FOREWORD:

Recent years have witnessed major advances in the practice of geotechnical engineering. Research has paid off in innovative technology and revolutionary tools and materials. The fragmented nature of transportation engineering, particulary highway engineering, has inhibited the rapid implementation of these innovations. A gap has developed between the current state of the art of geotechnical engineering and the state of the practice within the transportation community. The benefits of research and innovation are not realized on routine transportation projects.

Individual geotechnical engineers may be unaware of innovative technologies that might be applicable on specific projects. Even if the engineer is aware of these technologies however, he often lacks the detailed information that allows him to confidently interpret data, develop plans and specifications, or inspect and accept installations. Geotechnical engineering is most often pursued within tightly constrained design or construction projects. On routine projects time and money are not available for thorough evaluation of new technologies and the geotechnical engineer must forego their use even though they seem appropriate and their value has been demonstrated elsewhere.

Shared experience is the only mechanism available to overcome this inhibition to innovation. "Nuts and bolts" information developed by one agency must be made available to others. Such information would include significant items that should appear in the plans and specifications, appropriate test methods or inspection procedures, installation or operation procedures, limiting conditions and the like. Items such as these are seldom addressed in research reports or manufacturers bulletins, but they are essential for successful implementation of new technology on a routine basis.

This circular is an effort to share experience regarding wick drains, a significant ground improvement technology that has not yet achieved widespread utilization in transportation engineering. This circular was organized under the auspices of the TRB Committee on Transportation Earthworks. It contains individually authored articles that provide a technical introduction to the subject, information on materials specifications, design considerations and construction as viewed by a contractor and agency engineers. A very important feature is a list of recommended readings on the subject.

One final note needs stating. This "shared experience" is not a design or construction manual. An engineer should only use this as a first step in considering a wick drain installation. Specific questions regarding the materials covered in this circular may be addressed to the authors through TRB. Such questions should be addressed to the Engineer of Soils, Geology and Foundations.

Wick Drains - An Overview

by

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Introduction

Many soft, compressible clay deposits consolidate too slowly for economical construction procedures. Terzaghi's theory of consolidation showed that pore pressure dissipation is related to both the soil properties and the length of the maximum drainage path within the deposit (1). Innovative solutions for increasing the rate of pore pressure dissipation by providing vertical drains to allow consolidation in the radial direction appeared shortly after Terzaghi's original work. By 1934 the first field installation of vertical drains containing sand were installed in Northern California (2). The first vertical drains were made by driving a closed end mandrel through the clay layer and filling the resulting hole with sand. Over the years this technique was refined through various installation methods.

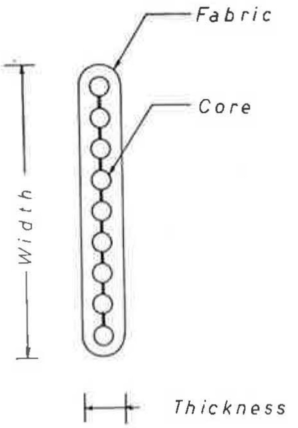
By the late 1930's, the first vertical drains using cardboard wicks were installed by Kjellman (3). This idea was, however, ahead of its time in that the concept and the technique of installation worked well but the cardboard wicks rotted in the wet clays. With the development of synthetic fabrics and plastic cores of sufficient strength, wicks have become a viable technique for forming vertical drains. In recent years wick drains have become the most common type of vertical drain.

Each vertical drain provides a path of high permeability through which the water entering horizontally from the clay can flow vertically up or down with little resistance. The speed of the consolidation process can be regulated through selection of drain spacing. The closer together the drains are installed the greater the rate of consolidation. To ensure that the water flow continues unimpeded, a sand blanket is usually provided at the soil surface to conduct the water to the edge of the installation.

Modern Wick Drains

A modern wick drain is shown schematically in fig. 1. The drain consists of two parts: the core and the fabric. In most drains the core is made from plastic, although in a few drains the core is a thick geotextile. The function of the core is to provide channels for water flow in the vertical direction and to support the fabric. The fabric is either a geotextile or treated paper. The fabric filters out the soil but allows water flowing out of the soil to enter the drain. The fabric must have sufficient strength to survive the installation procedures intact and resist the soil pressure without tearing or experiencing excessive elongation. The transmissivity is the capacity of the drain to transport water along its length. The capacity that the drain will maintain under soil pressure depends on the size, shape and amount of channel area remaining after the fabric has elongated under soil pressure. The stress and strain characteristics of the core material are also important to this transmissivity.

