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EFFICACY OF PARTIAL CUTOFFS FOR CONTROLLING UNDERSEEPAGE BENEATH DAMS AND LEVEES CONSTRUCTED ON PERVIOUS FOUNDATIONS

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SYNOPSIS

Control or prevention of seepage is required wherever dams, levees, or other hydraulic structures are underlain by perivious strata of sands and gravels at or near the surface. One method of control is the installation of an impervious cutoff from the base of the structure down to a more impervious stratum. However, in many cases the pervious strata are of such depth that it is impracticable, or would be extremely expensive, to extend the cutoff to an impervious stratum. This paper presents the results of a study of partial cutoffs or cutoffs that do not fully penetrate the pervious strata. This study indicates that, in general, partial cutoffs are not effective in reducing either underseepage or landside uplift pressures.

INTRODUCTION

A considerable portion of the levees in the lower Mississippi River valley are founded on a thin top stratum of relatively impervious soils underlain by deep strata of pervious sands and gravels. Where this condition exist, excessive seepage and sand boils usually occur during high water. In 1945 an investigation of partial cutoffs as a means for controlling underseepage was initiated by the Mississippi River Commission. In connection with this investigation, the Waterways Experiment Station conducted a series of sand and electrical model tests to study the effect of partial cutoffs on underseepage flow and substratum pressures landward of levees for various foundation conditions, seepage entrances, and landside top strata. This study also included the use of graphical flow nets and mathematical formulas for anylazing the effects of partial cutoffs on underseepage for some of the foundation conditions tested.

Three basic foundation conditions were studied with different seepage entrances and exist. These were: Case I, a homogeneous sand foundation 150 ft deep; Case II, a two-layer foundation consisting of a 50-ft stratum of fine sand overlying a 100-ft stratum of medium sand, the permeability ratio being 1 to 5; and Case III, a stratified foundation consisting of five alternate strata of very fine and medium sand, each 10 ft thick, underlain by a 100-ft stratum of medium sand, the permeability ratio being approximately 1 to 10. Details of the different conditions analyzed are discussed later and are given in table 1. In all cases the partial cutoff was located at the riverside toe of the levee, the base of the levee was 250 ft wide, and the foundation extended 500 ft landward of the levee.

METHODS OF ANALYSIS AND DESCRIPTION OF MODELS

The methods of analyses used in the study of partial cutoffs are described in the following paragraphs together with the general characteristics of the models used. The details of the conditions studied, including the foundation type, seepage entrance and exit conditions, methods of analysis used, and reference to pertinent figures, are included in table 1.

Theoretical

Mathematical analysis of the effect of partial cutoffs is geasible only for certain simplified boundary conditions in a homogeneous foundation. The formulas, with the applicable boundary conditions, which were used to compute the seepage flow and hydrostatic heads at various points in the foundation for Case I are presented in figure 1.

Graphical flow nets

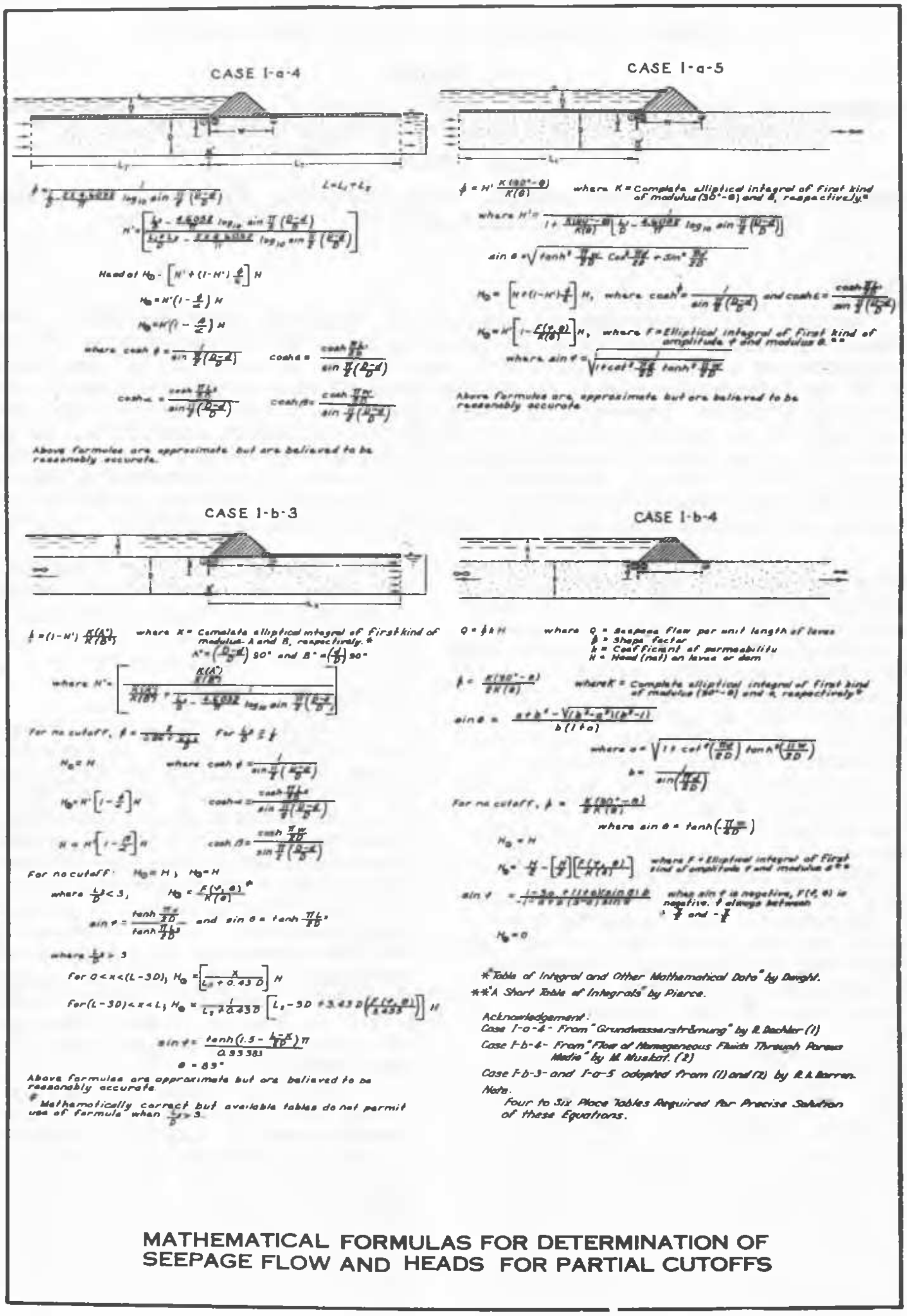
Graphical flow nets were used in analyzing some of the simplified boundary conditions for Cases I and II. These flow nets were drawn to an original scale of 1 to 500. The flow nets for the homogeneous foundation (Case I) were constructed in the usual manner of drawing flow lines and equipotential lines so that they intersected at right angles and approximated squares. The seepage flow was computed from the equation $Q = \frac{f}{} k\ h$ where f is the number of flow channels divided by the number of euipotential drops from the seepage entrance to the exit; k is the coefficient of permeability, and h is the net head. The hydrostatic head at any point was interpolated from the equipotential lines.

The flow nets for the two-layer foundation (Case II) were constructed in a similar manner, except that in the more pervious stratum the flow lines and equipotentials formed rectangles with sides in the ratio 1 to 5 to allow for the 1-to-5 ratio in the permeabilities between the strata. The permeability used in computing flow by means of the above equation was that for the stratum in which the flow and equipotential lines formed squares.

Sand model

Sand model tests were made for the homogeneous foundation (Case I) only. Because of excellent correlation between the results of this model and those obtained by mathematical and flow-net analyses and with the electrical model, sand model tests of the other foundation types were not performed.

The sand model tests were performed in the flume shown in figure 2. The model was approximately 19-1/3 ft long, 2 ft high, and 3-1/2 ft wide. The levee was 8 in. high and 3-1/3 ft wide at the base. A uniform, roundgrained sand was used for the pervious foundation. The scale of the model was 1 to 75. One side of the flume, constructed of steel, was tapped at numerous points for piezometers by means of which pressure within the foundation could be observed. The other side of the flume was constructed of plate glass which permitted the use of dye lines for tracing flow patterns.



MATHEMATICAL FORMULAS FOR DETERMINATION OF SEEPAGE FLOW AND HEADS FOR PARTIAL CUTOFFS

FIG. 1

The cutoff at the riverside toe of the levee was constructed of a 1/4-in. plastic plate, the sides of which were grooved to permit sliding along a plastic tube set in a vertical brass plate flush with the inside walls of the flume. The cutoff plate was installed with full penetration of the pervious stratum prior to placement of any sand. After the sand and levee were placed, the cutoff was tested for watertightness and then pulled up to the first cutoff penetration to be tested. All the tests for different seepage entrances and landside top strata were performed before raising the cutoff to the next penetration to be tested.

The relatively impervious landside top strata in the sand model were simulated with a 1/8-in. plastic plate perforated with 0.025-in. holes on different spacings. For top stratum A these holes were spaced on 2-1/2- by 5-in. centers; for top stratum B the holes were on 2-1/2- by 2-1/2-in. centers.

These top strata with no cutoff, resulted in residual hydrostatic heads at the landside toe of the levee of 49 per cent and 38 per cent of the net head, respectively, when the entranc was at the river 700 ft ftom the cutoff (Case I-a). When there was no river side top stratum (Case I-b), the relatively impervious top strata A and B caused residual hydrostatic heads at the landside toe of the levee of 68 per cent and 63 per cent of the net head, respectively.

