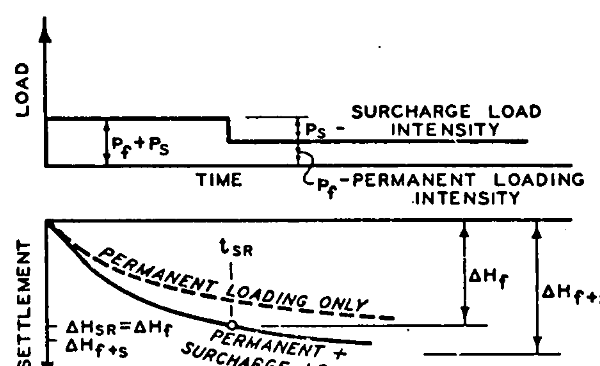


Figure 10. Preloading design—compensation for primary settlement by temporary surcharge fill.

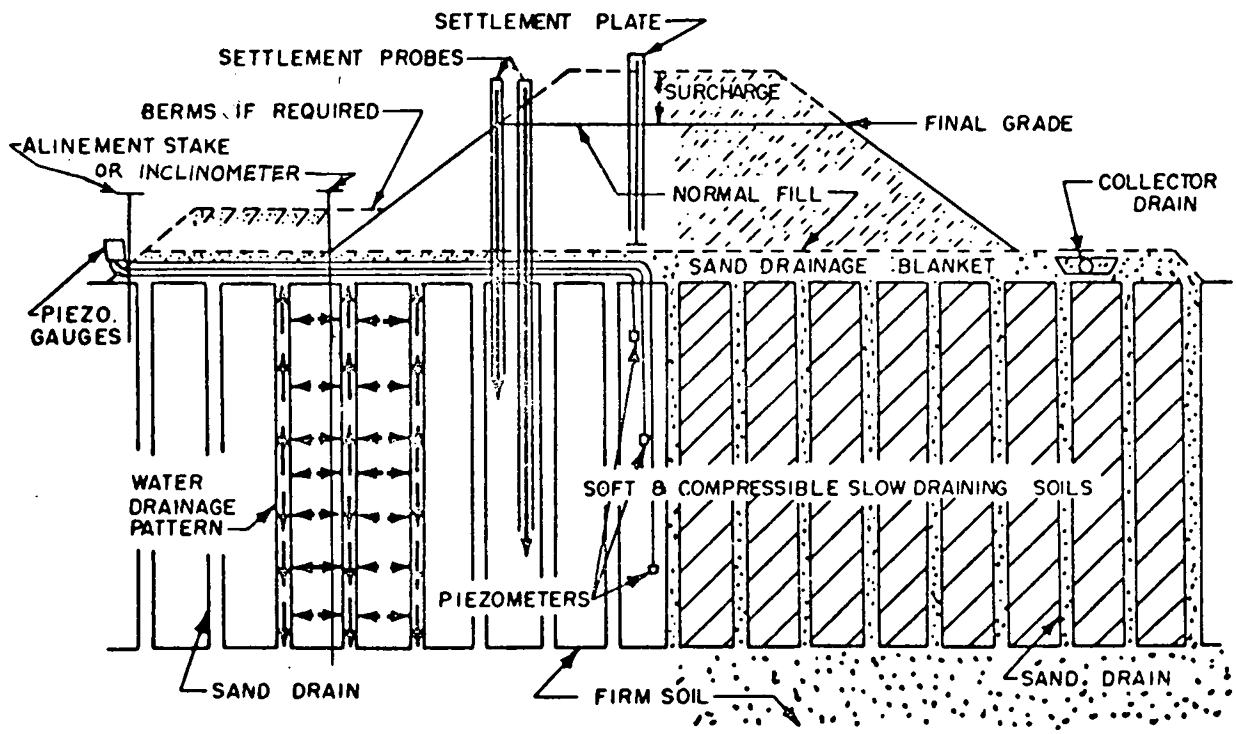


Figure 11. Design information for sand drain installation.

ability. Also, vertical drains are not useful for, nor intended to, reduce secondary compression settlements. Fibrous organic materials are frequently underlain by soft soils into which drains are sometimes beneficially installed. A variable (closer) spacing of drains is used near bridge abutments (e.g., in New York and California), where settlement requirements are severe. Vertical drains are especially beneficial in stratified soils because the drains permit pervious layers to function as horizontal drains. Nondisplacement types of drains are often used in stratified materials.

