natural safety valves already open and should not be regraded if such regrading may prevent the enclosed water from flowing out. The rest of the slope should be stabilized, however. Given two enclosed aquifiers of equal size located at equal horizontal distances from the slope but at different elevations the lower is more likely to produce a slide than the upper. This is because the rain water falling at the crest of the slope may reach the lower aquifier through fine fissures in the till and thus create in it pore pressures of considerable magnitude when the fissure is completely filled. As a rule, the higher the aquifier, the less the potential danger of slide provided that other circumstances are the same. Hence it is necessary to conduct the percolating rain water from the top of the slope to its foot thereby by-passing the lower aquifiers. This is cleverly done by the authors of the paper by conducting the rain water first vertically and afterwards practically horizontally thus creating a "safety zone" for the lower aquifiers. In some old important railroad cuts the same purpose used to be attained by constructing a deep drainage or even a continuous drainage gallery parallel to the slope. The comparative economic factor in this case is obviously in the favor of the authors of this paper. The idea of Professor Hennes consists in spotting the aquifiers by auger borings and providing exit for water before it accumulates in the aquifier which is done by placing horizontal pipes. This is a still more economical method, but in this case the pipes providing exit for water may be exposed to silting. Cleaning of these pipes is possible, but difficult. The work done at Seattle, Washington, as described in this paper is interesting and merits attention of engineers

EXPEDIENT METHODS FOR STABILIZING SWAMPS

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SYNOPSIS

Porous vertical drains appear to hold the greatest promise for stabilization of swamps for road construction. Vertical drains shorten the settling time and minimize differential settling.

Laboratory experiments are described using porous concrete piles (porous-walled pipe) in place of the usual sand drains. The concrete piles are easier to install and are unaffected by shearing stresses which may develop. They appear to plug less easily also. In the experiments the concrete piles were up to 29 per cent more efficient as drains than the sand columns.

An economic analysis shows that the concrete piles are approximately 30 per cent less expensive than sand drains, without considering the increased efficiency. It is concluded that on the basis of the laboratory tests, full-scale field trials of the porous concrete drains seems justified.

Stabilizing a swamp presents a problem of completely different aspect and nature from stabilizing a road sub-grade. Swamps cannot be called ready to support a road after stabilizing the uppermost few feet—on the contrary, such a procedure may lead to disastrous results.

So far, the four methods most commonly practiced in this country as a solution to the problem are: dumping the fill on the swamp, removing the muck completely; dynamiting after loading the muck, with the idea of pushing it to the sides; and lastly, vertical sand drains. To these methods should be added stabilizing by the use of vertical porous concrete drains.

Dumping leads to the formation of gigantic mud waves which, in addition to slowing the work, present an intricate and costly problem. The removal procedure is almost a foolproof method. (Removal can be effected in two ways, either by clamming the muck out or by dredging it, and dredging is not always 100 percent effective. Dredging was used on a section of the Baltimore-Washington Expressway, but when the fill was placed, mud waves and local failures were observed. Investigation revealed that the last couple of feet or so of muck were not completely eliminated.) Dynamiting is practiced quite extensively. Basically, the impact from the dynamite charges liquefies the muck; and to the liquefied muck is added the fill, with two objectives: to push as much of the muck as possible to the sides, and to push the sand into whatever muck is left and create a stable admixture. In this procedure, the paramount difficulty is the building up of immense muck waves as the work progresses. Dynamiting is also limited in its practicability, and becomes ineffective whenever the depth of the swamp is excessive. In addition, blasting is undesirable near inhabited areas. Here it may be mentioned that removal is also impractical whenever the depth of the swamp exceeds certain limits. Thus both of the foregoing procedures are limited to shallow swamps; for deep swamps the cost becomes prohibitive.