Figure 1 Schematic Representation of a Wick Drain



Suits and Gemme outline laboratory tests that address this behavior of the wick drains under load (4). Desired properties for drains can be specified and the product can be checked by laboratory testing. Drains could be manufactured that address this behaviour of wick drains load (4). Desired properties for drains can be specified and the product can be checked by laboratory testing. Drains could be manufactured to achieve any flow capacity necessary under stress. This is one of the advantages of prefabrication. Suits and Gemme give a description of the approach of the New York Department of Transportation to the laboratory screening of wick drains. Their paper begins on page 7. Research on wick drains sponsored by the Federal Highway Administration is presently underway. The scope of this project is outlined in the paper by A. F. DiMillio and J. J. Rixner that begins on page 13.

Wick drains are smaller in cross-section than sand drains and must in general be installed at closer spacings. This requires more linear feet of drain to service a clay deposit. Nevertheless, great economy of time and labor can be realized when the wicks are installed to full depth with a mandrel. In many clays the drains can be installed rapidly at about 1 meter per second with a substantial reduction of overall cost compared to sand drains.

Use of the mandrel may cause a disturbed zone around the drain which may retard the movement of water out of the clay. This effect can be anticipated in the design and the distance between drains decreased.

The machinery to install the wick drains requires a stable and level working platform. If the working platform contains boulders or rubble the hole for the wick drain may have to be partially predrilled which decreases overall production (6). Many other considerations for controlling costs of the installation are presented in the paper by M. J. Warren beginning on page 10.

Design of Wick Drain Installations

Project conditions may require a specific settlement at a certain time after filling or a rapid increase in effective stress during loading to insure stability. Staged filling, surcharging, preloading and vertical drains are among the most common methods of controlling strength and settlement rate of a clay foundation. The decision on the method to adopt depends ultimately on economics. Wick drains although costly to install, are economical in many cases because of time saved.

Design of a wick drain installation consists of selecting the configuration and spacing of drains to achieve the desired consolidation rate. The design also includes the drainage blanket and working platform from which the wick drains are installed. The design of the drainage blanket is the same as for vertical sand drains (7).

Good design depends on accurate subsurface information. Of particular importance is the location of any permeable layers in the soil profile that can function as drainage boundaries to the clay. A combination of borings and cone penetrometer soundings should be considered to develop a continuous soil profile. Representative piston samples recovered from the borings are usually tested in the laboratory for soil consolidation properties. Of primary interest is the coefficient of consolidation in the radial direction. The horizontal permeability and coefficient of consolidation measured in the laboratory have been greater than those properties in the vertical direction of many soils. Apparatuses for determining the radial coefficient of consolidation have been reported (8). However, as an alternative, samples are sometimes trimmed vertically from the center of the sample and then tested in the standard consolidometer. The disadvantage of this alternative is that the soil sample is being loaded in the laboratory at 90° to the direction in which it will experience applied stresses in the field.

The horizontal spacing of the drains is normally determined with the aid of theoretical calculations. Design calculations may use a simple theory such as that of Barron (9) or a more sophisticated computer solution (10). The calculation method selected depends on several factors the most important of which is the amount of subsurface information available. Only an approach using Barron's method will be discussed here.

Vertical drains theories use a computation model as shown in Fig. 2. The zone of influence of the drain in the horizontal direction is considered circular with a diameter d_e. The disturbed zone around the drain is considered to have a diameter d_s. The cross-section of the wick is replaced with an equivalent diameter d_w.

Barron's derivation assumes equal stain consolidation. The equation for average consolidation in the zone of influence is closely approximated as (9)(11)(12)(15):

$$U_R = 1 - \exp\{-[8T_R/F(n,M)]\} \quad (1)$$

$$T_R = C_R t/d_e^2 \quad (2)$$

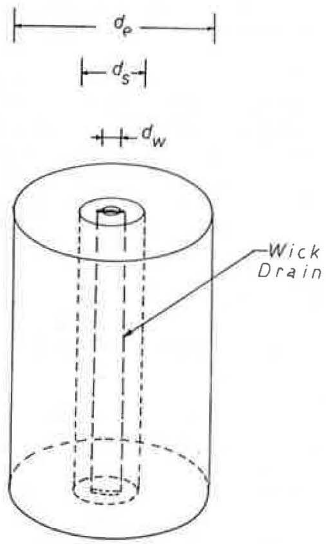
$$F(n,M) = [\ln(n) - 0.75] + M \quad (3)$$

$$n = d_e/d_w$$

$$M = (k_s/k_R)\ (S - 1) \quad (4)$$

Where: C_R = coefficient of consolidation in the radial direction; d_e = diameter of influence for the drain; $n = d_e/d_w$; d_w = equivalent diameter of the wick drains; k_R = undisturbed permeability; k_s = permeability in the smeared zone; $s = d_s/d_w$; d_s = diameter of the smeared zone.