Preloading and Pressure Relief Wells

Some soft foundations are strongly stratified and have continuous silt and sand layers capable of serving as drainage layers, thereby accelerating consolidation under the surcharge fill. This effect can obviate the need for vertical sand drains. Where the base width of an embankment is large, the volume of water squeezed from the soft soil into these horizontal drainage layers must flow laterally a long distance. This can result in large head losses and high pore-water pressures in intermediate drainage layers, so they become only partially efficient. This effect has been observed even in highly stratified materials; i.e. in varved soils, where pore-water pressures beneath the central portion of a wide embankment may virtually be the same as though intermediate drainage layers were not present.

Placement of embankment fill can increase pore-water pressures in intermediate drainage layers so much that instability either at the toe of the embankment or beyond may result, as indicated in Figure 13. Where this occurs, vertical sand drains, or even wellpoints with surrounding filters, flowing freely at the surface can be installed in the vicinity of the toe of the embankment fill. This decreases the pore-water pressure in the intermediate drainage layers, causing them to be effective. In some cases more than a single line of drains at the toe of the embankment is required. This can be determined by appropriate analysis.

A similar situation exists beneath wide fills where soft foundation soils are underlain by sands. In this event also, the pore-water pressure in the sand can become high unless relieved by sand drains or small pressure relief wells installed into the underlying sand stratum. The influence of width of embankment relative to the thickness of compressible soil is illustrated in Figure 14.

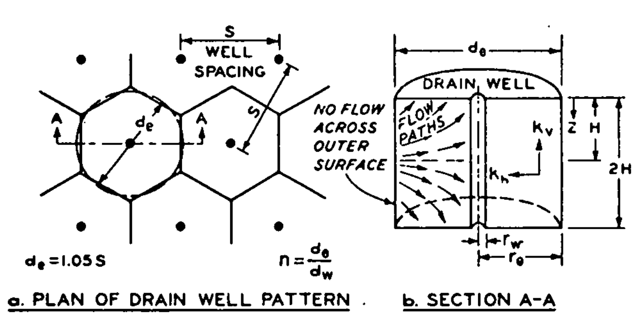


Figure 12. Flow to vertical sand drains.

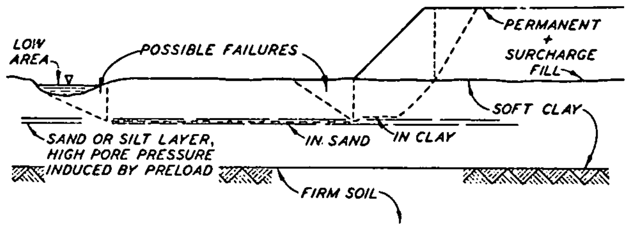


Figure 13. Effect of preload-induced pore-water pressure on stability.

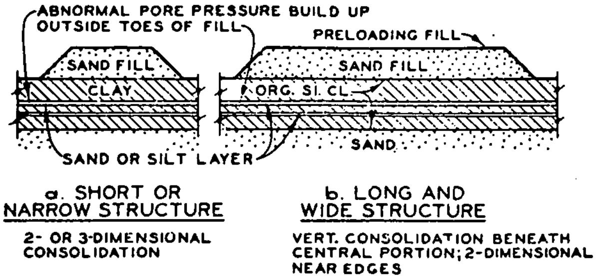


Figure 14. Influence of structure size relative to thickness of compressible soil.

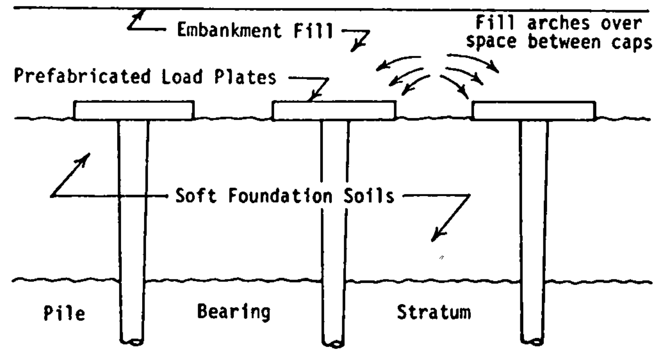


Figure 15. Pile-supported embankment.

PILE-SUPPORTED ROADWAYS

Conventional Elevated Structures

Conventional trestle or bridge construction is sometimes used in traversing areas of soft foundation soils, particularly where soft soils are extremely thick and slow-draining so that settlements are large and occur slowly. Precasting is, of course, common in such work. The use of a conventional type of elevated structure is advantageous in that the design is greatly simplified, as compared to embankment construction requiring foundation treatment. A few typical sections often suffice for the design of an elevated structure, whereas an embankment on soft soil must be designed for a relatively large number of different subsoil conditions to accommodate variations in thicknesses of soft soils and their properties together with varying embankment heights.

An elevated structure may involve low postconstruction maintenance costs. However, such costs depend heavily on the exposure of the structure and on numerous local factors and can also be excessive.

