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Study of Surging Flow in Canals with Energy Dissipation Blocks

by

Hilaire W. Peck

May 1, 1987

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Memorandum
Chairman, OCCS Committee

Denver, Colorado
May 4, 1987

Chief, Hydraulics Branch

Model Study of Unsteady Supercritical Flow Conditions in Open Channel Distribution Systems

The laboratory study for the subject model was completed in April. The enclosed report entitled "Study of Surging Flow in Canals with Energy Dissipation Blocks" by Hilaire W. Peck summarizes the results of the study.

The study indicated that more in-depth research is needed to obtain an analytical method for predicting surging flow in canals. It is feasible to use the hydraulic laboratory's tilting flume in a comprehensive study of the surging phenomenon. It is recommended that additional field data be gathered to better identify and understand the interrelations between the variables which produce surging flow in canals. As noted in the report, raft type wave suppressors appeared to effectively reduce wave heights of the surge flow.

Philip H. Burgi

Enclosure

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STUDY OF SURGING FLOW
IN CANALS
WITH ENERGY DISSIPATION BLOCKS

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INTRODUCTION

It is common practice to use blocks as energy dissipation systems in dam spillways, highway drainage chutes, culverts, and drainage ditches. The slopes of these structures are generally greater than 2 percent. The formation of waves in this type of energy dissipation system can be a major problem. These waves can decrease the carrying capacity of the channel and may cause damage to the downstream channel.

Recently, in at least one canal, blocks have been employed as an energy dissipation system and surge waves have caused problems. The bottom slope of this canal varies from 0.5 to 1.5 percent. A literature search indicated that little or no research has been done on surge wave phenomenon in channels with block energy dissipators at slopes of 1.5 percent or less.

One study that investigated flow in channels with block energy dissipaters and slopes between 1.25 and 30 percent was found in the literature search. This study was presented by Henry M. Morris of the Virginia Polytechnic Institute in bulletin no. 19 titled, "Hydraulics of Energy Dissipation In Steep, Rough Channels"(1). Most of the data in Morris' study were collected at slopes between 5 and 30 percent. Less data were taken at slopes between 1.25 and 5 percent.

The study presented in this report is primarily concerned with slopes of 1.5 percent or less. A decision was made to expand the range of slopes studied to the maximum obtainable with the hydraulic laboratory tilting flume (7.93 percent). This was done to determine if Morris' conclusions could be verified. If surging phenomenon at slopes greater than 5 percent were similar to surging phenomenon at slopes less than 1.5 percent, Morris' data could then be used to increase the data base. If applicable, Morris' results could also be extrapolated to the lower slopes of interest in this study.

The Open and Closed Conduit Systems (OCCS) committee provided partial funding for this study.

Appendix A contains data that were obtained during the study but were not used in the main body of this report. These data may be of use in future studies.

STUDY OBJECTIVE

In the early stages of this study it was found that self-generating surge flow could not be obtained in the laboratory at slopes where it occurred in the field delivery canal (0.5 to 1.5 percent). Surging in the field canal resulted from longer sections of canal than what was simulated in the laboratory. Surging in the field could also result from disturbances caused by changes in slope, alignment, diversions or other sources. To begin study of surge flow it was necessary to determine if surging could be produced in the laboratory. This was accomplished by increasing the slope of the flume and using a block spacing that Morris (1) suggested was most favorable for the production of roll waves. There were four objectives of this study. The first objective was to determine, for various combinations of block spacing and channel slope, the range of flowrates where surging occurred.

Chow (2) refers to two types of surge flow. "For roll waves to form ... the surface velocity of the undisturbed flow must be less than the wave velocity, and the channel slope must be supercritical. For slug flows to form, the surface velocity must be greater than the wave velocity." Morris (1) states that the waves produced in his study had a velocity, "less than the normal flow velocity". The waves in the field delivery canal appeared to have a velocity greater than the surface velocity corresponding to Chow's definition for roll waves. The second objective was to determine if the waves generated in the field delivery canal were the same type of waves as those generated at the higher slopes in laboratory studies.

The third objective was to determine a method to control the waves and provide immediate and practical help in field situations. It was felt that a raft type wave suppressor may accomplish this objective.

Unsteady flow in open channels is a difficult subject and has not been thoroughly investigated. Channels of non-uniform cross section and varying bottom slope further complicate the subject. An analytical method to predict flowrates and block spacings where roll waves form for a given design could have significant benefits. If such a method were available it would enable analysis of blocks as energy dissipation systems in delivery canals. In some cases this may be a cost effective solution.

The fourth objective of this study was to determine types of data that should be obtained and types of instrumentation that should be used in a more comprehensive study. An experimental procedure would also be recommended as an aid to further study.

STUDY APPARATUS

The study was conducted in a 60-foot long tilting flume located in the Hydraulic Laboratory at the Engineering and Research Center. The maximum slope that can be obtained in this flume is 7.93 percent. A trapezoidal channel with a 9-inch bottom width and 1.5:1 side slopes was constructed in the flume (figure 1). Three-quarter-inch thick waterproof resin-coated-plywood was used in the construction of the trapezoidal channel. Three-inch high blocks, similar to those used in the field (figure 2), were installed in the channel bottom. All but one of these blocks were constructed of polyurethane. One block was machined