Figure 2 Model Boundaries for Vertical Drain Theories



Field trials indicate values between 0 and 5 for the disturbance term M depending on the conditions at each site (11) (12) (13). In general, variability, the disturbance term M may be less significant than the range of values for C_R. Under these conditions a conservate value for C^R is assumed and M is taken equal to zero.

The equivalent diameter of a wick drain requires some consideration, since the typical wick drain has a width substantially greater than its thickness. The equivalent diameter of drain, d_w has been studied theoretically and experimentally (4)(15). Reasonable results in field trials have been obtained using the drain perimeter as the circumference of an equivalent drain: (12)(14)

$$d_w = 2[W + T]/\pi \quad (5)$$

where: W = width of drain; T = thickness of drain.

For a typical drain having a width of 100 mm and a thickness of 4 mm, this yields a d_w = 66 mm which is in the range of equivalent diameters determined in the laboratory by Suits and Gemme (3). In some cases small modifications have been made, but Eq. 5 is a good first approximation (16). Another approach is presented by J. Hannon in the paper that begins on page 5.

To account for average consolidation of the clay in the vertical as well as the radial direction, the theoretical solutions in each direction are combined as: (17)

$$U_c = 1 - [(1 - U_R)\ (1 - U_v)] \quad (6)$$

where

- U_c = average consolidation,
- U_R = consolidation due to radial drainage only, and
- U_v = consolidation due to vertical drainage only.

The vertical consolidation is computed from Terzaghi's theory (11). Including vertical and radial consolidation in the design insures that the most economical spacing of drains is used. The design usually begins with the desired percent average consolidation at a certain time after filling. The proper value for the diameter d_e is found by trying assumed values in eq. 1 through 3 and 6 until a suitable value for average percent consolidation is indicated.

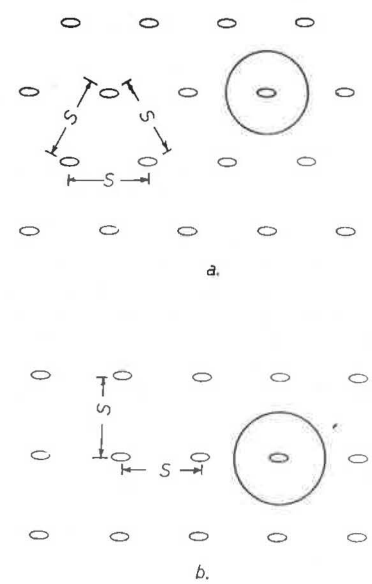
The drains are usually installed in either an equilateral triangular pattern as shown in Fig. 3a or a square pattern as shown in Fig. 3b. The spacing of drains, s, is related to d_e by:

$$d_e = 1.05\ s \quad \text{for triangular pattern} \quad (7)$$

$$d_e = 1.14\ s \quad \text{for square pattern} \quad (8)$$

The computed value for "s" is rounded down to a convenient dimension for installation.

Figure 3 Typical Horizontal Layout of Vertical Drains a) triangular pattern; b) square pattern



Field Instrumentation

Theoretical predictions have limitations. Some limitations are due to uncertainties about average soil properties, others are due to the fit of theory to real soils. Each design anticipates a certain rate of pore pressure dissipation and a certain rate of settlement. To monitor progress of consolidation and to compare actual behavior with predictions, field instrumentation is required. Most common are settlement platforms and piezometers. If the pore pressures are increasing more rapidly than predicted the rate of loading can be decreased until stability is assured. If the settlement is slower than predicted perhaps the postconstruction operations could be delayed. Data obtained from the instrumentation can often be used to backfigure soil properties. These properties can be compared to values used in design. Over a period of time design approaches can be refined with this feedback from field behavior.

Other instrumentation for monitoring and controlling construction are cited by T. J. Walsh in a paper that begins on page 9.

Field Testing Wick Drains

Testing a new concept or product can be a long and arduous task. Tests that demonstrate the validity of the concept or behavior of the product under appropriate field conditions must be developed. The New York State and California Departments of Transportation are to be commended for their pioneering work with wick drains.

All of the questions probably can not be answered by published case histories. Each potential user may have additional questions concerning the performance of wick drains in local soil deposits. The trial section of wick drains in the field may be needed to investigate all aspects of performance including installation procedures.

