A STUDY OF SUPPLEMENTAL DRAINAGE METHODS FOR PREVENTING FROST HEAVE IN FULL-DEPTH CONCRETE SHOULDERS

MICHIGAN DEPARTMENT OF STATE HIGHWAYS AND TRANSPORTATION

TESTING AND RESEARCH DIVISION
RESEARCH LABORATORY SECTION

A STUDY OF SUPPLEMENTAL DRAINAGE METHODS FOR PREVENTING FROST HEAVE IN FULL-DEPTH CONCRETE SHOULDERS

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INTRODUCTION

Differential shoulder heave has been a long-standing problem throughout the State of Michigan. Early studies of this phenomenon concluded that heaving was caused by frost action in the shoulder base gravel (1). The advent of full-depth shoulders should have eliminated much of this problem since heave potential is the same for pavement and shoulder, i.e., base and subbase layers are of equal thickness under both the shoulder and the pavement. However, full-depth shoulders also were found to be subject to differential heaving.

Paul Baumgartner, District 6 Soils and Materials Engineer, reported heave in full-depth shoulders of as much as 1.8 in., and recommended experimental placement of edge drains to see if improved subsurface drainage would prevent differential heave (2). This recommendation resulted in the construction of concrete shoulders with and without edge drains and observation of comparative heaving. The results, summarized in Table 1 of this report, showed no significant difference in heaving in either of the test sections, so that the study provided no information for comparing the two sections.

L. G. Wittman, District 8 Soils and Materials Engineer, also reported heaving of full-depth concrete shoulders and indicated that this created a particularly unsafe condition because of the exceptionally sharp edge projecting above the pavement surface (3). He proposed a special field study to evaluate the effectiveness of supplemental shoulder drains for alleviating this condition. The project was assigned to the Research Laboratory. This report summarizes results of this study and discusses the effectiveness of improved subbase drainage as a means of preventing differential heave of full-depth concrete shoulders.

Past observation of full-depth shoulder performance and the results of the previous supplemental shoulder drainage studies, reported by Mr. Baumgartner, indicate that shoulder heave does not always occur when no supplementary drainage has been provided. Limiting this study to measurement of differential shoulder heave would provide no meaningful information if no heave occurs in both the control and the supplementary drained shoulders. For this reason the drainability characteristics of the foundation materials were studied in addition to observing differential shoulder movement.

TABLE 1
SUMMARY OF DIFFERENTIAL SHOULDER HEAVE DATA FOR SEVERAL RAMPS LOCATED IN DISTRICT SIX

Location and Description	Differential Heave in Feet (Mean)								
	1970			1971		1972			
	Feb.	Mar.	April	Feb.	Mar.	Jan.	Feb.	Mar.	May
Belsay Rd and M 21									
Ramp "D"	0.06	0.05	0.05	0.03	0.03	0.03	0.04	0.03	0.03
Ramp "E"	0.05	--	0.04	0.02	0.02	0.02	0.02	0.02	0.02
Ramp "C"	0.06	--	0.04	0.01	0.03	0.04	0.03	0.03	0.03
Irish Rd and M 21									
Ramp "B"	0.07	0.06	0.13	0.06	0.02	0.03	0.04	0.03	0.03
Ramp "A"	0.07	0.10	0.05	0.05	0.04	0.06	0.06	0.04	0.04
Ramp "E"	0.07	0.08	0.06	0.04	0.04	0.07	0.06	0.06	0.05
Ramp "F"	0.05	0.06	0.06	0.03	0.02	0.06	0.05	0.04	0.04
M 15 and M 21									
Ramp "G"	0.08	0.09	0.08	0.05	0.04	0.03	0.03	0.03	0.03
Ramp "L"	0.08	0.09	0.04	0.02	0.03	0.03	0.04	0.03	0.02
Ramp "N"	--	--	--	0.03	0.02	0.03	0.03	0.05	0.04
Ramp "J"	0.09	0.09	0.06	0.03	0.04	0.04	0.03	0.04	0.04
Ramp "H"	--	--	--	0.05	0.04	0.00	0.01	0.01	0.01
Center Rd and M 21									
Ramp "A" (Edge Drains)	--	--	--	--	--	0.03	0.02	0.03	0.03
Ramp "B" (Control Section)	--	--	--	--	--	0.02	0.02	0.02	0.02

The drainage analysis of base-subbase layers is very complex and the addition of supplementary edge drains adds to the complexity. Casagrande's method of determining base-subbase drainability (4) was used in this study along with work reported by Hsia (5), who adapted Casagrande's method to drainage shapes found in standard Michigan pavement cross-sections. Conventional analyses were used to determine the relative rate that water, which saturates base and subbase layers, flows to the downslope toe of the subbase layer and the edge drains.

The drainage analysis was made to determine if the base and subbase layers can become saturated by water infiltrating the surface. If they can, then the time required for these layers to remove 50 percent of the gravity drainable water, t_{50}, can be determined. These data are used with the general assumption that the rate with which the base-subbase layers can remove gravity drainable water is inversely related to the probability that differential shoulder heave will occur.

DESCRIPTION OF THE TEST SECTIONS

The test areas chosen for this study are located on the Butterfield and Ainger Rd ramps of I 69 in southern Eaton County (Fig. 1). Each test area, located as shown in Figure 2, was originally divided into two test sections, the control which has the standard ramp cross-section and the experimental section whose only difference, compared to the control section, is the addition of edge drains. Sections containing shoulder hook-bolts were added, so that each test area consists of four test sites. The layout of each site, as constructed, is shown in Figure 3. The cross-section of each is shown in Figure 4.

Construction of the test areas was completed during the 1972 construction season except for placement of a bituminous shoulder cap over the concrete shoulders. Shoulder caps were paved early in 1973. Construction of each test section was observed closely and found to generally conform to the dimensions shown in Figure 4. Representative samples were collected from each pavement layer during the course of construction.

While observing construction of the supplemental shoulder drains it appeared that the scope of the excavation and backfilling operation, and the size of drain pipe used, all of which are standard for the Department, were much larger than needed for draining the base-subbase layers. Shallow 4-in. drains, placed in the subbase, should be much less expensive and just as effective in removing water from the base and subbase layers.

TESTING

As construction progressed, randomly selected samples were collected from each drainage layer, i.e., subgrade, subbase, base, and porous drain backfill materials Class I and II. When a pavement layer, such as the subbase, was placed in two or more sub-layers, each sub-layer was sampled. Each sample was a composite of five or more shovelsful of material from the general sampling area and weighed approximately 50 to 60 lb each.

Each field-collected sample was quartered into four smaller samples one of which was used to determine T-99 density, the other three were used to conduct permeability tests. Permeability test samples were compacted to between 95 and 100 percent of T-99 density. All permeability tests were conducted in accordance with ASTM specifications except that the piezometric head difference was measured at the center of the sample instead of at the edge and samples were capillary saturated rather than vacuum saturated. The average of the three permeability tests are recorded as