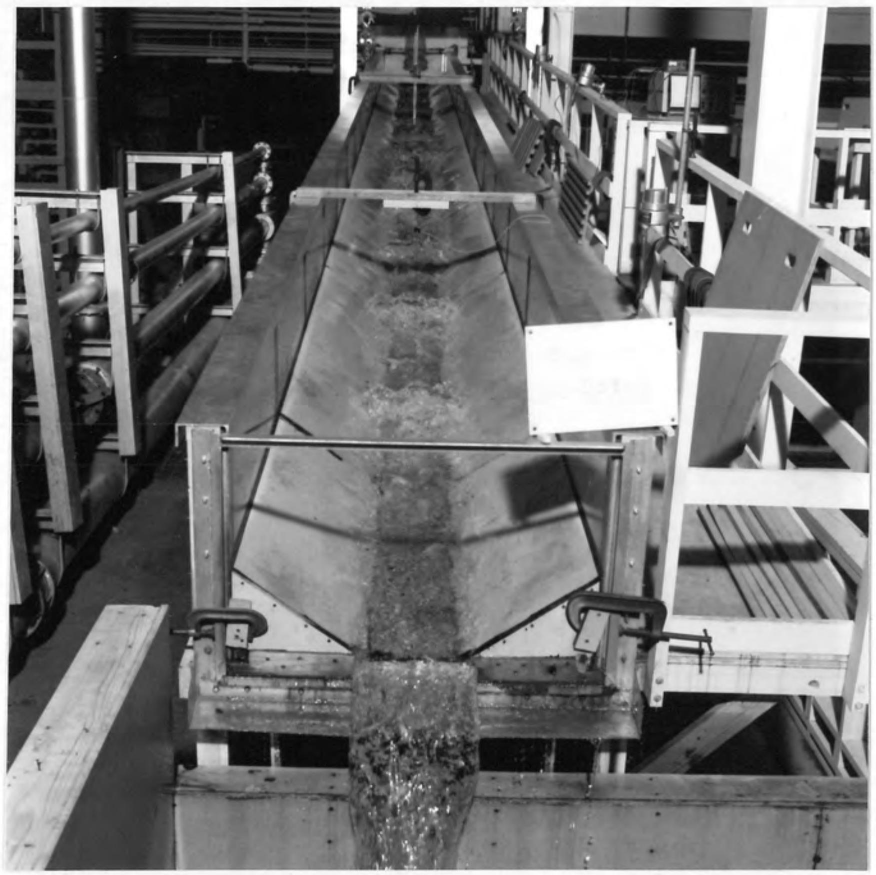

Figure 1. - Trapezoidal channel in 60-foot-long tilting flume.

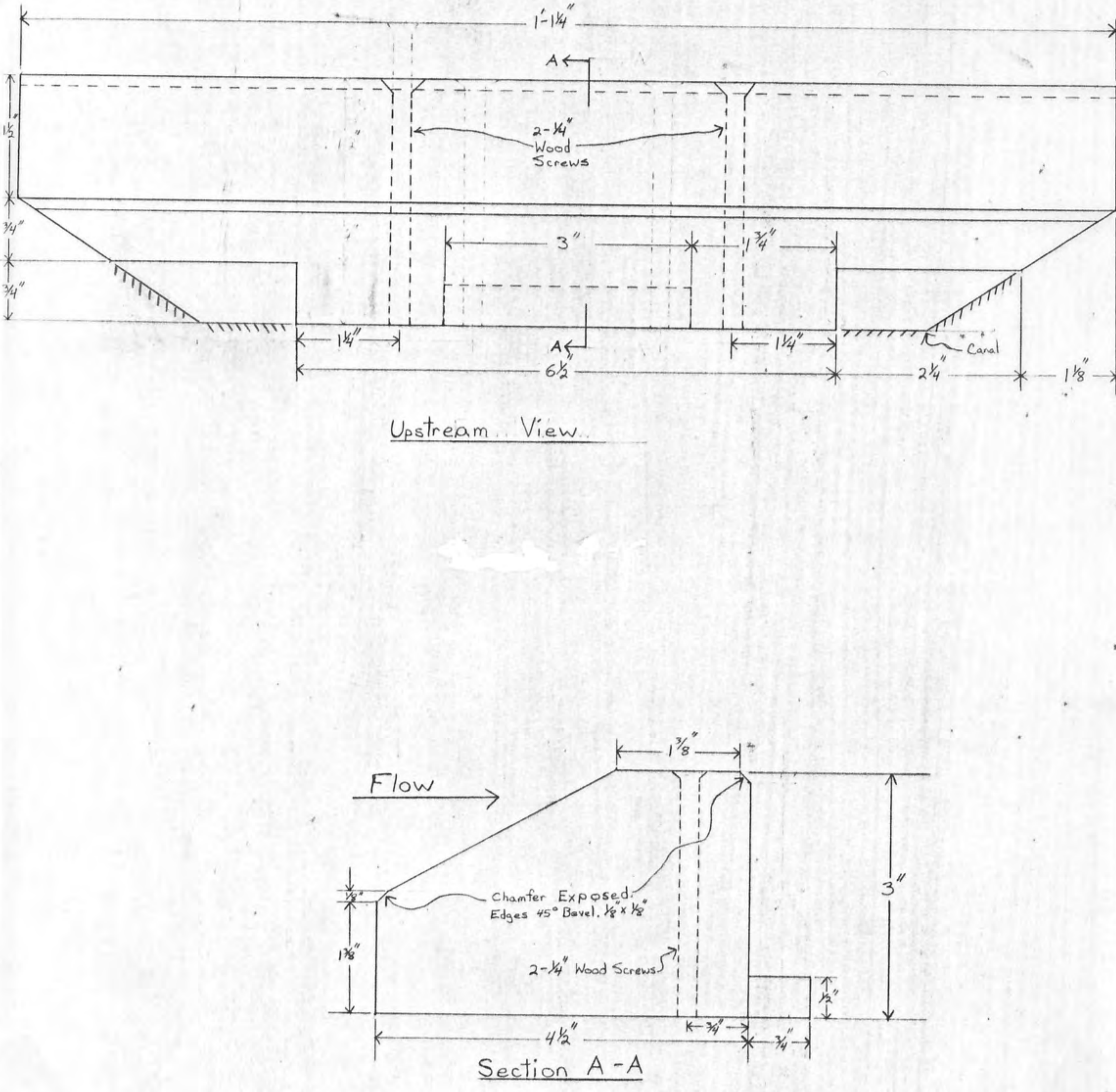

Figure 2. - Energy dissipation blocks.

out of aluminum and had a teflon sheet attached to the bottom surface to minimize friction. Another teflon sheet was attached to the channel bottom where the aluminum block was placed. A 50-lb. load cell was attached to the aluminum block for measurement of hydraulic forces on the block. Two water level capacitance probes were placed 1-inch upstream of blocks. Location of the aluminum block and probes varied depending on the block spacing being tested.

Prior to February 3, 1987, distances of the instrumentation from the upstream end of the flume were:
Upstream probe - 34 ft.-6 in.
Downstream probe - 48 ft.-3 in.
Aluminum block - 43 ft.-3 in.

