Economic Aspects of Vertical Sand Drains

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The highway engineer has a number of methods to consider as a solution to the problem of crossing marshland with road construction. His choice of method will depend on engineering aspects and economic considerations. It is assumed that the cost of bridge structures will generally exceed various types of fill construction. Hence, discussion is restricted to economic consideration of mud-excavation, surcharged-mud, and sand-drain methods.

Relationships are developed which indicate the construction cost differentials involved in considering mud excavation and the sand-drain method. The proper consideration of the surcharged-mud method as a solution to the problem is discussed. Sources of information related to these problems are numerous and the author is conscious that economic studies are given careful attention by all highway departments. However, work to date has shown that the economic considerations are a function of many parameters, the exact interrelationships of which the engineer can only estimate. Formulation, however, permits some compounding which makes the other parameters stand out prominently. Total cost differential involving costs related to time and maintenance are discussed.

● SELECTION of the vertical-sand-drain method for the stabilization of muck is dependent upon the exercise of keen engineering judgment and a careful study of economic aspects. A phase of the problem, but by no means the only requirement, dictates a comparison of sand drains to other methods of treatment.

Methods to be compared may be briefly summarized as follows: (1) complete removal of soft soil and replacement with acceptable embankment material; (2) partial removal of soft soil and replacement with acceptable embankment material; (3) drainage methods, including vertical sand drains; (4) floating embankment on soft soil; and (5) bridge structures.

In general, the use of bridge structures cannot compare favorably to the other methods on a construction cost basis. Accordingly, they will not be considered at this time.

The floating embankment is a specialized solution, applicable under rather stringent conditions and, therefore, is dismissed from this discussion,

The economic problem to be discussed reduces itself to a comparison of Methods 1 and 2 to Method 3. It is in this aspect of muck stabilization that interesting and conflicting ideas have been advanced. It is by no means accepted that complete removal of soft soil with the replacement of acceptable embankment material is restricted economically to depths of muck less than 10 feet. This statement, however, is frequently made. It appears that local circumstances may alter this contention considerably. This particular problem will be discussed in some detail.

GENERAL ECONOMICS OF STABILIZATION

The problem of economic comparisons of the various methods of muck stabilization may be stated in a general way, but data are not yet available to give conclusive results nor to permit a complete analysis.

In general, the total cost of a method includes right-of-way requirement costs, construction cost with its related problems, a charge applicable to the method due to time of construction, and annual maintenance costs as a result of the adoption of a given method.

The method using the vertical sand drain is so new, comparatively, that complete service records related to annual maintenance costs are meager and inconclusive. Prospective charges applicable to a method due to time of construction must be predicated on laboratory tests and keen engineering judgment. These estimates may be subject to appreciable change during actual field operations.

As a result of the factors briefly cited above, it appears that a comparison of construction costs represents the only firm index susceptible to analytical treatment at this time. Other phases of the economic problem must be reserved for actual situations and will serve to alter the conclusions arrived at by construction cost comparisons.

CONSTRUCTION-COST COMPARISONS

Complete generalizations of the methods of stabilizing muck cannot be made. One soon becomes impressed by the many variables involved and the interrelationships that exist adding more complication to the problem. One is conscious of the problems faced by the state highway departments and by the realization that a method which meets with success in one area may be inadvisable in another part of the country. Accordingly, the writer wishes to emphasize that demonstrations in this paper are not intended as generalizations. They represent a comparison of methods where engineering judgment indicates a reasonable measure of success.

A simplified geometric sketch of the sand drain method of construction is given in Figure 1. This formed the basis of costs applicable to this method and also lists the nomenclature in units suitable for calculation and comparable to field terminology.