The last two methods, which can be classified as one and labeled "vertical drains," are the most recent, and are receiving favorable attention. As the name implies, vertical drains are either dug-out wells that are backfilled with sand or vertical porous concrete drains that are pushed into position. In general, it may be said that vertical drains are more economical and present a better approach to the problem. While removal and dynamiting are "brute strength" methods, the vertical drains method embodies sound soil mechanics principles. The benefits gained from stabilizing a swamp by the use of vertical drains may result in (a) lowering construction cost, (b) avoiding alternate routes where property and land prices are high, (c) shortening time of settlement, (d) preventing excessive settlement after pavement is in place, (e) eliminating differential settlement due to pockets of muck, and (f) insuring stability against slides while placing the fill.

The purpose of vertical drains is to hasten the drainage of the water that is expelled from a foundation subjected to external pressure. When a soft, compressible soil is loaded, the excess pore-water pressure created by the load tends to squeeze out the water in the pores. Theoretically, the amount of settlement is equal to the volume of water squeezed out provided no subsidence occurs due to slides. The faster the water is expelled from the soil, the faster the soil settles and the sooner permanent pavement can be placed, a fact which leads to considerable savings in many instances. Vertical drains provide an accelerated means for consolidation by intercepting the horizontal flow of water and hastening its transmission to the surface.

Slides are an inherent characteristic of soft soils subject to a surcharge, and their avoidance is of primary importance in road construction. Such slides call for added amounts of borrow material and are liable to cause mud pockets with differential settlement that eventually manifests itself by the appearance of cracks on the paved surface. To insure stability, the shearing strength of the soil must not be exceeded at any time. Since swamp muck has a very low shearing strength, a surcharge higher than about five feet at one time may cause failure. As the pore water is squeezed out, the shearing strength of the muck is increased. The problem is to keep a balance between the increasing shearing resistance of the soil and the growing stresses resulting from the addition of layers of fill. If slightly permeable soils are being consolidated, then some means of accelerating the drainage should be resorted to; here vertical drains come into play.

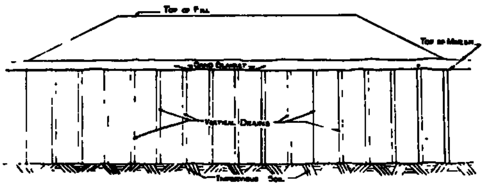

Figure 1. Schematic Representation of Vertical Drains

Figure 1 is a cross section showing vertical drains in place. The treatment which the surface of the swamp receives prior to installing the drains depends on the nature of the muck. If the upper layer of the swamp has a high content of organic material, it should be removed and replaced by a clean sand fill. If, however, the top layer does not differ materially from the soil at greater depths, a sand blanket about 3 ft. thick is spread on the top of the swamp and the work proceeds. Since this sand blanket serves the double purpose of a working platform and a drainage medium, the sand used for it should be clean and have a reasonably high coefficient of permeability.

Once the drains are in place the loading of the area begins. The rate of loading depends on the rate of settlement. Excessive, sudden settlements should be avoided as they are indicative of a flow in the subsoil. As an effective means for checking and controlling settlements, observation platforms and pore water pressure measuring devices are installed and systematic readings taken.

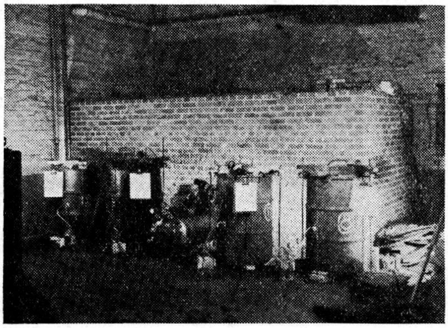

Figure 2. View of the Apparatus

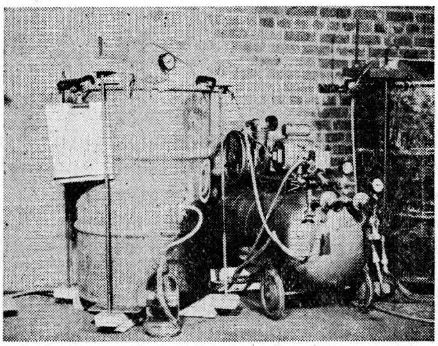

Figure 3. Drum and Air Compressor

EXPERIMENTAL

The State of Maryland has been struggling with its swamp problem for years. While the swamps are not of excessive depths, they are deep enough to present a problem which many times has caused insurmountable difficulties. A little over a year ago, the State Roads Commission of Maryland decided to initiate a program of swamp investigation, with experimental work carried on in its Testing Laboratory. The experimental setup finally adopted is shown in Figures 2–4.