Swedish Method of Pile-Supported Embankments

A novel type of construction (*12, 13, 14*) employs a large number of individual piles, each having a pile cap above which embankment fill is placed. The fill arches between individual pile caps so that piles carry the embankment and superposed roadway and traffic (see Fig. 15). This technique avoids problems from loading soft foundation soils.

The piles are normally timber piles (up to 1,000,000 m—3,000,000 ft—are used each year in Sweden). The pile caps generally cover from about 30 to 50 percent of the base area of the embankment. The lower figure corresponds to reasonably firm subsoils, whereas a greater coverage is used in extremely soft materials. The reinforced concrete pile caps or load plates are generally precast but can be cast in place. In Sweden the pile caps are secured to the pile by a simple drift pin, but in Norway, where the method has been widely adopted, a tapered recess is cast in the pile cap to receive a tapered upper portion of the pile. Deterioration of timber piling is not considered serious because the depth to groundwater where the method is used is generally about 4.9 ft (1.5 m) or less. It is believed that capillarity in the soft clays in which the piles are driven keeps the piles wet so they do not rot.

Beneath narrow embankments and adjacent to bridges, the piles are battered to resist lateral stresses; elsewhere, vertical piling is used. When this concept is used at bridge approaches but not elsewhere beneath embankments, vertical piles installed at some distance from the abutments have relatively little penetration into firm bearing soil, so they settle. As the bridge abutment is approached, the penetration of piling into the bearing stratum increases, so the roadway settles relatively little adjacent to the bridge abutment. At the end and exterior portions of embankment fills, battered piles are normally used.

This type of construction is more expensive than preloading (with or without vertical sand drains) but less costly than an elevated structure. It has not been used in the United States but may have applicability where an elevated structure would otherwise be selected.

CHAPTER FOUR

SPECIAL CONSIDERATIONS

CONSTRUCTION ON SANITARY LANDFILLS

Roads in urban areas must frequently be located on landfills and similar areas. Construction on sanitary landfills (*15*) is possible, but the nature of design problems depends on the nature of the landfill materials. In some cases landfill areas are relatively clean and consolidate rapidly, requiring only a surcharge load applied for a reasonably short time to compact them adequately. In other instances, difficulties have been experienced with noxious fumes. In some sanitary landfill areas it has been necessary to use deodorants and to exercise special rodent control measures when the area is opened up by excavation. Leaching by water may present special problems. Low-quality materials normally considered unsuitable for providing foundation support can be used in fills, especially in berms.

Postconstruction settlements of sanitary landfills under embankments are difficult to predict and may be large. This indicates that (a) field test sections have special benefits, (b) heaviest available compactors should be used (*16, 17*), (c) preloading and stage construction should be evaluated, and (d) accepting settlements with future maintenance may not be especially attractive. Grouting may occasionally be a practicable stabilization alternative.

GROUTING

Various types of grouting techniques such as (a) cement, (b) chemical, and (c) lime injection have been considered for soft subsoil stabilization, but they are all too expensive, or ineffective, to consider for foundation stabilization beneath embankments. For further discussion, see Mitchell (*18*). Electroosmosis is a possible stabilization technique but is also too expensive.

FIELD TEST SECTIONS

Where transportation agencies have used adequately designed roadways of the various types discussed, field test sections serve principally to achieve a minimum-cost design or to permit modification of initial designs during the course of the work to reduce quantity of materials required. This is an important objective and field test sections should often be considered either before final designs are made or as the first part of an over-all project plan. It may be feasible to construct a portion of a roadway in advance of remaining sections, treating the initial portion as a test section. Field test sections employing foundation consolidation have greatly increased value if a portion of the test area is loaded to failure. This permits evaluation of stability analyses and may reduce the size of berms, or eliminate them entirely.

Where engineering departments have not had experience with a technique that would apparently result in minimum construction, maintenance, and over-all costs, they may be reluctant to use the method. They should, of course, visit or contact other states to ascertain their experience. In addition, they should consider field test sections, because they afford an excellent opportunity to determine if the most economical procedure is capable of providing satisfactory results. After experience has been achieved and confidence in the various alternatives has been established, field test sections purely to establish the feasibility of a construction technique will not, of course, be required. Even then, however, field test sections are desirable to minimize construction costs and also to serve as a training ground for field inspection personnel. The training of field construction personnel is a continuing necessity and can be accomplished effectively when field test sections are constructed. As illustrated in Table 8, the quality of field inspection achieved can be a major factor in minimizing the cost of the work.

REINFORCED EARTH CONCEPTS

Instability of soft foundations results in part from the weight of overlying embankment fill materials and in part from a spreading tendency of the fill due to internal lateral pressures that are transferred to the foundation. Horizontal timber mattresses, a form of reinforced earth concept, have been used beneath levees to eliminate or reduce transference of horizontal shear stresses from the embankment to the foundation. This reduces shear stresses in the foundation, but the foundation must, of course, have sufficient strength to overcome shearing stresses imposed by the vertical load of embankment fill.