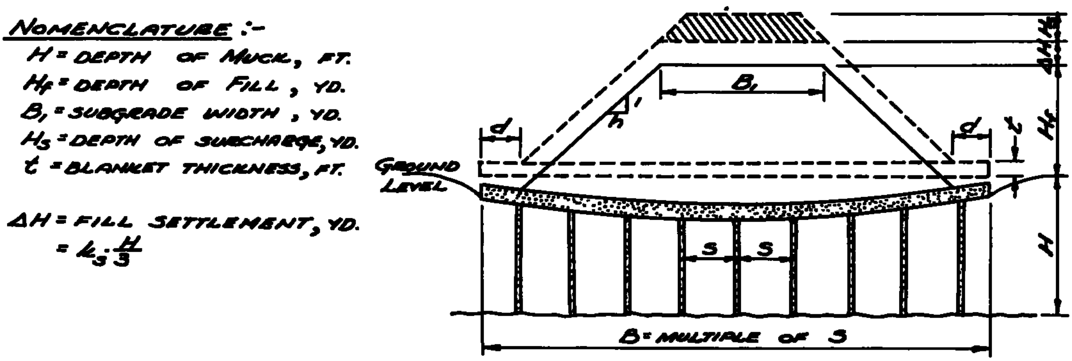


Figure 1. Cross-section for sand-drain method.

In general, the total fill material required is defined as the summation of the volume due to settlement, volume due to required embankment cross-section reflecting widening due to settlement, drainage blanket volume, and volume due to surcharge load. Hence, values for B, D_B, D_S and blanket volume follow directly from the geometry of the sketch. Settlement is expressed as a uniform percentage of muck depth, H, across the entire width, B, this percentage being expressed as K_S, in decimal equivalent form. It should also be pointed out that the depth of drains was taken as (H + t), i.e., the depth of muck including meadow mat and drainage blanket thickness with no overrun into lower support stratum considered. A geometric arrangement of tributary sand drain area is considered to apply, having a well ordered relationship to total blanket width, B.

In accordance with the geometry of Figure 1, the following relationships may be developed:

$$\text{Width} = B = B_1 + 2h\left(H_f + K_S\frac{H}{3} - \frac{t}{3}\right) + 2d$$

$$\text{Fill borrow, cu. yd. per yd.} = D_B = \left[B_1 + h\left(H_f + K_S\frac{H}{3} - \frac{t}{3}\right)\right]\cdot\left[\left(H_f + K_S\frac{H}{3} - \frac{t}{3}\right)\right]$$

$$\text{Surcharge borrow, cu. yd. per yd.} = D_S = \left[B_1 - h\,H_S\right]H_S$$

$$\text{Blanket volume, cu. yd. per yd.} = B \times \frac{t}{3}$$

These expressions of volume per lineal yard of fill may be combined in the following expression of [Cost per sq. yd.] $_{SD}$, this nomenclature being understood to mean cost per sq. yd. tributary to a sand drain:

$$\left[\text{Cost per sq. yd.}\right]_{SD} = \left[\frac{H + t}{A_S}\right]C_D + C_B\left[\frac{D_B}{B} + \frac{t}{3}r_B + \frac{D_S}{B}r_S\right]$$

in which:

C_D = Sand drain driving cost per ft.

C_B = Borrow cost per cu. yd.

A_S = tributary area in sq. yd. per sand drain

$$\text{Ratio } r_B = \frac{\text{Blanket cost per cu. yd.}}{\text{Borrow cost per cu. yd.}}$$

$$\text{Ratio } r_S = \frac{\text{Surcharge cost per cu. yd.}}{\text{Borrow cost per cu. yd.}}$$

This expression for cost is considered to be the unit construction cost directly attributed to the sand drain method. The ratios, r_B and r_S, will depend upon local conditions. The ratio, r_B, is considered to vary from 1.0 to 4.0 but has a relationship to C_B, which in turn is considered to vary from $0.30 to $1.60 per cubic yard. For high values of C_B, r_B will be relatively low; for low values of C_B, it will probably be quite high. The ratio, r_S, may vary from 1 to 2. If a separate item for overload removal and disposal is included in the bid proposals, this ratio will probably vary from 1.25 to 2.00.