Figure 2 shows a general picture of the experiment, the steel drums, air compressor, and other gadgets used. Nine drums were operated, one of which contained two windows which provided a means for measuring settlement of the muck as the experiment proceeded. The windows also enabled measuring the rebound when the pressure was released. Figure 3 shows one drum and the air compressor which delivers the necessary pressure. The valve on the compressor is used to step down the pressure and maintain it at the desired values of 5, 10, and 15 psi. as demanded by the experiment. The gage on the top of the drum serves as a further check on the pressure inside.

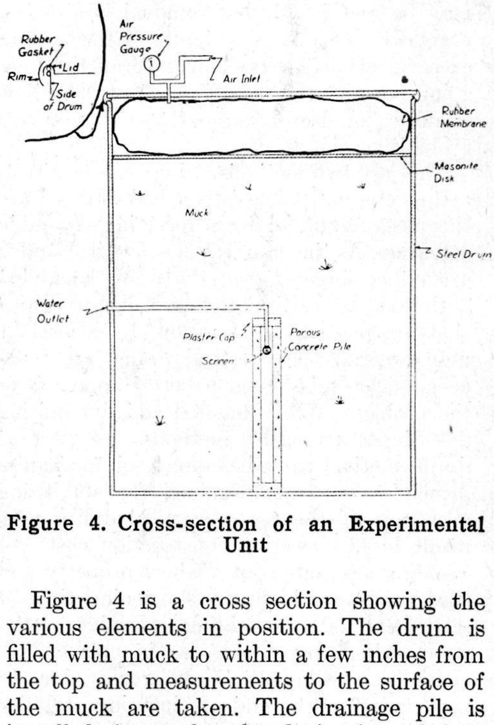

Figure 4. Cross-section of an Experimental Unit

Figure 4 is a cross section showing the various elements in position. The drum is filled with muck to within a few inches from the top and measurements to the surface of the muck are taken. The drainage pile is installed; for sand a closed pipe is sunk into position, filled with sand, and withdrawn; while for porous concrete, the hollow pile is pushed into place without any protection against peripheral smear, just as will be done in practice. To minimize peripheral smear in case it became excessive, the concrete piles could be jetted in without difficulty. The effect of peripheral smear has been well analyzed by Barron (*1*)[1]. The drainage piles are

[1] Italicized figures in parentheses refer to references listed at the end of the paper.

5 in. in diameter and 12 in. high. The lid with the balloon attached to it is clamped and the air pressure turned on. The drainage outlet is protected by a screen at its end to prevent unnecessary clogging in case muck infiltrates into the pile. Measurements of the discharged water are taken at predetermined intervals.

In the early experiments, no balloon was used, but it was discovered that whenever the air was dry it absorbed some of the moisture in the muck, and whenever it was wet it deposited some of its moisture. The balloon rests on a masonite disc, which in turn distributes the pressure evenly to the muck. Upon the completion of the experiment, settlement measurements are taken. Also, the moisture content of the soil is checked.