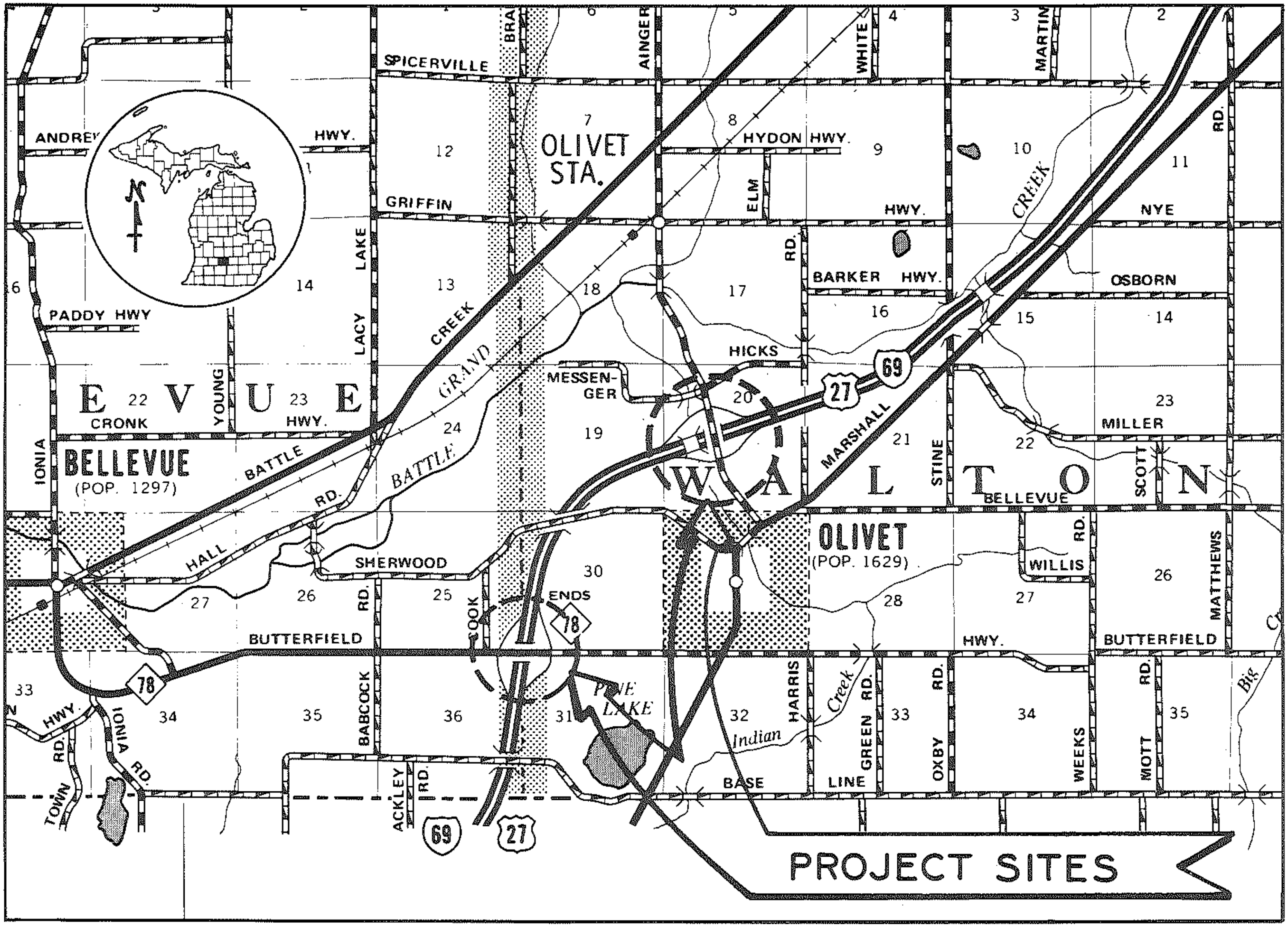


Figure 1. General location of Ainger Rd and Butterfield Rd ramp test sites.

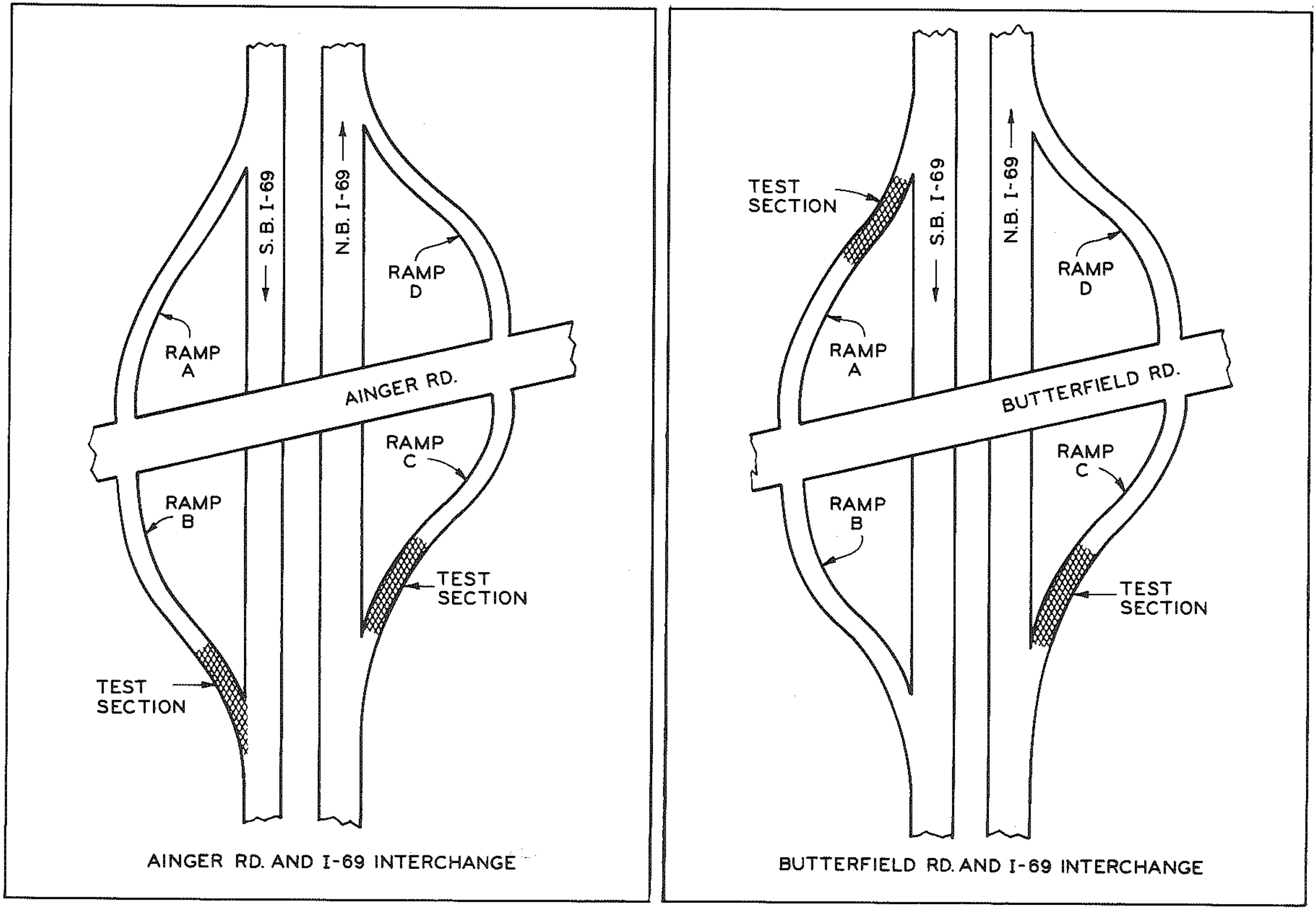


Figure 2. Location of test sections on the Ainger Rd and Butterfield Rd ramps.