After February 3, 1987, distances of the instrumentation from the upstream end of the flume were:
Upstream probe - 33 ft.-3 in.
Downstream probe - 48 ft.-3 in.
Aluminum block - 53 ft.-3 in.

Point gages were installed at the same locations as the water level probes for use in making in-place calibrations on the probes. Three point gages were also installed near a block that was 25 ft.- 9 in. downstream of the headbox. One point gage was installed 4-inches upstream of the block, one over the crest of the block, and one 4-inches downstream of the block. Some surface velocities of the flow were obtained with the use of circular styrofoam floats cut to a diameter slightly smaller than the surface width of the water in the channel. The length of time it took a float to travel a known distance gave a rough estimate of average surface velocity.

Artificially generated waves were produced by quickly removing water from the flow at the upstream end of the channel with a 5 gallon bucket. Waves created by dumping water into the flow were also experimented with. However, it was found that waves created by removing water from the flow more closely matched the speed and shape of the waves that formed naturally in the laboratory and waves observed in the field.

EXPERIMENTAL PROCEDURE

Five slopes were included in the study. Three slopes; 3.87, 5.90, and 7.93 percent were studied to enable comparisons with Morris' (1) data. Two other slopes; 0.47 and 1.52 percent covered the range of slopes where surging has been observed in the field delivery canal. The following is a list of data obtained at the five slopes studied.

(1) Oscillograph chart recordings of the water surface elevation at the two probe locations.
(2) Flowrates where self generating surging began and ended.

(3) Wave velocities at flowrates where self generating surging was clearly visible.
(4) Wave velocities of artificially generated waves at flowrates outside the range where surging was self generating.
(5) Force on aluminum block.
(6) Depth of flow 4-inches upstream, depth over the crest, and depth 4-inches downstream of a block upstream of where surging first became visible. This block was located 25-feet-9-inches downstream of the headbox.
(7) Surface velocities upstream of where roll waves were visible.

Morris states that a relative ratio of block spacing to block height of 5 is the most favorable for production of roll waves. This corresponds to a block spacing of 1.25 feet in the model. Data collection began with this block spacing at a slope of 7.93 percent. With this same block spacing, the slope was successively lowered and data collected at each slope down to a slope of 0.47 percent. The same procedure was repeated for block spacings of 2.5 feet and 5.0 feet. Data collected during this procedure were those listed in items (1) through (5).

Data in items (6) and (7) were collected separately for all five slopes and for all three block spacings. Data in item (7) and velocities of artificially generated waves were also obtained for a slope of 1.0 percent.

RESULTS

The following discussion of results is divided into sections corresponding to the first three objectives. Results from the fourth objective are discussed under the heading, "Recommendations For Further Study."

Range of Surge Flow

Surge flow was well developed at a slope of 7.93 percent and a block spacing of 1.25 feet. The flowrate where surging was first observed and the flowrate where surging was no longer visible was recorded for various slopes and block spacings. These data are presented in Table 1. Self generating surging was not apparent at other combinations of block spacing and slope. As the slope was decreased, the location where surging was first visible moved downstream and the wave fronts became less pronounced (figure 3). Similarly, as the block spacing was increased, the location where surging first became visible moved downstream and the wave fronts became less pronounced (figure 4). This indicates that surging may develop at lower slopes and at longer block spacings in longer channels than the one used in this study. The range of surging shown in Table 1 may also increase in a longer channel. However the data in Table 1 indicates some trends and helps to determine the effect of slope and block spacing on surging flow.

Table 1. - Surge Flow Range

Block Spacing (ft)	Slope (percent)	Lower Limit of Surging (cfs)	Upper Limit of Surging (cfs)	Range of Surging (cfs)
1.25	3.87	1.51	1.65	0.14
1.25	5.90	0.97	1.47	0.50
1.25	7.93	0.70	1.41	0.71
2.50	3.87	0.23	0.64	0.41
2.50	5.90	0.20	0.57	0.37
2.50	7.93	0.18	0.40	0.22
5.00	3.87	0.20	0.50	0.30
5.00	5.90	0.15	0.48	0.33
5.00	7.93	0.14	0.31	0.17

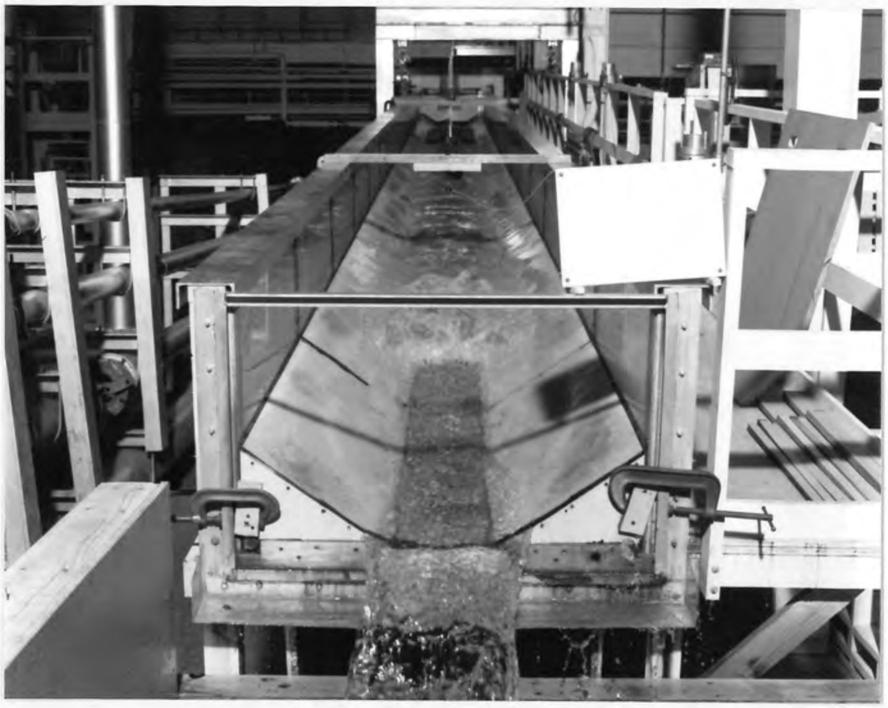

Figure 3a. - Surge wave at block spacing = 1.25 ft, slope = 7.93 percent, and flowrate = 1.10 ft^3/s

