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Unsteady Water Depth Measurement in A Partially Filled 7.6 cm Diameter Horizontal Pipe

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

A research program to investigate the wastewater solid transport in pitched horizontal drains is under way. The objective of the program is to develop data base and establish correlations for selecting drain pipe diameter, length, and slope for effective solid waste transport with reduced water usage.

The purposes of this portion of the research program were: (1) to measure the stream depth histories of unsteady, nonuniform, partially filled pipe flow that ensues when water from a plumbing fixture is discharged into the drain; and (2) to examine the effects of the presence of a cylindrical solids and other relevant variables on the stream depth. The variables selected for the study include: the water volume discharged from the fixture into the drain; the drain slope, and the diameter and length of cylindrical solids.

This report contains a description of the experimental apparatus, instrumentation and procedures; and a summary of the stream depth data acquired from experiments in a 7.6 cm diameter drain.

The depth of water stream at any given cross-section of the drain rises rapidly to a peak value and then gradually falls to zero. The peak value of stream depth at a pipe cross-section decreases as the distance from the drain entrance increases. At a given pipe cross-section the peak value of stream depth increases with an increase in the water volume used, a decrease in the pipe slope, and with the presence of a solid in the drain. The variations in the diameter of the solid influence the stream depth history more than the variation in its length.

PREFACE

This report is one of a group documenting National Bureau of Standards (NBS) ressearch and analysis efforts in development of water conservation test methods, models for technical and economic analysis, and strategies for implementation and acceptance of practices. This work is sponsored by the Division of Energy, Building Technology and Standards of the Office of Policy Development and Research, of the Department of Housing and Urban Development, under Interagency Agreement H48-78.

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1. INTRODUCTION

The purpose of this report is to discuss the depth measurement of transient water flow in horizontal branches of gravity drainage systems. Experimental apparatus, instrumentation and procedures employed for measuring water depth in unsteady partially-filled horizontal drains are described. A summary of results obtained from initial experiments is presented.

The requirements for water conservation as a national priority have emerged due to the recognition of the limited availability of water resources. Technological advances to effect significant savings of water usage in buildings depend on low volume or water-saving plumbing fixtures. In the routine operation of gravity drainage plumbing systems, reductions in the quantity of water may result in inadequate transport of wastes after their entry into the drainage system.

Water closet (WC) operations use about 40 percent of the total water used in residences [1 - 2]. It has been estimated that a reduction of 30 percent or more in this consumption can be realized by replacing the conventional water closets (20-26 liters/flush) with water saving or low volume units (10-13 liters/ flush) [2 - 4]. Some researchers and plumbing professionals [1 - 7], however, have expressed concern about the use of low-volume water closets. These concerned professionals indicate that the use of low-volume water closets may reduce the wastewater flow in the horizontal branches (i.e., pitched-horizontal drains or p-h drains) of the drainage systems below levels necessary for the transportation of solid waste and impair the effectiveness of gravity drainage systems.

To minimize the likelihood of drain clogging with reduced wastewater flows, p-h drains should be properly designed. That is, the selected drain pipe variables (diameter, length, and pitch or slope) should be such that the volume of water used in the plumbing fixture operation, V_w, can adequately transport the solid wastes through the p-h drain. The theoretical and/or empirical relationships among V_w, variables of the drain pipe, the hydraulic parameters of the wastewater flow in the drain, and effective solid waste transportation, however, are not well established. Hence, research programs to investigate the transient partially filled pipe flow transportation of solid wastes through the horizontal branches (p-h drains) of gravity drainage systems are needed.

Pipeline transportation of solids, both slurries (i.e., small mass elements or particles in suspension) and capsules (i.e., finite solids), with steady full bore (flowing full) liquid flows has been investigated by many researchers [8 - 12]. In these studies of pipeline transport of solids, the flow of the carrier liquid is controlled by pumps. The transportation of solids through the gravity drainage system pipeline as compared to the full bore pumped system is quite different, although in both cases solids are transported by a flowing liquid. The major differences include: the flow of water through the drainage system is controlled by the gravity field; the p-h drain is only partially filled; the flow is non-uniform, and transient; the depth of the water stream is variable and strongly influences the transportation of solids. The hydraulic parameters of flow (i.e., flow rate γ, velocity U, and depth h) and the duration of flow through a p-h drain are dependent upon the volume of water discharged, and the fixture and drain variables. The problem is further complicated because the flow parameters are not known and methods for predicting the flow parameter histories along the length of the drain as a function of V_w and other relevent variables are not yet fully developed. Also, standard instrumentation is not available for measuring unsteady parameters of water flow and motion of the waterborne solid without disturbing the flow field.

Kamata et al. [13] utilizing the two-point Laxe-Wondroff finite difference scheme for numerical integration of unsteady equations of flow in open channels obtained approximate values of local hydraulic parameters of transient flow introduced into horizontal drains by the flushing of a WC. They assumed that the volume flow rate history of water influx into the drain pipe, due to the flushing of WC, is equivalent to a triangular surge of relatively short duration (10-20 sec.). Based on the assumed triangular surge influx and the Manning formula, they assigned certain values to the hydraulic parameters of flow (i.e., γ, U, and h) at a drain cross-section near the drain inlet, and proceeded to calculate the corresponding values of flow parameters at various locations (drain cross-sections) along the length of the drain pipe. They also compared the flow parameter histories thus obtained with the experimentally measured histories and claimed a "good enough" agreement between the two, although, because of the experimental techniques utilized, their measured flow parameters represented only approximate values.

They used the following techniques to measure the flow parameter histories at various cross-sections along the length of a horizontal drain. They attached a horizontal pipe of certain length to the outlet of a WC; flushed the wc into the pipe which was discharging freely into an open tank containing a pressure transducer; and measured the unsteady flow rate of the efflux and the stream depth at the exit end of the pipe. They then considered that the flow rate and stream depth histories thus measured represented the local values for flow in a long drain pipe at a drain cross-section whose distance from the drain entrance was equal to the length of the relatively short pipe used in the measurement. To obtain the flow parameter histories at various locations along the length of a horizontal drain, they repeated the above-mentioned experiment with pipes of different lengths. The flow parameters thus obtained, however, are not true representatives of the local values at various cross-sections of a long h-drain because these measurements do not account for the effects of hydraulic elements of the flow downstream of the stipulated location of measurement.

Relatively few investigations have been undertaken to measure the unsteady depth of water stream in partially filled horizontal drains as a function of V_w and other relevant variables. The study presented in this report is from a research program underway to investigate the transport mechanism of solids in horizontal drains, and to develop the data base and establish correlations needed for selecting drain pipe variables for effective solid waste transport with reduced water usage.

The objectives of this portion of the research program were: (1) to develop instrumentation for measuring the unsteady depth of water stream in partially filled horizontal drains without disturbing the flow field; (2) to measure the stream depth histories at various locations along the length of the drain pipe for different values of water volume discharged into the drain from a plumbing fixture; and (3) to examine the effects of drain slope (or pitch) and the presence of a solid and its size on the stream depth.

2. EXPERIMENTAL EQUIPMENT AND PROCEDURES

2.1 EQUIPMENT

The apparatus used in the experiment is shown schematically in figure 1. A right circular cylindrical tank containing a flush valve and down pipe is utilized to simulate a water closet. The flush valve is operated by a solenoid switch. The down pipe is connected by a 90-degree elbow to a 7.6-cm diameter pitched horizontal drain. At the drain inlet, a tee is provided adjacent to the elbow to permit insertion of the selected solid. An indicator line is marked on the outside lower wall of the tee-section opposite to the opening; the indicator line is approximately at the center of the tee-section. Both the tee and the pipe are transparent, to facilitate visual observation of the flow field and solid transport phenomena. The pipe drain is secured to stands which are evenly spaced along the length of the drain; these stands can be adjusted to establish the pitch of the drain. The exit end of the drain is 5.1 m downstream of the indicator line and is open to the atmosphere. The efflux from the drain is caught in a container for proper disposal. All pipes and fittings used to construct the apparatus are standard plumbing sizes used in the U.S.

Hollow right circular cylinders with flat ends were used as experimental solids. These cylinders were constructed from opaque and rigid plastic tubing. One end of the hollow cylinder is completely plugged; the other end is only partially plugged with a plug containing a concentric hole. The partially plugged end is closed with a threaded cap (figure 2). The end plugs and threaded caps were made from the same plastic material and were so constructed that the center of gravity of the closed cylinder coincided with its geometric center. The hollow cylinder with threaded cap permits desired changes in the specific gravity of the solids used in the experiments, since the cylinders can be filled with any material. For these experiments, the specific gravity of the solids was made equal to one. The length to diameter ratios of the cylindrical solids used in the experiments are given in table 1.

Table 1. Length to Diameter Ratios of the Cylindrical Solids Used in the Experiment

	Length/Diameter				
Length - cm	2.5	3.8	5.0	6.3	7.6
Diameter - cm					
1.9	1.33	2.00	2.67	3.33	4.00
2.5	1.00	1.50	2.00	2.50	3.00
3.2	0.80	1.20	1.60	2.00	2.40
3.8	0.67	1.00	1.03	1.67	2.00

The water level depth is measured at a pipe cross-section by electrical conducting pins (point electrodes) inserted in the pipe wall at prescribed circumferential distances (figure 3). The discrete locations of the pins provide incremental stepwise signals when the water level contacts the pins. The level signal remains unchanged over the small spacing distance between the pins until another point of contact is made. The pins are peripherally located at 1 cm spacing along the circumference starting from the pipe invert; the pin spacing arrangement from the invert is staggered by 0.5 cm so that pins on opposite sides of the pipe wall provide peripheral resolution of water depth of 0.5 cm.

At each station (cross-section), the water level detector consists of 18 pins. The pins are installed flush with the inside wall surface so they do not interfere with waterborne solids. The water flowing through the pipe wets the pins to complete the electric circuit by passing the current through the water to the common pin; the signal current in the circuit feeds a summing operational amplifier (SOA) that produces a voltage proportional to the number of wetted pins. The voltage output signal from the SOA is fed to a strip chart recorder and/or to a floppy disk of a microcomputer where the water depth-time history is recorded. The logic circuit is shown schematically in figure 4. Four such water level detectors are used along the length of the drain pipe. The detectors numbered 1 through 4 are situated at distances respectively of 0.6, 0.9, 4.5 and 4.8 meters downstream of the indicator line in the tee-section.

2.2 EXPERIMENTAL PROCEDURES

The slope of the drain pipe was adjusted to the desired value. The water level detectors were energized and the selected volume of water was flushed into the empty drain. The flow of water through each cross-section containing the pins was detected and water stream depth history was recorded on a floppy disk of a microcomputer programmed to record the resolved vertical depth at every tenth of a second during the flow duration. These data were later used to plot the stream depth history profiles and maximum water depths, as a function of the selected experimental variables. For tests of solid transport, and for examining the effects of a solid on the water flow entering the drain, and subsequently on the stream depth history profiles at the four selected cross-sections of the drain, a solid was placed in the empty drain. The selected solid was inserted through the tee opening, and placed on the lower wall of the drain pipe with its upstream end aligned with the indicator line marked on the outer wall of the tee-section, and its axis aligned with the drain axis. With the solid at rest in the drain, the selected volume of water was flushed from the tank into the drain. The interaction between the stationary solid and the incoming water flow was observed. The water stream depth histories at the four drain cross-sections containing the detectors are recorded.

Each experiment with the selected test variables was run three times. The selected test variables were: water volumes equal to 11.4, 7.6, 3.8, 1.9, 1.5 and 1.1 liters (3, 2, 1, 0.5, 0.4, 0.3 gallons); drain pipe slopes (defined as sign θ, see figure 1). equal to 0.04 and 0.06; and single cylindrical solids with dimensions shown in table 1.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 VISUAL OBSERVATIONS

Before discussing the water flow in a horizontal drain serving a plumbing fixture such as the experimental water closet simulation (or the tank), it is instructive to describe the characteristics of the water flow leaving the fixture or entering the drain. The water leaves the tank at an unsteady volume rate of flow, and for a given fixture the efflux rate-history is primarily dependent upon the total volume of water dispensed from the fixture. In general the efflux rate rises rapidly from zero to a peak value as the valve is opened, and then gradually falls off to zero as the tank is emptied.

The water discharged from the tank into the empty horizontal drain enters the drain via the turning elbow and streams through the pipe unobstructed. The drain pipe is only partially filled, and the depth of water stream is both nonuniform and unsteady. The water depth history at any cross-section of the drain is dependent on the water influx rate history. Water depth history profile is similar to that of the influx rate history. That is, the stream depth in general rises rapidly to a peak value and then gradually falls off to zero. The peak value of the water depth for a given value of water discharged decreases as the distance from the drain entrance increases.

When the water from the tank is discharged into the horizontal drain containing the selected cylindrical solid on its lower wall, it encounters the stationary solid. The stationary solid blocks the flow resulting in a short-term buildup of some water behind (upstream of) the solid and passing of some water around the solid through the crescent-shaped space between the solid and the pipe wall. The depth of water stream behind the solid rises at a faster rate than that in front (downstream) of it, which causes a hydrostatic head difference across the solid. The stationary solid, in addition to its weight component, is also subjected to the following forces in the downstream direction: a pressure force due to the unequal liquid depth and velocity on the two faces of the cylinder; and shear force due to the streaming of liquid past the solid.

The flow induced forces acting on the solid increase with the increase of water influx to the drain. The solid remains stationary until the sum of forces acting in the downstream direction overcomes the force due to static friction between the solid and pipe wall. When this friction force is exceeded the solid starts to move, and accelerates until a balance of forces develops. If the resultant of forces acts off the center of gravity, a net moment occurs which may tilt the solid relative to the axis of the pipe.

The motion of the solid within the drain is dependent upon the volume of water used and the size of the solid. When water volumes equal to or greater than 1.9 liters were used, the test solid, regardless of its size, cleared the drain, and a portion of the water exited the drain after the solid. When water volumes less than 1.9 liters were used, some solids did not clear the drain; a solid, depending on its size traversed a certain distance and stopped within the drain while a portion of the water was still flowing through the drain.

The interaction of the solid with the incoming water flow modifies the stream depth histories along the length of the drain. As a result of water buildup behind the solid, the peak values of water depth at a drain cross-section adjacent to the upstream end of the solid are higher than the peak values of stream depth in the absence of a solid, for the same volume of water discharged. This effect of the solid on the water stream depth is very pronounced and visible during the early stages of duration of the flow and the motion of the solid. During the later stages of the flow duration, as the solid moves downstream picking up speed, the effect becomes less and less noticeable, disappearing completely as the solid leaves the drain. Hence, the stream depth histories in the upstream sections of the drain, where the solid is moving slowly, are modified to a greater extent than those in the downstream sections of the drain. The water stream depth histories, however, display the same basic patterns; that is, the depth rises rapidly to a peak value and then gradually falls off to zero; and for a given water volume the peak value of water depth decreases as the distance from the drain entrance increases.

3.2 WATER STREAM DEPTH DATA

The depth of water stream was measured at four cross-sections or stations along the length of the drain; these are numbered 1 through 4 in the downstream direction (figure 1). The stream depth at each station was recorded on the floppy disk of a microcomputer. These data were taken at every tenth of a second of the flow duration starting with the activation of the flush valve. The data are presented in figures 5 through 48. The values presented in these figures represent the average of three repeated experimental values under the same conditions.

Figures 5 through 28 show stream depth histories as nondimensional stream depth (i.e., the ratio of stream depth to drain pipe diameter) versus elapsed time, measured from the instant the flush valve was actuated. Figures 5 through 16 show the stream-depth histories at the four measuring stations for one value of water volume used, V_w, drain slope S, and with or without a solid in the drain. Figures 17 to 24 show the stream depth histories at measuring stations 1 and 3 for two values of V_w, one value of S, and with or without a solid in the drain. Figures 25 to 28 show the stream depth histories at measuring stations 1 and 3 for two values of S, one value V_w, and with or without a solid in the drain.

An examination of these figures indicates that all of the stream depth-history profiles display the same general pattern; each profile indicates that the stream depth rises rapidly to a peak value and then gradually falls off to zero. The peak value of the stream depth is highest at the first station and it decreases as the distance from the drain entrance is increased which implies that the average flow velocity is increasing. The elapsed times for the stream front to reach a station and for the stream depth to attain the peak value increase as the distance of the station from the drain entrance increases. At a given station the peak value of stream depth increases with an increase in V_w, a decrease in S, and with the presence of a solid.

Figure 29 shows the peak value of nondimensional stream depth versus water volume used (V_w) at measuring stations 1 and 3 for a drain slope (S) equal to 0.04, and with no solid, a 2.5 by 5.1 cm (diameter by length) solid, and a 3.8 by 5.1 cm solid in the drain. Figure 30 shows data similar to those of figure 29, for a drain slope of 0.04, and with no solid, a 2.5 by 6.4 cm solid, and a 3.8 by 6.4 cm solid in the drain. These data indicate that the peak value of stream depth increases with the increase of V_w; and for a given V_w the peak value of the stream depth at a station is higher when a solid is in the drain than when no solid is present.