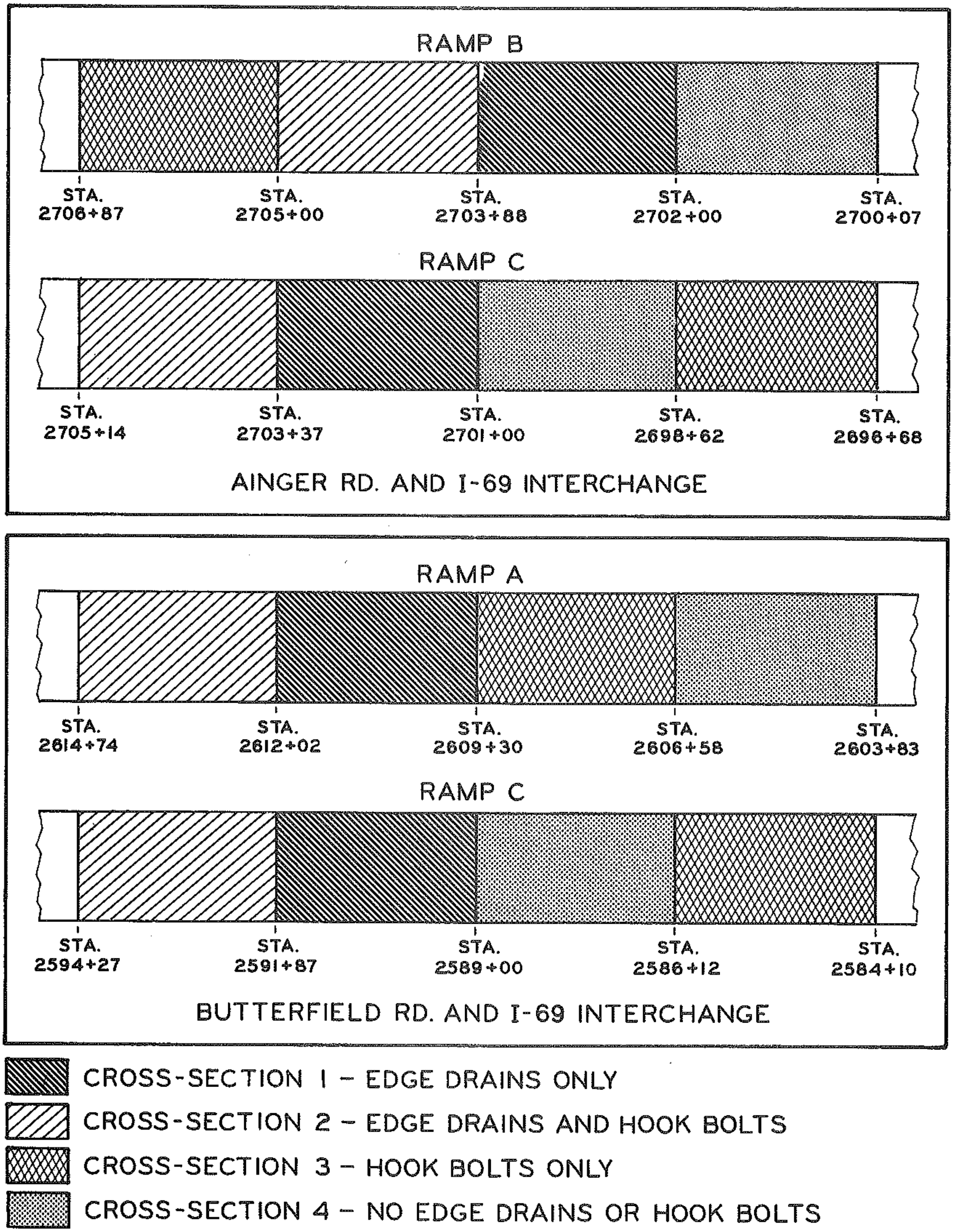
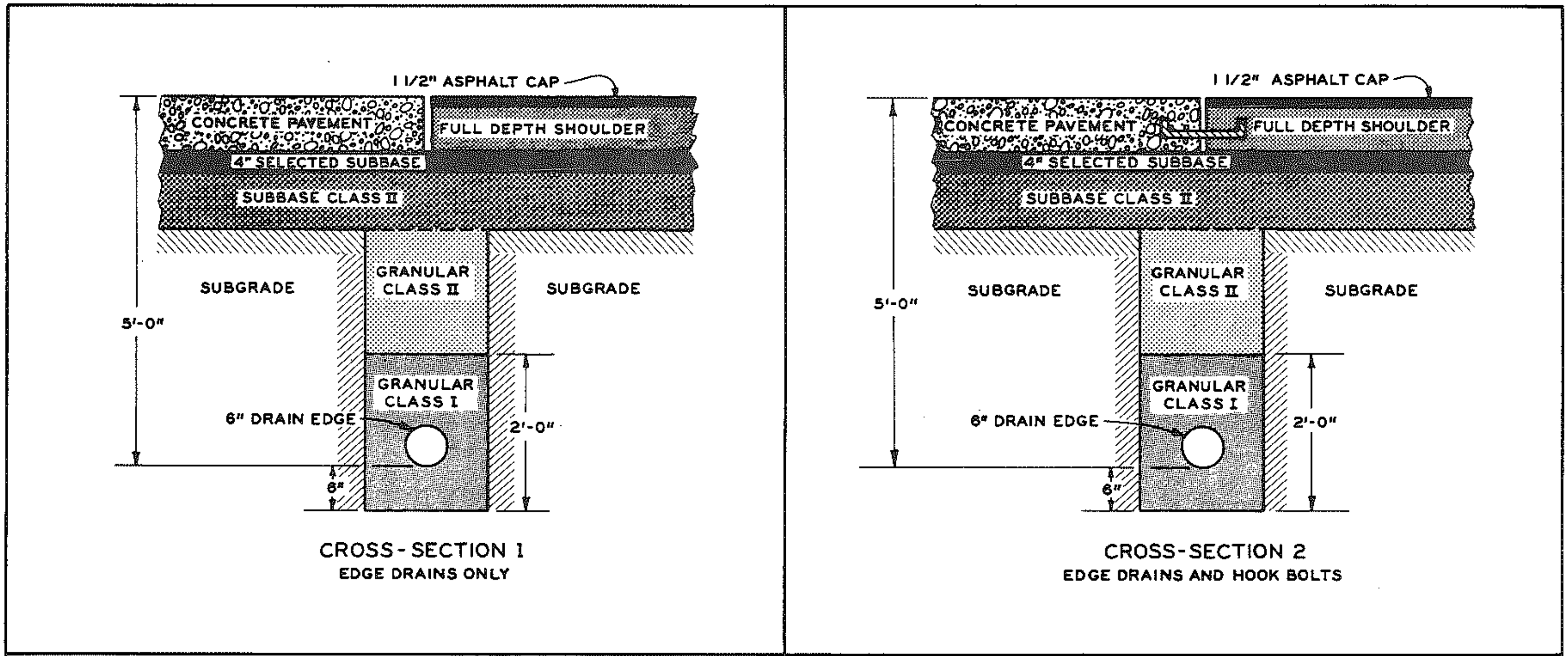
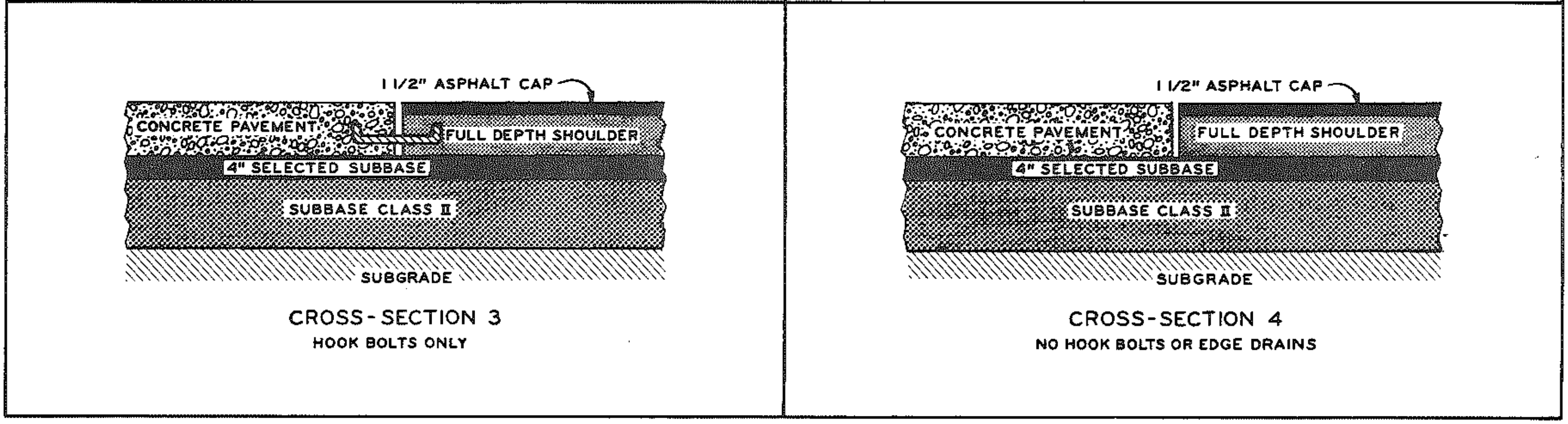


Figure 3. Edge drain and hook bolt layout of the two test sections.