Electrical models

The similarity between Darcy's law for the flow of fluids through porous media and Ohm's law dor the flow of electricity through a pure

FIG. 2

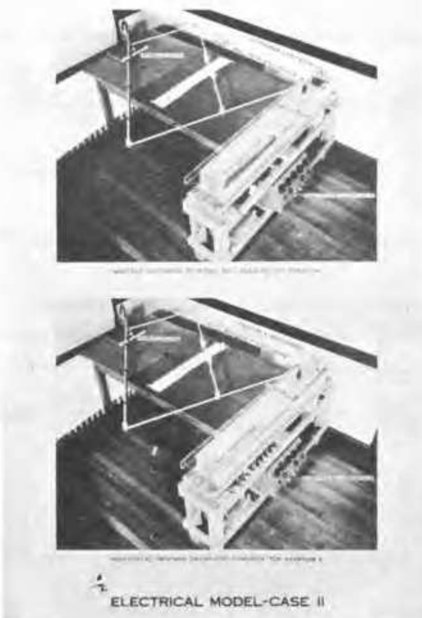


FIG. 3

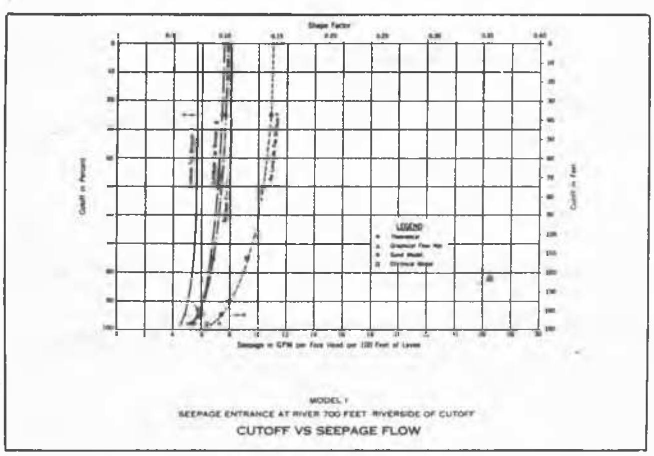


FIG. 4

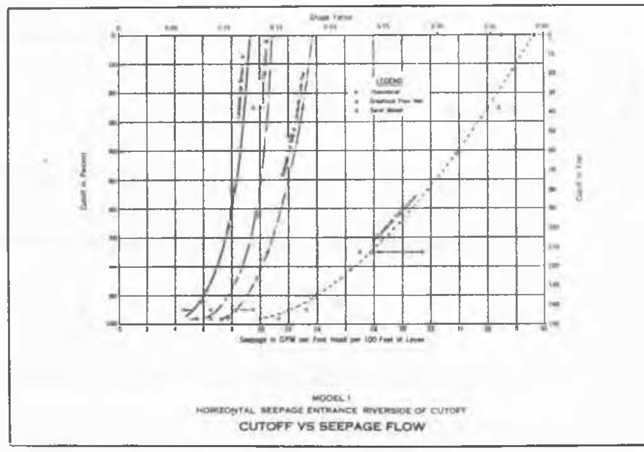


FIG. 5

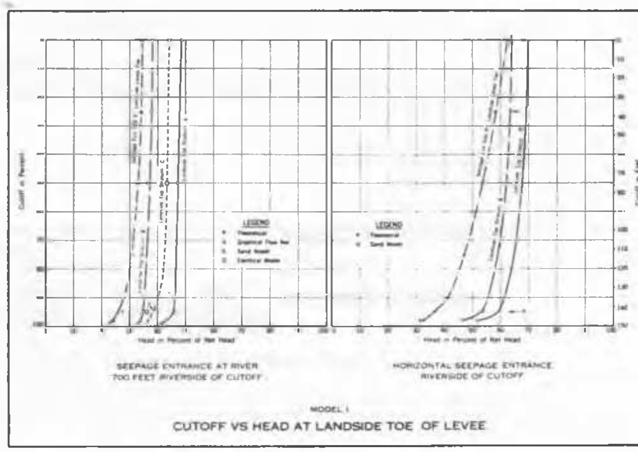


FIG. 6

resistance permits the use of electrical models to study seepage problems. In the mathematical expressions of these laws, the permeability in Darcy's law corresponds to the reciprocal of the resistivity of Ohm's law. Consequently, permeability ratios are represented in an electrical model by the inverse of the ratios of resistivities.

Two types of elctrical models were used in studying the three foundation conditions; the first type was used for Cases I and II, the second for Case III only.

The first model represented the homogeneous foundation (Case I). It consisted of a plexiglass tank 50 in. long by 6 in. wide filled to a depth of 5 in. with a copper sulfate solution. The model scale was 1 to 300. The width of the model represented the depth of the prototype pervious foundation; the depth of the model had no scale relation to the prototype. Electrical current was run through the model between sheet copper electrodes which extended down the sides of the tank to the bottom and were shaped and placed to represent the prescribed entrance and exit conditions. Cutoffs of various depths were simulated by thin pieces of plexiglass with the width scaled to represent the prescribed depth of cutoff. These were inserted into one side and the bottom of the tank so that no current could leak around them. (See figure 3.)

The electrical circuit consisted of a potential divider connected in parallel with