Figures 31 to 32 show the peak value of nondimensional stream depth versus V_w, for S equal to 0.04 and 0.06, with or without a solid in the drain. Each figure shows data at two measuring stations; figure 31 shows data at stations 1 and 3, and figure 32 represents data at stations 3 and 4. These data show that, in general, peak values at S equal to 0.06 are lower than those for S equal to 0.04.

Figures 33 to 40 show the variations of the peak values of nondimensional stream depth with the variation of solid-diameter to pipe-diameter ratios (i.e., non-dimensional solid diameter). Each figure shows data at two measuring stations, and for three different values of V_w, one value of solid length and pipe slope. These data indicate that the peak value of stream depth at each of the measuring stations increases with an increase in V_w.

These data also indicate that the variations of the peak value of stream depth with the variations of the solid diameter display different patterns at different pipe locations for the same values of other experimental variables, and different patterns at the same station for different values of other experimental variables. Hence these data suggest that the peak value of stream depth, and consequently the stream depth history, in addition to the experimental variable (i.e., V_w, S, solid diameter and length) is also dependent upon the velocity of the solid relative to the velocity of water flow. In the upstream section of the drain (i.e., in the vicinity of measuring stations 1 and 2), the solid is still accelerating and moving with a velocity slower than the flow velocity; in the downstream section of the drain (i.e., in the vicinity of measuring stations 3 and 4), depending on the value of V_w, the solid may be moving with a velocity very close to the flow velocity and accelerating, moving at a constant speed, or decelerating. A stationary solid produces a greater flow blockage than a moving solid, a slow moving solid produces more flow blockage than a fast moving solid, and a solid moving with a speed equal to the flow speed probably produces no flow blockage.

These data indicate that for V_w equal to 1.9 liters, peak value of the stream depth generally increases with an increase in the solid diameter; and for V_w equal to 3.8 and 7.6 liters, the peak value of stream depth first increases with an increase in the solid diameter and then decreases with a further increase in the solid diameter. These indications suggest the existence of a critical solid diameter for a given set of other experimental variables; and a solid with a diameter larger than the critical diameter moves faster than a solid of smaller diameter than the critical diameter. It also suggests that the solid with diameter larger than the critical diameter starts to move with less water buildup behind the solid than those with diameters smaller than the critical diameter. A possible interpretation of this phenomenon is as follows. Various forces acting on the solid increase in magnitude as the diameter of the solid is increased for the same values of the variables (V_w, S and solid length). Obviously volume and/or weight, cross-sectional area and surface area of a solid increase with an increase in the diameter. Therefore, for a given set of water flow conditions (i.e., stream depth and flow velocity) the areas of surfaces of solid-water interface increases with an increase in the solid diameter. An increase of the solid-water contact surface perpendicular to the flow direction (i.e., cross-sectional area of the solid) increases the flow induced pressure force F_p; and an increase in the solid-water contact surface parallel to the flow (i.e., peripheral or surface area) increases the flow induced shear force F_D: The volume of water displaced by the solid is also increased resulting in an increase of the buoyancy force F_b. Also, because of the increase in the weight of the solid, the force of static friction between the solid and pipe wall increases with an increase in the diameter of the solid.

If the sum of incremental increases in the flow induced forces due to an increase in the diameter solid is smaller than or equal to the incremental increase in the friction force, then the water buildup behind the solid needed to set the solid in motion increases with an increase in the solid diameter; this appears to be the case for solids with diameters less than or equal to the critical diameter. If the sum of the incremental increases in the flow induced forces is greater than the increase in the force of friction, then the water build up behind the solid needed to set the solid in motion decreases with an increase in the solid diameter; this appears to be the case for solids with diameters larger than the critical diameter.

Figures 41 to 48 show the variations of the peak value of the non-dimensional stream depth with the variations of solid length to pipe diameter ratio (i.e., non-dimensional solid length). Each figure shows data at two measuring stations and for three different values of V_w, and for one value of solid diameter and pipe slope. An examination of the figures indicates the followings. (1) At measuring stations 1 and 2 peak value of stream depth increases with an increase in the length of the solid; and the variations of the peak value of stream depth decrease with an increase in V_w and S, and with a decrease in the solid diameter. (2) At measuring stations 3 and 4 the peak value of stream depth is not appreciably effected by the variations in the length of the solid. It appears that the effects of the length of the solid on the stream depth are dependent upon the state of the motion of the solid. At measuring stations 1 and 2, the solid is accelerating and moving with a speed much less than the local speed of water, and at the measuring stations 3 and 4 the solid is moving at a speed very close to local speed of water stream.

4. CONCLUSIONS

The point electrode method provides a satisfying method to measure the stream depth history of nonuniform, unsteady, transient, partially filled pipe flows containing finite solids as flow constituents, without disturbing the flow.

The depth of water stream at any given drain cross-section rises rapidly to a peak value and then gradually falls off to zero. The peak value of the stream depth for a given value of water volume decreases as the distance from the drain entrance increases which implies that the flow velocity is increasing. The elapsed times for the stream front to reach a station and for the stream depth to attain the peak value increase as the distance from the drain entrance is increased.

At a given drain cross-section the peak value of stream depth increases with an increase in the volume of water used, a decrease in pipe slope, and with the presence of a solid in the drain.

The peak value of the stream depth first increases with an increase in the solid diameter and then decreases with a further increase in the solid diameter, suggesting the existence of a critical solid diameter for a given set of other experimental variables (i.e., water volume, pipe slope and perhaps the pipe diameter). The effects of the length of solid on the stream depth are dependent upon the solid velocity relative to the velocity of the water stream. The peak value of stream depth and/or the stream depth history are strongly influenced by the presence of a solid in the drain and by the velocity of the solid relative to the water stream.

ACKNOWLEDGMENT

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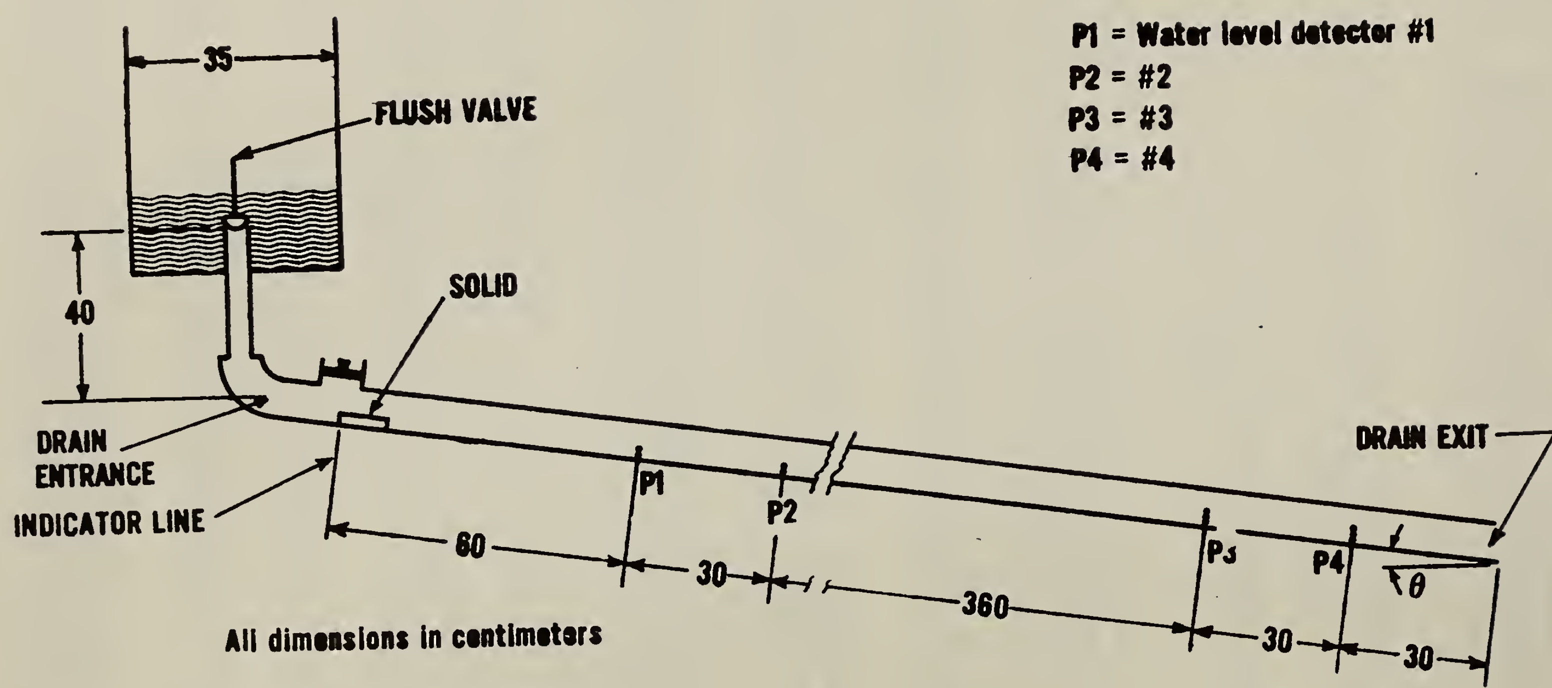