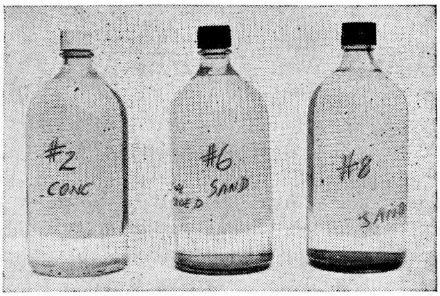

Figure 5. Samples of Drained Water

Figure 5 shows three samples of drained water with the markings on each. The water from the concrete was clear without any evidence of muck. The middle jar shows the water drained from the sand. Settlement at the bottom of the jar indicates that some of the sand particles were washed out. The jar on the right was filled with water discharged towards the end of the experiment. The deposit at the bottom shows that some muck has found its way through the sand filter.

Figure 6 shows the same jars after they have been shaken. The color in No. 6 has become sandy and that in No. 8 mucky, arousing the belief that the sand pile will get choked in time.

Figure 7 shows two concrete piles that were taken out of the experiments and broken. When the pile was opened and inspected, no muck deposit was found in the hole. These piles were allowed to dry and then shaken with the result that the muck peeled off and left no signs of infiltration under the outer surface of the concrete. The inside surface of the pile was as clean as at the time it was installed.

For an additional check on infiltration, water was poured into the concrete pile to a specified level. The pile started sweating from the water level down, an indication that the pile had remained permeable. The appearance of seeping water at the same level as the water inside the pile eliminates any possibility that the pores could have been opened by hydro-

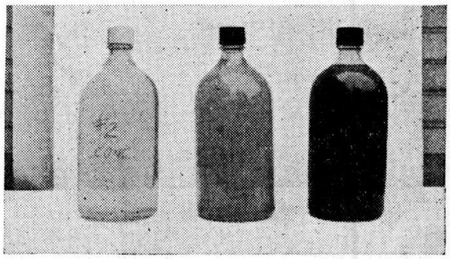

Figure 6. Samples of Drained Water After Shaking

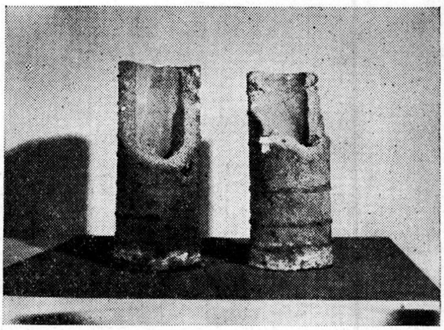

Figure 7. Concrete Piles After the Experiment

static pressure. On the other hand, inspection of sand drains that had operated under 15 psi. revealed that quite a bit of muck had found its way into the sand and would no doubt have clogged the drain eventually. Whether this clogging would occur in practice before the soil attained full settlement could not be ascertained in the laboratory. Nevertheless it can be speculated that the infiltrated muck will cut down the efficiency of the pile and decrease the permeability of the sand blanket, thus prolonging the time required for attaining full settlement.

The tests were performed on sand and porous concrete. In the early stages of the experiment, an attempt was made to get the most porous concrete mix by using various ratios of cement and pea gravel without any sand. Good porosity was obtained, but the life of the drain was very short. Muck seemed to find its way into the pile without much difficulty, and whenever even a minute hole occurred in the pile, drainage stopped quickly. The difficulty encountered in making such piles with an assurance of no holes led to the abandonment of these mixes in favor of precast concrete piles prepared by a commercial concrete products company according to furnished specifications. Three different gradations were used. The first two consisted of cement and two different gradations of commercial concrete sand in the ratio of 1:4 with enough water to make the mix workable. The third mix consisted of cement, concrete sand, and pea gravel in the ratio of 1:4:4. This third mix, upon experimentation, proved to be too coarse for the particular work involved and further tests on it were curtailed.