CROSS-SECTION 1
EDGE DRAINS ONLY

CROSS-SECTION 2
EDGE DRAINS AND HOOK BOLTS



CROSS-SECTION 3
HOOK BOLTS ONLY

CROSS-SECTION 4
NO HOOK BOLTS OR EDGE DRAINS

Figure 4. Cross-sections showing edge drain and hook bolt layouts.

the permeability of the sample. On completing each permeability test, the effective porosity (ratio of the volume of gravity drainable voids to soil bulk volume) was determined in accordance with procedures outlined on pages 18 and 19 of Ref. (6). The permeability and effective porosity data are summarized in Table 2.

TABLE 2
SUMMARY OF PERMEABILITY, k, AND
EFFECTIVE POROSITY, n_e, DATA

Shoulder Layer	Permeability, k, in ft/day and Effective Porosity, n_e							
	Butterfield				Ainger			
	Ramp A		Ramp C		Ramp B		Ramp C	
	k	n_e	k	n_e	k	n_e	k	n_e
Base	3.7	---	3.5	---	4.4	---	4.3	---
Subbase	6.3	0.083	13.8	0.077	2.3	0.080	2.7	0.079
Class II	0.9	0.071	2.0	0.078	6.8	0.085	2.7	0.077
Class I	6.7	0.080	29.4	0.062	10.5	0.079	6.8	0.080
Horizontal (base-subbase) k	5.6	---	10.9	---	2.9	---	3.2	---
Vertical k, to edge drain	1.4	---	2.9	---	4.9	---	3.0	---

$$k_{horz.} = \frac{t_1 k_1 + t_2 k_2}{t_1 + t_2}$$

$$k_{vert.} = \frac{t_1 + t_2 + t_3 + t_4}{\frac{t_1}{k_1} + \frac{t_2}{k_2} + \frac{t_3}{k_3} + \frac{t_4}{k_4}}$$

where: t_1 = thickness of layer 1, etc.
k_1 = permeability of layer 1, etc.

Pins were placed in each test section so that shoulder heave rates could be monitored with the aid of the specially constructed device shown in Figure 5. Readings were taken before the start of each freezing season, during November, and periodically thereafter. The initial (November) reading for each test site is plotted as zero.

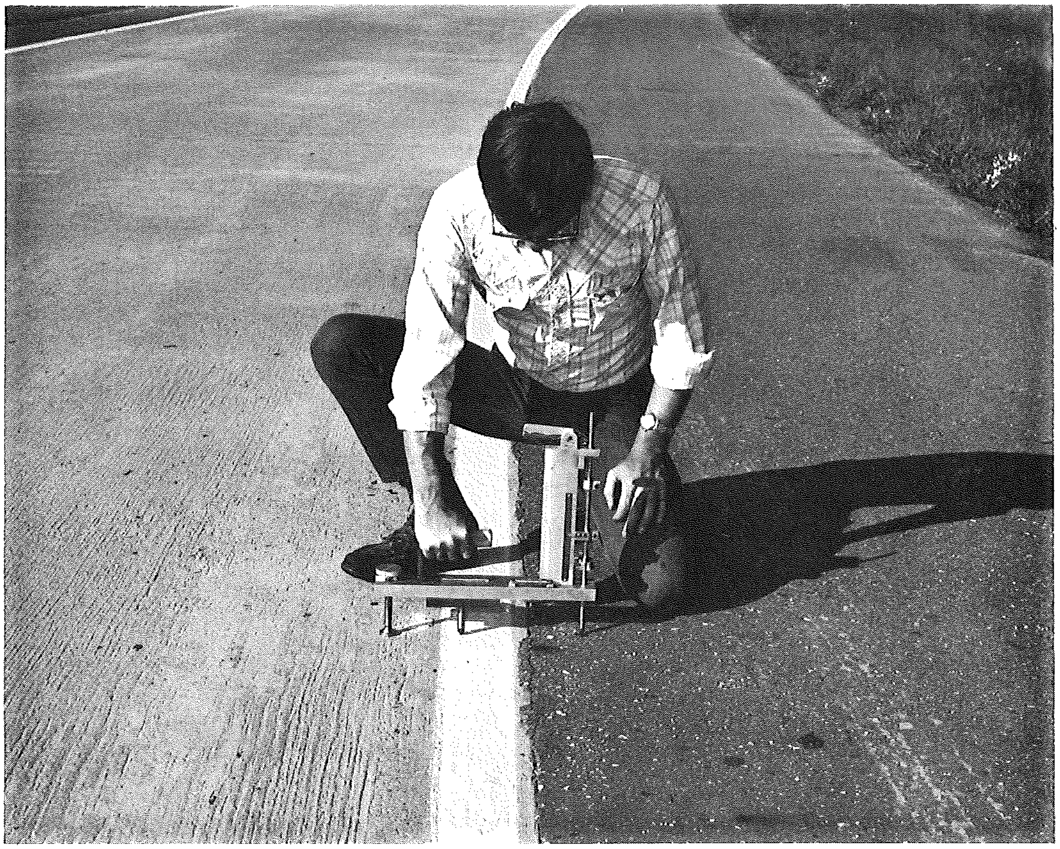


Figure 5. Device used to measure differential shoulder heave.

DRAINAGE ANALYSIS OF THE TEST SECTIONS

Just how full-depth shoulders can heave above the pavement when the foundation layers (base, subbase, and subgrade) of both shoulder and pavement are homogeneous and of uniform thickness is not known for certain. Shoulder heave has occurred only on the lower shoulder of superelevated ramps. Figure 6 illustrates a hypothetical condition that may result in shoulder heave. The hypothesis requires that the subbase under the shoulder be over 90 percent water saturated while being less than 90 percent saturated under the pavement. This assumes the subbase can cause heave (by expansion of the water in it due to freezing) only when it is over 90 percent saturated (1, 7). On the basis of the above, frost heave of the full-depth shoulders would be indirectly related to the drainability of the subbase layer since the greater the drainability, the less time it will take the subbase to drain to less than 90 percent saturation.