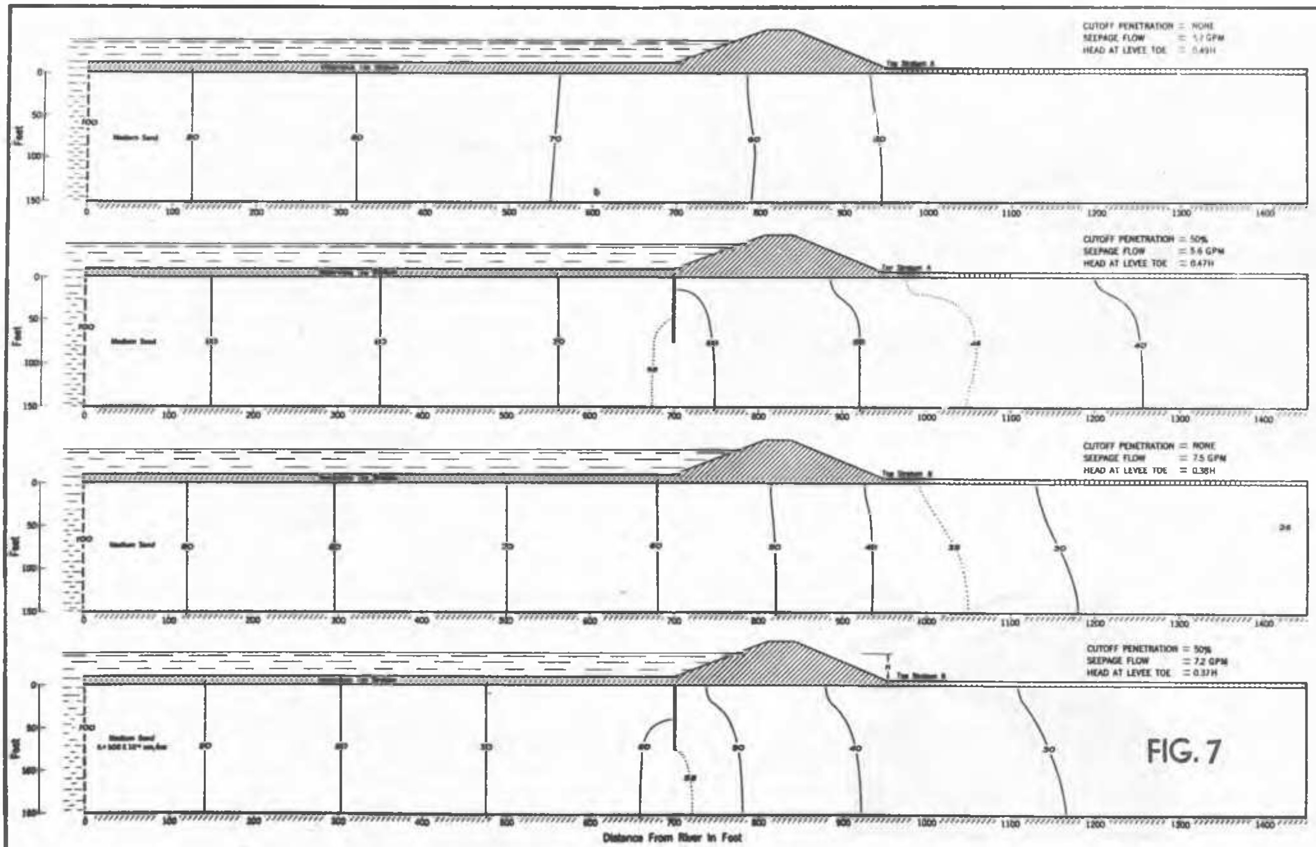


FIG. 7

MODEL I

SEEPAGE ENTRANCE AT RIVER 700 FEET RIVERSIDE OF CUTOFF – LANDSIDE TOP STRATA A AND B – SAND MODEL

EQUIPOTENTIAL LINES FOR 0 AND 50 PERCENT CUTOFFS

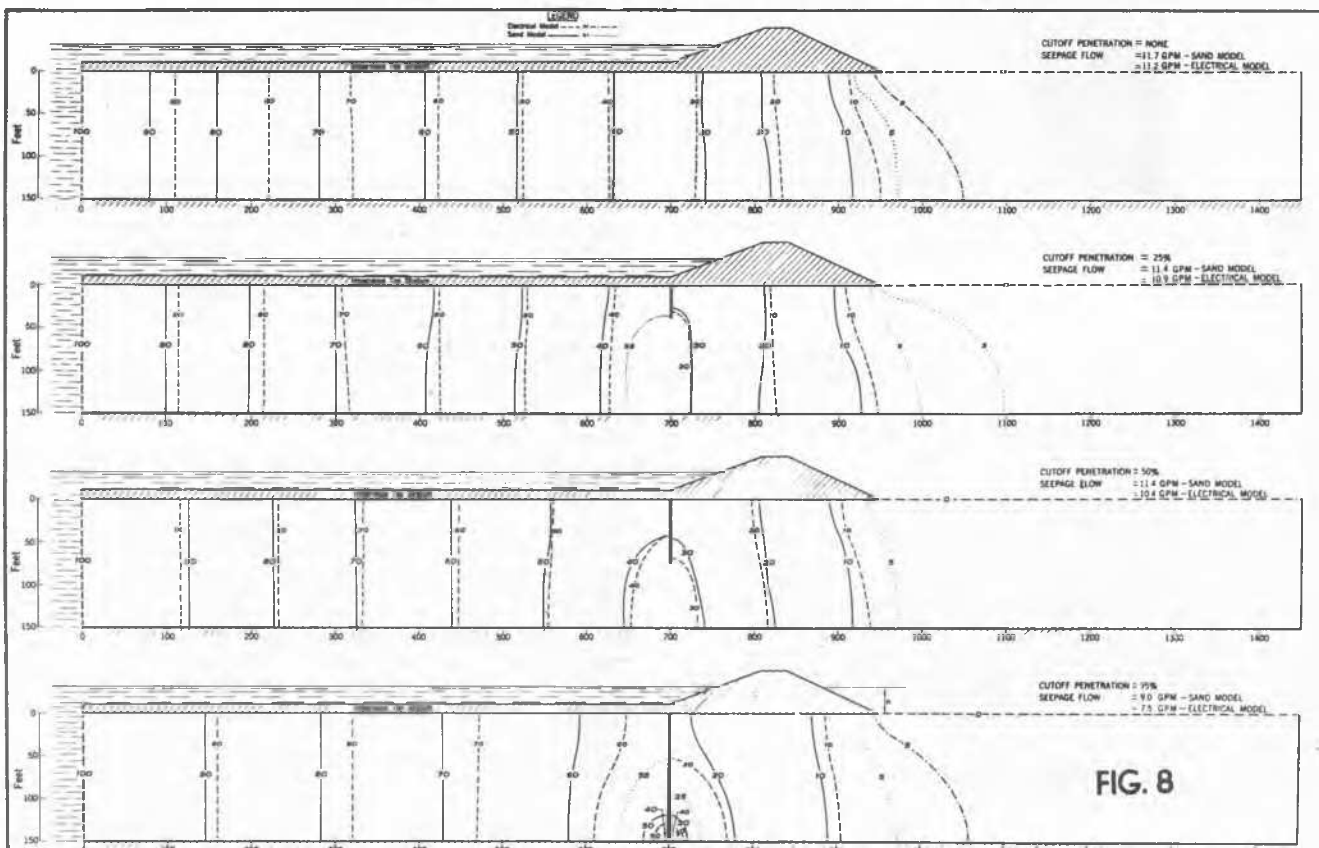


FIG. 8

MODEL I

SEEPAGE ENTRANCE AT RIVER 700 FEET RIVERSIDE OF CUTOFF – NO LANDSIDE TOP STRATUM – SAND AND ELECTRICAL MODELS

EQUIPOTENTIAL LINES FOR 0, 25, 50, AND 95 PERCENT CUTOFFS

TABLE 1

SUMMARY OF CONDITIONS INVESTIGATED AND METHODS OF ANALYSES

Case x)	Pervious Strata	Seepage Entrance	Seepage Exit or Landside Top Stratum	Method of Analysis	Figure References
I-a-1	150 ft medium sand, $k = 500 \times 10^{-4}$ cm/sec	At river 700 ft riverside of cutoff (riverside top stratum impervious)	500-ft top stratum (A), 49% H at (LS) levee toe with no cutoff	Sand model	4, 6, 7
I-a-2	do	do	500-ft top stratum (B), 38% H at (LS) levee toe with no cutoff	Sand model	4, 6, 7
I-a-3	do	do	500-ft top stratum (C) 44% H at (LS) levee toe with no cutoff	Electrical model	4,6
I-a-4	do	do	500-ft landward of (LS) levee toe (landside top stratum to this distance impervious)	Mathematical graphical flow net, and sand model	4, 6
I-a-5	do	do	No landside top stratum	Mathematical, sand model and electrical model	4, 6, 8
I-b-1 xa)	do	Horizontal surface riverside of levee (no riverside top stratum)	500-ft top stratum (A), 68% H at (LS) levee toe with no cutoff	Sand model	5, 6
I-b-2 xa)	do	do	500-ft top stratum (B), 63% H at (LS) levee toe with no cutoff	Sand model	5, 6, 9
I-b-3 xa)	do	do	500-ft landward of (LS) levee toe (landside top stratum to this distance impervious)	Mathematical and sand model	5, 6
I-b-4 xa)	150 ft medium sand, $k = 500 \times 10^{-4}$ cm/sec	Horizontal surface riverside of levee (no riverside top stratum)	No landside top stratum	Mathematical graphical flow net, and sand model	5, 6, 10
II-a-1	50 ft fine sand ($k = 100 \times 10^{-4}$ cm/sec) underlain by 100 ft medium sand ($k = 500 \times 10^{-4}$ cm/sec)	At river 500 ft riverside of cut-off (riverside top stratum impervious	500-ft top stratum (D), 75% H at (LS) levee toe with no cutoff	Electrical model	11, 12
II-a-2	do	do	500-ft top stratum (E), 50% H at (LS) levee toe with no cutoff	Electrical model	11, 12, 13
II-a-3	do	do	500-ft top stratum (F), 29% H at (LS) levee toe with no cutoff	Electrical model	11, 12
II-a-4	do	do	500-ft landward of (LS) levee toe (landside top stratum to this distance impervious)	Graphical flow net and electrical model	11, 12
II-e-5	do	do	No landside top stratum	Electrical model	11, 12, 14
II-b-1 xa), xb)	do	500-ft horizontal surface riverside of levee (no riverside top stratum)	500-ft top stratum (G), 50% H at (LS) levee toe with no cutoff	Electrical model	11, 12, 15
II-b-2 xa), xb)	do	do	No landside top stratum	Graphical flow net and electrical model	11, 12, 16
III-a	10 ft very fine sand ($k = 62 \times 10^{-4}$ cm/sec) xc) 10 ft medium sand ($k = 500 \times 10^{-4}$ cm/sec) 10 ft very fine sand 10 ft medium sand 10 ft very fine samd 100 ft medium sand	At tiver 500 ft riverside of cutoff (riverside top stratum impervious	No landside top stratum	Electrical model	17
III-b xa), xb)	10 ft very fine sand ($k = 50 \times 10^{-4}$ cm/sec xd) 10 ft medium sand ($k = 500 \times 10^{-4}$ cm sec) 10 ft very fine sand 10 ft medium sand 10 ft very fine dand 100 ft medium sand	500 ft horizontal surface river side of levee (no riverside top stratim) xe)	No landside top stratum	Electrical model	17, 18

x) The words "case" and "model" are used interchangeably in this paper.

xa) Case was to simulate a condition similar to one sometimes created in nature when the riverside top stratum is removed during construction of the levee or dam. Entrance at river was closed for these tests.

xb) With a 50-ft cutoff all seepage had to pass through the upper fine sand before it could reach the deeper coarser sand.

xc) Average horizontal permeability of upper 50 ft of strafified strata, $k_H = 238 \times 10^{-4}$ cm/sec; $k_V = 96 \times 10^{-4}$ cm/sec.

xd) Average horizontal permeability of upper 50 ft of stratified strata, $k_H = 231 \times 10^{-4}$ cm/sec; $k_V = 81 \times 10^{-4}$ cm/sec.

xe) Case was to simulate stratified conditions frequently found in the upper part of alluvial deposits.

