PLACEMENT RATES FOR HIGHWAY EMBANKMENTS

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ABRIDGMENT

•THE problems of increased urban development, zoning regulations, high land values, and high construction costs, together with the economic necessity to utilize the shortest and most direct routing, make it necessary to construct many highways on soft soils, such as organic silt, sensitive clay, peat, soft marl, muck, etc. Because the rapid construction of an embankment on a soft soil may result in excessively large settlements or a foundation failure or both, measures must be taken to ensure stability of the embankment during and after construction and to eliminate excessive settlements that would adversely affect the pavement performance or riding characteristics of the roadway. These problems usually have more than one solution, and the various techniques that may be employed to achieve the solution include removal of unsuitable soil by excavation or displacement, controlled rate of construction, stabilizing berms, sand drains, lightweight fill, and surcharging. The first method requires removal of the soil, and it is usually quite expensive. Whenever the situation permits, the controlled rate of construction method, perhaps in combination with one or more of the latter methods, is normally most economical. One of its main advantages is that it requires few if any additional construction materials; its major disadvantage is the time required.

The problem considered in this study involves the construction of a highway embankment on a layer of soft soil underlain by a relatively firm or rigid substratum, and the analysis entails two main aspects—stability and differential settlement, both with respect to time. On one hand, it is desired to apply the load as rapidly as possible, so as to accelerate the consolidation process and the resulting strength gain; however, on the other hand, if the load is applied too rapidly, the required strength gain does not have time to occur, and a bearing capacity failure may result. Because the controlled rate of construction technique takes advantage of the soil strength increase resulting from consolidation, soft soil deposits can often be made suitable for the support of highway embankments.

The companion problem to that of stability is concerned with differential settlements. Very often, embankments are constructed to surcharge levels to decrease post-construction settlements and not necessarily to increase the stability under the final design load. In many cases vertical sand drains have served to accelerate the consolidation process and to shorten the time required for large settlements to occur; desirably, of course, the settlement should take place prior to construction of the pavement.

OBJECTIVE

The objective of this study is to provide a series of charts and computer programs that the practicing engineer may employ as guidelines in establishing a suitable rate at which a highway embankment resting on a layer of soft soil may be preloaded without exceeding the bearing capacity of the soft layer and the associated settlements.

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GENERAL APPROACH

As considered herein (1, 2, 3), the problem is divided into four parts that deal with the initial distribution of excess pore water pressures due to the applied load, the process of consolidation, the resulting settlements, and the stability of the embankment-foundation system. The pore water pressures are computed by means of Skempton's pore pressure coefficients A and B and a solution for the total stress distribution. Based on the assumption of plane strain conditions and Poisson's ratio equal to one-half, the stresses are determined for the mixed boundary value problem in which a vertically loaded layer of finite thickness and infinite extent rests on a rough, rigid substratum. The dissipation of pore water pressures is evaluated by means of an extended consolidation theory, which includes radial flow toward sand drains, variable coefficients of consolidation, and partial saturation; the associated nonlinear partial differential equation is solved by use of a numerical procedure. Total settlements are computed on the basis of consolidation test results, excluding immediate and secondary effects; increases in effective stresses are assumed to be equal to the dissipated pore water pressures at any given time. The stability analysis is performed in terms of total stresses, and shear strength increases of the underlying soft soil due to consolidation are taken into account by means of the $c/\bar{p}$ ratio.

SUMMARY OF RESULTS

The results of this study are presented (1, 2, 3) in a series of charts and a set of computer programs. The charts include the following:

1. Maximum embankment height versus subsoil thickness—These charts, which have been established for a commonly used set of soil parameters, allow the determination of the maximum embankment height corresponding to a safety factor of unity against failure along a circular arc.
2. Stability charts—These charts are dimensionless and allow the determination of the factor of safety against failure along a circular arc for the cases where the undrained strength of the subsoil is a fraction of the strength of the embankment material.
3. Average pore water pressures under symmetrical trapezoidal loads—These charts have been established for a fully saturated soil with Poisson's ratio equal to one-half and the pore pressure coefficient A equal to one-half or unity. They can be conveniently used to estimate the ultimate consolidation settlements that can be expected under a trapezoidal embankment load.
4. Increases in shearing resistance due to complete dissipation of excess pore water pressures—These charts have been established for a specific set of soil parameters and the assumption that the maximum possible trapezoidal load is applied at time equal to zero. After complete consolidation under this load, the observed nonuniform strength increase is evaluated for two different $c/\bar{p}$ ratios and two different pore pressure coefficients A. This nonuniform distribution is then converted to an equivalent uniform strength increase such that the same factor of safety is obtained for both cases. These charts may be used to determine whether the controlled rate of construction procedure can be used successfully for the case where the initial shear strength of the subsoil is insufficient to sustain the final embankment load.
5. Consolidation-time curves—These curves represent the average degree of consolidation versus a dimensionless time factor for linearly increasing construction loads and for different ratios of the sand drain radius and the subsoil thickness to the radius of influence of the sand drain installation. These charts can be used to estimate the time dependency of the consolidation settlements and the strength increase.