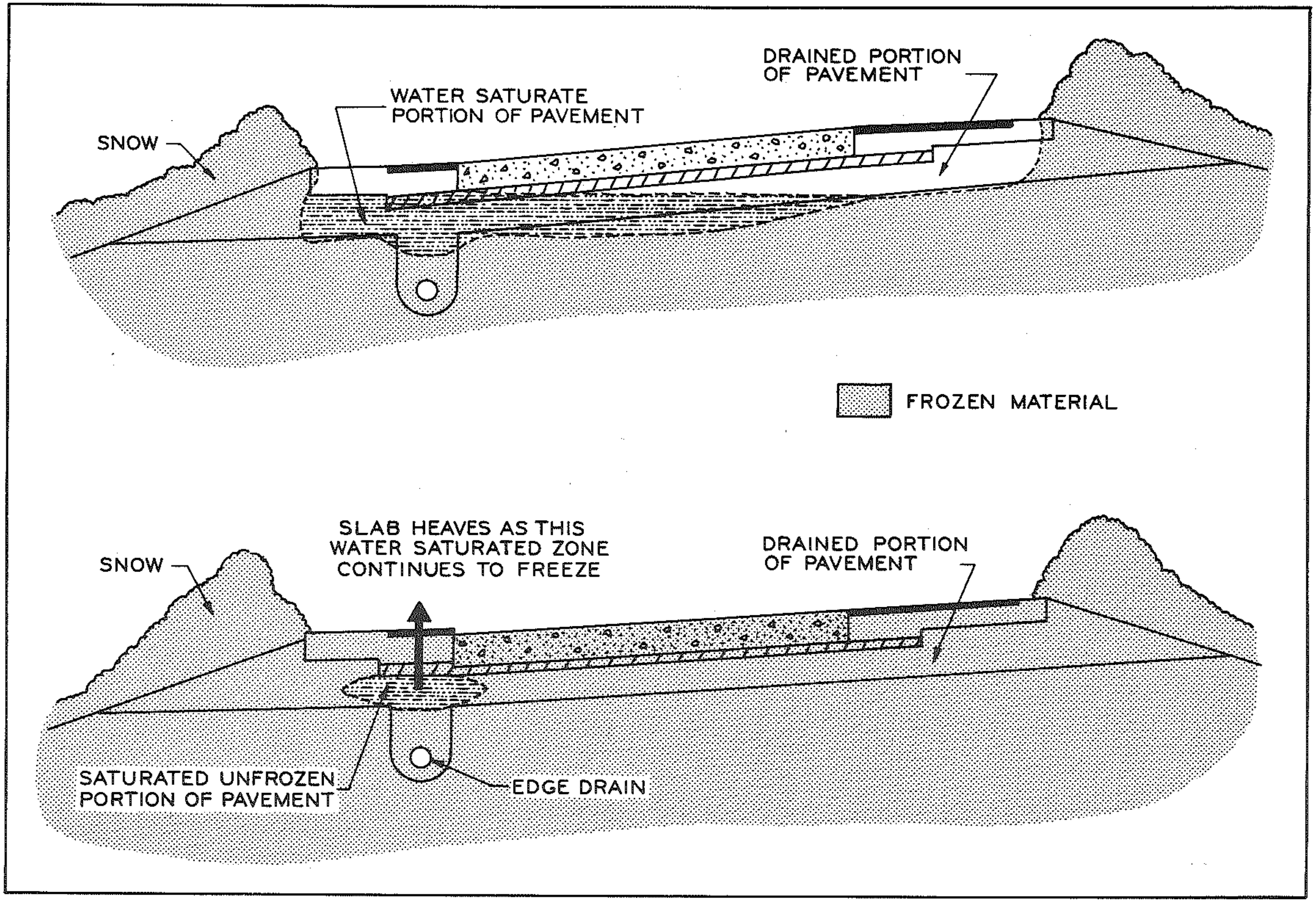


Figure 6. Refreezing of the pavement when in the condition shown in the upper drawing leaves a zone of saturated, unfrozen subbase (lower drawing) and when this freezes it expands about 10 percent, thus heaving the shoulder only.

The determination of subbase drainability is very complex and no methods of dealing directly with the problem could be found in the literature. Because of this complexity, development of an exact solution is beyond the scope of this project. Instead, existing approximate methods are used so that the relative base-subbase drainage rates, with and without edge drains, can be estimated. The assumptions made for drainability analysis are as follows:

1) Casagrande's analysis is valid for horizontal flow,

2) the base, subbase, and edge drain backfill materials are homogeneous and isotropic,

3) flow occurs in either the horizontal or vertical direction,

4) Darcy's law can be applied to an isotropic flow medium, and

5) the principal source of water in the foundation is surface water that infiltrates the crack at the pavement-shoulder interface.

The basic concept used in this study is that surface-infiltrated water, through horizontal and vertical seepage, can cause 100 percent saturation of the pavement foundation layers, if the rate at which water can infiltrate the crack at the pavement-shoulder interface exceeds the rate at which the edge drain (vertical flow) or flow through the toe of the subbase (horizontal flow) can remove infiltrated water. For vertical seepage it is assumed that the drainage area, A, is a function of the diameter of the drain pipe, D, and that the edge drain discharge can be computed as follows:

$$q = k i A \tag{1}$$

where q = seepage quantity

k = permeability in vertical or horizontal directions

i = hydraulic gradient

Permeability in the vertical direction, k_V, can be determined using the equation

$$k_V = \frac{t_1 + t_2 + --- + t_n}{t_1/k_1 + t_2/k_2 + --- + t_n/k_n} \tag{2}$$

The horizontal seepage quantity, q, can also be computed from equation (1) and using the permeability in the horizontal direction, k_h, which can be determined by using the equation:

$$k_h = \frac{k_1 t_1 + k_2 t_2 + --- + k_n t_n}{t_1 + t_2 + --- + t_n} \tag{3}$$

where k_1 = permeability of layer 1, etc.

t_1 = thickness of layer 1, etc.

Table 3 summarizes the rate at which surface-infiltrated water can be removed from ramps with edge drains and from those which drain through the toe of the subbase. These results indicate that the use of edge drains increases the rate at which water can be drained from the subbase but that their effectiveness is reduced when the porous backfill material is of low permeability.

TABLE 3
SUMMARY OF RATE OF DRAINAGE FROM TOE OF THE SUBBASE LAYER AND FROM EDGE DRAINS AND RATE OF SURFACE WATER INFILTRATION OF THE JOINT AT THE PAVEMENT SHOULDER INTERFACE

Description	Infiltration and Drainage Rates, Q, in cu ft/day/ft			
	Butterfield		Ainger	
	Ramp A	Ramp C	Ramp B	Ramp C
Rate of Drainage From:				
Toe of Subbase Layer	0.75	1.46	0.39	0.43
Edge Drain, where: A = 0.5D[1]	0.60	1.23	2.08	1.28
A = D	1.19	2.47	4.16	2.55
A = 1.5D	1.79	3.70	6.25	3.82
A = 2D	2.38	4.93	8.33	5.10
Rate of Infiltration	7.44	7.44	6.24	6.24

[1] The area, A, through which vertical drainage takes place is assumed to be a function of the diameter of the edge drain, D.

The rate at which water can infiltrate through a crack in the pavement has been reported by several researchers. For this study, the method of computing the rate of infiltration was that proposed by Ridgeway (8) and is calculated using the following equation:

$$Q = 0.1 \left(N + 1 + \frac{W}{S}\right)$$

where Q = rate of infiltration in cubic feet per hour per linear foot of pavement

0.1 = infiltration rate of 0.1 cubic foot per hour per foot of crack

N = number of lanes

W = pavement width

S = length in feet of portland cement concrete.

The width of the Butterfield and Ainger Rd ramps is 16 ft and their respective joint spacings are 20 and 72 ft. The number of lanes is considered to be 1.33 since the standard lane width is 12 ft. On the basis of these values Butterfield ramps have an infiltration rate of 0.31 cu ft/hr/ft and Ainger of 0.26 cu ft/hr/ft.

These data show that the rate of infiltration would exceed the rate of discharge from either the toe of the subbase or from the edge drains. Therefore, the base and subbase layers of all the ramp test sections included in this study can become saturated by infiltration of surface water.

On the basis of the above drainage analysis, it is concluded that the subbase of all ramp sections included in this study will at times be saturated by surface infiltrated water. The next question is, how long will it take for this water to drain away assuming no more infiltration or other sources of water are entering the base-subbase system? For this analysis Casagrande's basic method (4) is used to determine the time required for 50 percent of the gravity drainable water to be removed. The complicated shape of Michigan's standard pavement cross-sections made it necessary to modify and adapt Casagrande's method to these cross-sections. Using procedures outlined in Ref. (5) drainage times, t_{50}, were calculated for maximum 0.07 ft/ft, and minimum 0.02 ft/ft, superelevations for both control and edge-drained test sections. These results, summarized in Table 4, show that edge drains greatly improve drainability, but that all sections, with the exception of Ainger ramp B with a 0.02 ft/ft superelevation, drained within the maximum time limit established by Casagrande.