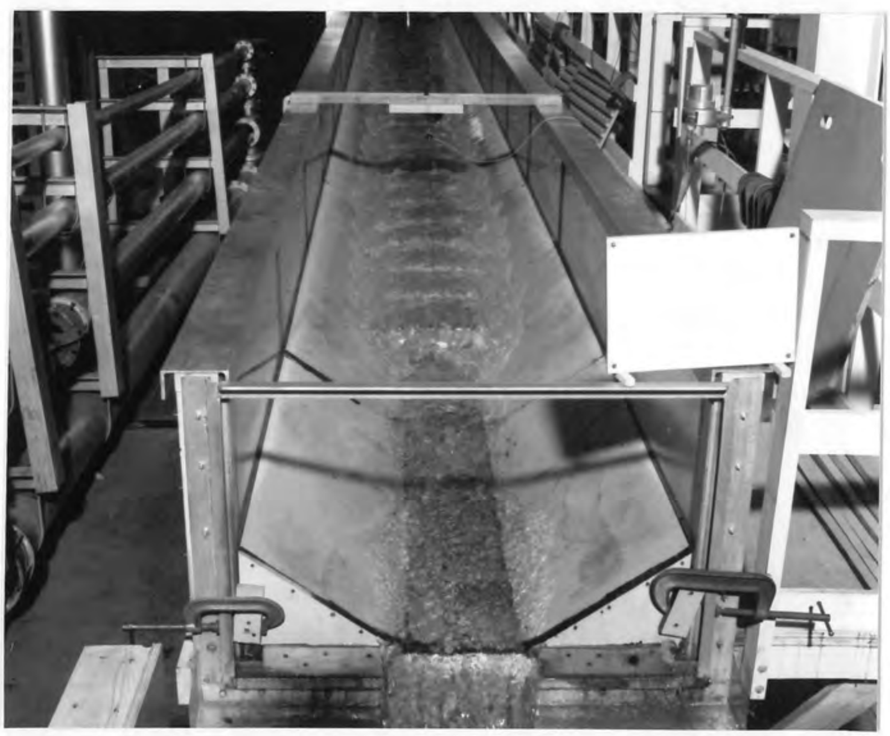

Figure 3b. - Surge wave at block spacing = 1.25 feet, slope = 5.9 percent, and flowrate = 1.10 ft^3/s.

Figure 4a. - Surge wave at block spacing = 1.25 ft, slope = 7.93 percent, and flowrate = 1.10 ft^3/s.

Figure 4b. - Surge wave at block spacing = 2.50 ft, slope = 7.93 percent, and flowrate = 0.26 ft^3/s.

As block spacing is increased the flowrates where surging begins and ends decreases (Table 1). This is also true for increasing slope. For slopes of 5.90 and 7.93 percent the range of flowrates where surging occurs decreases as the block spacing is increased. The data at a slope of 3.87 percent do not indicate this. However, surging was difficult to detect visually at a slope of 3.87 percent, therefore the data probably are not as accurate as it is at the higher slopes. It is possible the range of surging at the 3.87 percent slope may also be decreasing for increasing block spacing.

Wave Characteristics

Despite the fact the cross-sectional geometry of the channel and blocks used in this study were different than those used in Morris' study, some similar results were obtained. The relative ratio of block spacing to block height of 5 that Morris stated was the most favorable for production of roll waves was the most effective of the relative ratios included in this study.

Morris presents plots of the lower limit of surging flow for a relative ratio of block spacing to block height of 5. The axes of these plots are discharge per unit width and flume slope. A separate plot is presented for each block height. The data for these plots were obtained from a rectangular channel. It was not practical to present flowrates in this study in terms of discharge per unit width because of the trapezoidal cross-section of the channel. Data obtained from Morris' plots were used to calculate hydraulic depth assuming a rugosity of 0.0002 feet for plywood, no blocks in the channel, and flow at normal depth. Hydraulic depth is equal to the cross-sectional area of flow divided by the top width of the flow. Rugosity, the equivalent sand grain roughness, is used in the Colebrook-White flow equation to determine flow depth. Each curve on figure 5 represents a different relative ratio of block height to channel bottom width (k/b). The bottom three curves (k/b ratios of 1/24, 1/12, and 1/6) were plotted using data obtained from Morris' plots. The top curve (k/b ratio of 1/3) was plotted from data obtained from this study. It should be noted that the k/b ratio for a trapezoidal channel cannot be precisely compared to the k/b ratio for a rectangular channel. However, Morris found in his study that sloping side walls (trapezoidal channels) did not affect the data and the general trend exhibited in the bottom three curves of figure 5 can be expected to continue. As can be seen from figure 5 the trend in Morris' data is continued with the curve plotted from data obtained in this study.

Surface velocity of the flow and velocity of the waves are presented in Table 2. These data were obtained when the instrumentation were located as indicated for dates after February 3, 1987 in the section titled "Study Apparatus." Wave velocities marked with an asterick (*) were obtained on waves created by quickly removing water from the flow at the