Various techniques for reducing transference of horizontal shear stresses from the embankment to the foundation are being investigated. These include membranes along the surface of the ground and tie rods spanning across the base of the embankment between internal or external retaining walls. This construction is sufficiently flexible to accommodate differential settlements. These concepts are essentially in the research stage and do not appear ready for routine construction. An exception is, of course, the old log roads that were used in swampy areas and that constitute a form of reinforced earth construction. Reinforced earth concepts of the type developed by Videl as reported by Schlosser (*19*) also may be applicable to embankments supported on soft foundations. This aspect of reinforced earth concepts could utilize the usual horizontal straps or ties between Videl-type walls to confine the fill laterally and hence reduce transference of horizontal shear stresses to the foundation. Recent work on this aspect of reinforced earth concepts is described in References *20-23*. Membrane-encapsulated soil layers also might be used to reduce transference of horizontal shear stresses to the foundation (*24*).

CULVERTS AND BRIDGES

Culverts in embankment fills present special problems, as do bridges. If the culvert is supported on piles and the adjacent embankment settles, the culvert will tend to project through the pavement. This is a particular problem where foundation consolidation has not been achieved prior to culvert construction; i.e., where foundation consolidation is not attempted and where settlements are accepted on the premise that they will be essentially uniform in nature. For the latter condition, and especially where settlements will be substantial, it is essential that the culvert not be supported on piles.

Bridge abutment areas present special problems similar to those discussed for culverts. These problems are discussed in *NCHRP Synthesis 2* (*2*). Settlement effects on culverts can be minimized by locating the culverts near the edges of swamps, where the thickness of soft soils may be less. Culverts should be designed with a camber so that the grade line after settlement satisfies hydraulic requirements.

CHAPTER FIVE

SUBSURFACE INVESTIGATION AND TESTING

SUBSURFACE INVESTIGATION

Subsurface investigations, as regards types and details, are described in *NCHRP Synthesis 8*, "Construction of Embankments" (*1*), and in a synthesis on "Acquisition and Utilization of Geotechnical Information" to be published later in 1975. Reference should be made to these for appropriate reconnaissance and detailed subsurface investigation procedures and for laboratory testing. A geological study should routinely be made for soft foundation areas. Available air photos should always be obtained and analyzed.

The principal subsurface investigational requirements introduced by soft foundations are (a) the need for closely spaced borings, (b) the frequent use of undisturbed sample borings, and (c) the use of field vane and Dutch cone sounding tests to supplement, but not replace, undisturbed sample and exploratory borings. The spacing of borings depends on local soil conditions. Where a design is being investigated that accepts substantial postconstruction settlements of a uniform nature, closely spaced borings are necessary and these may be as close as 50 ft (15 m) on center when defining the extent of soft deposits. This close spacing may also be used for determining excavation and backfill quantities.

Preliminary Subsurface Investigations

The necessity of conducting public hearings that frequently become binding makes it essential to obtain detailed subsurface information as part of preliminary soils investigations. Consequently, undisturbed sample borings are now frequently made during the preliminary soils investigation and even during the planning phase prior to public hearings.

Undisturbed soil samples in soft foundation areas are generally obtained using drilling mud and fixed-piston samplers. Samples 3 in. (75 mm) in diameter are commonly obtained.

Importance of Undisturbed Sampling

Undisturbed samples of high quality are difficult to obtain but are especially important because of their influence on subsequent analyses comparing types of foundation treatment. Poor-quality undisturbed samples, when tested in the laboratory, yield values for the preconsolidation stress and for the coefficient of consolidation that are too low. These effects may lead the designer to conclude that foundation treatment is required where this is not the case. For example, if final soil stresses induced by the embankment are less than the preconsolidation stress of subsurface materials, foundation treatment to reduce settlement is almost certainly not required, but this may not be apparent if samples are partially disturbed and yield preconsolidation stresses less than their true value. Similarly, if the coefficient of consolidation is low because of poor-quality undisturbed samples, the designer may conclude that foundation treatment is necessary, whereas subsurface soils may consolidate without treatment rapidly enough to obviate the need for expensive foundation treatment.

Field Tests

Field in-place permeability tests are often desirable as (a) part of piezometer installation, (b) pumping tests, or (c) falling or rising permeability tests in boreholes. The last is more difficult and much less reliable than the other methods. Field permeability data so obtained can be used in conjunction with laboratory consolidation tests to furnish the best available estimate of the coefficient of consolidation. Where field tests of this type are made, however, it should be realized that the coefficient of permeability will decrease as consolidation occurs and the initial in situ or field test value will be too high for design purposes. It should be reduced to correspond to in situ stresses caused by the completed embankment.