TABLE 4
DRAINAGE TIME, t_{50}, IN DAYS

Drainage Condition	Drainage Time, t_{50}, in Days			
	Butterfield		Ainger	
	Ramp A	Ramp C	Ramp B	Ramp C
Rate of Super = 0.02 ft/ft				
No Edge Drain (Control Sections)	5.0	2.3	10.4	9.2
Right of Edge Drain (Test Sections)	0.4	0.2	1.1	0.9
Left of Edge Drain (Test Sections)	1.1	0.5	4.1	3.1
Rate of Super = 0.07 ft/ft				
No Edge Drain (Control Sections)	2.2	2.2	8.9	8.1
Right of Edge Drain (Test Sections)	0.2	0.2	1.5	1.3
Left of Edge Drain (Test Sections)	0.4	0.4	4.3	3.2

SHOULDER PERFORMANCE OBSERVATIONS

Figures 7 through 10 summarize the differential shoulder movement data collected during the first three freezing seasons after their construction. These figures indicate that no significant shoulder heave occurred in either the control or the edge drain sections, duplicating, essentially, the results reported by Baumgartner (2). However, some shoulder sections settled as much as 1/3 in. This settlement, as Figure 7 illustrates, did not occur in hook-bolt sections.

The edge drains have been observed to carry intermittent water flow as is illustrated by the deposits of eroded fines leading out of the drain outlets (Fig. 11). However, the drains have been found to carry water only after periods of heavy rainfall. The erosion of porous backfill material which almost clogs the drain outlets is an indication that drain pipe holes are too large or that the porous backfill material gradation is not providing adequate filtration.

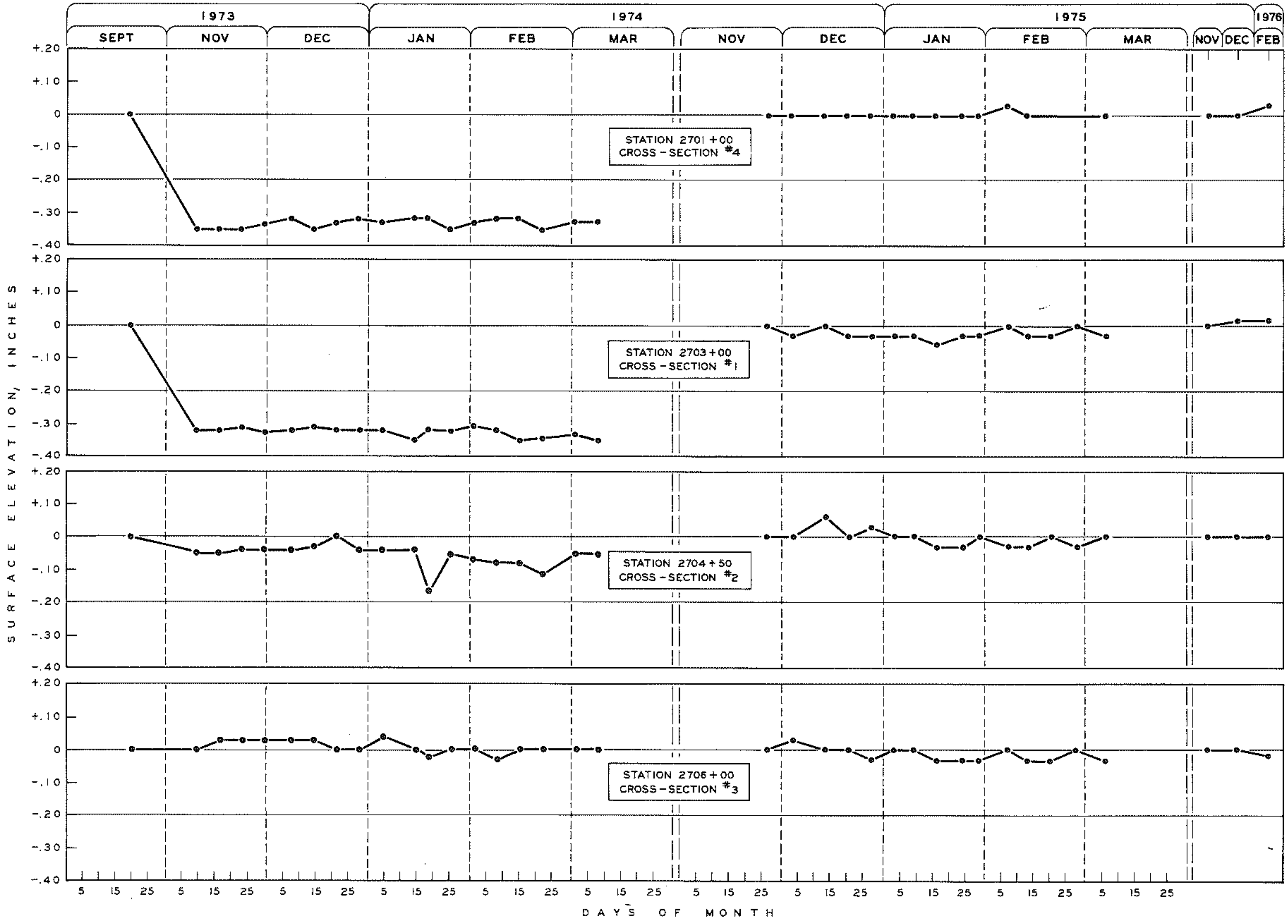


Figure 7. Differential shoulder movement of Ainger Rd Ramp B test sections.