A simplified geometric sketch of a total excavation and replacement method following the standard practice of the Michigan State Highway Department is given in Figure 2.

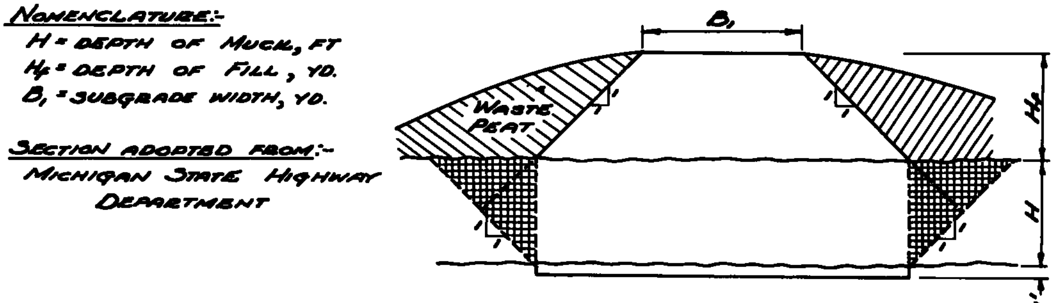


Figure 2. Cross-section for total-replacement method.

This arrangement is reported as applicable for depths of muck, H, up to 10 feet, but it is the author's opinion that some increase in depth is possible. The unit construction cost directly attributed to this total replacement method is given as:

$$\left[\text{Cost per sq. yd.}\right]_{TR} = C'_B\left[\frac{R_B}{B} + \frac{R_E}{B}r_e\right]$$

in which:

$$\text{Total excavation, cu. yd. per yd.} = R_E = \left[B_1 + 2H_f\right]\cdot\left[\frac{1+H}{3}\right] + \left[\frac{H}{3}\right]^2$$

$$\text{Total borrow, cu. yd. per yd.} = R_B = \left[B_1 + H_f\right]\cdot\left[H_f\right] + R_E$$

C'_B = Borrow cost per cu. yd. for total replacement method

B = Total width, sand drain section

$$\text{Ratio } r_e = \frac{\text{Excavation cost per cu. yd.}}{\text{Borrow cost per cu. yd.}}$$

The insertion of width B, of the sand-drain method, reduces data to an evaluation comparable to sand drain construction. The ratio, r_e, will be a function of local conditions and may assume wide variation. The author recognizes that it bears a functional relationship to depth h, but no reliable data could be obtained to estimate this variation. Data to permit such an evaluation would be most welcomed. The borrow cost per cubic yard has been expressed as C'_B, with the recognition that conditions of the bid proposal may result in a value differing from C_B, the borrow cost per cubic yard of the sand-drain method.

With determinable values for the unit construction cost for comparable methods, a unit cost increment can be expressed as:

$$\Delta C = \left[\text{Cost per sq. yd.}\right]_{SD} - \left[\text{Cost per sq. yd.}\right]_{TR} = \frac{H+t}{A_S}C_D + C_B\left[\frac{D_B + r_B\,t/3\,B + D_S r_S}{B}\right] - C'_B\left[\frac{R_B + R_E r_e}{B}\right]$$

Hence, for positive values of ΔC, the total-replacement method is economically favorable; for negative values, the sand-drain method controls. This equation may be further modified by introducing the relationship:

$$C_D \approx K_d\left[\frac{7}{H+t} + 1\right]$$

where K_d is a constant varying from 0.60 to 1.20. The value of C_D, so determined, includes both the driving cost and porous sand fill. It reflects the functional relationship of driving cost with respect to length of drain including the unit driving cost and a chargeable cost per foot for equipment moving and setup. Hence, it may be noted that as the drains get very short, the unit price rises to extreme values.