TABLE 2

SUMMARY OF TEST DATA -- MODEL I

	Cutoff	Seepage		Shape Factor ($\$ = \frac{n_F}{n_E}$)				Seepage Flow per 100 ft of Levee per ft Head*								Head in Per Cent of Net Head						
								Theoretical		Flow Net		Sand Model		Elect. Model		Head at L.S. Toe of Levee				Head at 50-Ft Depth at L.S. Toe of Levee		
Test	Per Cent	Entrance	Exit	Theoretical	Flow Net	Sand Model	Electrical Model	gpm	%	gpm	%	gpm	%	gpm	%	Theoretical	Flow Net	Sand Model	Elect. Model	Flow Net	Sand Model	Elect. Model
I-a-1	0	R	A	---	--	.076	---	---	---	---	---	5.7	100	---	---	---	--	49	---	--	---	---
	25			---	--	.063	---	---	---	---	---	4.7	83	---	---	---	--	--	---	--	---	---
	50			---	--	.076	---	---	---	---	---	5.6	100	---	---	---	--	47	---	--	---	---
	95			---	--	.065	---	---	---	---	---	4.9	86	---	---	---	--	46	---	--	---	---
	98			---	--	.061	---	---	---	---	---	4.6	81	---	---	---	--	43	---	--	---	---
I-a-2	0	R	B	---	--	.101	---	---	---	---	---	7.5	100	---	---	---	--	38	---	--	---	---
	25			---	--	.099	---	---	---	---	---	7.4	99	---	---	---	--	38	---	--	---	---
	50			---	--	.096	---	---	---	---	---	7.2	95	---	---	---	--	37	---	--	---	---
	95			---	--	.079	---	---	---	---	---	5.9	78	---	---	---	--	35	---	--	---	---
	98			---	--	.068	---	---	---	---	---	5.1	68	---	---	---	--	34	---	--	---	---
I-a-3	0	R	C	---	--	---	.087	---	---	---	---	---	---	6.5	100	---	--	--	44	--	---	---
	50			---	--	---	.082	---	---	---	---	---	---	6.1	94	---	--	--	44	--	---	---
	95			---	--	---	.071	---	---	---	---	---	---	5.3	81	---	--	--	36	--	---	---
I-a-4	0	R	TB	.103	.103	.104	---	7.7	100	7.7	100	7.8	100	---	---	35	35	34	---	--	---	---
	25			.102	.102	---	---	7.7	99	7.7	99	---	---	---	---	34	34	--	---	--	---	---
	50			.099	.099	---	---	7.4	96	7.4	96	---	---	---	---	33	33	--	---	--	---	---
	75			.092	.092	---	---	6.9	89	6.9	89	---	---	---	---	31	31	--	---	--	---	---
	90			.083	--	---	---	6.2	81	---	---	---	---	---	---	28	--	--	---	--	---	---
	95			.078	--	.083	---	5.8	75	---	---	6.2	79	---	---	26	--	27	---	--	---	---
	98			.071	--	.074	---	5.3	69	---	---	5.6	72	---	---	24	--	24	---	--	---	---
I-a-5	0	R	N	.148	--	.160	.148	11.0	100	---	---	11.7	100	11.2	100	0	--	0	0	--	7	8
	25			.146	--	.155	.146	10.9	99	---	---	11.4	97	10.9	97	0	--	0	0	--	6	8
	50			.139	--	.156	.139	10.4	94	---	---	11.4	98	10.4	93	0	--	0	0	--	6	7
	75			.125	--	.136	.124	9.4	85	---	---	10.1	87	9.3	83	0	--	0	0	--	5	7
	90			.109	--	---	.107	8.2	74	---	---	---	---	8.0	72	0	--	0	0	--	-	7
	95			.100	--	.121	.100	7.5	68	---	---	9.0	77	7.5	67	0	--	0	0	--	4	7
	98			.090	--	.097	.084	6.7	61	---	---	7.3	62	6.3	56	0	--	0	0	--	3	5
I-b-1	0	H	A	---	--	.125	---	---	---	---	---	9.3	100	---	---	---	--	69	---	--	---	---
	95			---	--	.062	---	---	---	---	---	4.6	49	---	---	---	--	69	---	--	---	---
	98			---	--	.074	---	---	---	---	---	5.5	59	---	---	---	--	52	---	--	---	---
I-b-2	0	H	B	---	--	.146	---	---	---	---	---	10.9	100	---	---	---	--	63	---	--	---	---
	25			---	--	.128	---	---	---	---	---	9.6	88	---	---	---	--	66	---	--	---	---
	50			---	--	.136	---	---	---	---	---	10.2	94	---	---	---	--	60	---	--	---	---
	95			---	--	.087	---	---	---	---	---	6.5	60	---	---	---	--	54	---	--	---	---
	98			---	--	.087	---	---	---	---	---	6.5	60	---	---	---	--	46	---	--	---	---
I-b-3	0	H	TB	.184	--	---	---	13.7	100	---	---	---	---	---	---	61	--	--	---	--	---	---
	25			.175	--	---	---	13.1	96	---	---	---	---	---	---	58	--	--	---	--	---	---
	50			.161	--	---	---	12.0	88	---	---	---	---	---	---	54	--	--	---	--	---	---
	75			.141	--	---	---	10.6	77	---	---	---	---	---	---	47	--	--	---	--	---	---
	90			.121	--	---	---	9.1	66	---	---	---	---	---	---	41	--	--	---	--	---	---
	95			.110	--	.127	---	8.2	60	---	---	---	---	---	---	37	--	--	---	--	---	---
	98			.097	--	.104	---	7.3	53	---	---	7.8	---	---	---	33	--	32	---	--	---	---
I-b-4	0	H	N	.392	.404	.361	---	29.3	100	30	100	27.0	100	---	---	0	0	0	---	17	14	---
	25			.350	.355	.346	---	26.1	89	27	88	25.9	96	---	---	0	0	0	---	17	13	---
	50			.300	.300	---	---	22.4	77	22	74	---	---	---	---	0	0	--	---	13	---	---
	75			.239	.227	.286	---	17.8	61	17	56	21.4	79	---	---	0	0	0	---	9	10	---
	90			.187	--	---	---	14.0	48	---	---	---	---	---	---	0	--	--	---	--	---	---
	95			.160	--	.177	---	12.0	41	---	---	13.2	49	---	---	0	--	0	---	--	7	---
	98			.132	--	.151	---	9.9	34	---	---	11.3	42	---	---	0	--	0	---	--	---	---

* Seepage flows are based on a coefficient of permeability (k) = 500 x 10^{-4} cm/sec.

Notes:
- R - Seepage entrance at river 700 ft riverward of cutoff. Riverside top stratum impervious.
- H - Horizontal seepage entrance riverside of levee. No riverside top stratum.
- A - Landside top stratum A. Head at landside levee toe with no cutoff 49% H.
- B - Landside top stratum B. Head at landside levee toe with no cutoff 38% H.
- C - Landside top stratum C. Head at landside levee toe with no cutoff 44% H.
- TB - Seepage exit 500 ft landward of levee toe. Landside top stratum impervious to this point.
- N - No landside top stratum. Sand extended to surface.
- LS - Landside of levee.
- RS - Riverside of levee.

the model across the low-voltage output of a transformer and a null-indicator circuit connected between the variable contact on the potential divider and the model probe. Alternating current was used to preclude polarization at the electrodes. The probe, consisting of a copper wire embedded in a lucite rod, was carried on one leg of a pantograph. The stylus of the pantograph was positioned on another leg to give a scale reduction of one-half from the model to the map. The null-indicator, which was an electron-ray indicator tube, a "Magic-eye" tube, was mounted together with its bias control on the pantograph arm beside the probe.

The two-strata foundation (Case II) was simulated by altering the cross section of the model so that the depths of the solution differed in the portions representing the different strata. The depth ratio of 1 to 5 in the model corresponded to a permeability ratio of 1 to 5 in nature.

The entrance and exit conditions were varied for both (Case I and II) models described above. Solid sheet copper electrodes were used for all entrance conditions and for exit electrodes where no landside top stratum was ot be simulated. A relatively impervious landside top stratum was simulated by a number of wire electrodes uniformly spaced along the landside of the model and extending to the full depth of the electrolyte. Each wire electrode was connected through a resistor to the output side of the potential divider. All resistors were of the same magnitude so that the multiple electrodes in parallel represented the same condition as a uniform, low permeability blanket. Proper choice of resistors permitted adjustment of the model to represent any desired residual head at the landside toe of the levee. In Case I-a this simulated landside top stratum resulted

TABLE 3

SUMMARY OF TEST DATA -- MODELS II AND III

Test	Cutoff Feet	Seepage: Entrance	Seepage: Exit	Shape Factor***: Flow Net	Shape Factor***: Electrical** Model	Seepage* Flow per 100 Ft of Levee per Ft of Head: Flow Net gpm	Flow Net %	Electrical Model** gpm	Electrical Model** %	Head in Per Cent of Net Head: Head at L.S. Toe: Flow Net	Head at L.S. Toe: Electrical Model	Head at 50-Ft Depth L.S. Toe of Levee: Flow Net	Head at 50-Ft Depth L.S. Toe of Levee: Electrical Model
II-a-1	0	R	D	---	.185	---	---	2.8	100	---	75	---	---
	25			---	.184	---	---	2.8	99	---	75	---	---
	50			---	.183	---	---	2.7	99	---	75	---	---
	100			---	.176	---	---	2.6	95	---	74	---	---
	140			---	.169	---	---	2.5	91	---	68	---	---
II-a-2	0	R	E	---	.362	---	---	5.4	100	---	50	---	---
	25			---	.360	---	---	5.4	99	---	49	---	---
	50			---	.346	---	---	5.2	96	---	49	---	---
	100			---	.320	---	---	4.8	89	---	49	---	---
	140			---	.262	---	---	3.9	72	---	47	---	---
II-a-3	0	R	F	---	.504	---	---	7.6	100	---	29	---	---
	25			---	.500	---	---	7.5	99	---	29	---	---
	50			---	.496	---	---	7.4	98	---	29	---	---
	100			---	.455	---	---	6.8	90	---	28	---	---
	140			---	.382	---	---	5.7	76	---	24	---	---
II-a-4	0	R	TB	.440	.440	6.6	100	6.6	100	40	41	---	---
	25			.440	.440	6.6	100	6.6	100	40	41	---	---
	50			.430	.436	6.4	98	6.5	99	39	41	---	---
	100			.413	.422	6.2	94	6.3	96	37	39	---	---
	140			---	.358	---	---	5.4	81	---	32	---	---
II-a-5	0	R	N	---	.600	---	---	9.0	100	---	0	---	19
	25			---	.596	---	---	8.9	99	---	0	---	19
	50			---	.591	---	---	8.9	98	---	0	---	19
	100			---	.567	---	---	8.5	94	---	0	---	18
	140			---	.456	---	---	6.8	76	---	0	---	17
II-b-1	0	H	G	---	.569	---	---	8.5	100	---	50	---	---
	25			---	.568	---	---	8.5	100	---	49	---	---
	50			---	.538	---	---	8.1	95	---	49	---	---
	100			---	.482	---	---	7.2	85	---	48	---	---
	140			---	.376	---	---	5.6	66	---	40	---	---
II-b-2	0	H	N	.972	.982	14.5	100	14.7	100	0	0	27	25
	25			.946	.929	14.2	97	13.9	95	0	0	26	24
	50			.921	.896	13.8	95	13.4	91	0	0	25	23
	100			.875	.835	13.1	90	12.5	85	0	0	22	22
	140			---	.559	---	---	8.4	57	0	0	---	20
III-a	0	R	N	---	---	---	---	9.5	100	---	0	---	22
	25			---	---	---	---	9.5	99	---	0	---	22
	50			---	---	---	---	9.4	98	---	0	---	22
	100			---	---	---	---	8.5	89	---	0	---	20
	140			---	---	---	---	7.0	74	---	0	---	17
III-b	0	H	N	---	---	---	---	15.3	100	---	0	---	33
	25			---	---	---	---	14.7	96	---	0	---	30
	50			---	---	---	---	14.0	92	---	0	---	27
	100			---	---	---	---	11.6	76	---	0	---	23
	140			---	---	---	---	8.0	52	---	0	---	16

* Seepage flows are based on coefficients of permeabilities shown in table 1.
** Computed from equipotential lines.
*** Shape factor based on upper stratum of fine sand, $k = 100 \times 10^{-4}$ cm/sec.