TABLE 1. RESULTS OF TESTS

Hours of Run	% Moisture (Average of 4 Experiments)	Pressure	% Diff. in Efficiency on Basis of Sand	Efficiency Difference In Favor of
		psi.		
24	161.3	5	0.5	Sand
48	161.3	5	1.9	Concrete
96	161.3	5	15.3	Concrete
192	161.3	5	6.9	Concrete
384	161.3	5	8.9	Concrete
720	161.3	5	10.8	Concrete
24	161.3	10	14.3	Concrete
48	161.3	10	13.2	Concrete
96	161.3	10	12.2	Concrete
192	161.3	10	11.5	Concrete
384	161.3	10	10.8	Concrete
720	161.3	10	10.2	Concrete
24	161.3	15	10.8	Concrete
48	161.3	15	9.6	Concrete
96	161.3	15	6.4	Concrete
192	161.3	15	10.6	Concrete
384	161.3	15	2.1	Concrete
720	161.3	15	0.1	Concrete
24	152.5	5	29	Concrete
48	152.5	5	23.1	Concrete
96	152.5	5	14.2	Concrete
192	152.5	5	11.5	Concrete
384	152.5	5	9.8	Concrete
720	152.5	5	1.7	Concrete
24	152.5	10	9.44	Concrete
48	152.3	10	13.10	Concrete
96	152.3	10	14.10	Concrete
192	152.5	10	16.70	Concrete
384	152.5	10	19.0	Concrete
720	152.5	10	21.9	Concrete
24	152.5	15	1.21	Concrete
48	152 5	15	1.42	Concrete
96	152.5	15	3.37	Concrete
192	152.5	15	0	None
384	152.5	15	8.57	Sand
720	152.5	15	11.44	Sand

The sand tested was taken from available commercial sand such as various grades of concrete sand, beach sand, and mortar sand, all of which met the specifications of the Maryland State Roads Commission. Also, tests were run on graded sand filters designed in accordance to $5D_{15}$ and $5D_{85}$. Since the muck was too fine, it was hard to comply with this rule, but it was followed as closely as possible without introducing too much fines into the filter.

The results of the experiments were plotted and a formula $Q = aT^b$ was established, in which Q = volume of water discharged in cc., T = time in hours, and a and b are experimental constants. Computed results by this equation checked actual results within 1 to 2 percent for all three pressures of 5, 10, and 15 psi. With straight line plots, it was considered permissible to extend the lines beyond the actual runs. Table 1 gives some of the results.

The seven hundred and twenty hours represents thirty days. After the equivalent of this time in the field, the muck will have consolidated enough to support an additional load from increased height of the fill. A comparison of the results shows that the concrete is more efficient than sand for all times and pressures, except in three cases. The 0.5 percent in favor of sand at 24 hr. is insignificant. The 8.57 and 11.44 percent at 384 and 720 hr. are durations beyond the operation of the experiments and were obtained on the assumption that the plot of discharge versus time remains a straight line.

Measurements to determine settlement were taken at the beginning and at the end of the experiment when the drum was opened. The total settlement was from 10% to 25% higher than that expected on the basis of the discharged water. Air traps included in the apparatus failed to indicate the presence of entrapped gas. There remains only the possibility that the muck was not compacted enough when placed in the drums. It should be mentioned that the muck was mixed with a Hobert mixer holding about ⅛ cu. ft., and dumped into a 30-cu. ft. box. Further mixing in the box afforded good uniformity of moisture content, as ascertained by mositure samples taken from the drums. But since the same conditions prevailed for both concrete and sand, the percent settlement charged to light compaction does not affect the comparative efficiencies of the two types of drains.

Soil as it occurs in nature lacks homogeneity and isotropy. Horizontal stratification is not uncommon in natural soils. Both of these factors tend to introduce variations in the horizontal and vertical coefficients of permeability. The construction of a model, the results from which could be extended to the prototype proved to be impractical, for analysis reveals that the coefficient of permeability would have to be reduced. Even if this were possible by using a liquid other than water, the difficulty of reducing the grain sizes of the soil used in the model is obvious.

In the face of these difficulties, it is necessary to use a model which gives only a comparative analysis of the problem. All indications support the conclusion that the two drainage elements will perform in the field as in the laboratory, and in the field the concrete drain should show a higher efficiency than the sand.