Dutch cone and field vane shear tests are useful, but in soft foundation areas they may give misleading results because of fibrous organic material or strain rate effects as discussed by Bjerrum (*13*). Field vane shear tests should not be used directly unless correlated with tests on undisturbed samples. Field vane tests may give a useful indication, however, of variations in the preconsolidation stress. The Menard pressuremeter is used for in situ strength testing.

Critical Soils

Critical soils are those that become unstable under some loading conditions. Soils may be critical under one set of conditions and noncritical under another. Hence, it is not normally desirable to attempt to classify soils as being of a critical or a noncritical type. Instead, it is desirable to describe soils in detail and to subject them to sufficient laboratory tests to enable their properties to be adequately described.

SOIL TESTING

Laboratory Testing

The conventional laboratory testing program for soils in soft foundation areas includes triaxial compression, consolidation, Atterberg limtis, and similar tests. Consolidation tests are generally performed on specimens of 2½-in. (64 mm) diameter by about ¾ in. (19 mm) high or larger. The coefficient of consolidation, C_v, obtained from such tests is generally regarded as a lower limit for probable field behavior. Triaxial compression tests must be performed slowly when pore-water pressures are measured.

Evaluation of Test Data

It is essential to prepare generalized soil profiles both longitudinally and transversely in areas of soft foundation soils. These generalized soil profiles should contain the soil type, natural moisture content, penetration resistance where standard penetration borings have been made, and the locations of each of the various soil types and soil tests. Generalized profiles should be constructed based on geological reconnaissance as well as study by soils engineers.

CHAPTER SIX

FOUNDATION TREATMENT DESIGN

STABILITY ANALYSIS

Circular arc analyses by both the simplified Swedish method (or method of slices) and by Bishop's method are currently used for stability analysis (*25, 26*). These have been programmed for computer utilization and it appears that little design work is done manually. When using computers, the designer is responsible for assuring credibility of the results. A wide range of computer programs is available for use with the method of slices and the analyses have been adopted for programmable desk-top calculators.

Wedge analyses are used to some extent but evidently not widely (*25, 26*). It is considered that wedge analyses are often more applicable to stability problems in soft subsoil areas than are circular arc analyses. The base of the sliding wedge should be near the lower boundary of soft zones.

Appropriate safety factors to use in stability analyses vary depending on local soil conditions and especially on the estimated rate of construction and rate of consolidation. Safety factors as low as 1.25 to 1.20 are commonly used. Occasionally safety factors as low as 1.0 are used, but this is feasible only where consolidation is expected to be so rapid that a large gain in strength during construction is expected. Low safety factors are appropriate only where detailed and careful investigations, testing, and analyses are performed. A safety factor less than 1.0, without considering strength gain from consolidation during the construction period, is not considered prudent.

STABILITY BERMS

Stability analyses will often indicate the need for berms to provide adequate resistance against sliding. The thickness and extent of berms will be obtained from the detailed stability analysis. Required berm widths affect right-of-way requirements and length of drainage structure; hence, possible berm requirements must be known in the planning phase. Conversely, available right-of-way may preclude use of alternatives requiring large berms.

The cost of stabilizing berms may be large enough to affect selection of a final type of construction. Hence it is desirable to reduce the cost of berms to a minimum. Occasionally, the excavation and backfill technique is used for constructing a portion of the work that must be opened to traffic relatively early, whereas other sections will not be required until a later date and stabilization by consolidation is practicable. In these cases it may be economically attractive to use excavated materials to construct berms. In some cases even stumps have been placed in stabilizing berms because the principal contribution of berms is from their dead weight. Highly organic soils have been used in berms but their low unit weight below groundwater level, and above after drying, limits their effectiveness. Berms are not generally compacted. An illustrative section showing berms combined with stage construction is shown in Figure 16, but the dimensions shown should not be considered typical. Detailed stability analyses are necessary to assure stability of the outer edge of the berm because a failure may occur encompassing only the outer edge of the berm, whereas a trial failure surface encompassing the maximum thickness of embankment is stable. Berms may increase total settlements, especially of the outer edges of the embankment.

SETTLEMENT ANALYSES

In general, settlement analyses are based on one-dimensional consolidation as considered by the usual Terzaghi approach. Estimates of total settlement in soft foundation areas are generally reasonably close to observed values and are considered satisfactory for normal purposes. More detailed two-dimensional analyses are sometimes used.