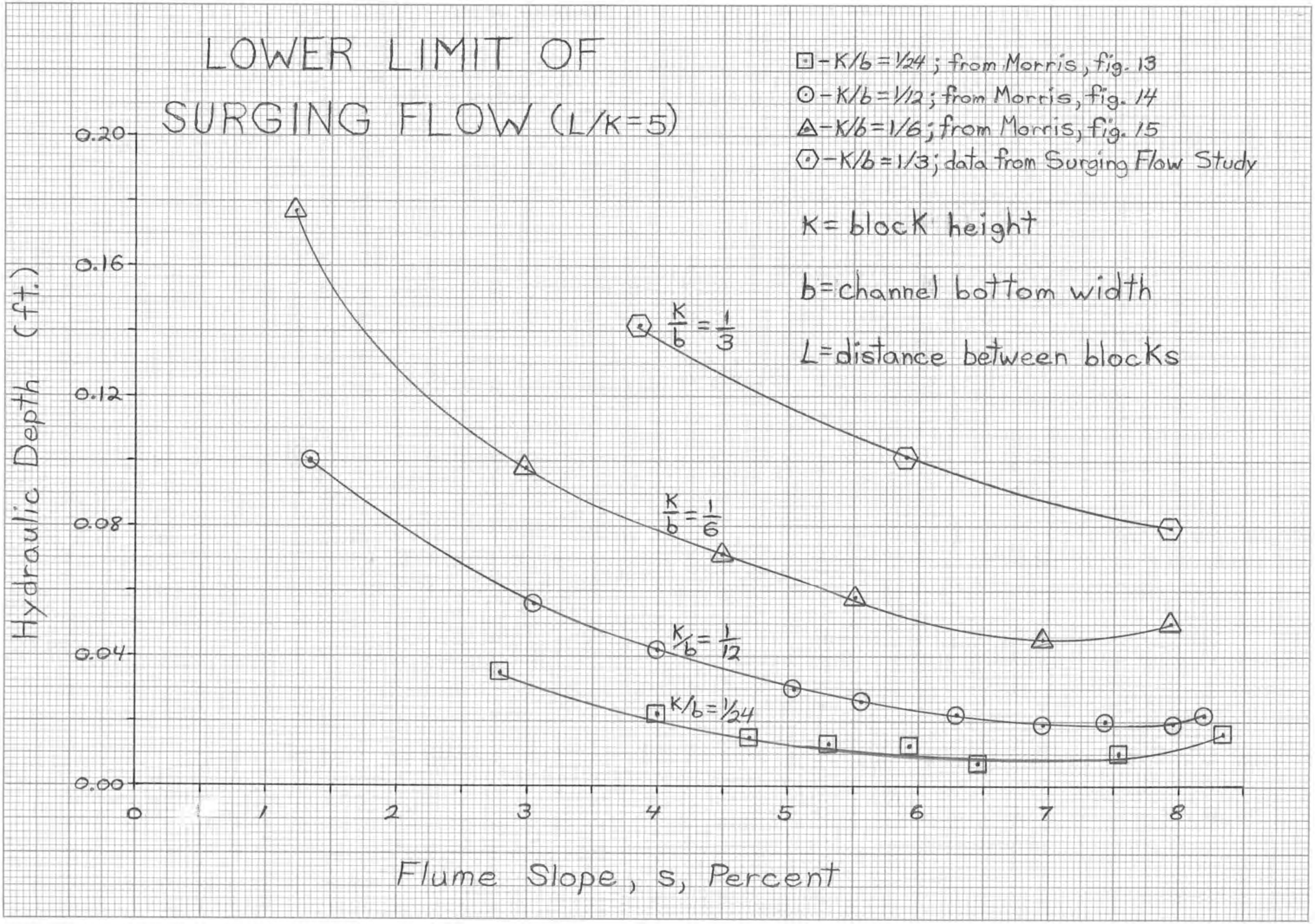

Figure 5. - Lower limit of surging flow.

Table 2. - Wave Velocities

Run Number	Block Spacing (ft)	Slope (percent)	Flowrate (cfs)	Velocity of Surface (ft/s)	Normal Velocity (ft/s)	Velocity of Wave (ft/s)	Depth Upstream of Block (inches)	Depth Over Block (inches)	Depth Downstream of Block (inches)
1	1.25	3.87	1.57	3.90	8.60	6.7*	-	-	-
2	1.25	5.90	1.10	2.60	9.00	5.7	-	-	-
3	1.25	7.93	1.11	2.60	10.00	5.6	-	-	-
4	2.50	1.52	0.58	1.60	4.50	4.3*	-	-	-
5	2.50	3.87	0.50	1.10	6.10	4.1*	-	-	-
6	2.50	5.90	0.40	1.00	6.50	4.1	4.13	1.18	-
7	2.50	7.93	0.33	2.30	6.70	3.9	-	-	-
8	2.50	7.93	0.43	1.70	7.40	4.3	-	-	-
9	5.00	0.47	1.10	1.60	3.50	4.5*	-	-	-
10	5.00	1.00	0.72	1.30	4.10	4.3*	-	-	-
11	5.00	1.00	1.10	1.70	4.60	4.5*	-	-	-
12	5.00	1.52	0.57	1.40	4.50	4.1*	5.11	1.61	3.19
13	5.00	1.52	0.90	1.80	5.10	4.6*	-	-	-
14	5.00	1.52	0.91	2.00	5.20	4.5*	5.85	2.26	3.21
15	5.00	1.52	1.10	2.10	5.40	4.6*	-	-	-
16	5.00	1.52	1.12	2.40	5.50	4.6*	6.20	2.57	3.66
17	5.00	1.52	1.63	2.30	6.10	5.1*	6.89	3.39	4.65
18	5.00	3.87	0.29	1.70	5.10	3.5*	3.70	0.93	0.87
19	5.00	3.87	0.65	2.90	6.60	4.5*	4.88	1.69	1.93
20	5.00	5.90	0.36	3.50	6.20	4.1*	2.72	1.10	1.73

* - indicates artificially generated waves

Normal Velocity = average velocity of flow calculated with the Colebrook-White equation assuming no no blocks in the channel, a rugosity of 0.0002 feet, and flow at normal depth.

upstream end of the channel. At some combinations of block spacing and slope the waves dissipated too quickly to obtain wave velocities. Data presented in Table 2 are only for those combinations of block spacing and slope at which wave velocities could be obtained.

Velocities of the waves in Table 2 are greater than the surface velocities of the flow. This corresponds to the type of wave Chow (1) refers to as roll waves.

Normal flow velocity in Table 2 was computed assuming no blocks in the channel, a rugosity of 0.0002 feet, and flow at normal depth. Morris computed normal flow velocities greater than observed wave velocities in his study. All of Morris' data were taken at slopes greater than 1.25 percent and mostly at slopes greater than 5 percent. All computed normal flow velocities came out greater than the wave velocity except in runs 9 and 10 (Table 2). These two normal flow velocities were at the two lowest slopes: 0.47 percent and 1.0 percent. This may indicate that roll waves at lower slopes are a different phenomenon than roll waves at higher slopes. It is felt that Morris' data and results should not be extrapolated to lower slopes unless future data collection and analysis confirms that roll waves at higher slopes have similar characteristics as roll waves at lower slopes.