By introducing the approximate relationship for C_D and rearranging terms, we obtain

$$\frac{\Delta C}{C_B} = \left[\frac{K_d}{C_B A_S}\right] \cdot [7+H+t] + \left[\frac{D_B + r_B t/_3\, B + D_S r_S}{B}\right] - \frac{C'_B}{C_B}\left[\frac{R_B + R_E r_e}{B}\right]$$

The primary objective of this study is to present a basis for the determination of the critical muck depth, H_{CRIT}, i.e., the depth for which the cost of the sand-drain method balances the replacement method. Hence a reduction of the labor of calculation is realized by expressing the equation in a grouped constant form. If the condition $C'_B = C_B$, is considered to exist, we obtain the result:

$$\frac{\Delta C}{B} = \left[\frac{K_d}{C_B A_S}\right] \cdot [7+h+t] + \left[\frac{D_B + r_B t/_3\, B + D_S r_S - R_B - R_E r_e}{B}\right]$$

This is the form that has been utilized for studies in this paper.

A simplified geometric sketch of a partial excavation and displacement method of muck stabilization following the standard procedure of the Michigan State Highway Department is shown in Figure 3. For details of the method, the reader is referred to published standards and data of this organization. For a comparison of the sand drain method and this partial replacement method we get the following relationship:

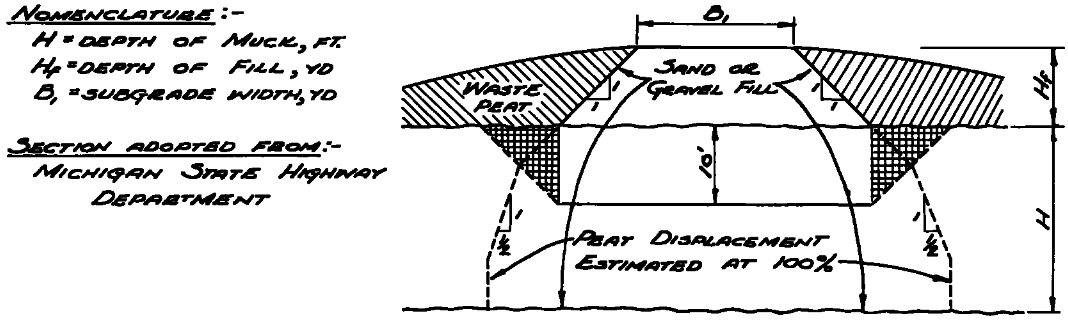


Figure 3. Cross-section for partial-replacement method.

$$\frac{\Delta C}{B} = \left[\frac{K_d}{C_B A_S}\right] \cdot [7+H+t] + \left[\frac{D_B + r_B t/_3\, B + D_S r_S - P_B - P_E r_e}{B}\right].$$

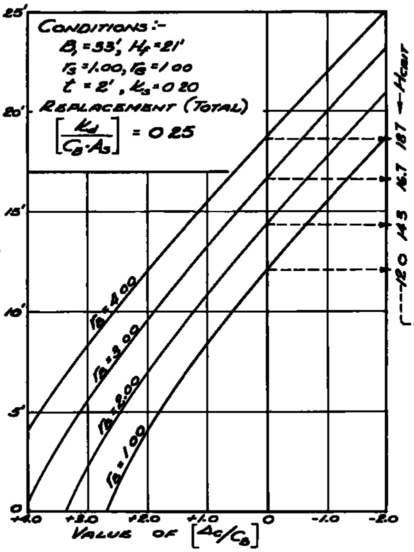
in which the nomenclature is identical to that given previously, except for:

Total excavation, cu. yd. per yd. = $P_E = \left[B_1 + 2H_f + \frac{10}{3}\right] \cdot \left[\frac{10+H}{6}\right] - \left[\frac{10H}{36}\right] + \left[\frac{H}{6}\right]^2$

Total borrow, cu. yd. per yd. = $P_B = \left[B_1 + 2H_f + \frac{10}{3}\right] \cdot \left[\frac{H}{3}\right] + \left[B_1 + H_f\right] H_f + \frac{H}{12}\left[\frac{3H - 20}{6}\right]$

An example of the determination of the critical muck depth, H_{CRIT}, for a defined set of conditions is shown in Figure 4 together with a tabulation of all the data developed for one set of curves.