CREEP DEFORMATIONS

Laboratory triaxial compression tests are normally performed too rapidly to include creep effects, and vertical movements resulting from lateral creep deformations are normally not considered in making either stability or settlement analyses. Nevertheless, field observations of slope indicators show that lateral deformations occur commonly, although their full extent was not appreciated previously. The term "creep deformations" generally refers to shear deformations that result in lateral and vertical movements, often without occurrence of significant consolidation. Vertical movements resulting from secondary compression are sometimes grouped with creep deformations but probably should be considered separately. When safety factors are low, lateral creep deformations can become high. This behavior is especially important where soft foundation soils are thick and consolidation occurs slowly. Under these conditions lateral creep deformations, under essentially undrained shear conditions, can result in substantial lateral deformations and, hence, in vertical settlement of the embankment, which may be large. Where consolidation is expected to be slow, excessive lateral creep deformations can be reduced to tolerable amounts by using higher stability safety factors such as 1.4 to 1.5. Where this is not done and slow consolidation is expected, estimates of lateral and vertical creep movements can be made using special laboratory tests and finite element analyses but such techniques are still in the research stage. Creep effects can adversely affect culverts.

VERTICAL SAND DRAIN DESIGN

The most generally accepted procedure for designing systems of vertical sand drains is that presented by Barron (*27*). Detailed discussions are also presented by others (*11*) and, hence, are not repeated. Nevertheless, a few comments regarding design details appear appropriate.

The design should consider the effect of submergence of a portion of the foundation or lower portion of embankment as consolidation occurs. This will reduce the effectiveness of the available weight of embankment and surcharge loading.

The theories generally used assume that the coefficient of consolidation is constant with increasing stress. Actually, this is not the case and the coefficient of consolidation, C_v, normally decreases with increasing consolidation; i.e., with increasing effective stress as indicated on Figures 17 and 18. This introduces the necessity of determining for what value of effective stress the design value of C_v should be selected. Consolidation analyses for sand drains including the effect of a variable C_v are complex but analysis of them indicates that Barron's procedure with constant C_v can be used if the coefficient of consolidation is selected for an effective stress somewhat less than the ultimate effective stress under the completed roadway but substantially greater than the value corresponding to initial in-situ stress conditions or to the indicated preconsolidation stress. For average purposes, it is suggested that the coefficient of consolidation be selected for a stress that corresponds to ap-

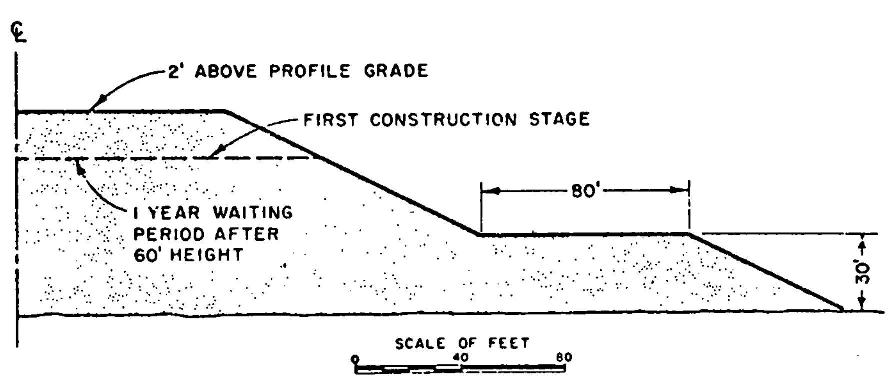


Figure 16. Half-section showing berm and stage construction.

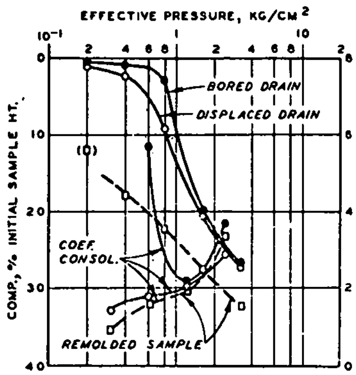


Figure 17. Consolidation test with central sand drain (After Hansbo (28)).

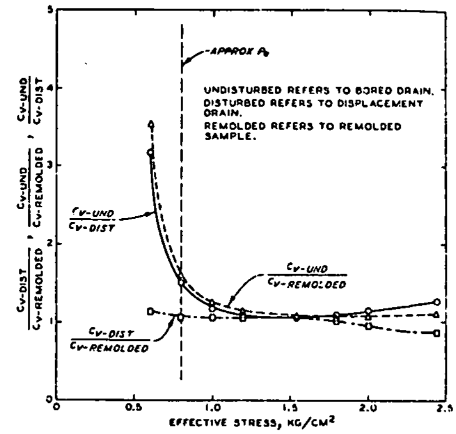


Figure 18. Effect of disturbance and variation of C_v with effective stress (After Hansbo (28)).

proximately three-fourths of the difference between the initial and the final effective stresses.