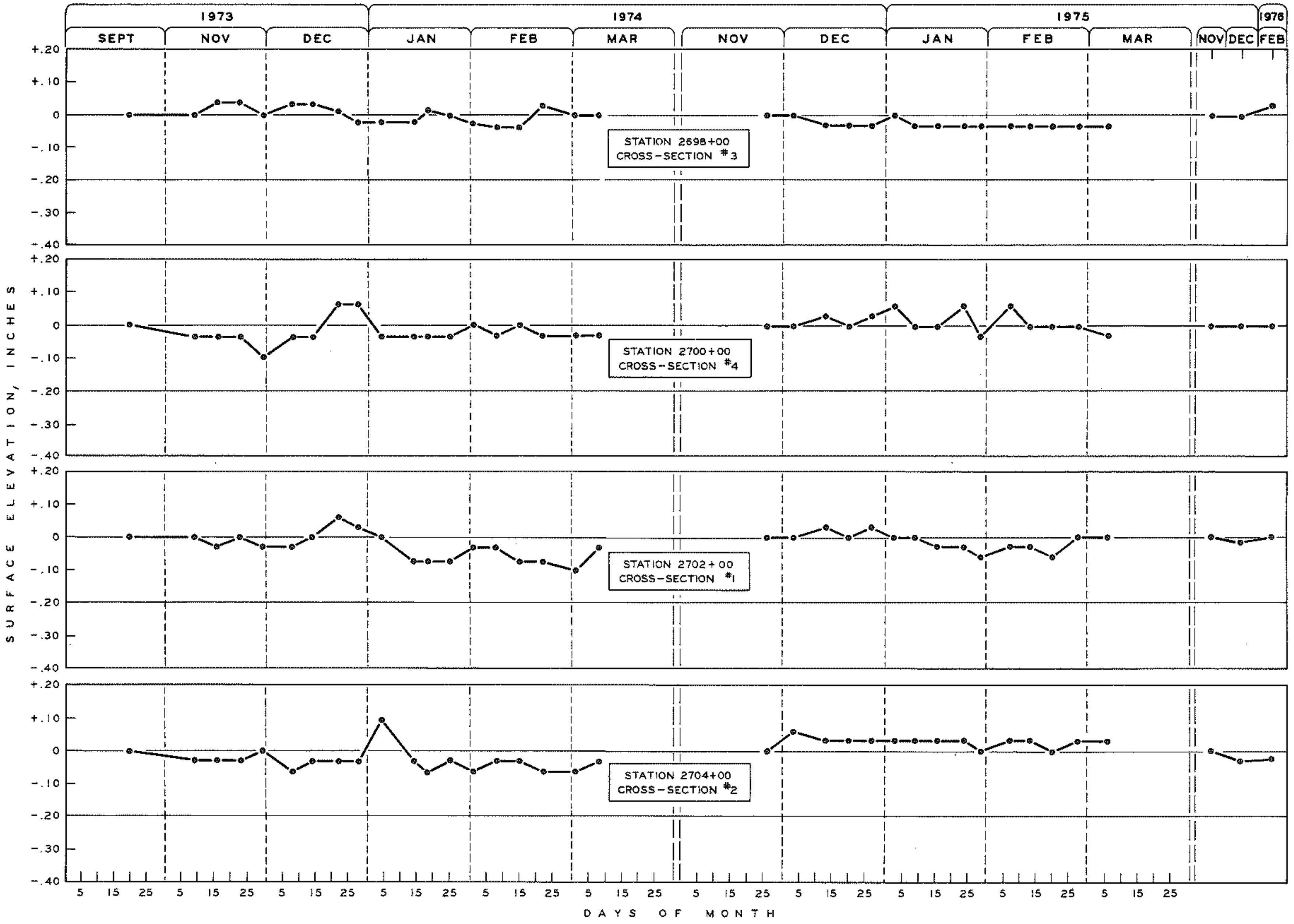


Figure 8. Differential shoulder movement of Ainger Rd Ramp C test sections.

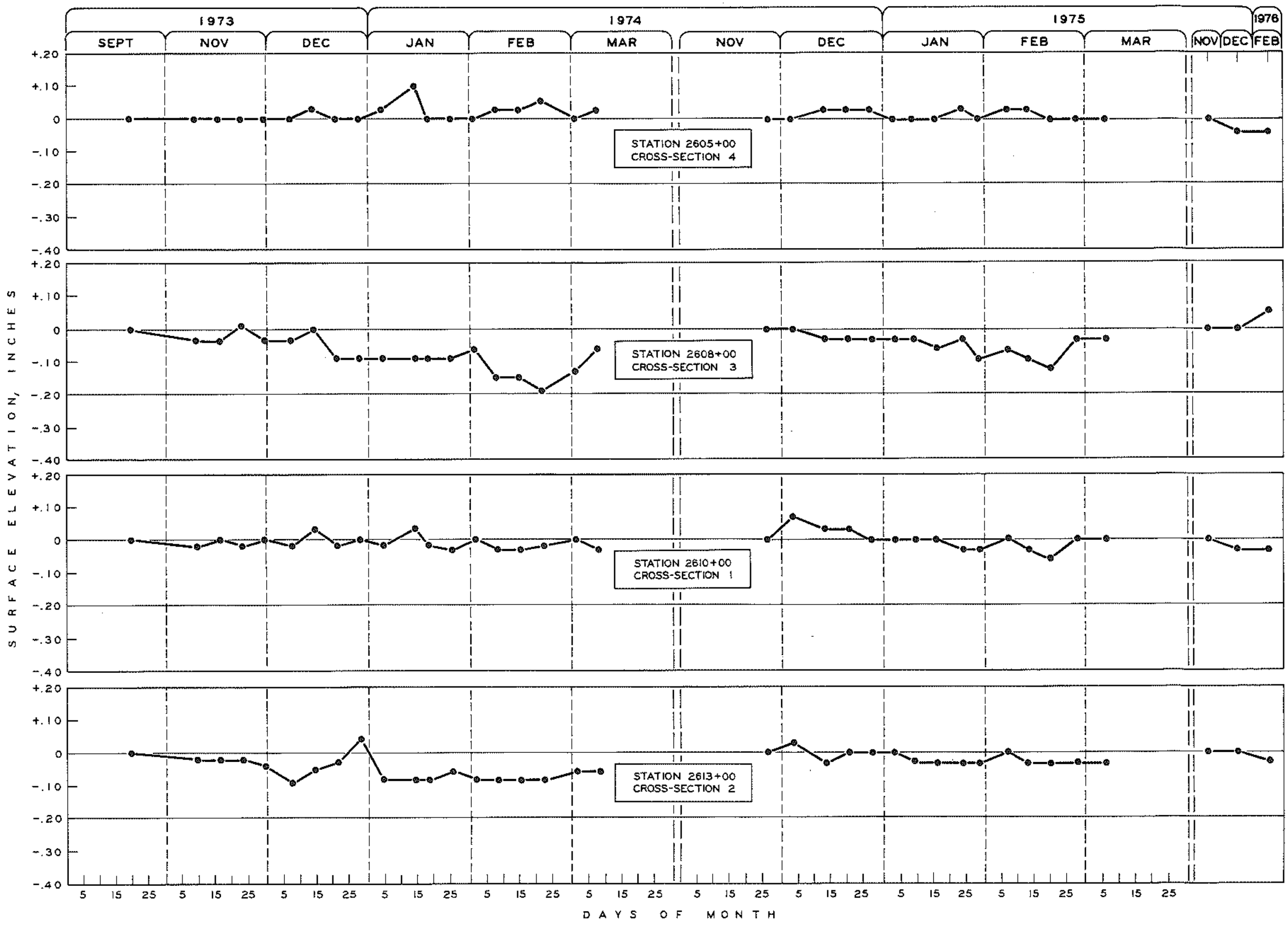


Figure 9. Differential shoulder movement of Butterfield Rd Ramp A test sections.