Figure 1. Schematic of experimental apparatus

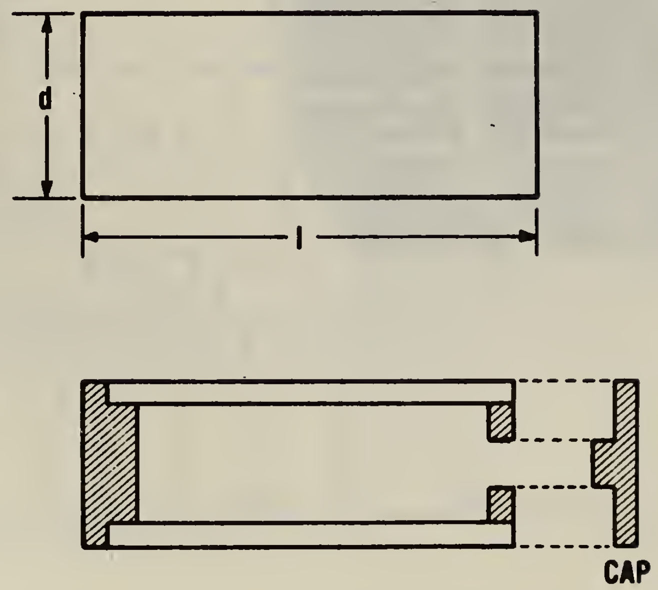


Figure 2. Schematic of a typical experimental solid

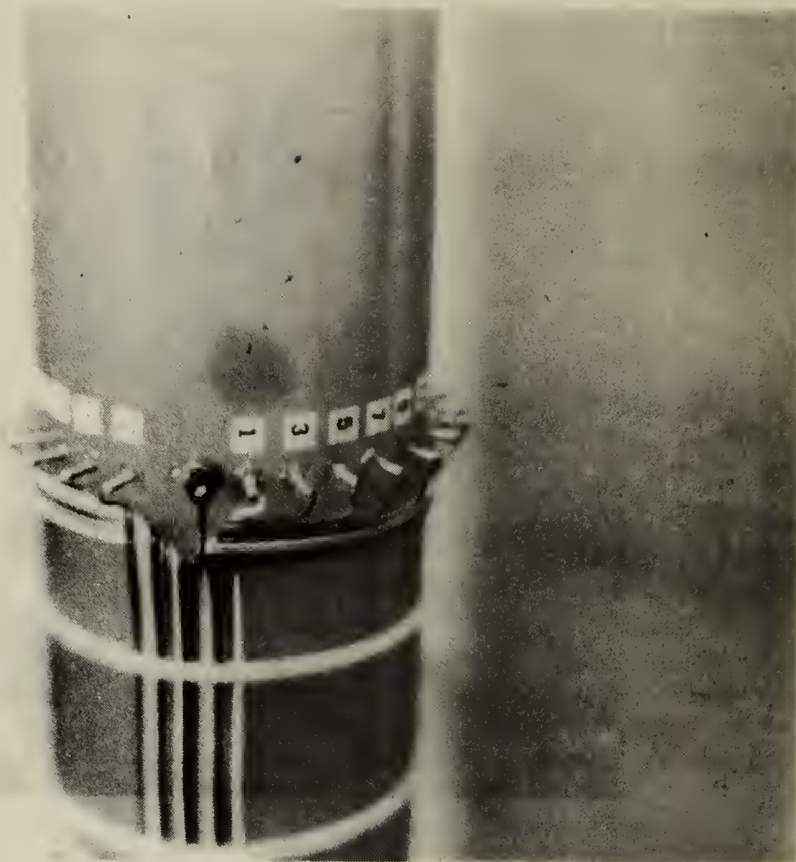


Figure 3. Photograph of a water level detector

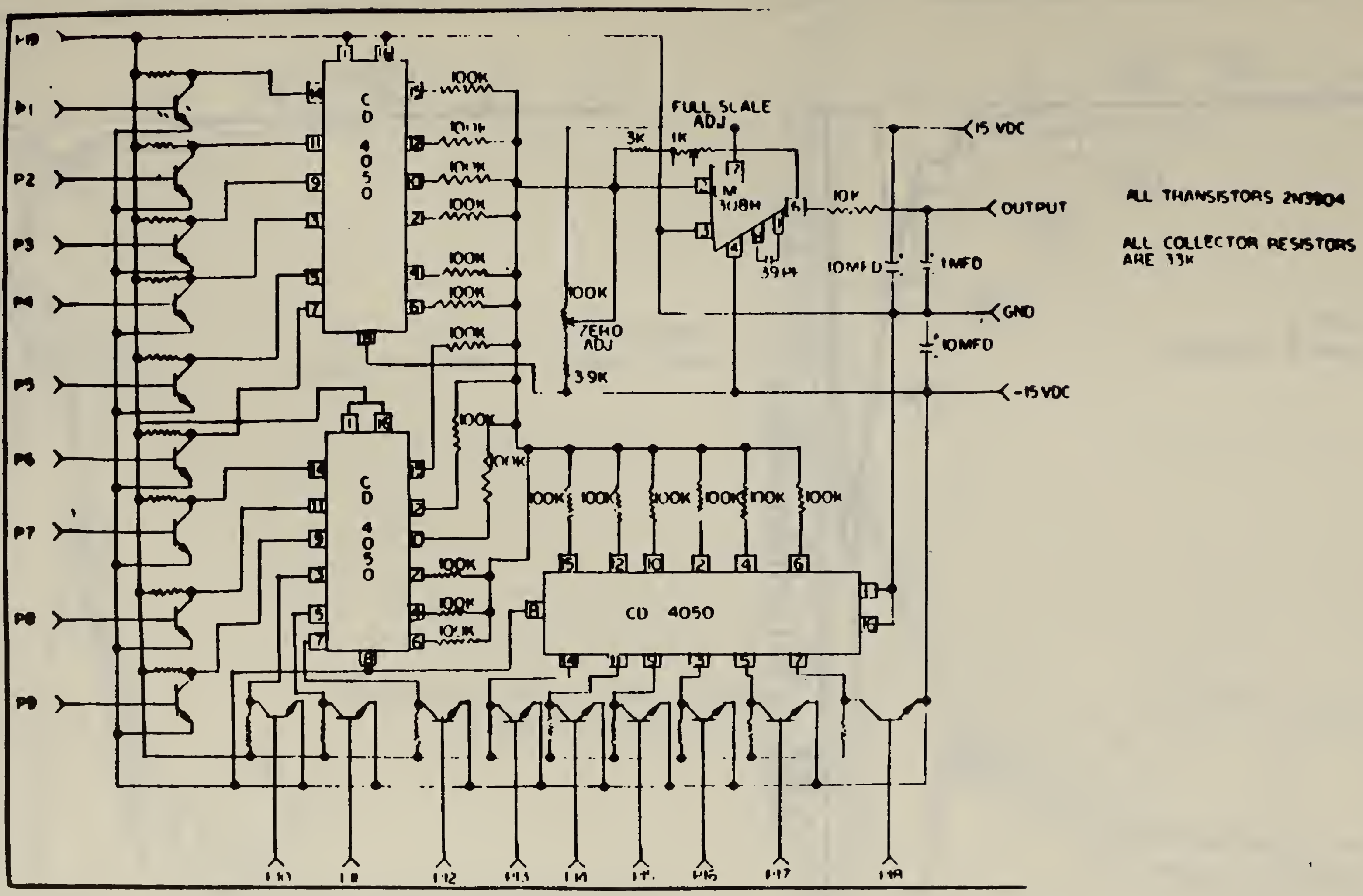


Figure 4. Logic circuit for water level detector

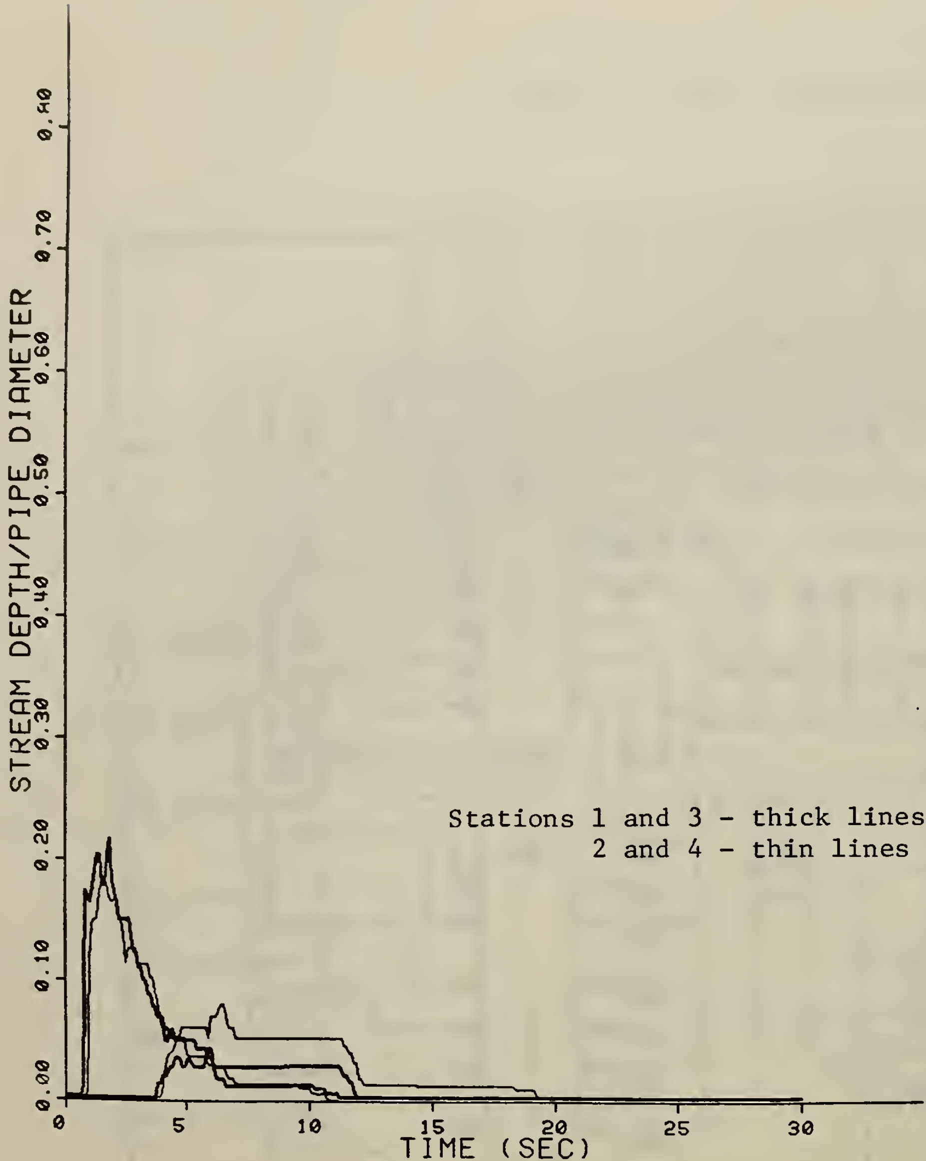


Figure 5. Stream depth histories at the four measuring stations for $V_w = 1.9$ L, S = 0.04, and for no solid in the drain.

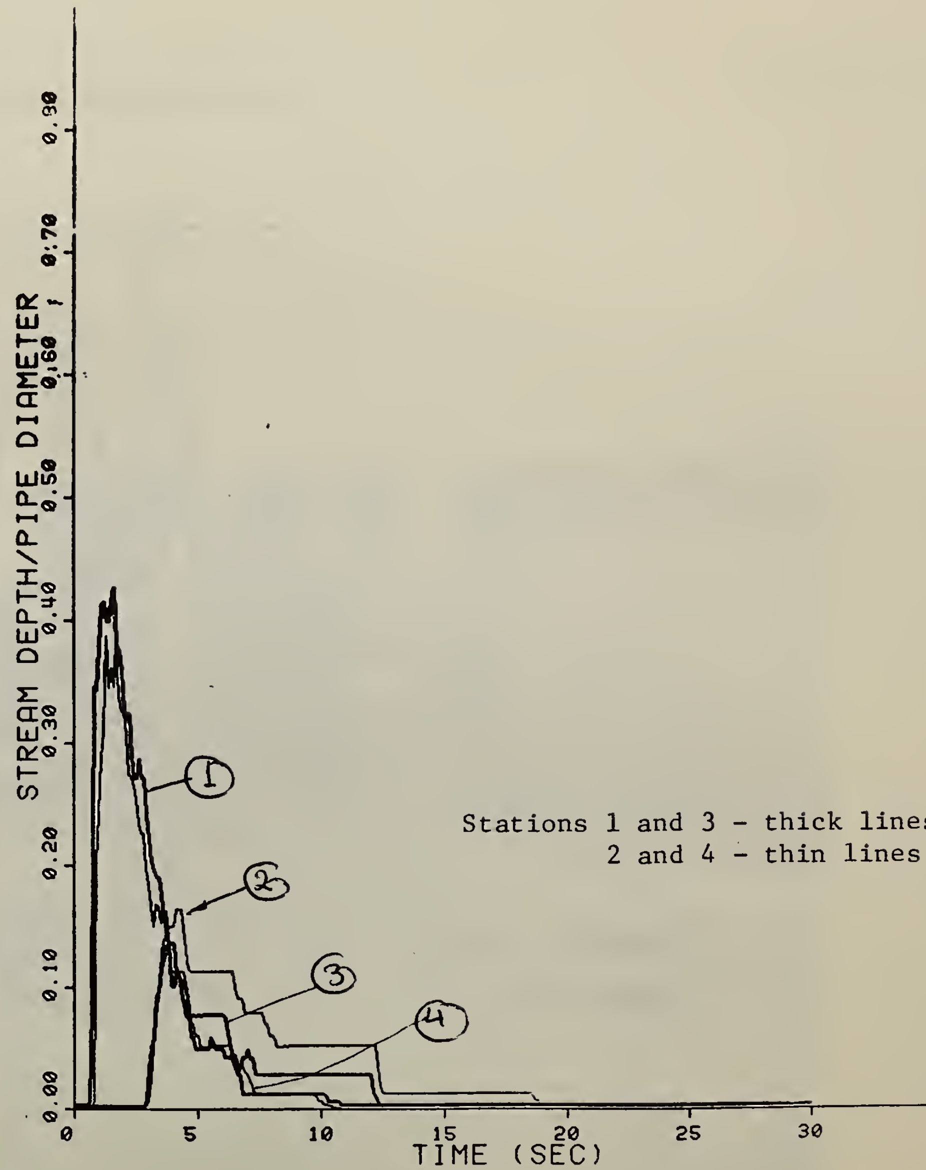


Figure 6. Stream depth histories at the four measuring stations for $V_w = 3.8$ L, S = 0.04, and for no solid in the drain.

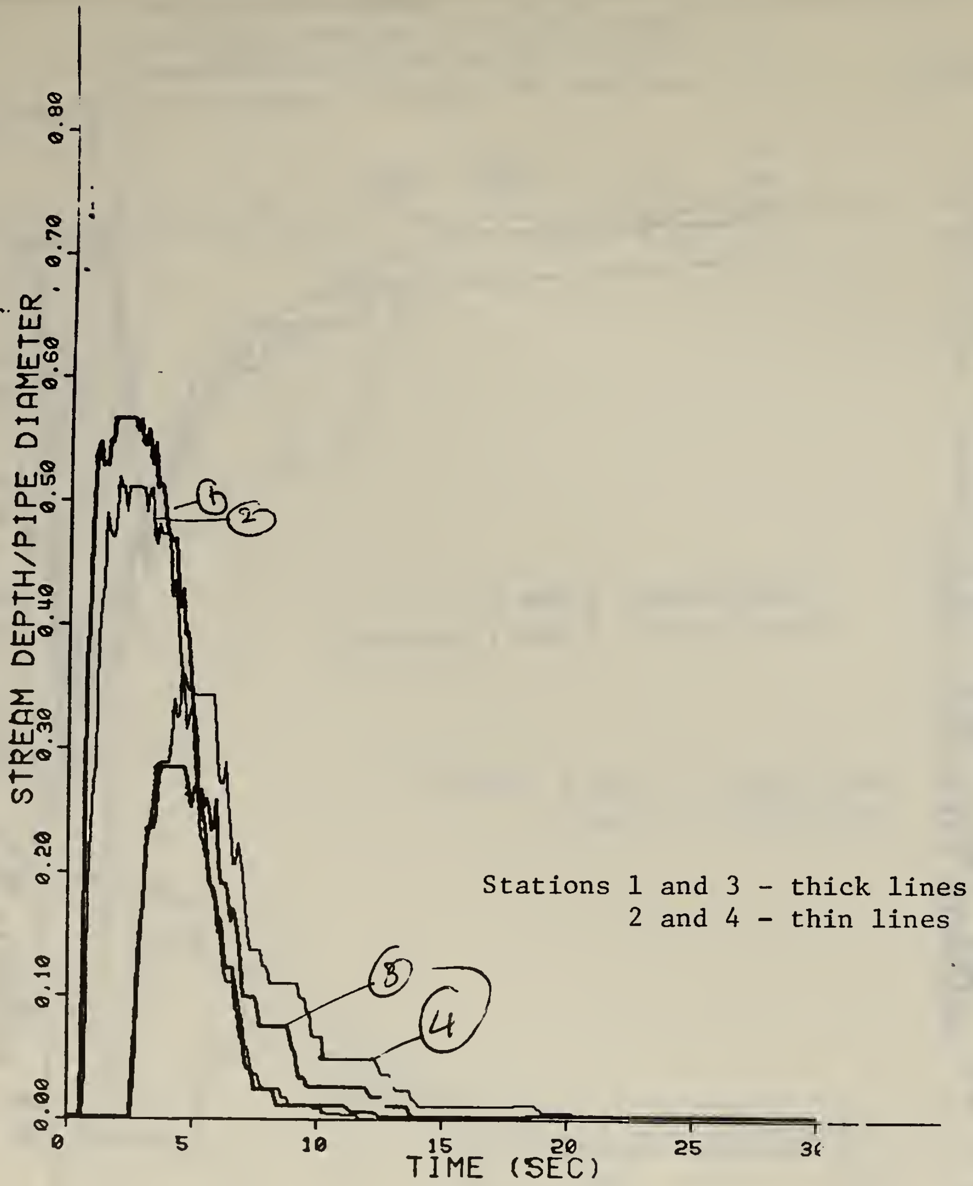


Figure 7. Stream depth histories at the four measuring stations for V_w = 11.4 L, S = 0.04, and for no solid in the drain.

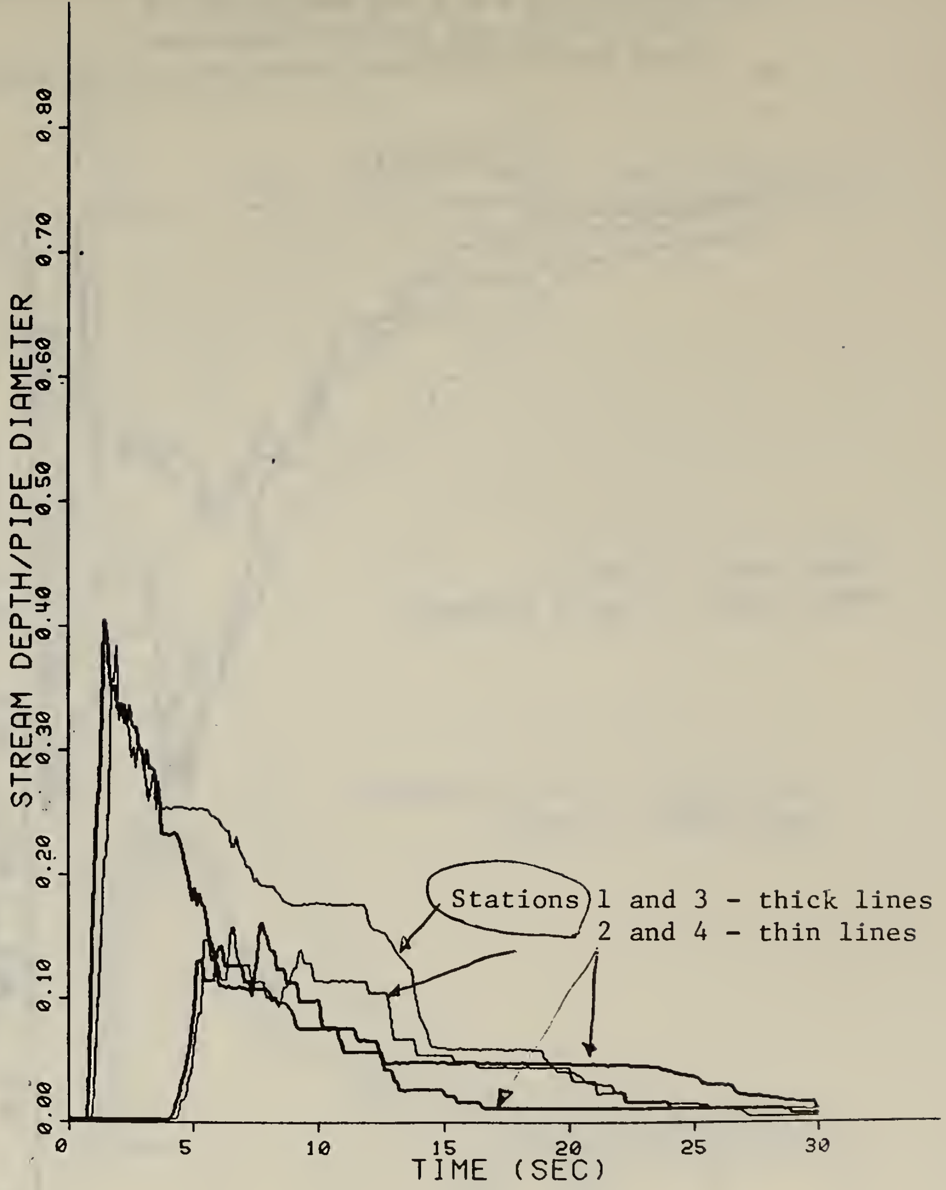


Figure 8. Stream depth histories at the four measuring stations for V_w = 1.9 L, S = 0.04 and a 3.8 by 7.6 cm solid in the drain.

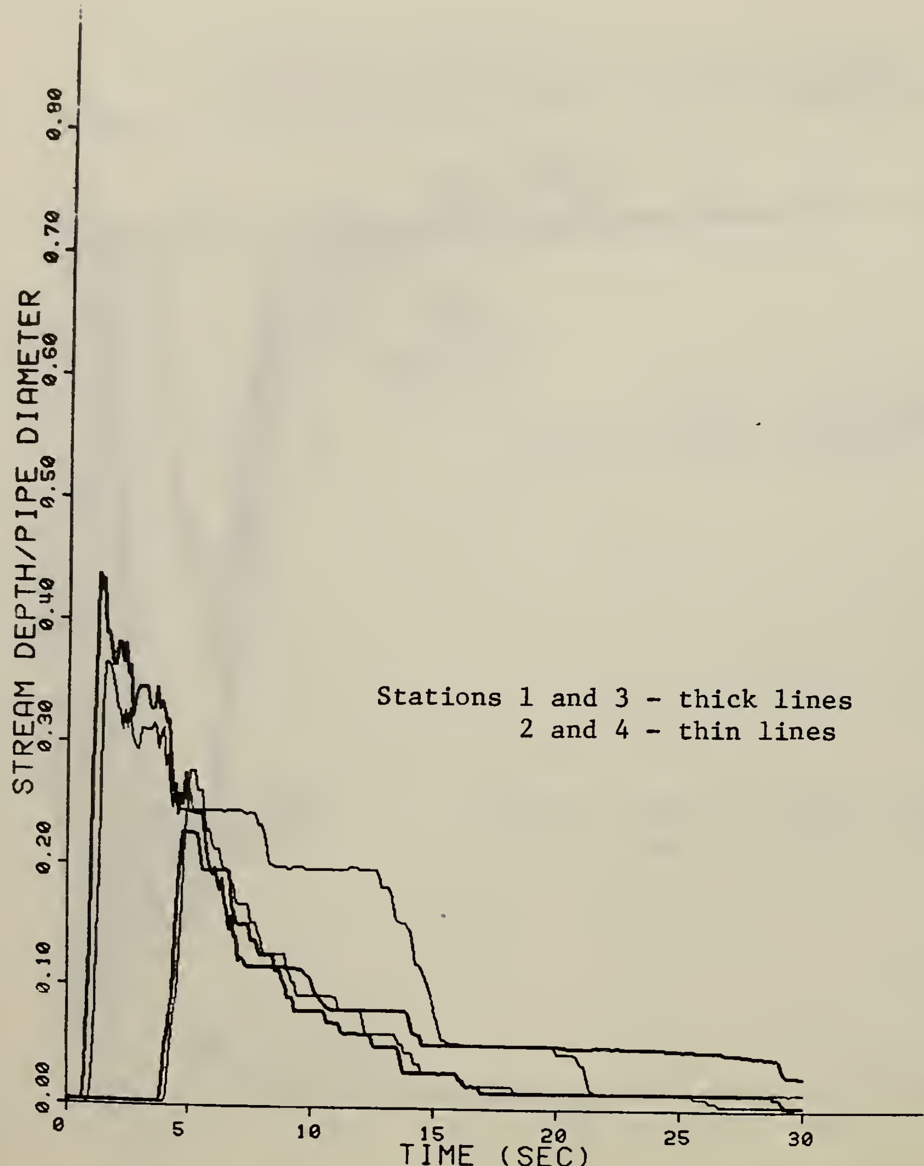


Figure 9. Stream depth histories at the four measuring stations for V_w = 3.8 L, S = 0.04, and for a 3.8 by 7.6 cm solid in the drain.