Another phase of the problem concerns the installation of drains in the field. A preliminary investigation of the swamp is essential. This investigation should be centered around consolidation and shear tests on undisturbed samples, and a mechanical and physical analysis of the muck and its moisture content. During the investigation horizontal stratification should be noted. The results of these tests will enable the engineer to choose the proper spacing for the drains. The effect of drains on consolidation has been covered by Barron (*1*).

"The most economical pattern of drain wells is one where the drain wells are located at the apexes of an equilateral triangle. This places each well at the center of a hexagonal-shaped zone of influence. For the purpose of an approximate analysis of this report, the hexagonal area is replaced by a circle of the same area. If "S" is the spacing of the drain wells, then the diameter of the circle having an equivalent zone of influence is:

$$d_c = S\sqrt{\frac{2\sqrt{3}}{3}} = 1.05S"$$

See Reference 2.

For a sand drain, a closed-end mandrel is driven into position, filled with sand, and withdrawn, preferably under pressure. Despite its apparent simplicity this operation is intricate and time-consuming. Filling and withdrawing the mandrel requires care because of the possibility of arching by the sand. Arching causes discontinuity of the drain, permitting the muck to seep through and obstruct the flow of water. Wherever arching occurs the part of the swamp below that level remains undrained and represents a potential later failure. There is little doubt that arching can be virtually eliminated by measuring the exact amount of sand that should go in each pile and then withdrawing the mandrel under pressure; but here again these manipulations are lengthy and expensive.

A vertical drain of the type under discussion should satisfy two requirements: it should have an infinite permeability compared with that of the muck, and it should offer resistance to the infiltration of muck. Possessing only one of these qualifications is not satisfactory although each must exist at the expense of the other. The compromise is arrived at by using washed, graded sand. Pouring the sand into a long mandrel results in some degree of segregation of the sand particles, thus affecting the gradation of the pile and reducing its efficiency. To investigate the status of a sand pile is rather difficult, for the slightest deviation from plumb will lead the drill into the muck after a few feet of boring.

Whenever sand drains are employed, differential settlement presents a serious problem, since shearing of the sand drains defeats their purpose. Since soil slides occur mostly near the toes of the fill, one or two rows of drains should be added beyond the toe of the fill, on both sides of it, and running the whole length of the swamp.

With porous concrete drains, however, the piles can be pushed into place without much difficulty since the muck does not offer much resistance, and the use of a mandrel is eliminated altogether. The concrete used in the experiment had an ultimate compressive stress of 1,500 psi. Hence, should any resistance to the sinking of the concrete pile arise, light dynamic driving can be resorted to. All these operations may be performed by light equipment as compared with the heavy equipment required to drive the mandrel; therefore the working platform need not be as elaborate and substantial as that demanded by sand. The danger of having the concrete piles sheared off either by slides or differential settlement is insignificant, since the piles themselves offer a good resistance against shear. The worst that can happen is tilting of the pile, but even in this position the pile will continue to be effective.

The additional rows of piles beyond the toe of the fill required by the sand drains are not needed when concrete drains are used. Elimination of these additional rows is an important economic factor. Inspection of the concrete piles is not a problem since they are nothing more than porous concrete pipes closed at both ends.

From an economic point of view, which is the foremost consideration in many cases the cheapest installation that the writer has been able to ascertain for sand drains is $1 per running foot; in many cases the figure ran double this value. On the other hand, an economic survey on porous concrete drains yielded the following:

12-in. diam. with 2-in. wall thickness	30¢ per ft.
Transportation within 30-mile radius	5.2¢ per ft.
Installation by 5-ft. and 10-ft. sections to a depth of 40 ft.......	30–50¢ per ft.
	65.2–85.2¢ per ft.