Wave Suppression

Two raft type wave suppressors (figure 6) similar to the type described in Section 4 of the Bureau of Reclamation's Engineering Monograph No. 25 "Hydraulic Design of Stilling Basins and Energy Dissipators" (3) were designed for the model. Wave suppressors are discussed beginning on page 47. Figure 7 is reproduced from Engineering Monograph No. 25.

Two raft wave suppressors were placed in the flume three times the raft length (L) apart as recommended in figure 7. They were not held stationary, but instead were allowed to float. They were tethered to prevent movement downstream.

On page 48 of Monograph No. 25 it is recommended that the ratio of hole area to total area of the raft be from 1:6 to 1:8. Ratio of hole area to total area of the raft of the model wave suppressors was 1:7.6.

Monograph No. 25 recommends the minimum dimension of the length (L) be 8-feet. This is for the situation shown in Figure 7. This 8-foot dimension has little meaning for the widely varying conditions encountered with roll waves in canals. A raft type wave suppressor is most effective when its length is as great or greater than the wave length. However, it was discovered in the model study that rafts less than one wave length still reduced wave heights and, in many cases, appeared to completely dissipate the

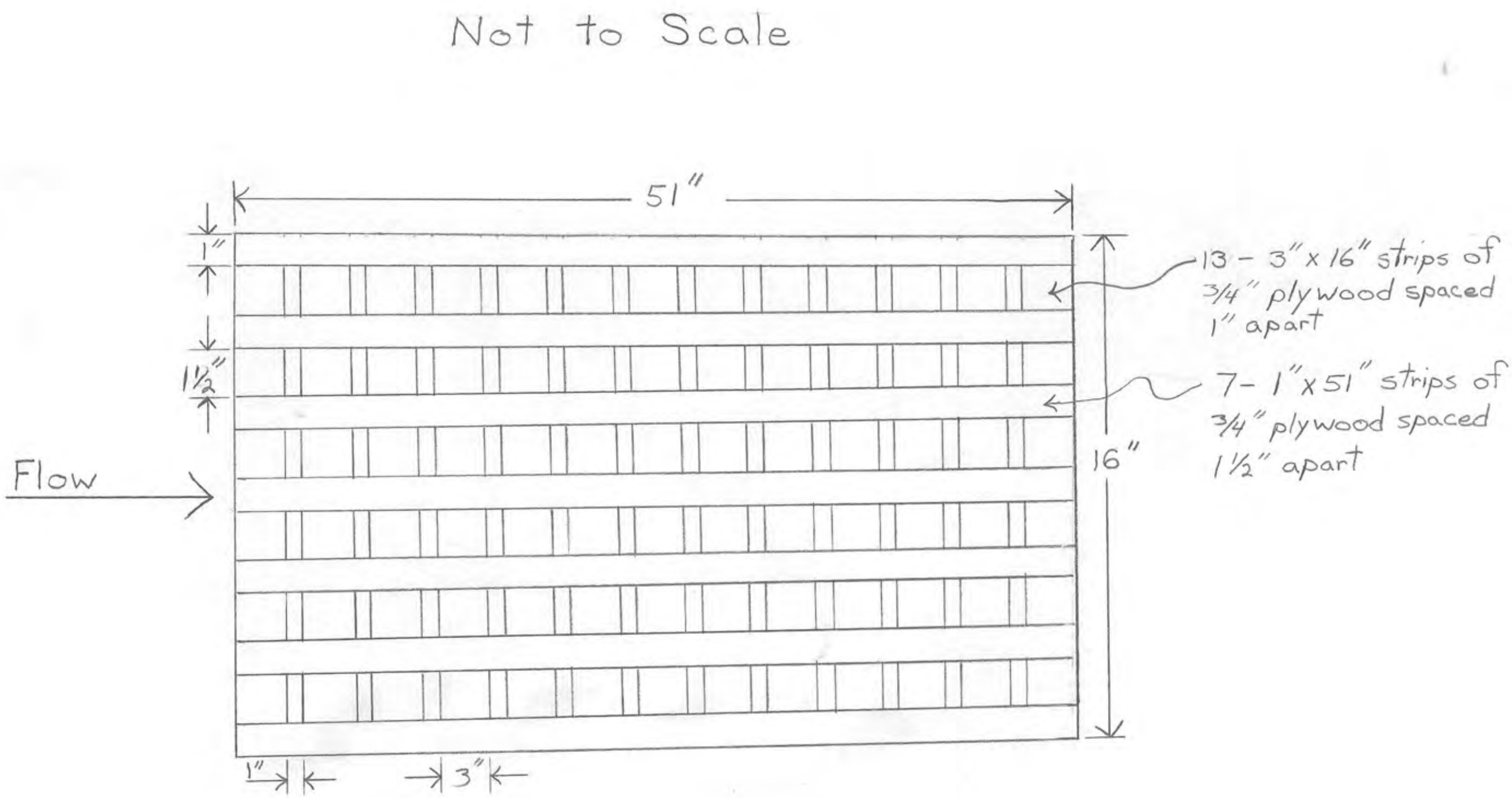

Figure 6. - Raft wave suppressor (top view).