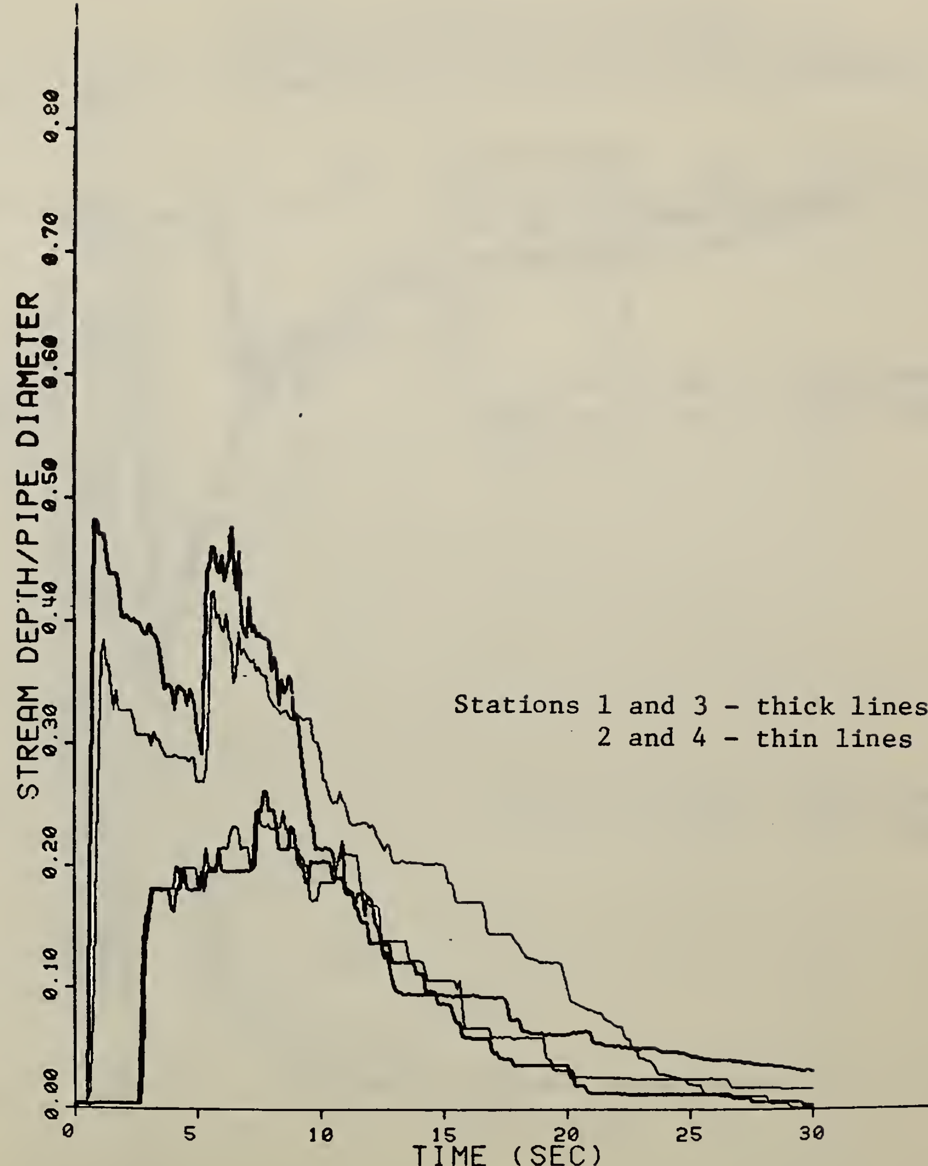


Figure 10. Stream depth histories at the four measuring stations for V_w = 11.4 L, S = 0.04, and for a 3.8 by 7.6 cm solid in the drain.

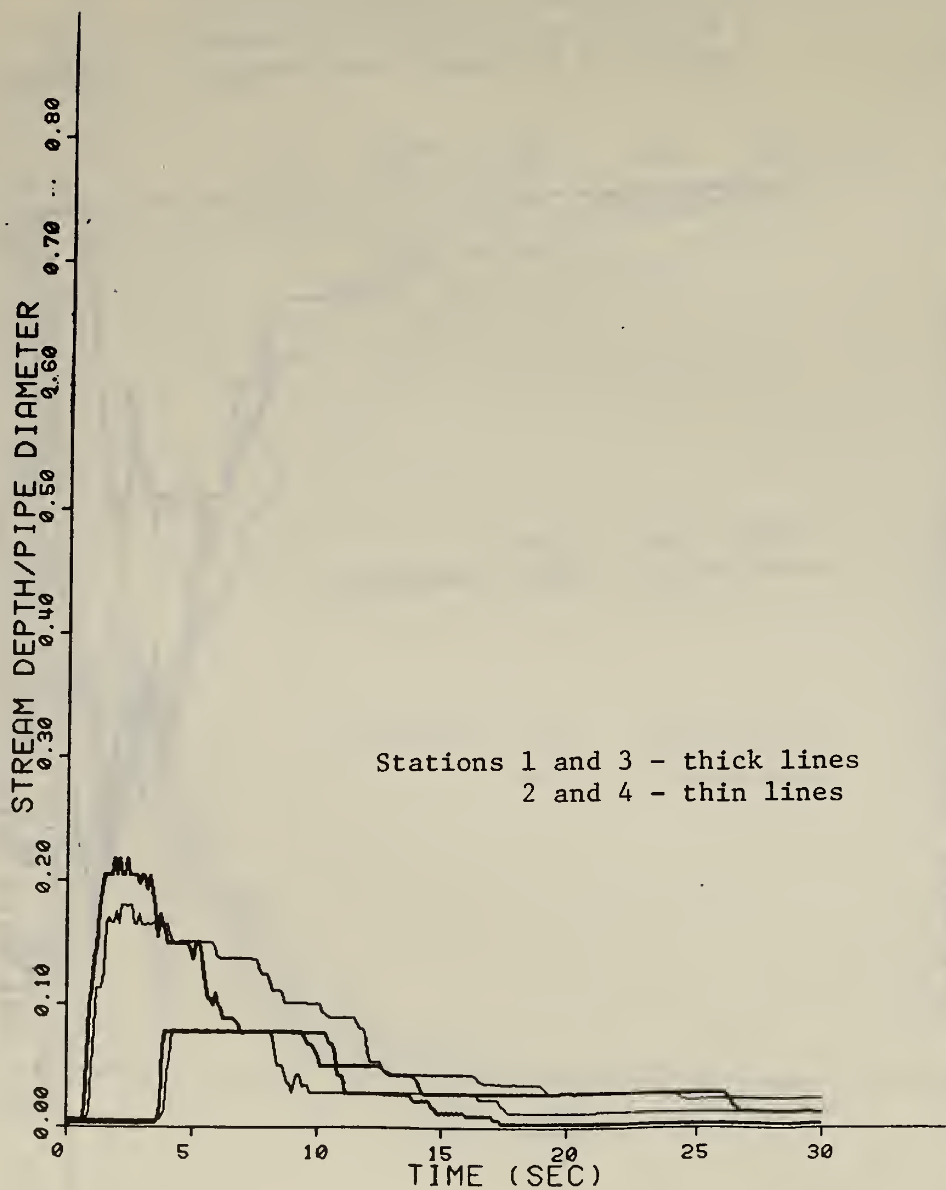


Figure 11. Stream depth histories at the four measuring stations for V_w = 1.9 L, S = 0.06, and for no solid in the drain.

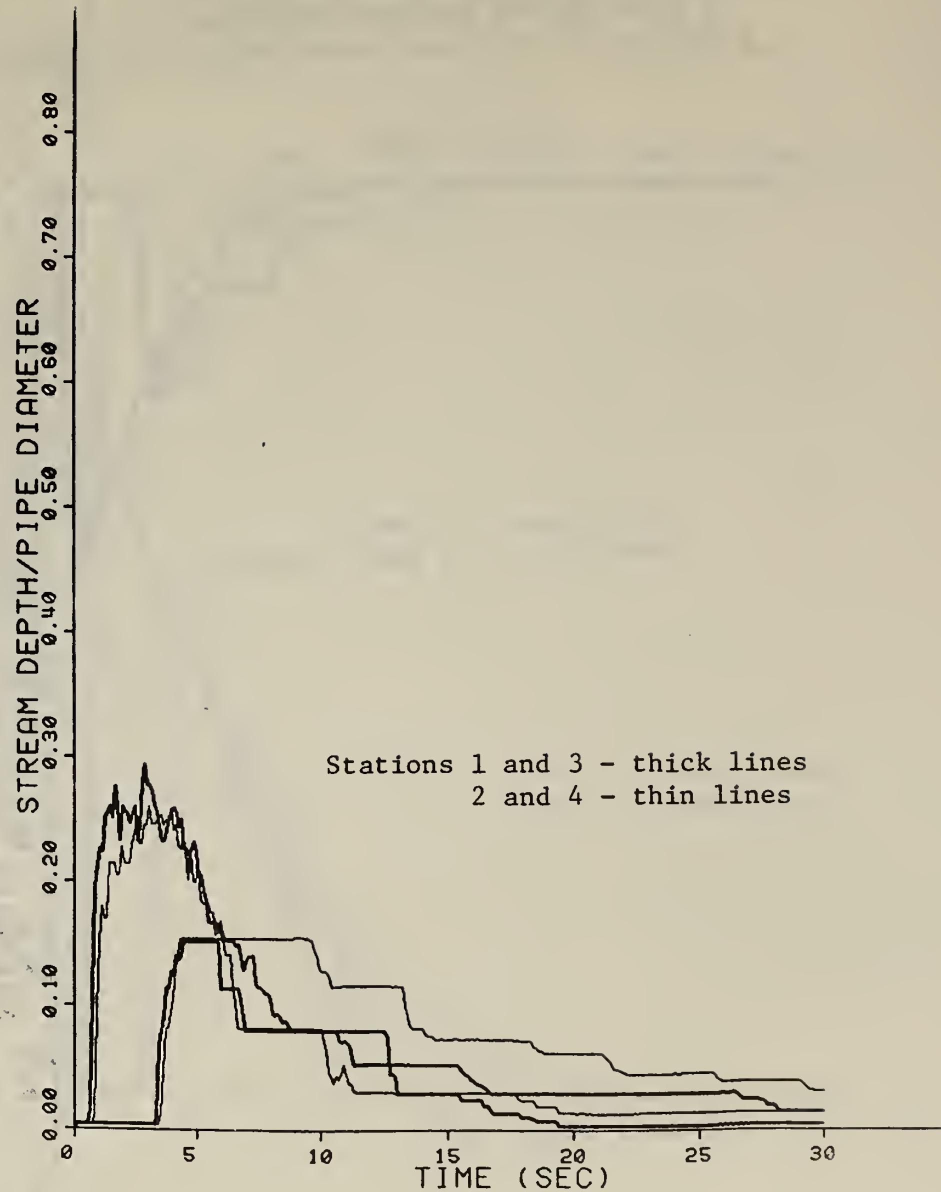


Figure 12. Stream depth histories at the four measuring stations for V_w = 3.8 L, S = 0.06, and for no solid in the drain.

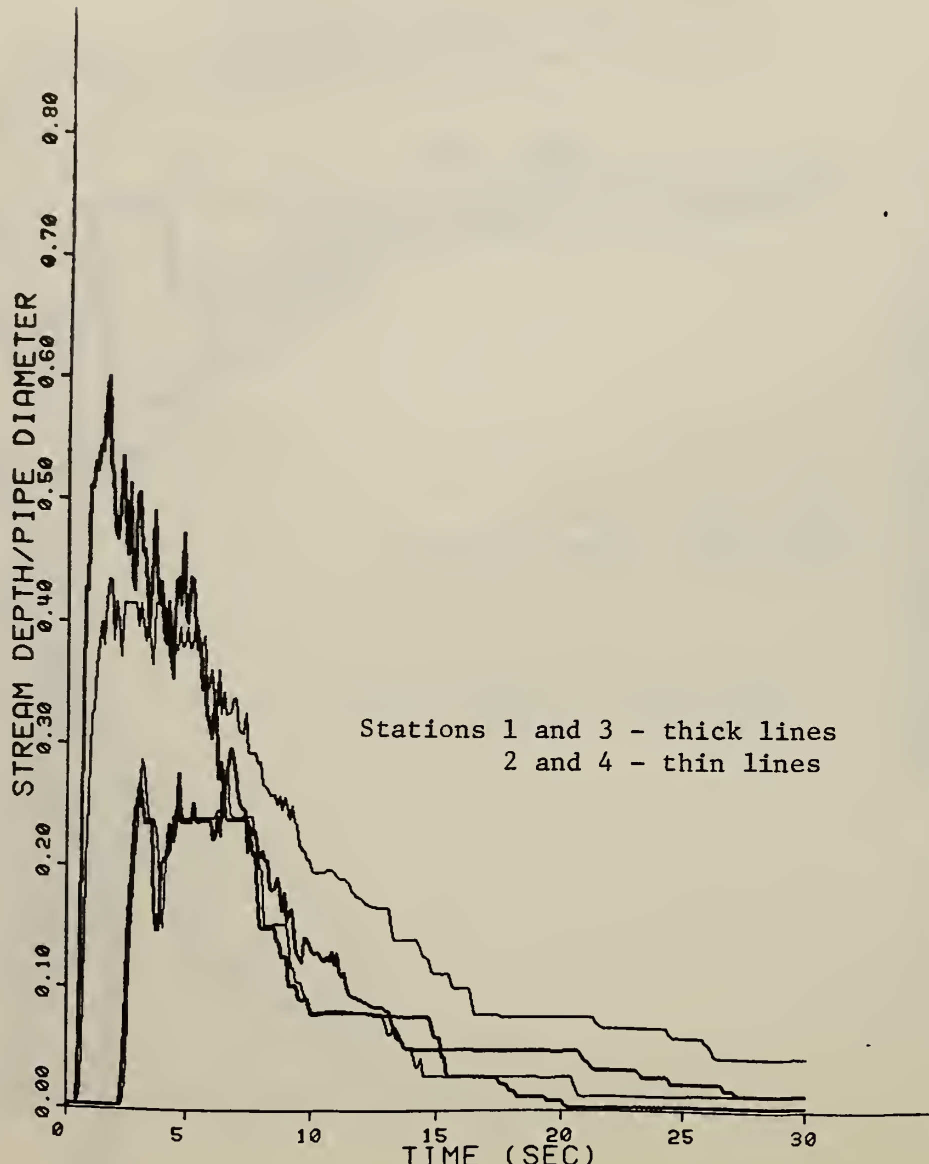


Figure 13. Stream depth histories at the four measuring stations for V_w = 11.4 L, S = 0.06, and for no solid in the drain.