Where the coefficient of consolidation is computed by combining the results for the coefficient of compressibility and void ratio from laboratory tests with the coefficient of permeability determined from field tests, it is essential to reduce the field coefficient of permeability to account for the reduction that will occur under effective stresses equal to the loading conditions. The direct use of a field coefficient of permeability would give C_v values that are substantially too high.

In preconsolidation design, a minimum thickness of surcharge fill should be used regardless of the results of computations. Values of 3 to 5 ft (0.9 to 1.5 m) are often used.

Where extremely large berms are necessary to maintain stability during the surcharge loading period, the use of stage construction may be advantageous if time permits (see Fig. 16). In this procedure, the embankment is constructed to an intermediate elevation and a waiting period allowed during which the subsoils consolidate and gain strength. Upon resumption of embankment fill placement, the increased strength of the subsoils permits a significant reduction in volume of berms and, hence, a substantial reduction in cost. Waiting periods for consolidation under the first stage fill may vary from three months to a year or more. Design of surcharge fills should, almost always, eliminate all primary consolidation. A number of projects have also been designed to remove one cycle of secondary compression settlements (*10, 11*), and this is recommended for heavily traveled roads.

SHALLOW SURFACE EXCAVATIONS

Thin deposits of soft soils (i.e., about 5 ft (1.5 m) thick) are normally stripped. In addition, near-surface soils, especially where they are highly organic, are sometimes excavated to shallow depths (i.e., about 10 ft; 3.0 m) and replaced by suitable fill materials, even where soft soils exist to considerable depth. The necessity for excavating surface soils, especially where they are of a highly fibrous organic nature, is questionable for high grade lines. Such soils consolidate rapidly and primary consolidation is frequently completed as rapidly as embankment fill is placed. With low grade lines, organic soils should be excavated to avoid rough pavements. Many engineers have concluded that fibrous organic soils are not as troublesome as soft inorganic clays often, but not always, found beneath them. Vertical sand drains serve no function in highly fibrous organic soils but often have a beneficial effect in underlying soft clays and are needed where this condition exists. Where deep stabilization is accomplished by sand drains, surface materials are usually left in place because they will be stabilized together with underlying soft soils.

Secondary compression, even in highly organic materials, can be reduced through proper preloading design to acceptable values. This conclusion is based on field performance where proper designs have been made, such as the Christina River interchange near Wilmington, Delaware, and highway construction in Vancouver, British Columbia. Equally important are some of the experiences in New Jersey where fibrous organic soils have been preloaded.

LIGHTWEIGHT EMBANKMENT FILL

Settlement can be reduced and stability increased by using lightweight embankment fill. In addition, required berm sizes can be greatly reduced or berms may be eliminated, substantially reducing construction cost. Various types of lightweight embankment fill materials discussed by Flaate (*13*) are listed in Table 9, together with materials tested by New York State (*7*). Some expanded shale has poor freezing resistance and must be kept dry, but New York State finds lightweight aggregate to be stable. Compressed and baled peat, sawdust, bark, and similar materials must be maintained in a submerged condition to avoid deterioration. According to Flaate, foundation soils have been excavated in some cases and replaced with lightweight fill to minimize subsequent settlement and instability problems. When using lightweight fills, it may be necessary to use conventional base course and subbases to avoid crushing the lightweight fill. Lightweight fill materials oftentimes cannot be compacted because crushing will develop a powder on the top of the fill. Expanded shale seems to be a favorite lightweight fill material because of its more certain behavior. Waste lightweight concrete also has been used but a significant volume decrease results from plant purchase to in-place conditions. Lightweight fills have been used on the pile-supported embankment type of construction previously described.

Lightweight fill materials are often expensive, but adjacent to bridge abutments, costs of \$8 to \$10 per cubic yard (\$10 to \$13/m³) have been considered satisfactory because of the decrease in settlements that can be achieved. Transverse culverts in lieu of part of the fill have also been used to reduce loads on soft soils.

Clam shells have been used as lightweight fill in a "floating" embankment of low height in Louisiana, on an experimental basis. The shell appears to "lock" and develops a high strength. The results to date have been better than expected, possibly because of a layered system action that develops. The shell weighs about 63 pcf (1000 kg/m³) air dry and 74 pcf (1200 kg/m³) compacted.