A graphical presentation of the variation of critical muck depth, H_{CRIT}, versus variation of the economic ratio ($K_d/C_B A_S$) for both the total-replacement method and partial-replacement method compared to the sand-drain method is depicted in Figure 5. It must be emphasized that generalizations should be drawn with caution from this graph. The



$\frac{K_d}{C_B A_s}$	Value of H_{crit} when r_e = 1.00	2.00	3.00	4.00
0.01	1.2	3.0	4.4	5.9
0.05	2.6	4.1	5.7	7.3
0.10	4.2	5.9	7.7	9.3
0.15	6.1	8.1	10.0	12.0
0.20	8.7	11.0	13.1	15.0
0.25	12.0	14.3	16.7	18.7
0.30	16.3	19.2	21.8	24.4
0.35	22.7	25.2	28.0	31.0

Table of Values - $H_{crit.}$
Depth of Muck for which Total Replacement Cost Balances Sand Drain Cost

Figure 4. Example of determination of critical muck depth, H_{crit}.

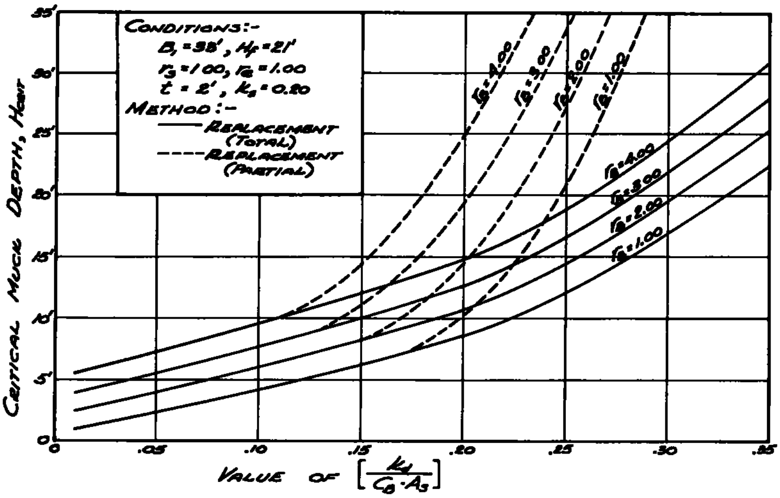


Figure 5. Graph of variation of critical muck depth with economic ratio with method as a variable.

conditions depicted, may in their extreme, bear little resemblance to reality. The use of value, r_e = 1.00, is unrealistic for values above 15 feet, since it reflects inordinately on the value of C_B, and additionally, this depth is probably the extreme condition of stability for material of the type represented. Because of the construction procedure, these remarks are not so directed to the partial-replacement method.

The graph of Figure 5 shows quite emphatically why the partial-replacement method is utilized for muck depths above 10 feet and also shows how the blanket cost ratio influences economical depth. For conditions of low borrow cost, together with close spacing of drainage wells, the replacement method may compare favorably with sand drains in the range from 0 to 30 feet.

The variation of critical muck depth due to fill width is depicted in Figure 6. It should be noted that fill width exerts a minor influence.