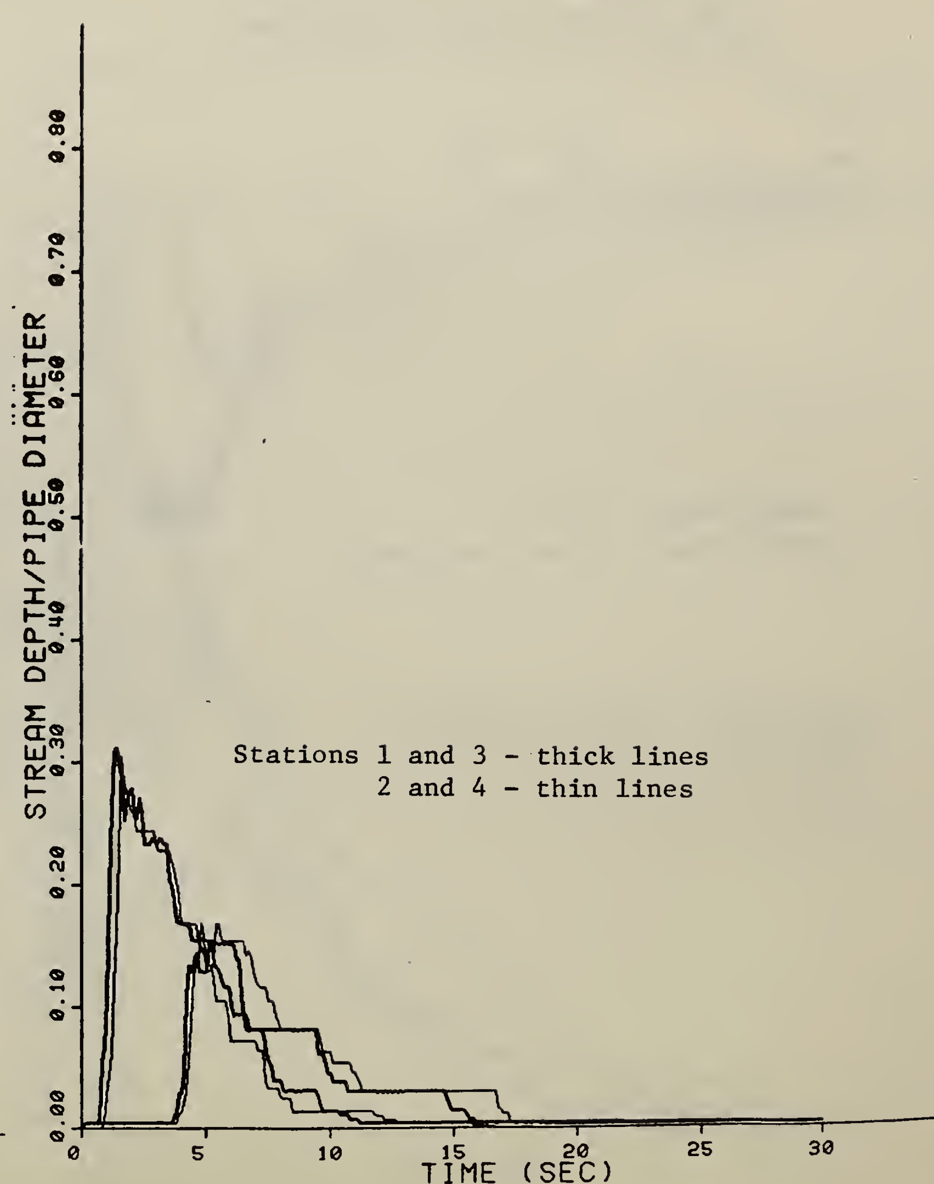


Figure 14. Stream depth histories at the four measuring stations for V_w = 1.9 L, S = 0.06, and for a 3.8 by 7.6 cm solid in the drain.

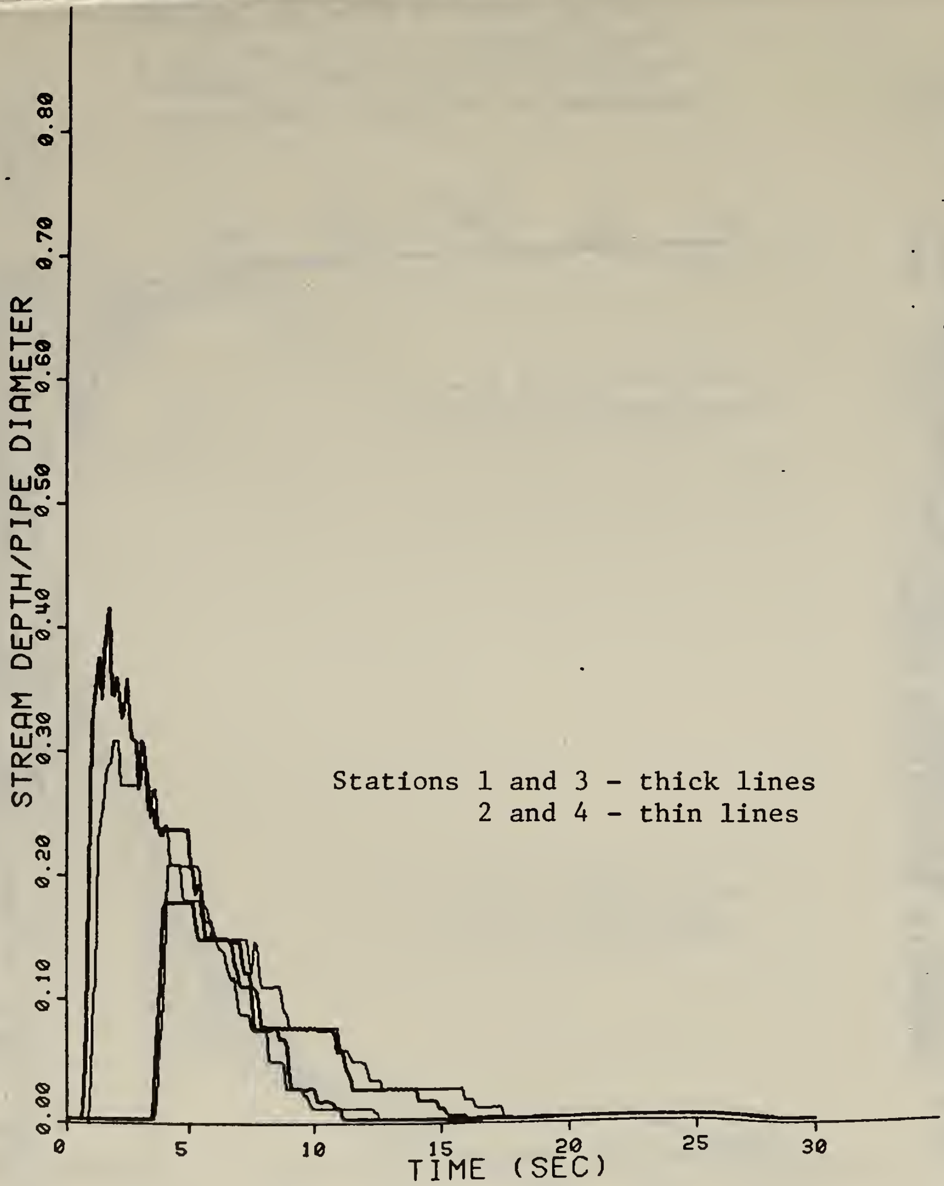


Figure 15. Stream depth histories at the four measuring stations for V_w = 3.8 L, S = 0.06, and for a 3.8 by 7.6 cm solid in the drain.

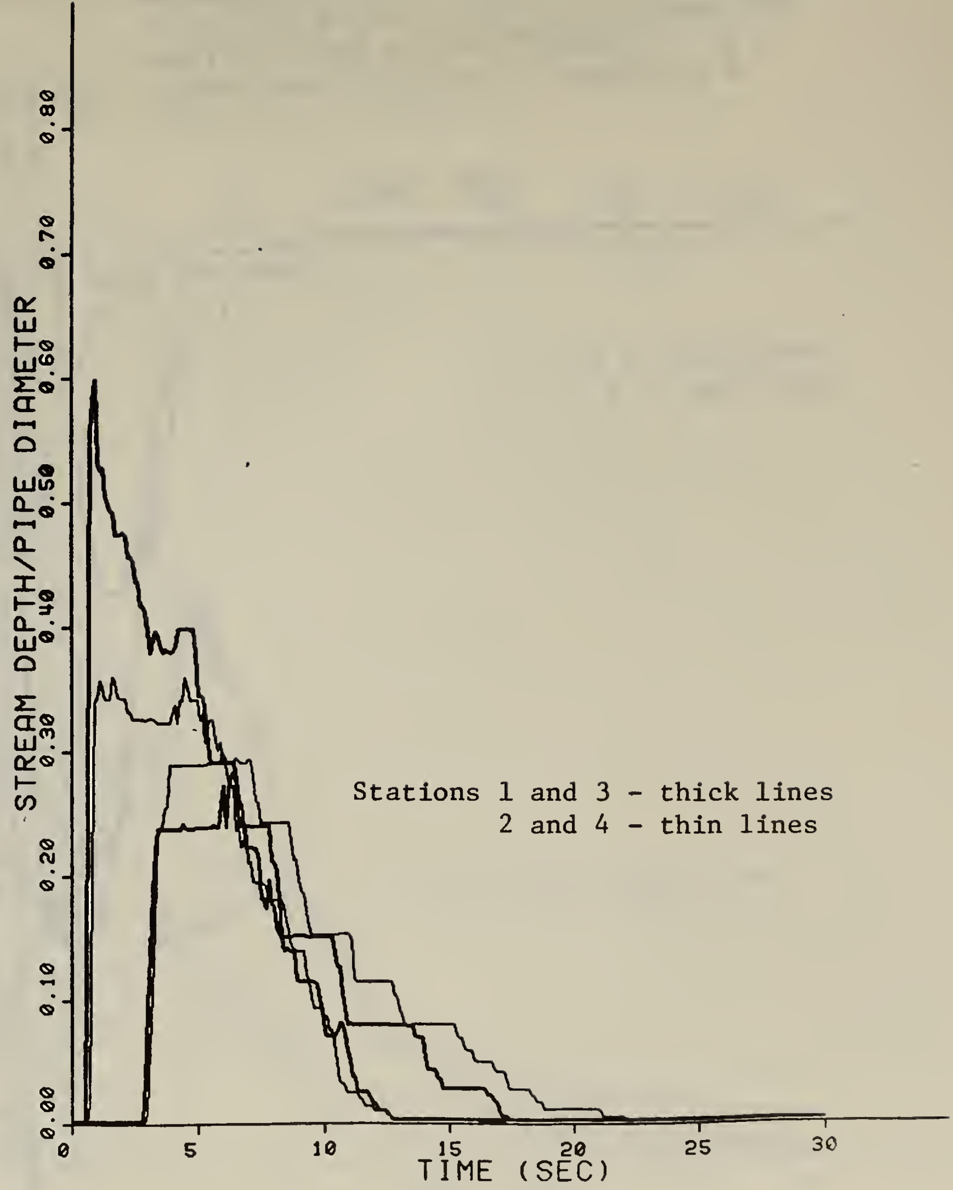


Figure 16. Stream depth histories at the four measuring stations for V_w =11.4 L, S = 0.06, and for a 3.8 by 7.6 cm solid in the drain.

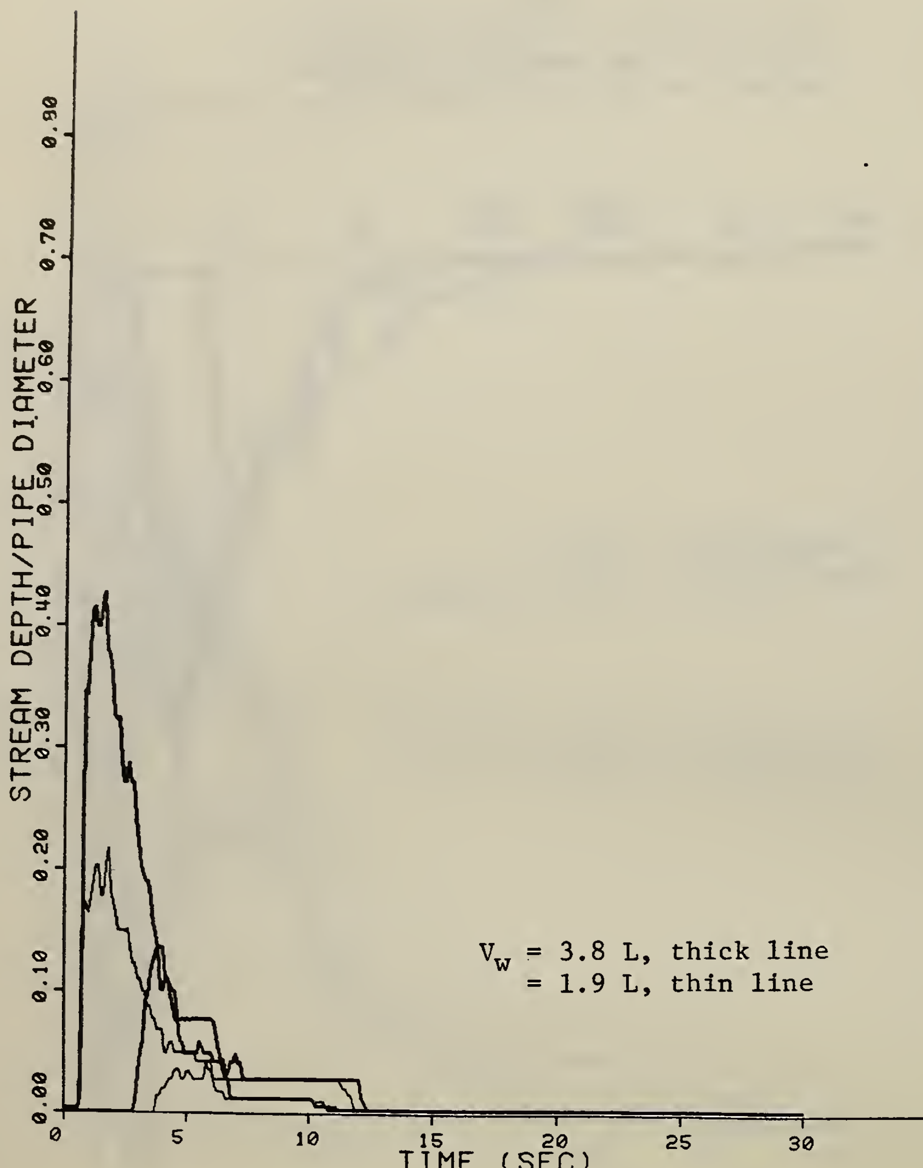


Figure 17. Stream depth histories at measuring stations 1 and 3, for V_w equal to 1.9 L and 3.8 L, at a drain slope of 0.04 and with no solid in the drain.

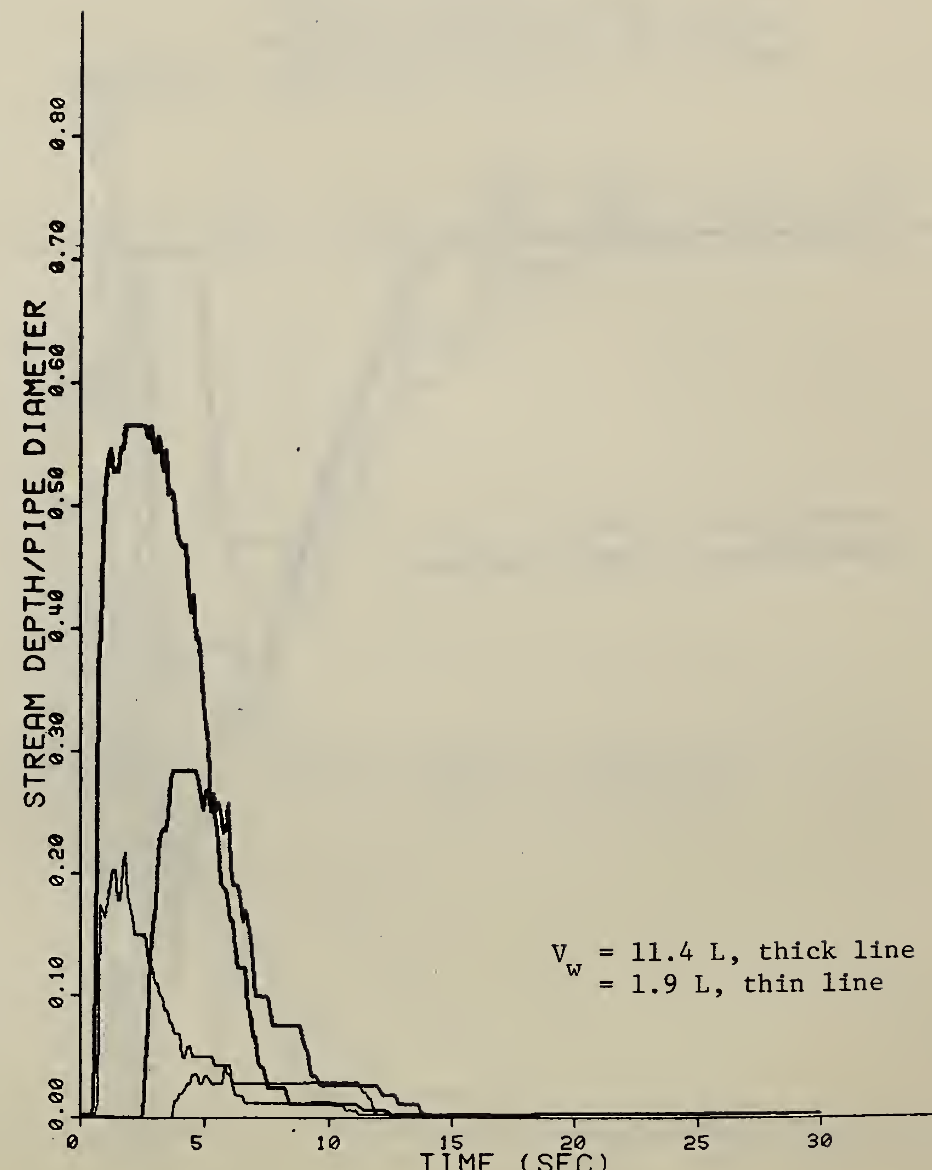


Figure 18. Stream depth histories at measuring stations 1 and 3, for V_w equal to 1.9 L 11.4 L, at a drain slope of 0.04 and with no solid in the drain.