FIELD INSTRUMENTATION

Little or no instrumentation is required where the method of construction consists of an elevated structure of the conventional type or where soft soils are completely excavated and replaced by suitable fill materials. In contrast, considerable instrumentation is needed where foundation treatment consists of surcharge loading with or without vertical sand drains. For these cases, appropriate types of instrumentation are listed in Table 10; also see *NCHRP Synthesis 8* (*1*). The types listed in Table 10 are those generally used for observing and controlling construction of embankments (see *Highway Focus* (*29*) and Fig. 19). The extent of instrumentation depends on circumstances surrounding a local project and may be extensive or limited. If a project is large and the construction time required will be long, much instrumentation in the early phase of a

TABLE 9

LIGHTWEIGHT EMBANKMENT FILL MATERIALS

(a) ACCORDING TO FLAATE (*13*)

FILL MATERIAL	BULK SPECIFIC GRAVITY: SOAKED IN AIR	BULK SPECIFIC GRAVITY: SUBMERGED
Compressed peat bales	1.1	0.1
Sawdust	1.1	0.1
Bark	1.1	0.1
Slag	1.0–1.1	0.1
Cellular concrete, scrap	1.0	—
Expanded clay, loose	0.7	—
Expanded clay, concrete	0.8	—
Compacted clay, fill	2.2	1.2
Compacted gravel	1.9	0.9

(*b*) ACCORDING TO MOORE (*7*)

FILL MATERIAL	COMPACTED UNIT WEIGHT [a] (PCF)	BULK SPEC. GRAVITY	WEIGHT RATIO [b] LTWT MATL / EARTH
Blasted rock	100	1.8	0.85
Crushed stone	100	1.6	0.78
Blast furnace slag	90	1.4	0.70
Water-cooled slag	70	1.1	0.55
Cinders	80	1.3	0.62
Burned coal	70	1.1	0.54
Expanded shale (lightwt aggregate)	60–70	1.0	0.50
Polystyrene plastic	2–7	0.07	0.03

[a] After compacting and soaking to field conditions.
[b] For earth fill weighing 130 pcf, bulk specific gravity = 2.1.

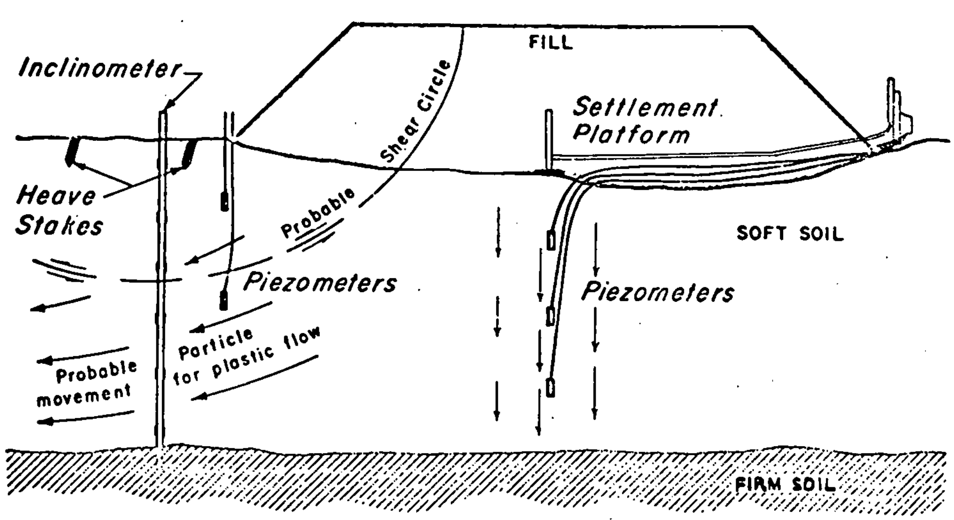


Figure 19. Installation of devices used to measure embankment and foundation soil movement.

TABLE 10

INSTRUMENTATION OF EMBANKMENT FOUNDATIONS

FUNCTION	TYPES AND LOCATIONS
Vertical settlements	Settlement platforms on original ground surface.
	Settlement plugs on surface of surcharge loading fills.
	Settlement plugs at intermediate depths in soft foundations.
Lateral movements	Slope indicators at toe of fill and along slope.
	Slope indicators at toe of berms.
Pore pressures	Piezometer at middepth and, if possible, at quarter points in soft foundation.
	Install piezometers midway between vertical sand drains, where used.

project is desirable because it may permit a reduction in size of berms or other features that will materially reduce construction cost.

Although it may seem unlikely, field observational data are often obtained but not analyzed as construction proceeds. A principal value of field data is to obtain information that relates to the progress of the work; hence, data obtained have meaning only if promptly analyzed. This generally requires a deliberate effort and designation of personnel for this purpose.

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II. *Displacement of Soft Materials*
   A. *By Fill Placement*
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      b. Weber, William G., Jr., "Construction of a Fill by a Mud Displacement Method," Proceedings HRB, Vol. 41, 1962, pp. 591-610.
   B. *By Blasting*
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III. *Underwater Fill Placement*
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  A. *Without Sand Drains* (No Excavation of Highly Organic Soils, If Present)
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