Notes:
- R - Seepage entrance at river 500 ft riverward of cutoff. Riverside top stratum impervious.
- H - Horizontal seepage entrance riverside of levee. No riverside top stratum.
- D - Landside top stratum D. Head at landside levee toe with no cutoff 75% H.
- E - Landside top stratum E. Head at landside levee toe with no cutoff 50% H.
- F - Landside top stratum F. Head at landside levee toe with no cutoff 29% H.
- G - Landside top stratum G. Head at landside levee toe with no cutoff 50% H.
- N - No landside top stratum. Sand extended to surface.
- TB - Seepage exit 500 ft landward of levee toe. Landside top stratum impervious to this point.
- LS - Landside of levee.
- RS - Riverside of levee.

in a residual head at the landside toe of the levee. In Case I-a this simulated landside top stratum resulted in a residual head at the landside toe of the 44 per cent of the net head with no cutoff. For the two-strata model, Casw II-a with an entrance 500 ft from the levee, the three relatively impervious top strata simulated (D, E, F) resulted in residual heads of the landside toe of the levee of 75, 50, and 25 per cent of the net head with no cutoff. With no riverside top stratum (Case II-b) a relatively impervious landside top stratum (G) with a residual head at the landside levee toe of 50 per cent of the net head with no cutoff was simulated.

A dry electrical model was used to study the stratified foundation (Case III). In this model, an aqueous colloidal suspension of graphite was sprayed on tempered masonite board. The different strata (five alternate 10-ft strata of very fine and medium sand overlying a 100-ft stratum of medium sand) were achieved by masking the areas for the higher resistivity (less pervious) portions of the model during the nnitial spraying operations and removing the mask for the final coatings. The prescribed permeability ratio of the very fine sand to the medium sand was 1 to 10; the resistivity ratios obtained were 8 to 1 for Case III-a and 9.6 to 1 for Case III-b. The permeability assumed for the medium sand was 500×10^{-4} cm/sec. The model scale for these two cases was 1 to 240. Entrance and exit connections to the model were made through brass strips cemented at the appropriate part of the models and connected elctrically to the graphite coating by a thin line of silver lacquer. Cutoffs were simulated by a saw cut through the model at the riverside toe of the levee extending to the proper depth. These graphite models were operated with direct cur-