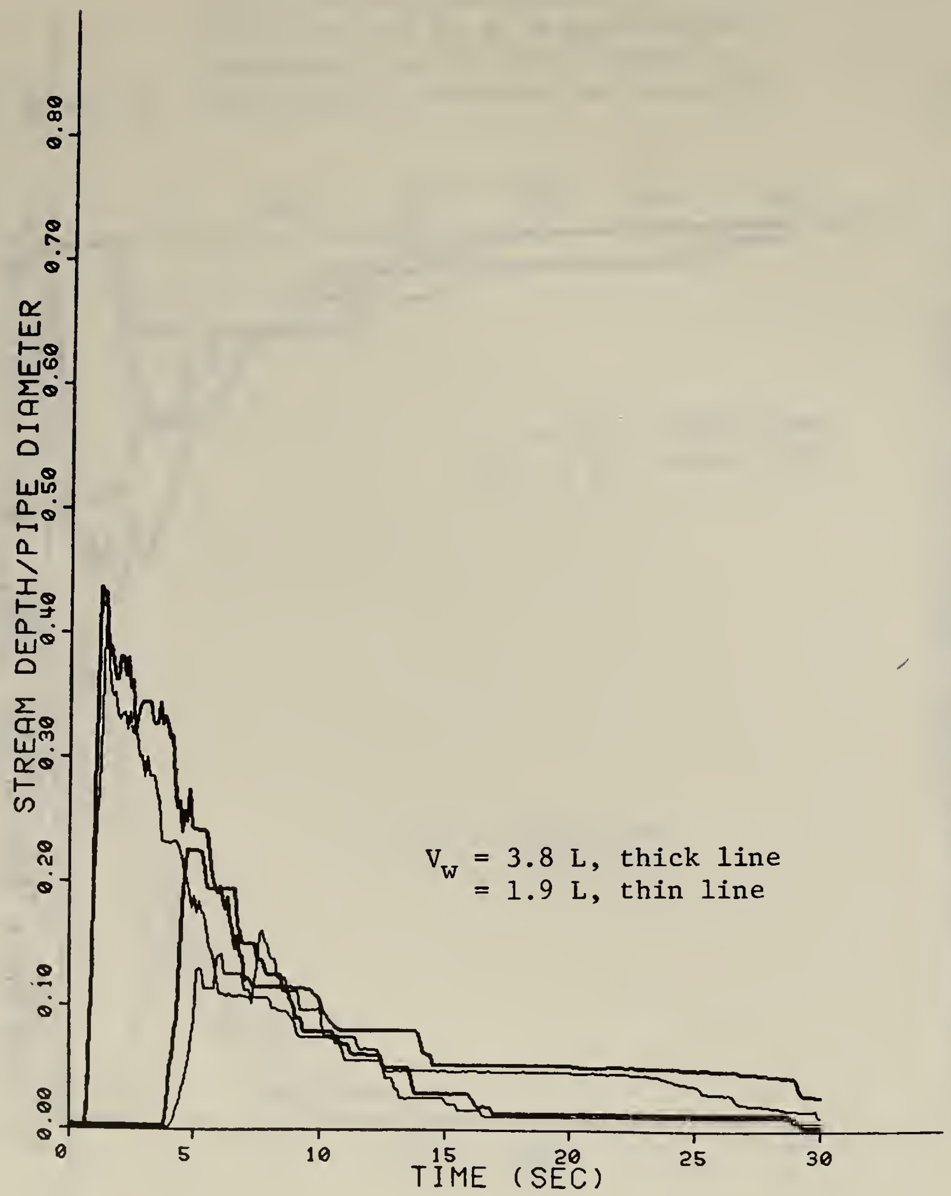


Figure 19. Stream depth histories at measuring stations 1 and 3, for V_w = 1.9 L and 3.8 L, at a drain slope of 0.04 and with a 3.8 by 7.6 cm solid in the drain.

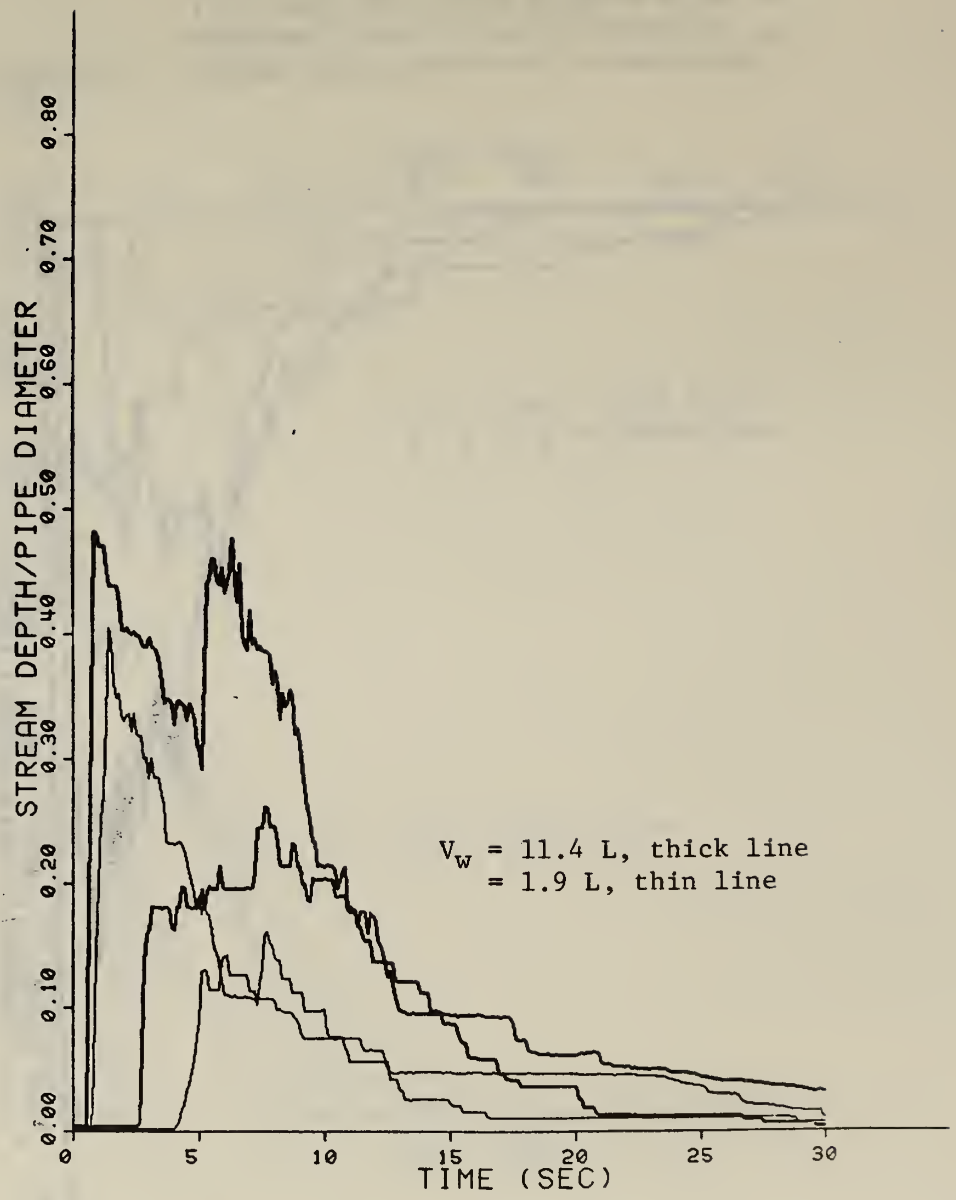


Figure 20. Stream depth histories at stations 1 and 3, for V_w equal to 1.9 L and 11.4 L, at a drain slope of 0.04, and for a 3.8 by 7.6 cm solid in the drain.

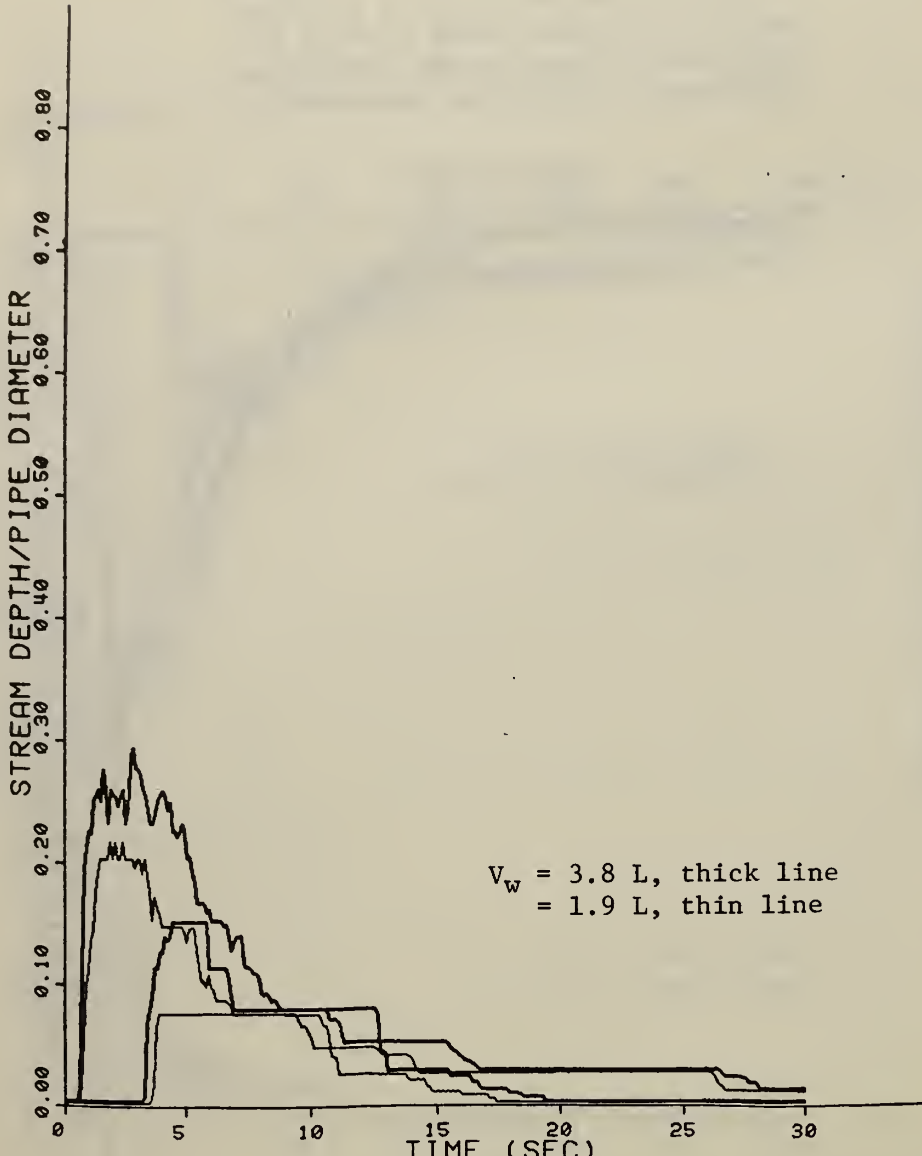


Figure 21. Stream depth histories at measuring stations 1 and 3, for V_w equal to 1.9 L and 3.8 L, at a drain slope of 0.06, and with no solid in the drain.

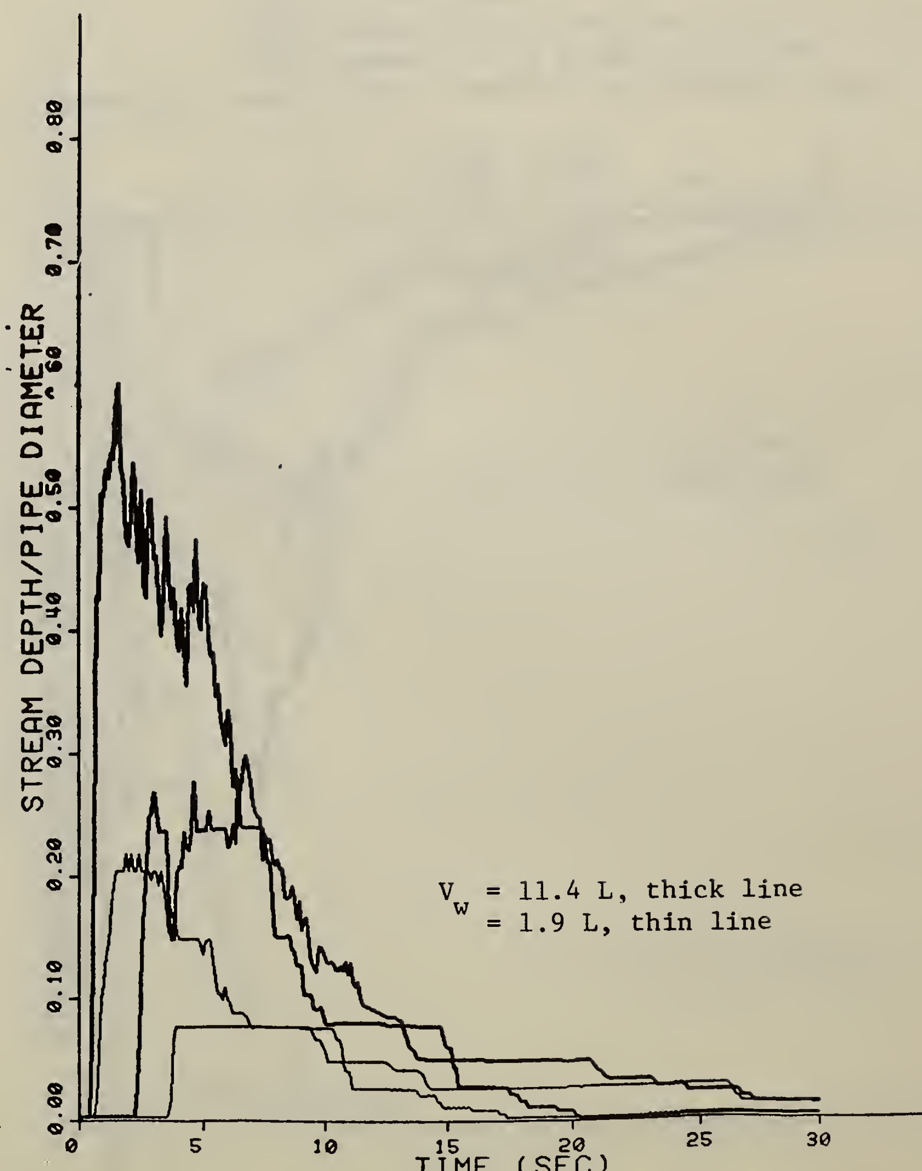


Figure 22. Stream depth histories at measuring stations 1 and 3, for V_w equal to 1.9 L and 11.4 L, at a drain slope of 0.06, and with no solid in the drain.