Although the charts can be used most advantageously for preliminary design purposes, the computer programs can best be employed for a detailed final design or for checking an existing embankment-subsoil system. The set of computer routines consists of the main programs SAND and DETR plus 24 subroutines, and all programs are written in FORTRAN IV. Program SAND determines the times at which new load steps can be applied, depending on whether a specified portion of the ultimate consolidation settlement under a reference load or a specified factor of safety or both are obtained at the time of the new load application. If the different load increments and the times of load application are provided as input, the program can also be used to analyze the consolidation process and the time dependency of settlements without performing any stability analyses.

Program DETR determines the sand drain spacing by checking whether a specified amount of settlement or factor of safety or both at a specified time are ensured for the case where the load intensity increases linearly from time equal to zero to the full intensity at some specified time. Although program SAND allows the use of variable coefficients of consolidation, program DETR requires that these coefficients be constant.

ACKNOWLEDGMENT

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ANNOTATED REFERENCES

1. Krizek, R. J., and Krugmann, P. K. Placement Rates for Highway Embankments Volume 1: Development of Design Charts and Computer Programs. Dept. of Civil Engineering, Northwestern Univ., June 1972.

The controlled rate of construction procedure is investigated with regard to highway embankments resting on a soft, compressible soil layer that is underlain by a firm substratum. Special attention is given to the advantages of using vertical sand drains, and typical soil conditions, as well as sand drain installation procedures and their effect on the performance of a sand drain design, are considered. A precompression analysis involves problems associated with the distribution of initial excess pore water pressures, the dissipation of these excess pore water pressures, the resulting settlements, and the stability of the embankment-subsoil system. Solutions to each of these problems are presented, and charts are given to facilitate a preliminary precompression design. A well-documented set of computer programs, to illustrate the handling of input parameters, together with flow diagrams, is included to aid in making the final design or in checking a given design. Three examples are presented to elucidate the use of the programs.

2. Krizek, R. J., and Krugmann, P. K. Placement Rates for Highway Embankments, Volume 2: Listings and Flow Charts for Computer Programs. Dept. of Civil Engineering, Northwestern Univ., June 1972.

Given in this volume is a self-contained set of computer programs that can be used to analyze the behavior of an embankment constructed on soft soil. The individual routines, consisting of the main programs SAND and DETR and 24 subroutines, are written in FORTRAN IV. Complete listings are given for all programs, and detailed flow diagrams are provided for the main programs. Based on consideration involving the consolidation process and the stability of the embankment-subsoil system, program SAND determines the times at which new load increments can be applied; the criteria depend on whether a specified portion of the ultimate consolidation settlement under a reference load or a specified factor of safety or both are obtained at the time of a new load application. If the load increments and the times of load application are provided as input, the program can also be used to analyze the consolidation process and the time-dependency of settlements without performing a stability analysis. Program DETR calculates the required spacing of vertical sand drains by checking whether a specified amount of settlement or a specified factor of safety or both are ensured at a specified time. Although program SAND can handle variable coefficients of consolidation, program DETR requires that these coefficients be constant.

3. Krizek, R. J., and Krugmann, P. K. Placement Rates for Highway Embankments, Volume 3: Theoretical Background and Programmed Formulae. Dept. of Civil Engineering, Northwestern Univ., June 1972.

The general precompression analysis for a highway embankment resting on a soft soil can be divided into four parts that deal with the initial increase in pore water pres-

sures due to the application of an embankment load, the associated settlements, the process of consolidation, and the stability of the embankment-foundation system. The four problem areas are described, possible approaches reported in the literature are investigated, and the formulas incorporated into the computer programs are derived. The pore water pressures are computed by use of Skempton's pore pressure coefficients A and B and a solution for the total stress distribution, assuming linear elasticity and plane strain conditions. The dissipation of excess pore water pressures is evaluated by means of an extended consolidation theory, which includes radial flow toward sand drains, variable coefficients of consolidation, and partial saturation. Total settlements are computed on the basis of consolidation test results, excluding immediate and secondary effects. The stability analysis is performed in terms of total stresses, and shear strength increases of the soft soil due to consolidation are taken into account by means of the $c/\bar{p}$ ratio.