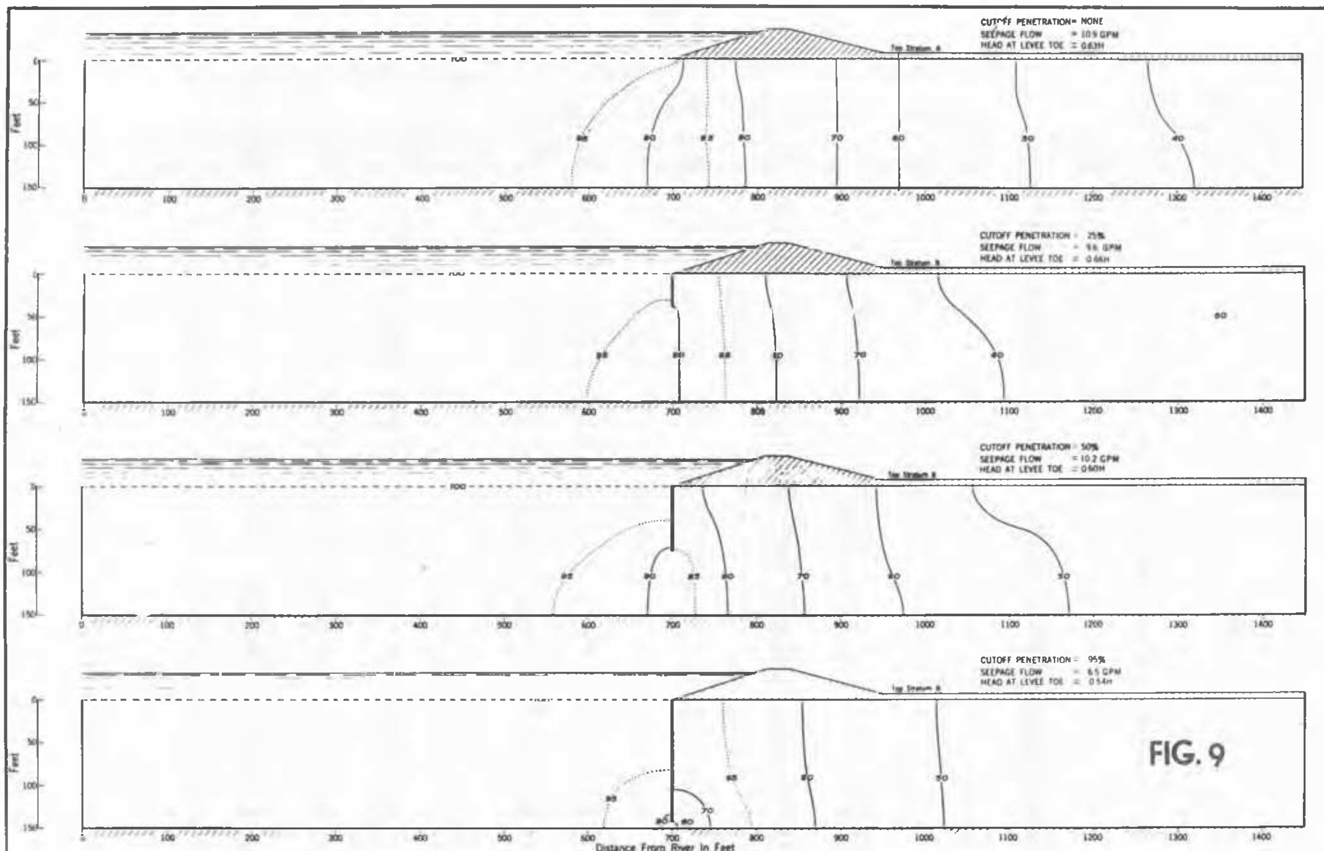


FIG. 9

MODEL I

HORIZONTAL SEEPAGE ENTRANCE RIVERSIDE OF CUTOFF-LANDSIDE TOP STRATUM B-SAND MODEL

EQUIPOTENTIAL LINES FOR 0, 25, 50, AND 95 PERCENT CUTOFFS

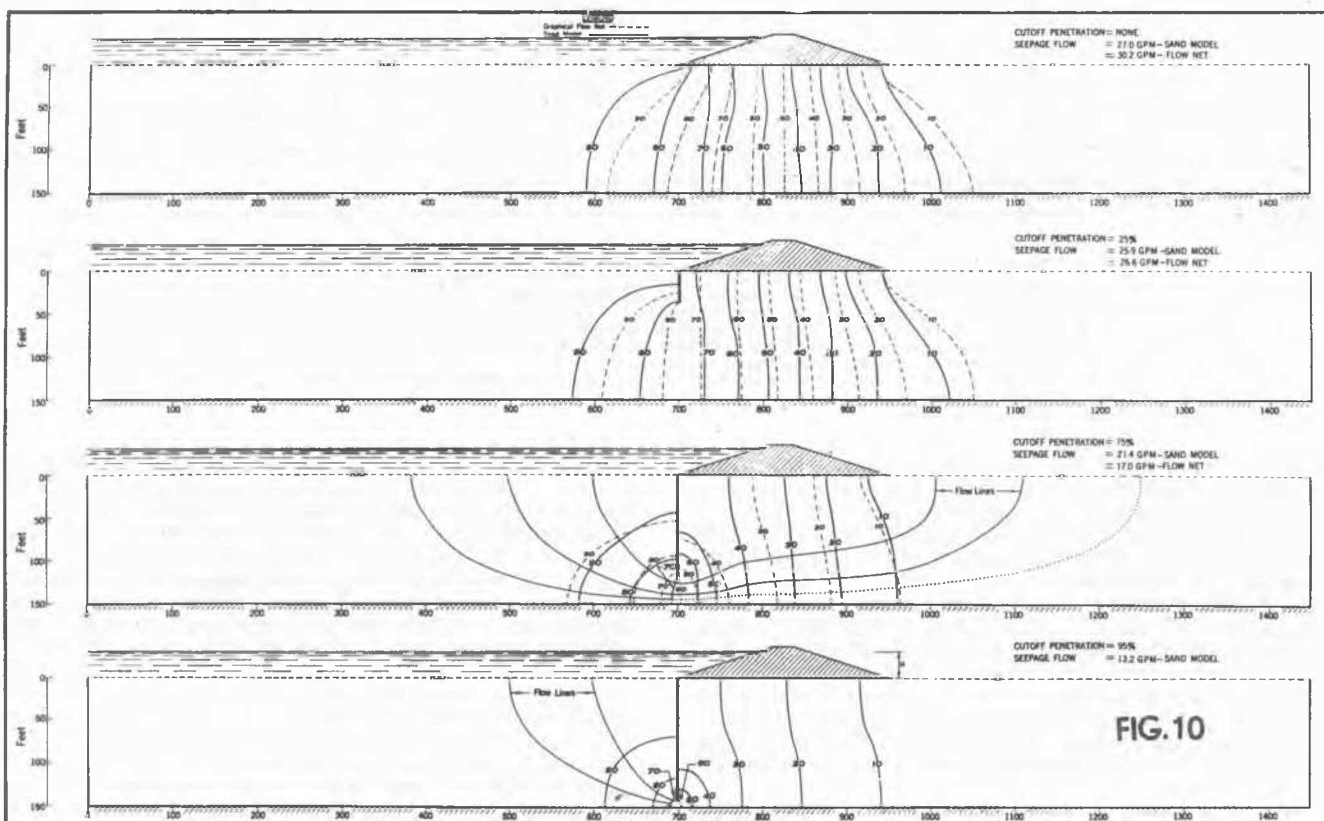


FIG. 10

MODEL I

HORIZONTAL SEEPAGE ENTRANCE RIVERSIDE OF CUTOFF–NO LANDSIDE TOP STRATUM–SAND MODEL AND GRAPHICAL FLOW NET

EQUIPOTENTIAL AND FLOW LINES FOR 0, 25, 75, AND 95 PERCENT CUTOFFS

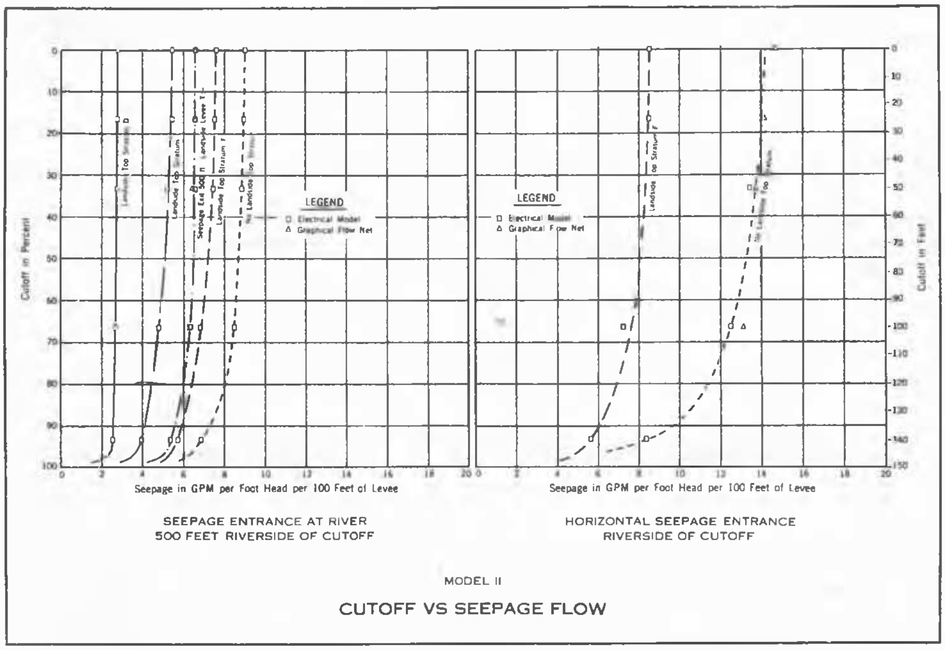


FIG. 11

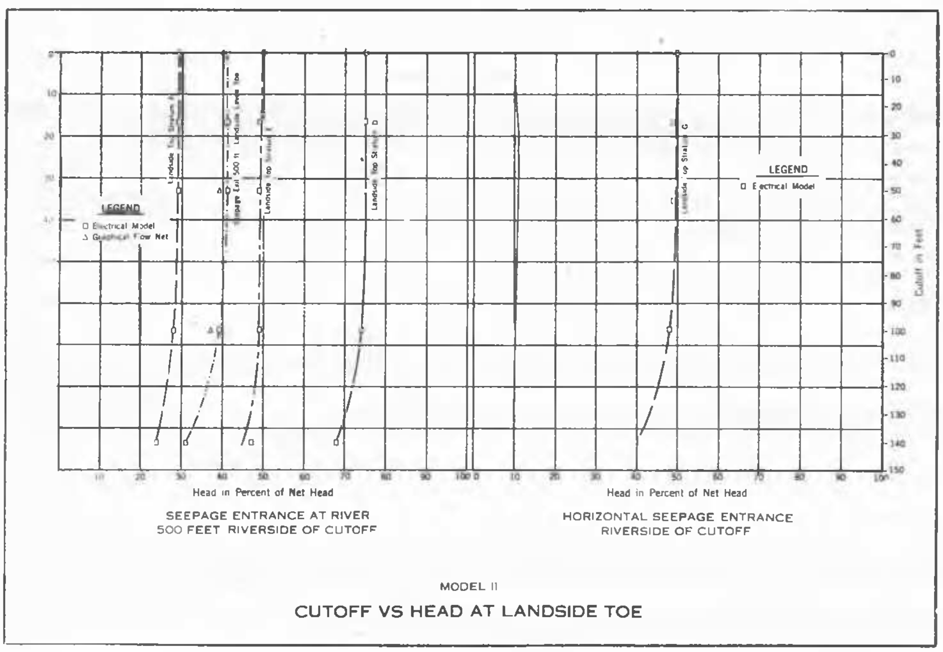


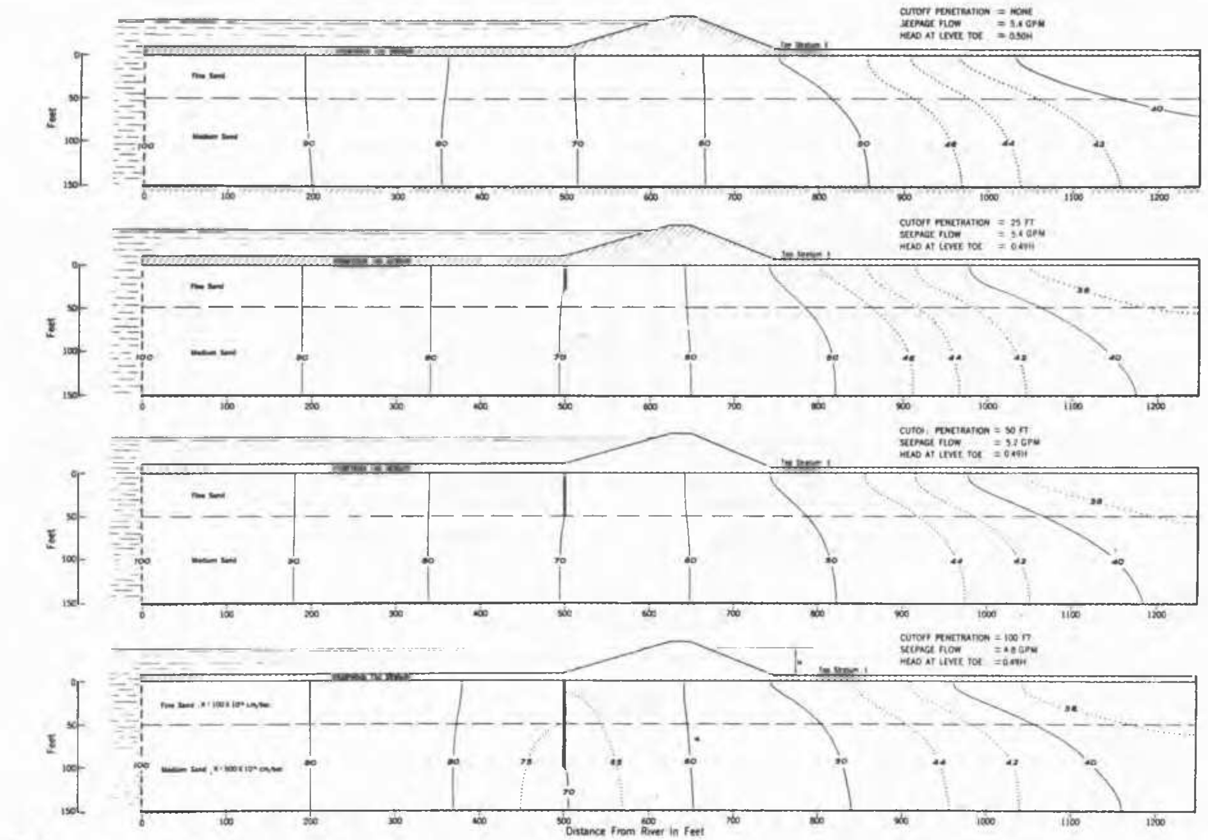
FIG. 12

rent after it was found that an apparent distortion of the equipotentials in the high resistivity strata resulted when alternating current was used.

The seepage flows in the electrical models were computed from the equipotential lines using a portion of the potential pattern where the equipotential lines were vertical and uniformly spaced (i.e., the effective cross-section area of flow was essentially constant). The flow was computed from the formula, $Q = k \frac{\Delta h}{L} A$, where Δh = head drop between equipotential lines, L = distance between equipotential lines, and A = crosssectional area of seepage flow. The shape factor was computed from the formula, $\xi = \frac{Q}{kH}$. Seepage flows can also be derived from measurement of the model resistance, R, and resistivity, ρ, since the shape factor equals $\frac{\rho}{R}$.