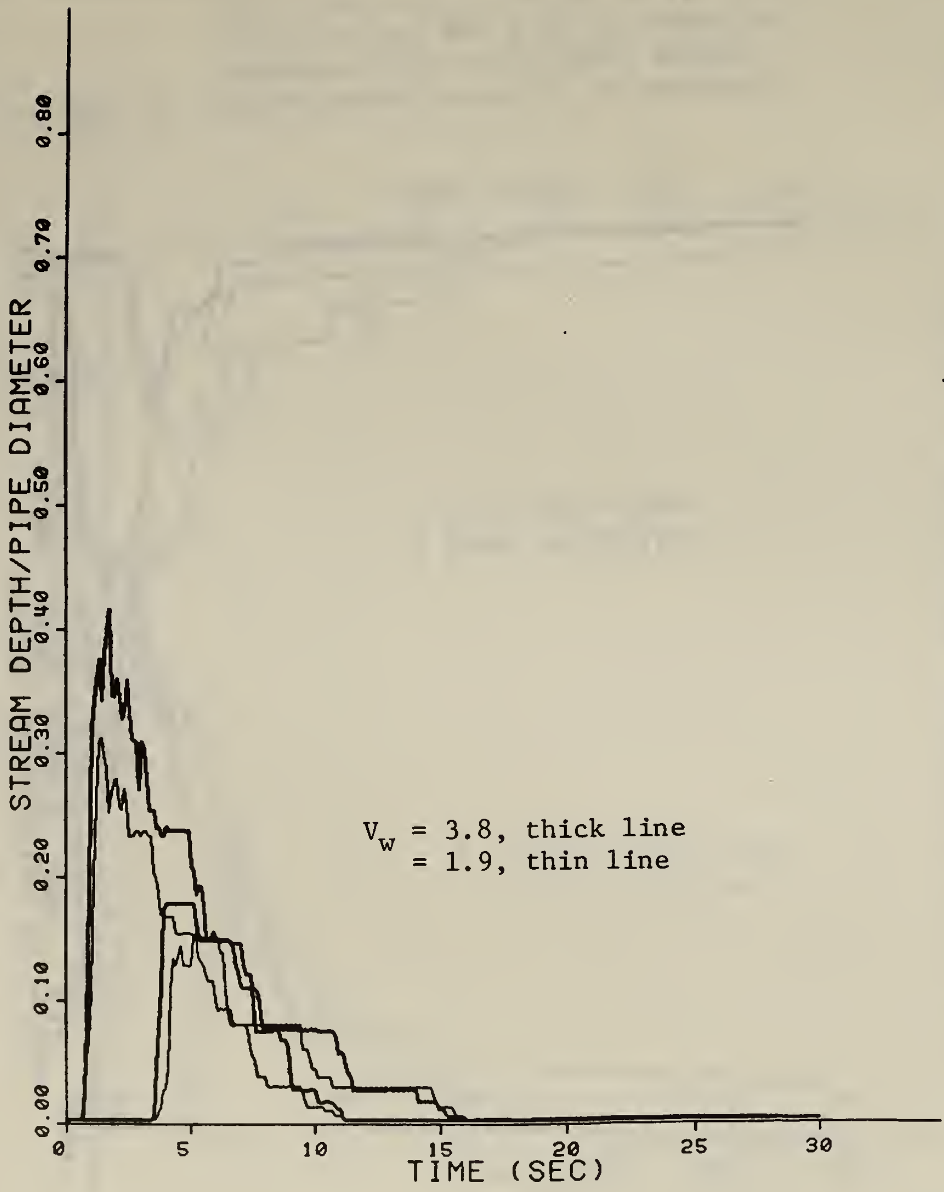


Figure 23. Stream depth histories at stations 1 and 3, for V_w equal to 1.9 L and 3.8 L, at a drain slope of 0.06, and with a 3.8 by 7.6 cm solid in the drain.

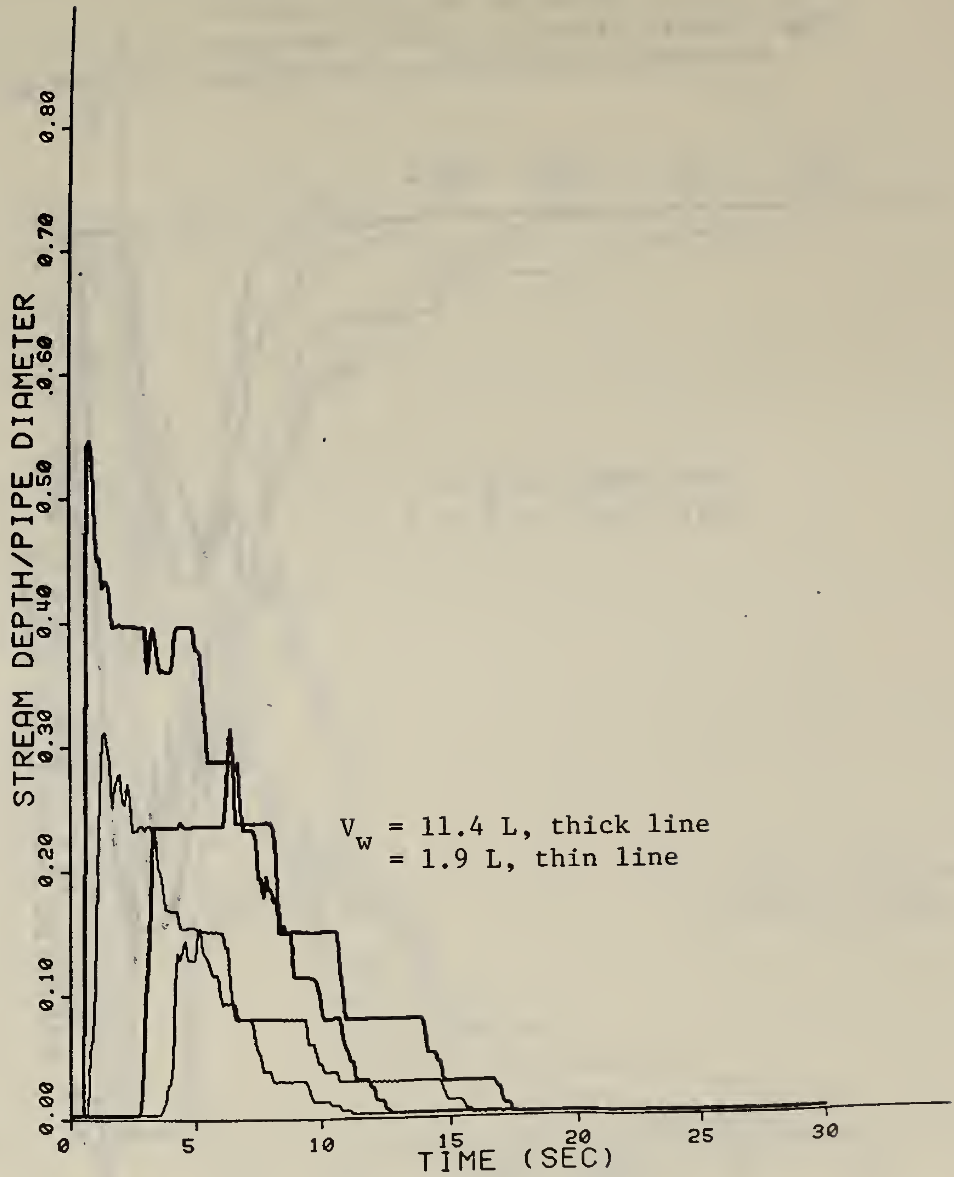


Figure 24. Stream depth histories at measuring stations 1 and 3, for V_w equal to 1.9 L and 11.4 L, at a drain slope of 0.06, and with 3.8 by 7.6 cm solid in the drain.

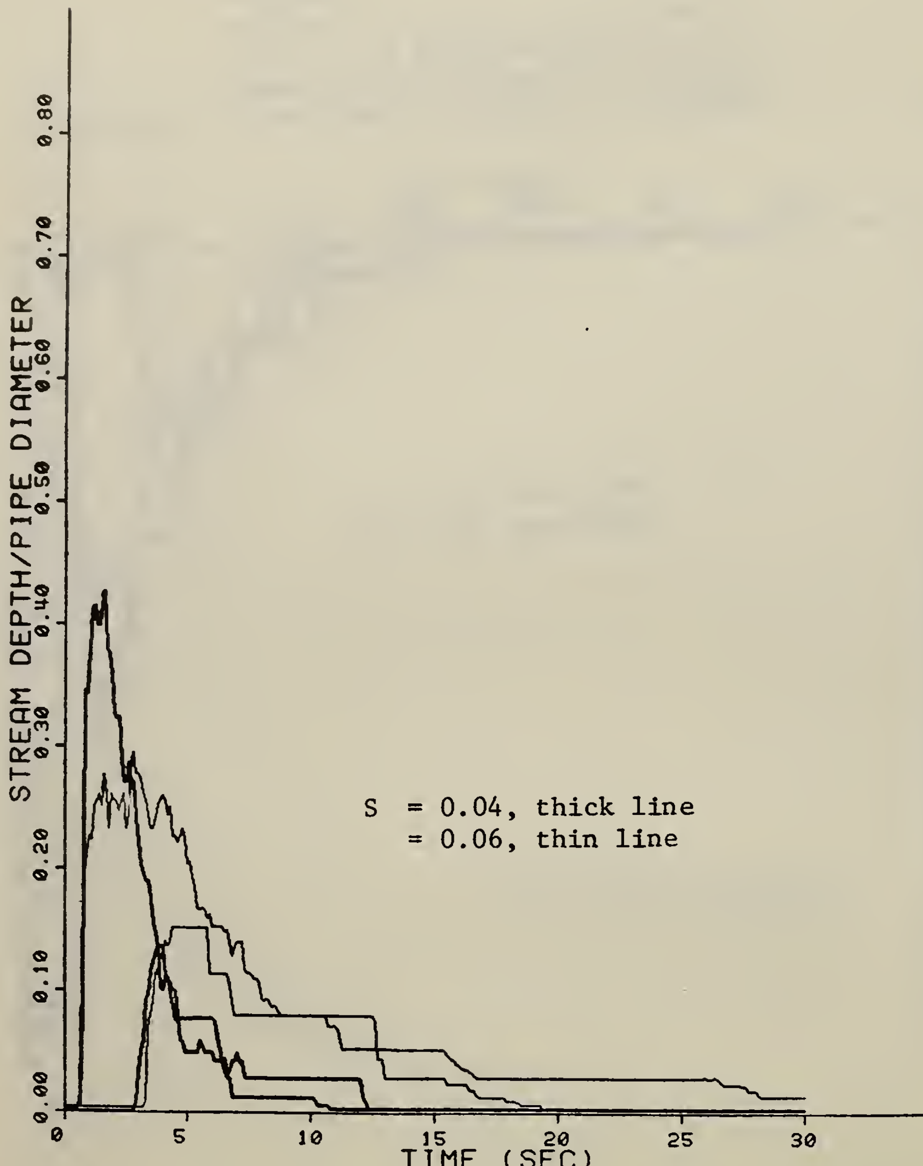


Figure 25. Stream depth histories at measuring stations 1 and 3, at drain slopes equal to 0.04 and 0.06, V_w equal to 3.8 L, and with no solid in the drain.

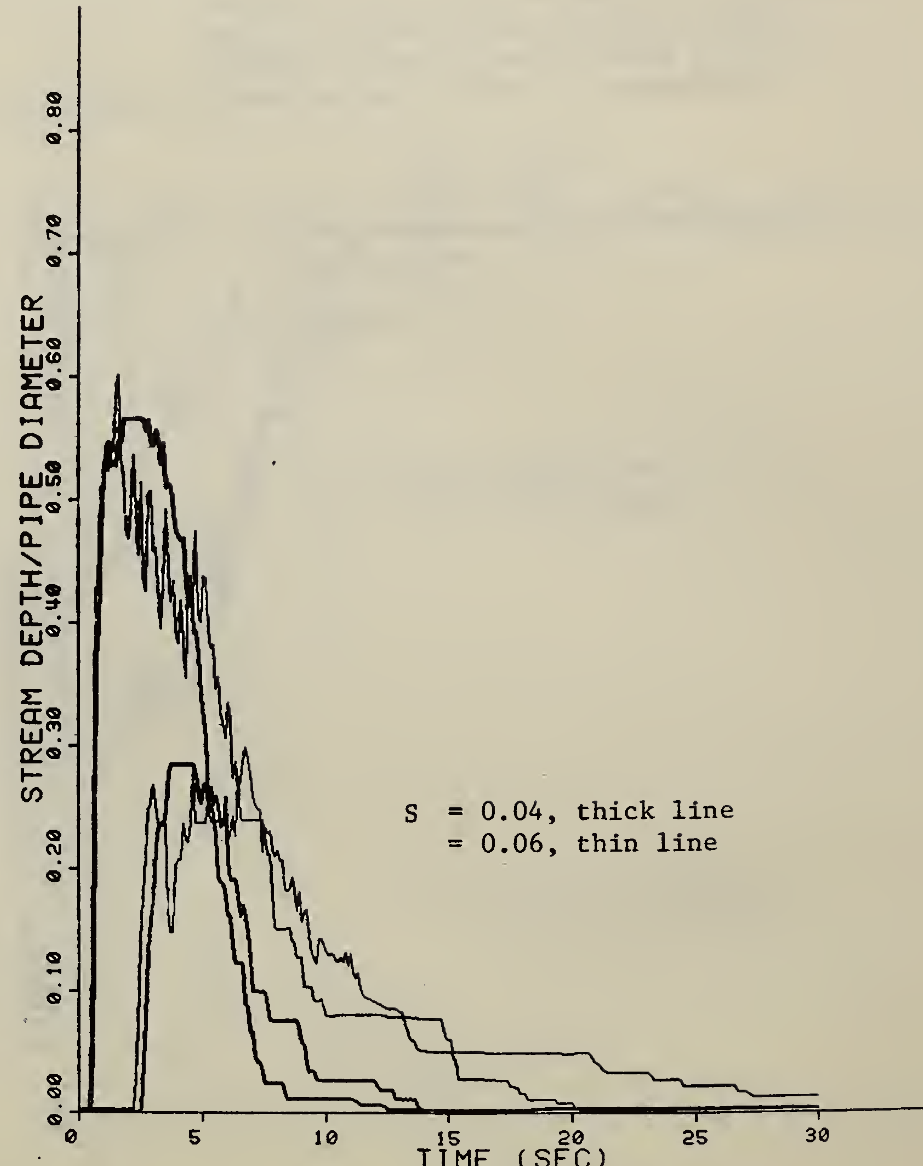


Figure 26. Stream depth histories at measuring stations 1 and 3, at drain slopes equal to 0.04 and 0.06, V_w equal to 11.4, and with no solid in the drain.

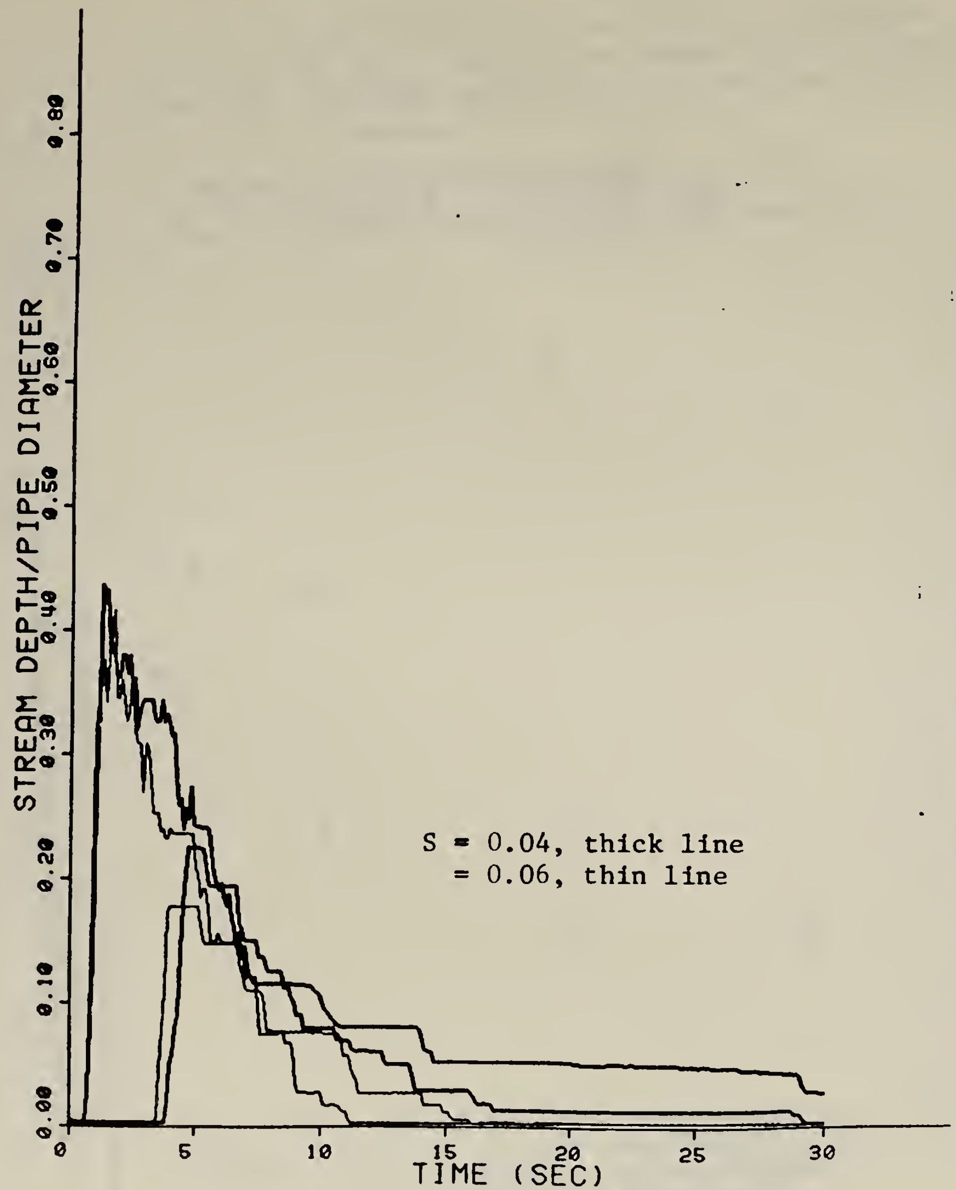


Figure 27. Stream depth histories at measuring stations 1 and 3, at drain slopes equal to 0.04 and 0.06, V_w equal to 3.8 L, and with a 3.8 by 7.6 cm solid in the drain.