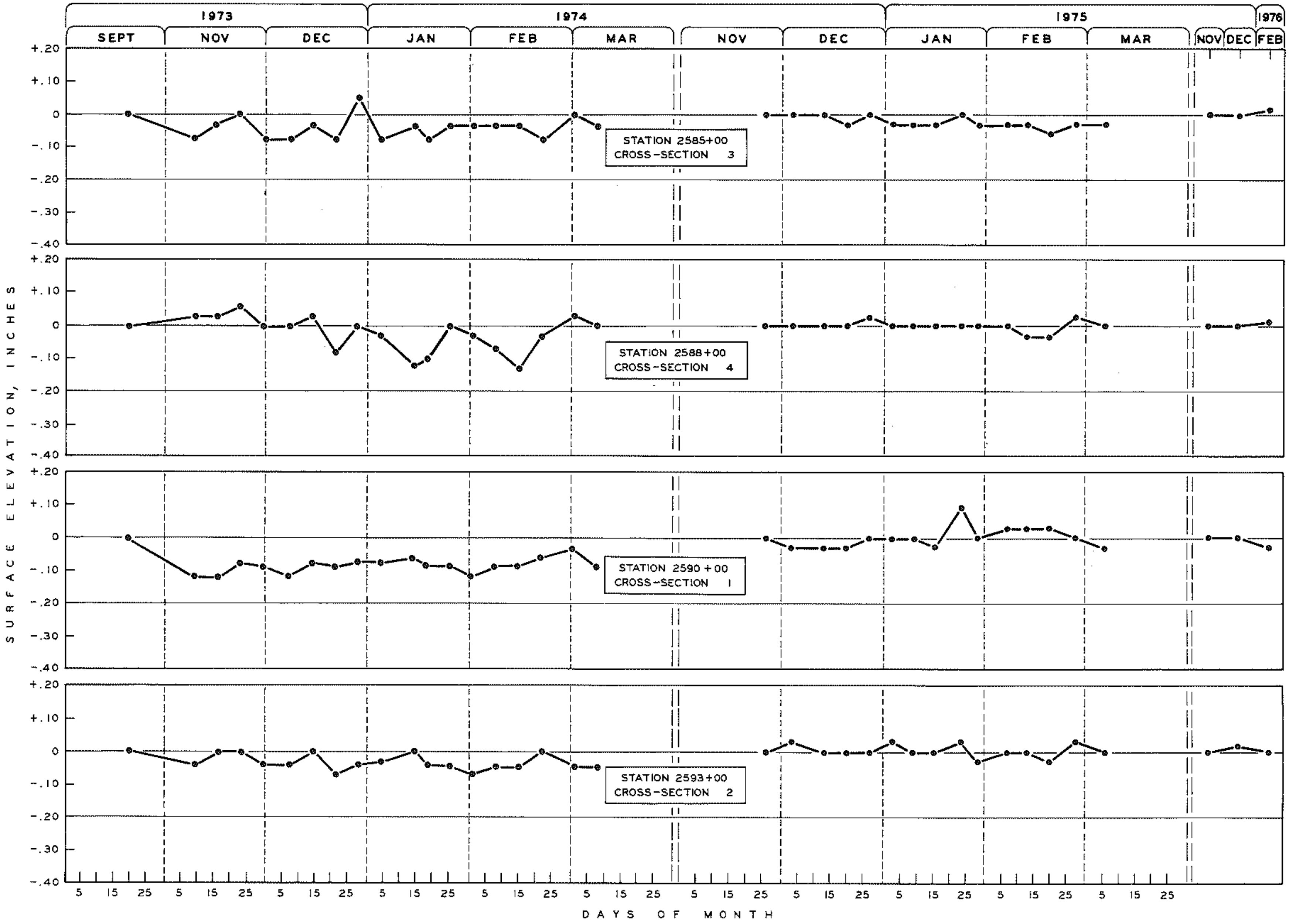


Figure 10. Differential shoulder movement of Butterfield Rd Ramp C test sections.

Ainger Rd Ramp C

Butterfield Rd Ramp A

Figure 11. Edge drain outlets.

DISCUSSION

The use of edge drains to prevent differential shoulder heave has been investigated in this study, as well as in a previous study, and both have failed to indicate that installation of edge drains will prevent shoulder heave. The reason for this is that no significant shoulder heave has taken place in any of the test sections involved in the studies.

Drainage analysis conducted for this study shows that both the control and edge-drained sections can become saturated by infiltrating surface water but that once infiltration stops, gravity drainage time for 50 percent drainage (t_{50}) generally takes place in less than 10 days, with 10.4 days being the maximum drainage time. Casagrande indicates that if 50 percent drainage occurs in 10 days or less, the drainability of the base-subbase should be adequate for good pavement performance. Had this drainage criteria, as proposed in Refs. (5) and (9) been used to determine the need for supplementary subbase drainage, it would have been found that edge drains were needed only on Ainger Rd ramp B, but that this need is borderline because drainage time, t_{50}, only slightly exceeded the 10-day limit.

Figure 6 shows that the base and subbase can be thawed and accept surface-infiltrated water while frozen layers prevent its drainage. Under these conditions it makes no difference if the base-subbase layers are adequately drainable or not since there is no place for the surface-infiltrated water to drain. Thus, conditions which are believed to cause differential shoulder heave may exist even though edge drains have been installed or the base-subbase layers are adequately drainable. However, the longer the base-subbase layers take to drain, under normal conditions, the longer they will be susceptible to differential heave conditions. In the absence of any data it can only be assumed that the probability of differential shoulder heave is inversely related to the time it takes the base-subbase layer to drain.

The drainability results summarized in Table 4 shows that edge drains greatly improve base-subbase drainability. However, the standard edge drain is placed 5 ft below plan grade so that, during the critical spring break-up period, drainage to these edge drains may be blocked by frozen soil.

The fact that shoulders heave only during the winter and early spring months is positive evidence that excess water in the pavement foundation layers is responsible for shoulder heave. The installation of hook-bolts can prevent differential movement of the shoulders but this does not preclude the possibility that excess water will manifest itself through some other form of distress. It is well known that pavement foundation strength is indirectly related to its water content. Thus, pavement foundations which rapidly drain away surface-infiltrated water are stronger and have more uniform strength through the season than those which do not drain readily. Therefore, providing rapid and positive base-subbase drainage should preclude the occurrence of shoulder heave and improve long-term pavement performance characteristics.

Subbase drains placed in the subbase layer, as indicated in Ref. (10), are preferable to standard edge drains for improving base and subbase drainability, primarily because they can drain these layers during thaw. Furthermore, subbase drains are much cheaper. The use of subbase drains, such as shown in Figure 12, can provide positive drainage of the base-subbase layers under all conditions, thus eliminating, for all practical purposes, any potential for differential shoulder heave.

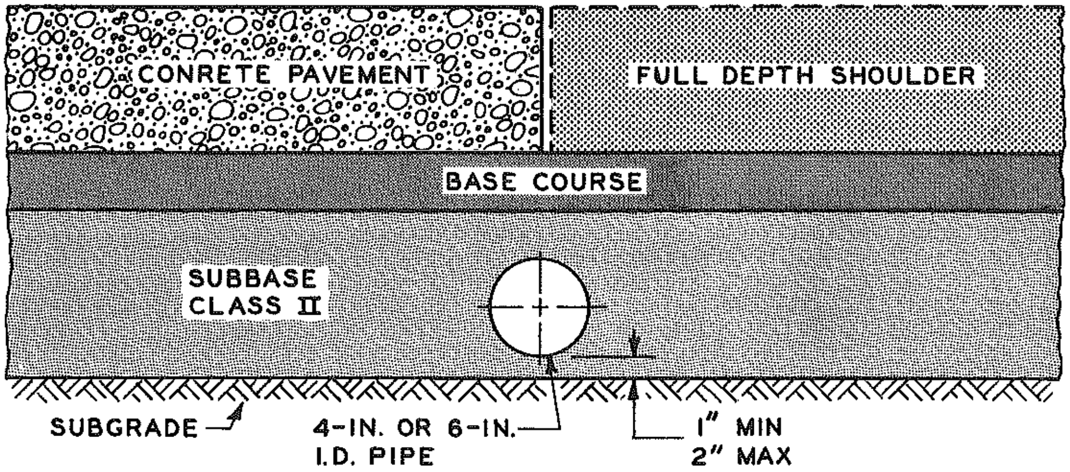


Figure 12. Typical subbase drain cross-section.

Although this project did not achieve its intended purpose of determining if edge drains would eliminate or reduce differential shoulder heave, it did point out that attaching the shoulder to the pavement slab with hook-bolts essentially eliminated the shoulder settlement that occurred in the non-hook-bolted sections (Fig. 7). The most positive method of preventing differential shoulder movement should be to hook-bolt them to the pavement slab.

SUMMARY AND CONCLUSIONS

Four separate ramps were constructed to include four test sections each. The control section has the standard ramp cross-section and the drained section also has the standard ramp cross-section but includes a supplementary edge drain. The purpose of this study was to determine if the supplementary drainage would prevent differential shoulder heave. The results show that neither the control nor supplementary drained test sections heaved, so that no specific information concerning the value of the supplementary drainage was obtained.

Drainage analysis of the control and test sections indicated that surface infiltrating water could cause the base and subbase layers to become completely saturated but that once surface infiltration stopped the drainage rate was reasonably fast with the longest drainage time, t_{50}, equal to only 10.4 days, which compares favorably with the maximum time of 10 days recommended by Casagrande.

Installation of supplemental edge drains greatly reduced drainage time but, because of their deep placement, the drains are at times cut off from the base-subbase layers by frozen soil. The placement of subbase drains in the subbase layer would prevent this problem by providing positive drainage whenever the subbase thaws, and would be much less expensive to construct than the standard edge-drains.

The use of hook-bolts to rigidly attach shoulder and pavement slabs essentially eliminated significant settlement of the shoulders included in this study. The use of hook-bolts, however, should not preclude the use of good foundation drainage practices because excess water, if not removed, can reduce the long-term performance of any pavement foundation.

The rationale behind differential heave of full-depth shoulders could not be determined in this study. However, because all of the shoulders studied have good to excellent internal drainability and have not heaved, it is good circumstantial evidence that these two characteristics are related. The implication is that differential shoulder heave can be prevented by insuring that the drainability, t_{50}, of the base and subbase layers meets Casagrande's 10-day limit. Such action should also improve long-term pavement performance.

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