The price of 30¢ per foot can be reduced once mass production is started, in the opinion of the manufacturer who supplied this price. Taking the highest figure, 85.2¢ per ft., the saving is about 15 percent when compared with the cheapest price for sand drains. It was mentioned that additional rows of drains beyond the toe of the fill were not necessary whenever concrete drains are used. If the distance between the toes of a fill is 108 ft., for example, and concrete drains are used at 12 ft., center-to-center, 10 rows of piles will be needed. If sand were used with only one row beyond the toe of the fill on either side, 12 rows of piles would have to be installed. Let us assume this swamp is d ft. deep and l ft. long. Comparing the cost at 85.2¢ per foot for concrete and $1 per foot for sand, the cost for concrete drains will be $10 \times .852 \times d \times \frac{l}{12} = \frac{\$8.52\ dl}{12} = \$.71\ dl$, and that for sand $12 \times 1.00 \times \frac{dl}{12} = \$1\ dl$. The saving is 29 percent without even considering the fact that the concrete has a higher efficiency. From these results, it is not hard to predict that concrete drains will afford a one-third saving over the cost of sand. From the economic analysis and laboratory tests, it seems evident that a field test is the next logical step.

When the results with porous concrete were compared with those with a graded filter ($5D_{15}$ and $5D_{85}$) the efficiency of the concrete was as much as fifty percent higher than that of the sand filters. This is because the fine sand necessary in the graded filters became more of a hindrance than a help.

The moisture content of the muck tested ranged from 136.0 to 177.1 percent. On the wet mixes, *i.e.* those with high moisture content, the fine gradation concrete proved to be the most effective, while for the mixes with low moisture content the intermediate concrete was the best suited. Since the muck used in all tests was the same, no conclusion can be drawn relating the type of concrete to be used and the grain sizes of the muck. In general, for coarse-grain muck the intermediate concrete will be more efficient than the fine. But since the moisture content enters the picture, a clear-cut recommendation for the type porous concrete to use for a swamp cannot be set forth; each swamp should be investigated separately. Since the experimental procedure is simple, it is advocated that before choosing any type concrete, experimental tests should be conducted and the best concrete selected. A test as described does not require more than a month or so and usually ample time is available between planning, submission of bids, and start of construction.

The effect of the bedding plane on the horizontal coefficient of permeability cannot be ignored.[2] But despite its importance, it is very difficult to reproduce in experimental work and should be studied on full-scale experiments in the field. The presence of

[2] Alluvial deposits which comprise most of compressible soils have a greater permeability coefficient in the direction of stratification than in a direction at right angles to it.

horizontal stratification will affect concrete and sand drains equally and will have no bearing on the comparative results.

In addition to the foregoing advantages offered by the concrete, it should be mentioned that porous concrete piles add to the rigidity of the sub-base, especially whenever the depth of the swamp is not excessive. There is a possibility that the porous concrete piles will result in bumps at the surface of the fill. This may happen during the process of construction, and in some cases on jobs where the surface was placed before complete settlement of the sub-base had been attained. A swamp by its nature is in general low land, and a fairly high fill is required to bring it up to grade. The higher the fill, the less pronounced is the effect of the bumps. From the construction angle, no surfacing is laid until the foundation has reached almost one hundred percent consolidation; the surface of the road will crack rather due to differential settlement. Therefore if bumps develop, the top of the fill can be leveled prior to placement of the surface.

Arching of the load due to the stiffness of the pile is not of much consequence. Its effect on consolidation is not large, as may be seen from Figure 8, Ref. 1. The shearing off and deformation of a sandpile under vertical strains is more serious.

In some experiments, it was noticed that the volume of water drained was not increased substantially by raising the pressure from 5 to 10 psi. This leads to the belief that the capacity of the drains is mostly the controlling factor rather than the pressure itself. Evidently in order to achieve considerably accelerated drainage, the number of drains should be increased and their spacing decreased. For such cases, the engineer will find that concrete drains are very well adapted since by increasing their number, smaller diameter piles, *e.g.*, 8 in., can be readily used. Reducing the diameter decreases the weight of the pile and makes it easier to handle. For sand piles, diameters below 12 in. are disadvantageous because filling the mandrels is more time-consuming and the danger of arching greater.

ACKNOWLEDGEMENT

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