Planning a field test begins with choosing the location. The test site should have a reasonably well defined soil profile and drainage boundaries over a large enough horizontal area so that the behavior of different installations can be compared. A comprehensive test installation should include: an area containing no vertical drains, an area serviced by sand drains and one containing wick drains. If the soil and drainage conditions are the same, the three areas will compare the behavior of vertical drains to the natural drainage conditions. The wick drains should be installed at three different spacings. Each of the areas must be instrumented to obtain enough data to properly analyze the consolidation of the clay deposits. Piezometers are needed to characterize the excess pore pressures between the drainage boundaries. In the area with vertical drains piezometers are normally placed mid-way between drains. In areas without vertical drains they are usually placed at various elevations to measure the excess pore pressures and estimate the progress of dissipation throughout the layer. Settlement platforms and anchors are also important and should be observed often to establish the settlement patterns.

The settlement devices should be installed close to the piezometers so that the data can be correlated. The field instrumentation must be protected so that it remains functional as long as possible. Malfunctioning piezometers should be replaced. Contractor operations must be monitored and controlled.

The data collected from the field instrumentation must be properly analyzed. This requires some comparisons through theory. Usually the rate of consolidation is checked by backfiguring the coefficient of consolidation from both the pore pressures and the settlements (18)(19)(20). Every attempt should be made to separate various components of the field data (21).

Summary

Vertical drains are helpful when the consolidation of soft soils can be accelerated by shortening the maximum drainage path. Wick drains made from synthetic materials have become the dominant method of forming vertical drains in recent years. The design of wick drain installations requires an equivalent drain diameter which can be approximated from the cross-sectional area of the wick. Field tests should compare wick drain to conventional drain performance. The field test sites must be properly instrumented so that appropriate parameters can be backfigured.

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WICK DRAIN SELECTION AND DESIGN

By

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Vertical sand drains have been used effectively in the past by Geotechnical Engineers for accelerating the consolidation of soft compressible foundation soils. However, their use has been virtually eliminated in the United States during the last few years by the use of prefabricated wick drains. The innovative efforts of Caltrans and others have helped stimulate this new technology (1), (2), (3), (4).

The first version of the wick drain originated from the "cardboard wick" invented by Kjellman in 1939 (5). Several other versions later developed into presently available technology.

Prefabricated wick drains or band-shaped drains as they are sometimes called are generally about 4-inches wide and vary in thickness from 1/16 to 1/4 inch. These drains usually consist of a center core of plastic or cardboard providing vertical drainage channels. The core is usually wrapped with an outer sleeve of either pervious paper or a nonwoven synthethic geotextile. Wick drains offer several advantages over vertical sand drains. For example:

1. Wick drains are flexible and can withstand considerable deformation without failure, thus maintaining drainage continuity and function. Sand drains would probably shear under the same conditions and cease to function.

2. Wick drains can also be installed rapidly and at lower cost than sand drains and soil disturbance is generally less.

Wick drains are designed using the same theoretical considerations as sand drains based on Barron's adaptation of Terzaghi's theory of consolidation (6). Because wick drains are not round, to use Barron's equations, an "equivalent sand drain diameter" is necessary, and several interpretations of equivalent diameter have been developed by various investigators. For example, one method gives the equivalent diameter as the diameter of a circle having a circumference equal to the perimeter of the wick drain (7). Another method uses the concept of a "free filter area" of a drain (8).

Since there is considerable disagreement on the proper procedure for determination of equivalent diameter, Caltrans has arbitrarily assumed that the best performing wick drains are approximately equivalent to a 6-inch diameter sand drain. This assumption recognizes the possible existence of sand lenses, which provide more favorable horizontal drainage, and a general conservatism in predicting the coefficient of consolidation. The effect of disturbance is impossible to predict without considerable experience.

To ensure predictable performance of a given installation, proper wick selection is one primary key to a successful project. The second key to success is a reasonable prediction of the coefficient of consolidation of the soft foundation material to be consolidated.

When wick drains were first introduced in California, one consultant was unsure of the performance of this new technology. He therefore applied a "suspender and belt" approach to vertical drain design. His design called for sand drains with wick drains installed in the center of each sand drain. Reliance on wick drains has since improved through several successful installations.

Caltrans has found through field installation and laboratory testing that good performance can be expected from drains supplied by several different vendors, if properly installed and monitored with instrumentation.

Other wick drains may also provide good performance but must be pretested since some may have questionable flow characteristics that are undesirable and can result in excessive pore pressures and foundation instability during loading. New York State's basis for acceptance and specification of wick drain material is described in the following article by Suits and Gemme.

The time required for consolidation for a given installation can be determined for wick drains using the following simplified