SUMMARY OF TEST RESULTS

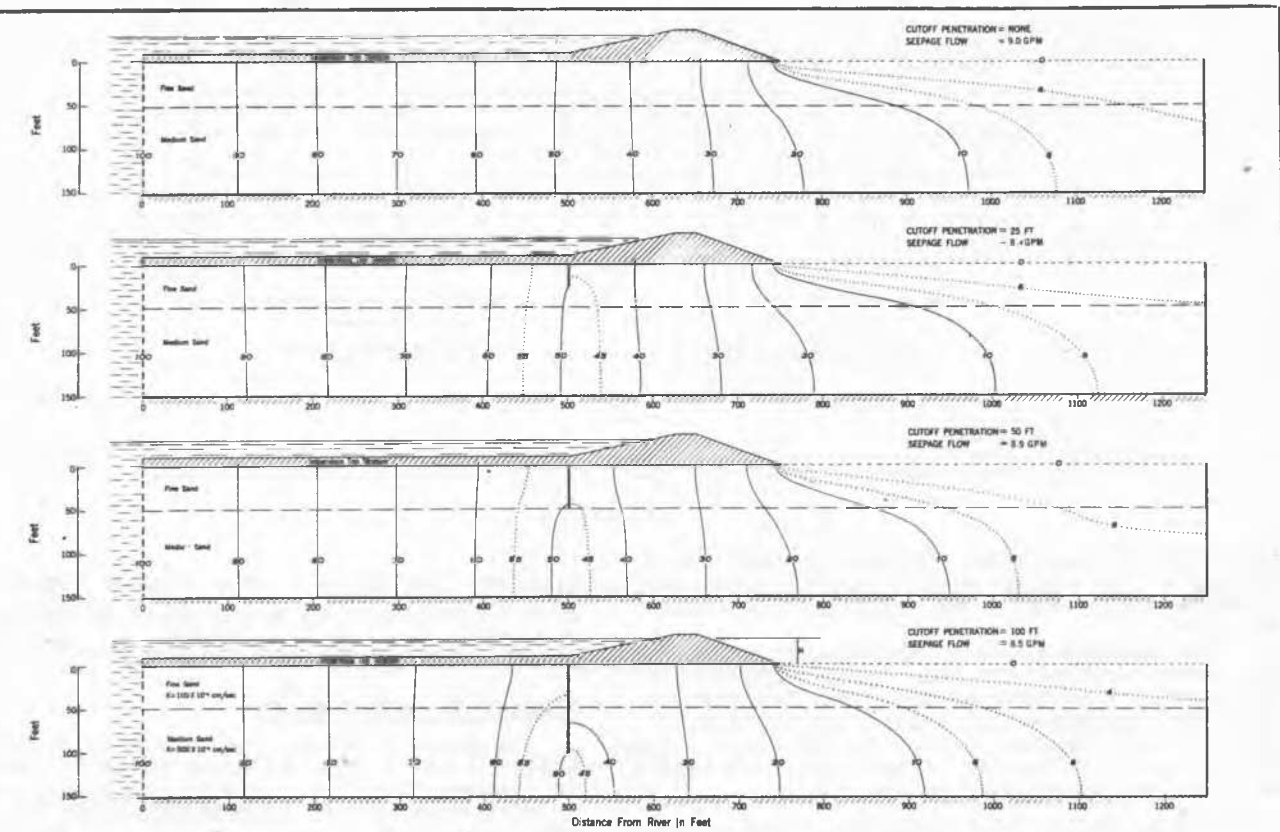
A summary of the test results is given in tables 2 and 3. The effects of partial cutoffs on seepage flow and landside pressures, together with some of the equipotential and flow lines developed from the graphical flow nets, sand models, and electrical models, are shown on figures 4 throgh 18. All information regarding seepage entrance and foundation conditions,



MODEL II

FIG. 13 SEEPAGE ENTRANCE AT RIVER 500 FEET RIVERSIDE OF CUTOFF – LANDSIDE TOP STRATUM E – ELECTRICAL MODEL

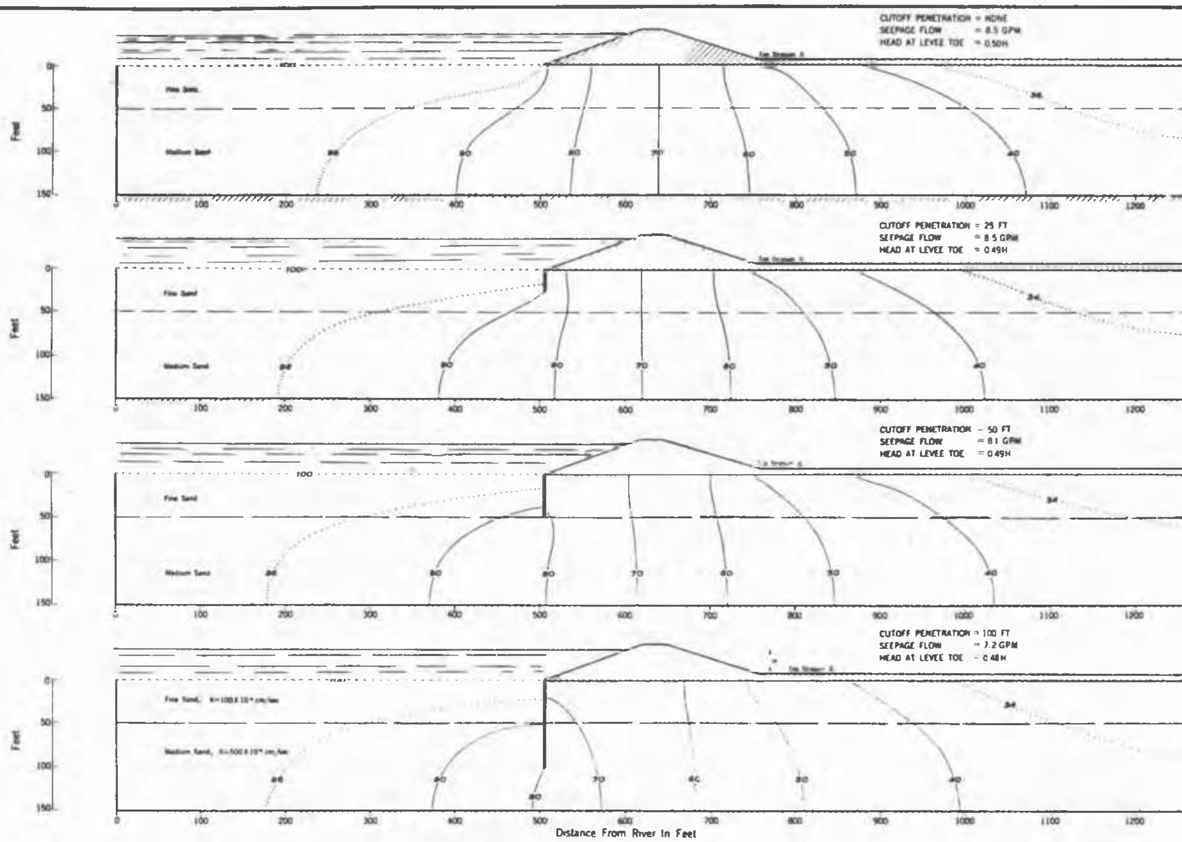
EQUIPOTENTIAL LINES FOR 0, 25, 50, AND 100-FOOT CUTOFFS



MODEL II

FIG. 14 SEEPAGE ENTRANCE AT RIVER 500 FEET RIVERSIDE OF CUTOFF – NO LANDSIDE TOP STRATUM – ELECTRICAL MODEL

EQUIPOTENTIAL LINES FOR 0, 25, 50, AND 100-FOOT CUTOFFS



MODEL II

FIG. 15 500-FOOT HORIZONTAL SEEPAGE ENTRANCE RIVERSIDE OF CUTOFF-LANDSIDE TOP STRATUM G-ELECTRICAL MODEL

EQUIPOTENTIAL LINES FOR 0, 25, 50, AND 100-FOOT CUTOFFS

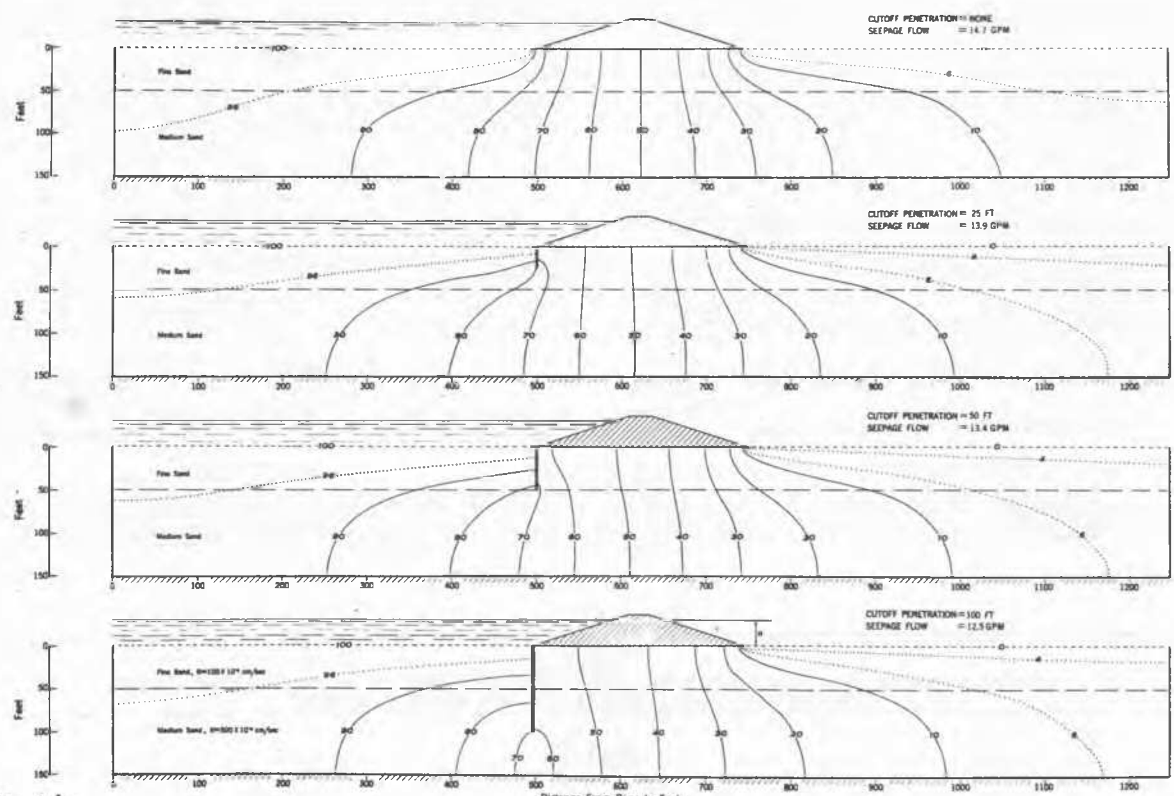
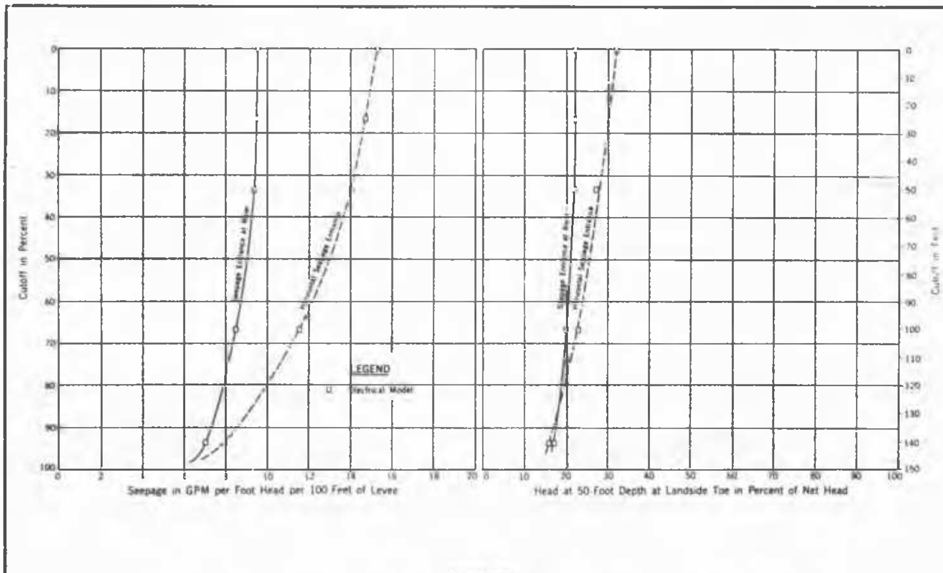