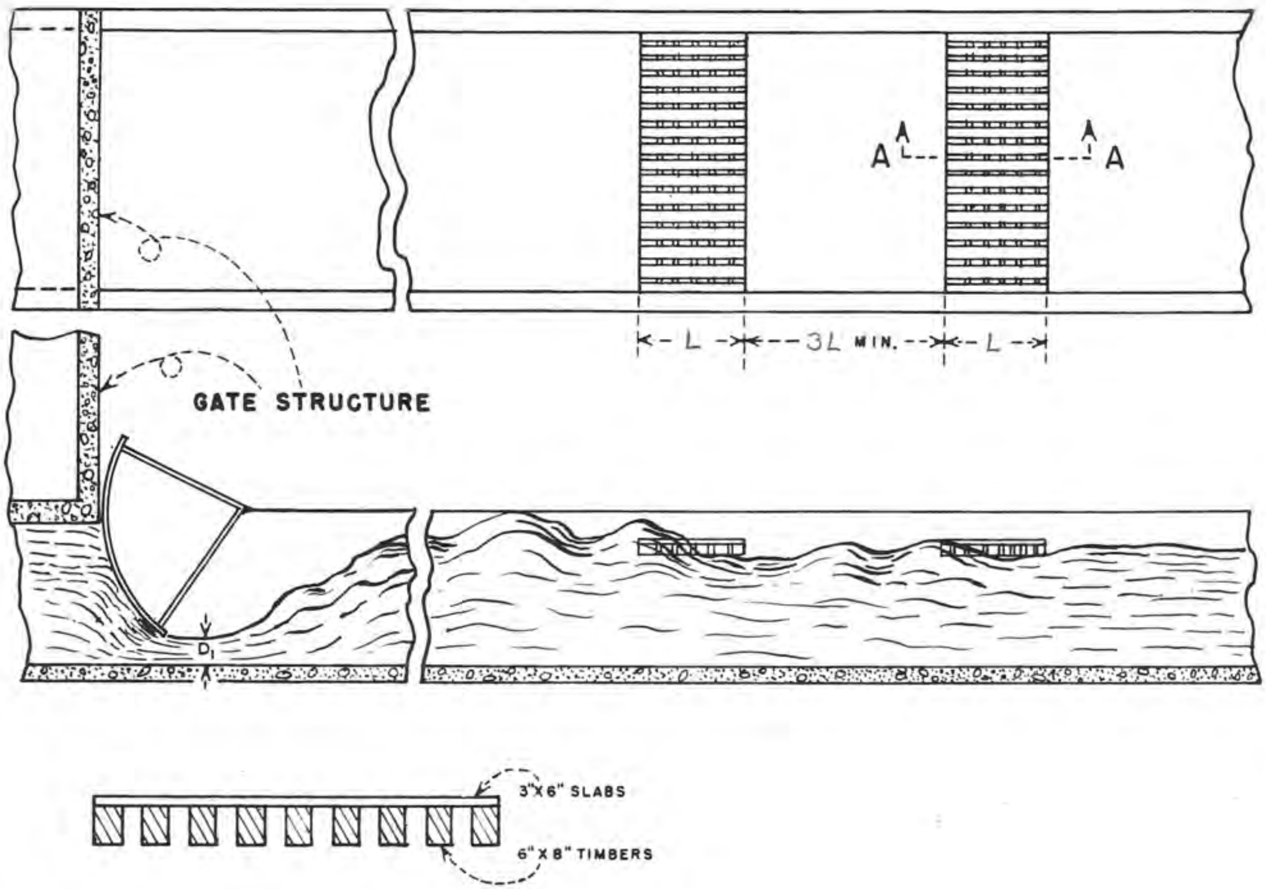

Figure 7. - Raft wave suppressor (Type IV) for Froude numbers 2.5 to 4.5.

waves. Wave lengths in the model varied from approximately 7 to 30 feet. The 4-foot-3-inch long wave suppressors almost completely dissipated the shorter length waves and considerably reduced the heights of the longer length waves. For effective wave dissipation it is recommended that the length of the wave suppressors be at least six-tenths of the longest wave lengths that are expected (where one wave length is the crest to crest length in a wave chain).

The more closely the width of the wave suppressor matches the width of the water surface the more effective the wave suppression. It is recommended that for a trapezoidal channel, the width of the wave suppressor be designed to be slightly narrower than the water surface in the channel at the lowest flowrate where surging is a problem. The minimum wave suppressor width is the top width of the energy dissipation blocks.

RECOMMENDATIONS FOR FURTHER STUDY

To our knowledge this is the first study to deal with surging initiated by block energy dissipators in channels with slopes less than 1.5 percent. Therefore this was essentially an exploratory study to determine what can be simulated in a laboratory model and what direction further study should take. Funding constraints precluded an in depth general study of surging phenomenon.

General

The channel cross-section and shape of blocks used in this study were chosen because they were similar to those used in a field delivery canal where surging was known to occur. In a general study on surging it would be better to keep the geometry of the channel cross-section and of the blocks as simple as possible. This will simplify the calculation of flow parameters and also reduce the construction cost of the model. It is recommended that future studies be conducted in rectangular channels. It is also suggested that thin rectangular weirs of the same width as the channel be used in place of energy dissipation blocks.

With the methods used in this study no self-generating surging was detectable at slopes less than 3.87 percent. This made it difficult to study surging at the slopes of interest. It is undetermined if results obtained at higher slopes can be properly applied to surging at lower slopes. It was reported in the results section that the lower the slope the further downstream surging first became visible. It is reasonable to expect that surging may be produced for the slopes where it occurred in the field if a long enough laboratory flume were available. The channel length can, in effect, be increased without using a longer flume. This is possible by reducing the model scale. It is recommended that the smallest scale be used for which scale effects are not significant.

Load cells could be attached to several weirs and computer spectrum analysis performed on the data. Correlation between the data from any two load cells will filter the data of random fluctuations due to hydraulic jump and water surface fluctuations. Anything that is left which is common to both load cells should identify surge waves. This will aid in surge detection and give better information on whether artificially generated waves are amplifying or attenuating. The 50-lb. load cell used to measure forces on the aluminum block in the initial study was not sensitive enough to obtain accurate force measurements on the smaller waves. In future studies more sensitive load cells should be used. The sensitivity needed depends on the model size. The smaller the model the more sensitive the load cell should be. In this study a 15-lb. load cell would have worked better.

Experimental Procedure

The situation in the field where surging is occurring is much more complicated than can be modeled in the laboratory. The slope of the canal changes many times. It is known that surging is a problem on many of the slopes. But it is not known if all of these slopes produce self-generating waves or if the waves are generated on some slopes and merely translated through canal sections of different slopes. A wave may be generated on one slope and not be a problem. This same wave may reach a canal section with a different slope, where waves would not generate, and be a problem. A change in canal slope may be initiating or contributing to the surging problem. Pumping at turnout structures and lateral curves in the canal may be sources of instability in the flow regime that may have a relationship to the surging flow. Before final design of a model for any future study is completed, it is recommended that additional field data be collected to answer as many of the above unknowns as possible. Wave velocities, surface velocities, and; if possible, ranges of surging should also be obtained during the field tests.