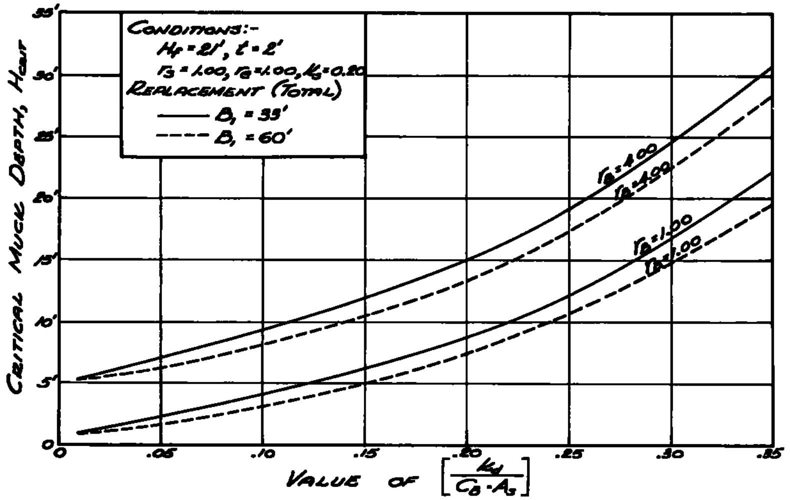


Figure 6. Graph of variation of critical muck depth with economic ratio with fill width as a variable.

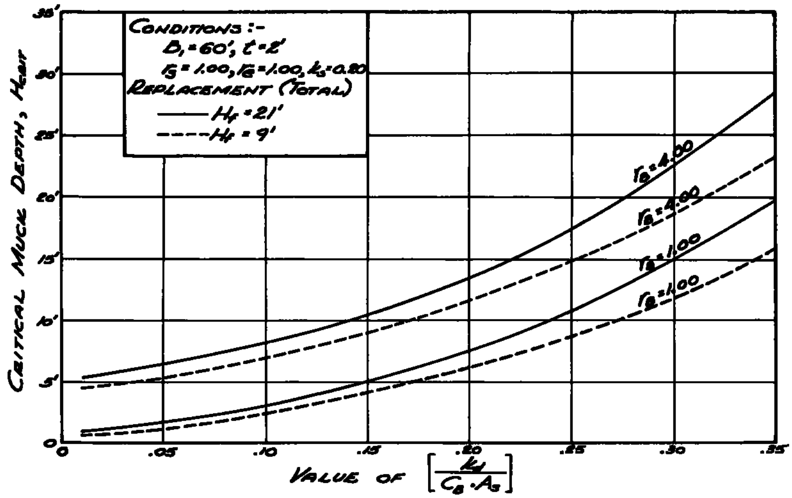


Figure 7. Graph of variation of critical muck depth with economic ratio with fill depth as a variable.

The graph of Figure 7 indicates that the replacement method becomes less favorable as the depth of fill decreases.

CONCLUSIONS

This presentation has been intended to focus attention on a number of interesting problems related to economic comparisons of methods of muck stabilization. It is felt that a mode of study permitting rapid comparisons of the important parameters may result.

A number of interesting cases rate investigation: (1) section geometry variation; (2) critical muck depth versus variation of r_e; (3) critical muck depth versus variation of

K_S & t; (4) critical muck depth versus variation of r_S; (5) the effect of including an approximate expression for the variation of r_e with depth, H; (6) effect of economic value of construction time for comparable methods; and (7) effect of relative maintenance costs on economic depth determinations.

ACKNOWLEDGMENT

This paper is an outgrowth of an investigation on swamp drainage being carried out under a research contract sponsored by the Maryland State Roads Commission at Johns Hopkins University, Civil Engineering Department.

The contractual arrangements were made before the recent resignation of William F. Childs, Jr., as chief engineer of the commission, and the subsequent appointment of Norman Pritchett, who succeeds him. J. Trueman Thompson is chairman of the department and research contract director. The contract is administered by a Coordinating Research Committee composed of Walter C. Hopkins, deputy chief engineer of the commission; C.A. Goldeisen, A. L. Grubb, and Allan Lee, representing the commission; and J. Trueman Thompson, Robert S. Ayre, Walter C. Boyer, and Wen-Hsiung Li, representing the department.

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