FIG. 16

MODEL II

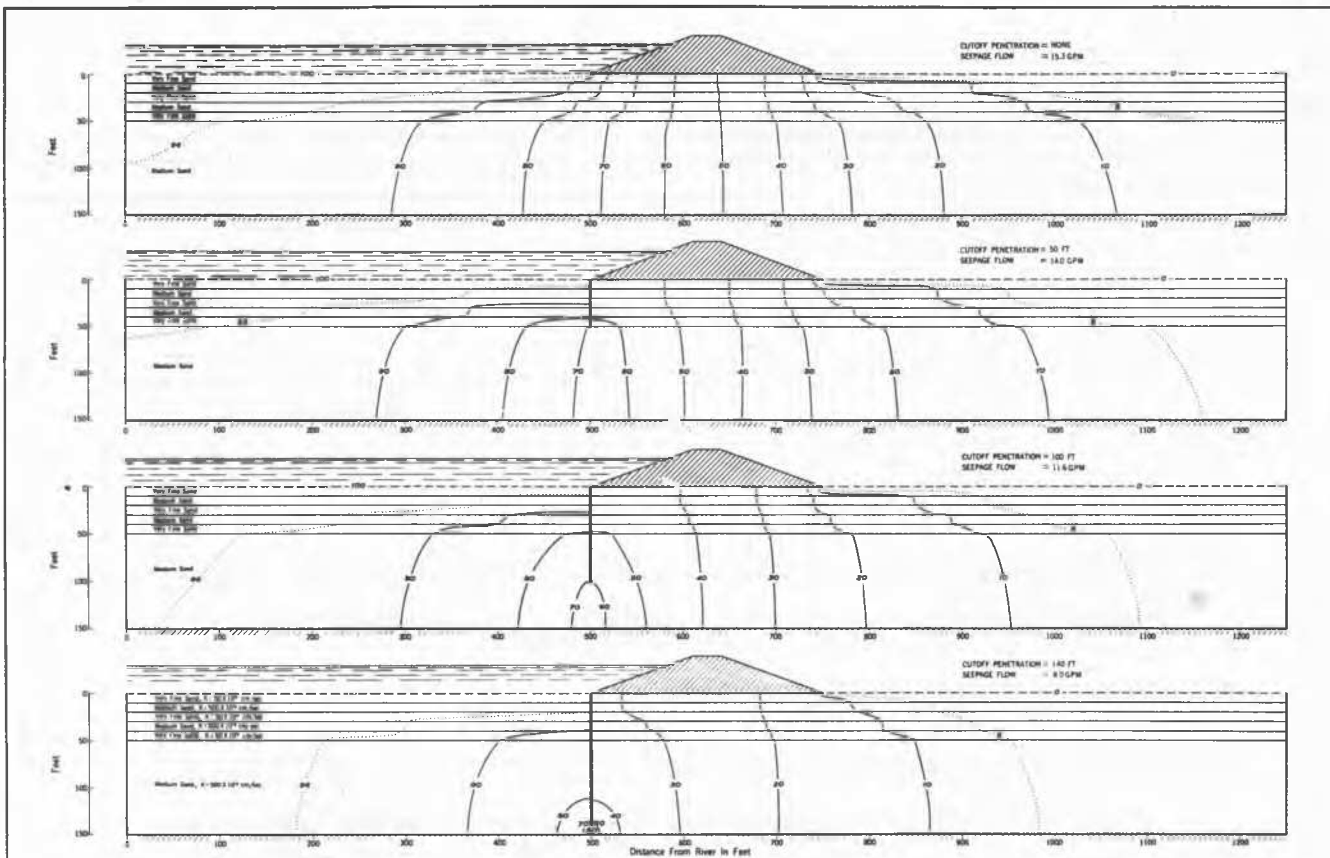
500-FOOT HORIZONTAL SEEPAGE ENTRANCE RIVERSIDE OF CUTOFF- NO LANDSIDE TOP STRATUM- ELECTRICAL MODEL

EQUIPOTENTIAL LINES FOR 0, 25, 50, AND 100-FOOT CUTOFFS



MODEL III
CUTOFF VS SEEPAGE FLOW AND HEAD AT LANDSIDE TOE OF LEVEE
NO LANDSIDE TOP STRATUM

FIG. 17



MODEL III
500-FOOT HORIZONTAL SEEPAGE ENTRANCE RIVERSIDE OF CUTOFF–NO LANDSIDE TOP STRATUM–ELECTRICAL MODEL
EQUIPOTENTIAL LINES FOR 0, 50, 100, AND 140-FOOT CUTOFFS

FIG. 18

landside top strata and cutoff penetration, pertinent ot the data, is presented on each figure. A list of these figures is given in table 4. Space limitations do not permit a complete and detailed discussion of all the information shown on the included figures.

Homogeneous foundation -- Case I

Case I-a. The results of the various methods of analyses show that partial cutoffs into a homogeneous pervious foundation have very little effect on seepage flows or landside pressures, regardless of the landside top strata (see figures 4 and 6). For the same seepage entrance, the more impervious the landside top stratum, the less effective was a cutoff. This is because a landside top stratum increases the resistance to flow, and the more initial resistance to flow the less effect a partial cutoff has. A cutoff of 50 per cent reduced the seepage and landside pressure by only 1 to 5 per cent for the landside conditions tested.

Case I-b. The shorter the path of seepage flow, the more effective is a partial cutoff. Therefore, partial cutoffs were slightly more effective in reducing seepage and landside pressures where the seepage entrance was at the levee toe rather than 700 ft distant as in Case I-a (see figures 5 and 6). However, even for this extreme entrance condition, a partial cutoff of 25 per cent (38 ft) reduced the seepage and landside pressures only about 1 to 10 per cent. Flow lines obtained with dye in the sand model for the case of no top stratum on either side of the levee are shown on figure 10.

Two-layered foundation -- Case II

Case II-a. In this case the deeper, more pervious sand simulated in the electrical model was overlain by a 50-ft stratum of finer sand, five times less pervious. As for the homogeneous foundation, partial cutoffs had practically no effect on seepage flows or landside pressures, regardless of the landside top strata (see figure 11).

Case II-b. When the cutoff reached a depth of 50 ft in this case, all water entering the deep, more pervious sand, had to pass through the upper finer sand (see figure 15). As might be expected, partial cutoffs were slightly more effective in reducing seepage and landside pressures for this case than in Case II-a, but again the amoung of reduction was small for any moderate cutoff penetration regardless of the landside top stratum (see figures 11 and 12).

Stratified foundation -- Case III

Case III-a. In this case, the deeper more pervious sand was overlain by alternate strata of very fine and medium sand, the finer sand being 8 to 10 times less pervious than the coarser sand. Where the seepage water entered at a point 500 ft from the levee, a partial cutoff completely penetrating the stratified sands reduced the seepage flow 2 per cent and the head at a depth of 50 ft at the landside toe of the levee zero per cent (see figure 17).

Case III-b. As in Case II-b with a 50-ft cutoff, all water entering the deep, more pervious sand had to pass through the upper stratified layers of sand (see figure 18). Because of the entrance condition and the fact that there was no landside blanket to create resistance to flow, partial cutoffs should be more effective in reducing underseepage and landside pressure for this case than any of the other cases tested. However, a 50-ft cutoff, extending through the upper stratified sands, reduced the seepage flow by only 8 per cent and the head at the landside levee toe at a 50-ft depth by 18 per cent (see figure 17 for other penetrations).

Correlation of methods of analysis

The correlation of results as obtained from the different methods of analysis in best shown on the various plates and in tables 2 and 3. In view of the numerous variables which enter into sand and electrical seepage models the correlation of the results obtained from mathematical analyses, graphical flow nets, sand models, and electrical models was good. In most cases there was not more than 5 to 10 per cent deviation in the results.

CONCLUSIONS

The results of the model studies and other analyses presented in this paper indicate the following conclusions:

a) Partial cutoffs with penetrations less than 98 per cent had relatively little effect on reducing underseepage or landside pressures for the range of conditions tested. Cutoffs with penetrations less than 25 per cent had practically no effect.

b) The longer the path of seepage flow the less effective were partial cutoffs. Correspondingly, the more impervious the landside top stratum the less effective were partial cutoffs.

c) Very good correlation was obtained between the results obtained from theoretical analysis, graphical flow nets, sand models, and electrical models.

d) By similarity, it may be reasoned that not only must cutoffs completely penetrate the pervious strata, but there must also be no openings in the cutoff in order for it to be materially effective in reducing seepage flows and landside pressure.

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