A numerical analysis using momentum principles should be performed to obtain mathematical equations that predict when surging will occur for a given weir spacing, weir height, and channel slope. It was evident in this study that surging occurred only when hydraulic jumps were present between blocks. Chow (1) on page 395 states that an oscillating jump (Froude number, F1, of 2.5 to 4.5) is characterized by, "an oscillating jet entering the jump bottom to surface and back again with no periodicity. Each oscillation produces a large wave of irregular period which, very commonly in canals, can travel for miles." The Froude number, F1, is calculated immediately upstream of where the jump begins. It is believed oscillating hydraulic jumps may be the cause of surging flow. It is therefore recommended that an initial prediction method of surging be accomplished through the prediction of when hydraulic jumps with Froude number (F1) of 2.5 to 4.5 occur.

Next the model should be operated at combinations of weir spacing, weir height, and channel slope where predictions of surging were made with the mathematical equations. Data from the load cells will indicate when surging is occurring. Measurement of y1, the depth immediately upstream of the hydraulic jump, will enable the calculation of F1. Comparison of this data to the prediction method will demonstrate the validity of the mathematical equations.

Once a mathematical method is obtained for predicting when surging will occur for this simple geometry, recommendations can be made for further studies. Further studies may be able to extend the mathematical prediction method to channels and blocks of more complicated cross-sections.

CONCLUSION

The literature search indicated that little research has been conducted on surging flow in channels employing blocks as energy dissipators at slopes of 1.5 percent or less. This study indicated that a comprehensive general study on surging flow utilizing the Hydraulics Laboratory tilting flume is feasible, if the correct type of instrumentation is employed, and if a correct analytical approach is used.

The model indicated that raft type wave suppressors are effective in reducing wave heights if they are properly dimensioned. Two wave suppressors should be used, spaced three-times the raft length apart. The raft length should be at least six-tenths of the longest wave lengths that are expected (where one wave length is the crest to crest length in a wave train). The raft width should be slightly less than the width of the water surface in the channel at the lowest flowrate where surging is a problem. The raft wave suppressors should be tethered to prevent movement downstream but should otherwise be allowed free movement to float on the water surface. It is recommended that the ratio of hole area of the raft be from 1:6 to 1:8.

REFERENCES

(1) Morris, H. M., "Hydraulics of Energy Dissipation in Steep, Rough Channels", Virginia Polytechnic Institute, Bulletin 19, November 1968.

(2) Chow, V. T., "Open-Channel Hydraulics", McGraw-Hill Book Company, Inc., New York, 1959, pp. 581, pp. 395-396.

(3) Peterka, A. J., "Hydraulic Design of Stilling Basins and Energy Dissipators", U.S. Bureau of Reclamation Engineering Monograph No. 25, January 1978, pp. 47-48.

APPENDIX A : Data

Table A1.

FORCES ON ALUMINUM BLOCK
AT
BLOCK SPACING OF 1.25 FEET

Slope (percent)	Flowrate (cfs)	Force on Block Without Waves (lbs.)	*Maximum Horz. Force On Block (lbs.)	*Minimum Horz. Force On Block (lbs.)
0.47	0.71	4.14	-	-
0.47	2.36	4.36	-	-
1.52	0.64	3.84	-	-
1.52	1.25	3.85	-	-
1.52	1.59	4.36	-	-
1.52	2.34	4.36	-	-
3.87	1.05	4.55	-	-
3.87	1.55	4.72	-	-
3.87	1.60	4.77	-	-
3.87	2.01	4.84	-	-
3.87	2.34	4.84	-	-
5.90	0.97	4.91	-	-
5.90	1.31	5.26	7.74	5.39
5.90	1.47	5.34	6.60	6.22
5.90	2.00	5.23	-	-
5.90	2.34	5.15	-	-
5.90	2.36	5.49	-	-
7.93	0.46	4.66	-	-
7.93	0.61	4.66	-	-
7.93	0.70	5.44	-	-
7.93	0.87	5.36	6.47	5.75
7.93	1.09	4.53	8.64	6.20
7.93	1.24	4.91	9.40	5.90
7.93	1.32	5.06	8.33	6.35
7.93	1.41	5.29	7.58	6.05
7.93	1.51	5.33	-	-
7.93	1.75	5.60	-	-
7.93	2.01	5.75	-	-
7.93	2.19	5.90	-	-
7.93	2.34	5.90	-	-
7.93	2.36	5.97	-	-

* includes hydraulic force on block due to waves

Table A2.

FORCES ON ALUMINUM BLOCK
AT
BLOCK SPACING OF 2.5 FEET

Slope (percent)	Flowrate (cfs)	Force on Block Without Waves (lbs.)	*Maximum Horz. Force On Block (lbs.)	*Minimum Horz. Force On Block (lbs.)
3.87	0.23	4.35	-	-
3.87	0.41	4.67	-	-
3.87	0.49	4.86	-	-
3.87	0.64	4.86	-	-
5.90	0.18	5.56	-	-
5.90	0.20	5.60	-	-
5.90	0.24	5.60	-	-
5.90	0.32	5.60	-	-
5.90	0.57	5.84	-	-
7.93	0.18	5.26	5.26	5.26
7.93	0.19	5.41	5.41	5.41
7.93	0.20	5.35	6.44	5.41
7.93	0.22	5.35	6.84	5.48
7.93	0.23	5.38	6.72	5.22
7.93	0.35	5.69	6.90	5.60
7.93	0.40	5.83	-	-

* includes hydraulic force on block due to waves

Table A3.

FORCES ON ALUMINUM BLOCK
AT
BLOCK SPACING OF 5.0 FEET

Slope (percent)	Flowrate (cfs)	Force on Block Without Waves (lbs.)	*Maximum Horz. Force On Block (lbs.)	*Minimum Horz. Force On Block (lbs.)
1.52	0.26	4.77	-	-
1.52	1.30	5.32	-	-
1.52	1.56	5.45	-	-
1.52	1.81	5.45	-	-
3.87	0.17	5.22	-	-
3.87	0.21	5.41	-	-
3.87	0.26	5.35	-	-
3.87	0.93	5.54	-	-
5.90	0.37	4.64	-	-
5.90	0.45	4.95	-	-
5.90	0.67	5.07	-	-
7.93	0.17	4.54	-	-
7.93	0.25	4.54	-	-

* includes hydraulic force on block due to waves