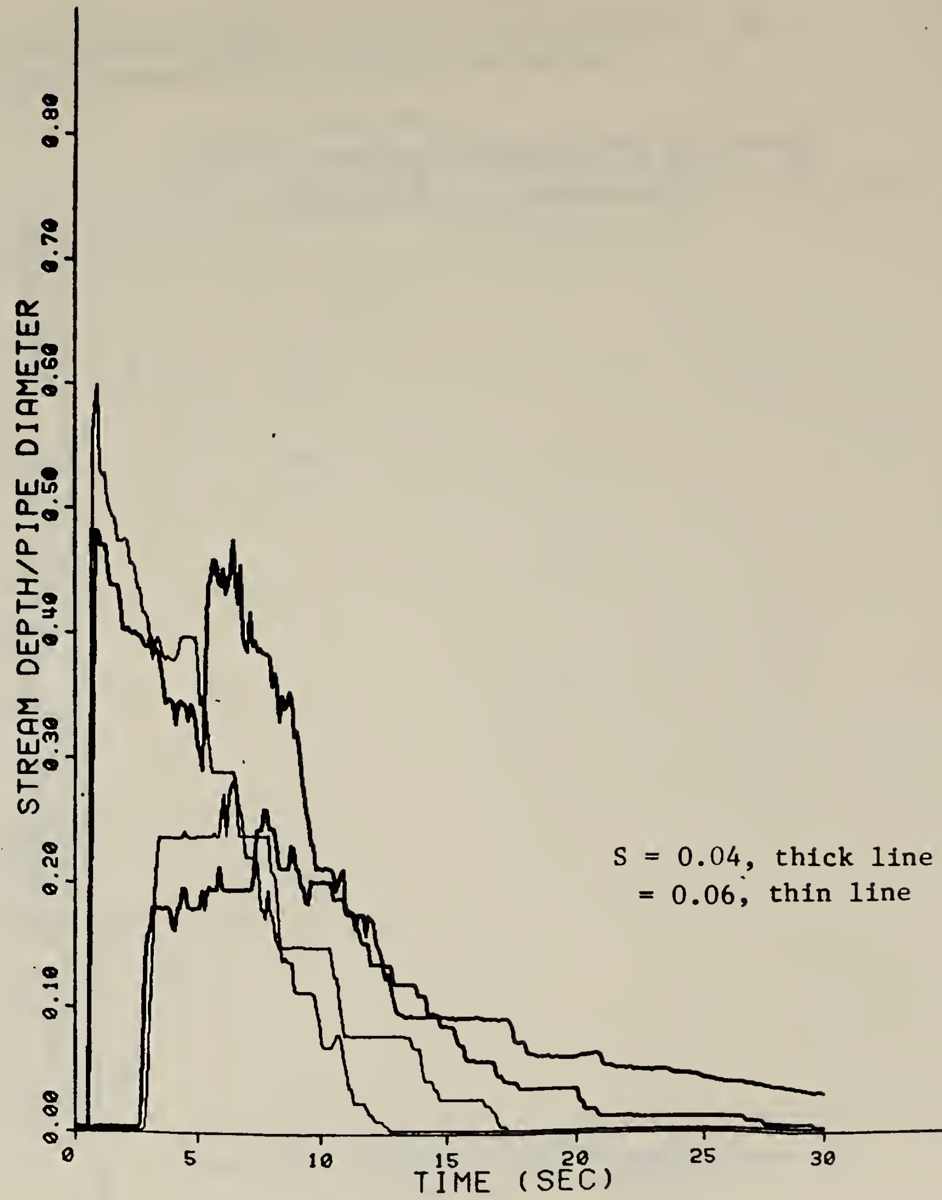


Figure 28. Stream depth histories at measuring stations 1 and 3, at drain slopes equal to 0.04 and 0.06, V_w equal to 11.4 L, and with a 3.8 by 7.6 cm solid in the drain.

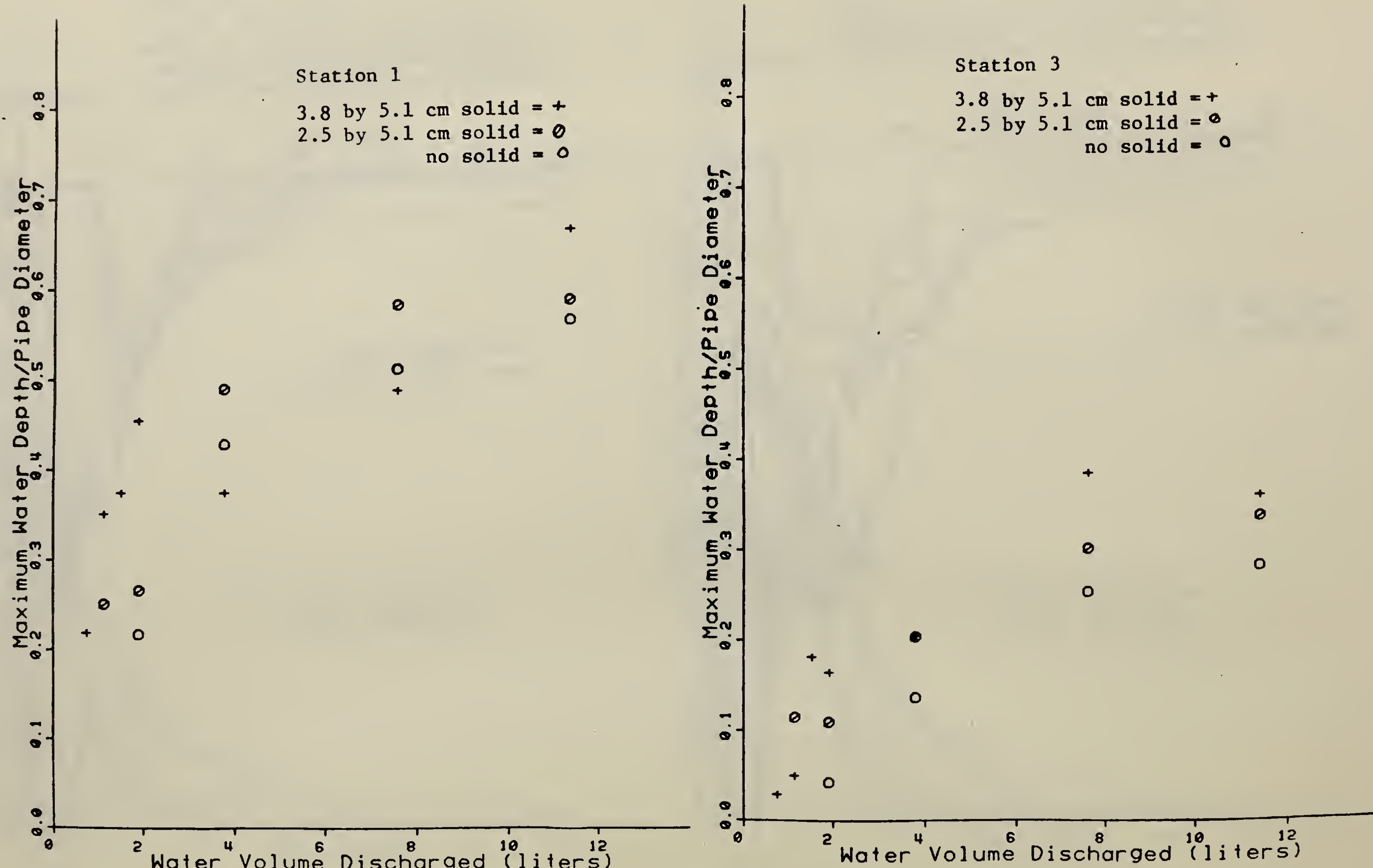


Figure 29. The peak value of non-dimensional stream depth versus V_W at measuring stations 1 and 3, at a drain slope equal to 0.04, and with no solid, a 2.5 by 5.1 cm solid, and a 3.8 by 5.1 cm solid in the drain.

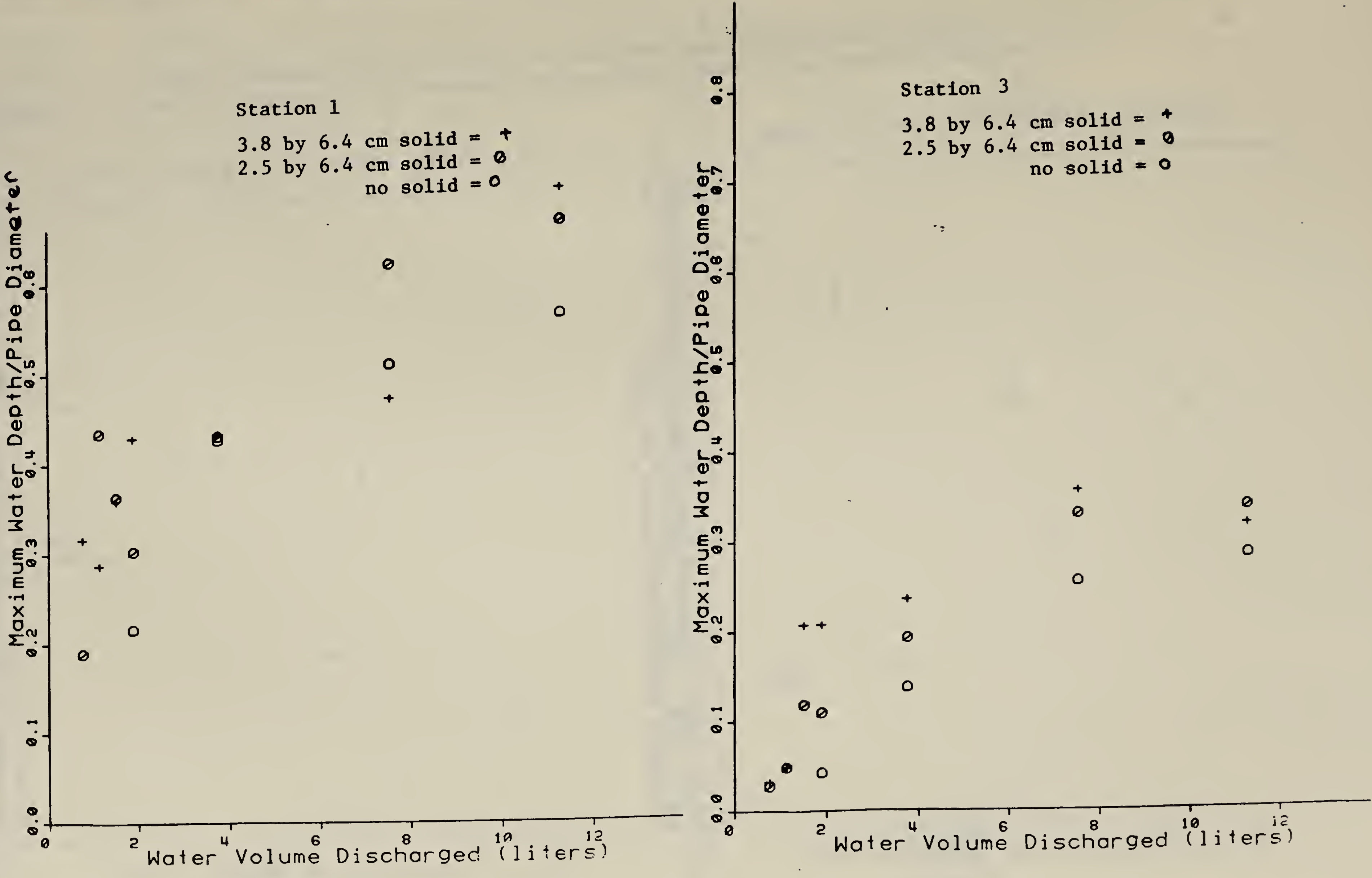


Figure 30. The peak value of non-dimensional stream depth versus V_w at measuring stations 1 and 3, at a drain slope of 0.04, and with no solid, a 2.5 by 6.4 cm solid, and a 3.8 by 6.4 cm solid in the drain.

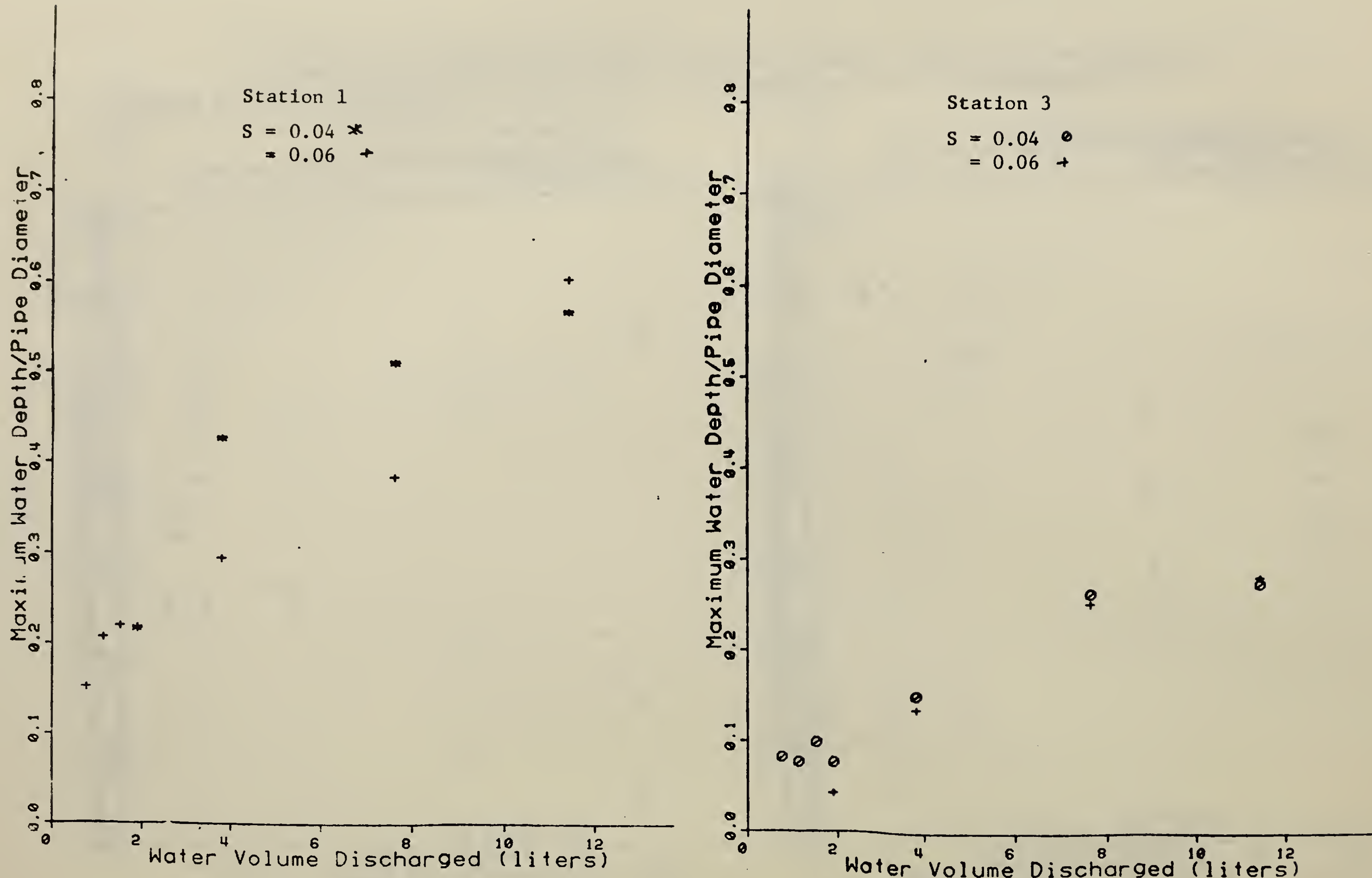


Figure 31. The peak value of non-dimensional stream depth versus V_w at measuring stations 1 and 3, at drain slopes of 0.04 and 0.06, and with no solid in the drain.

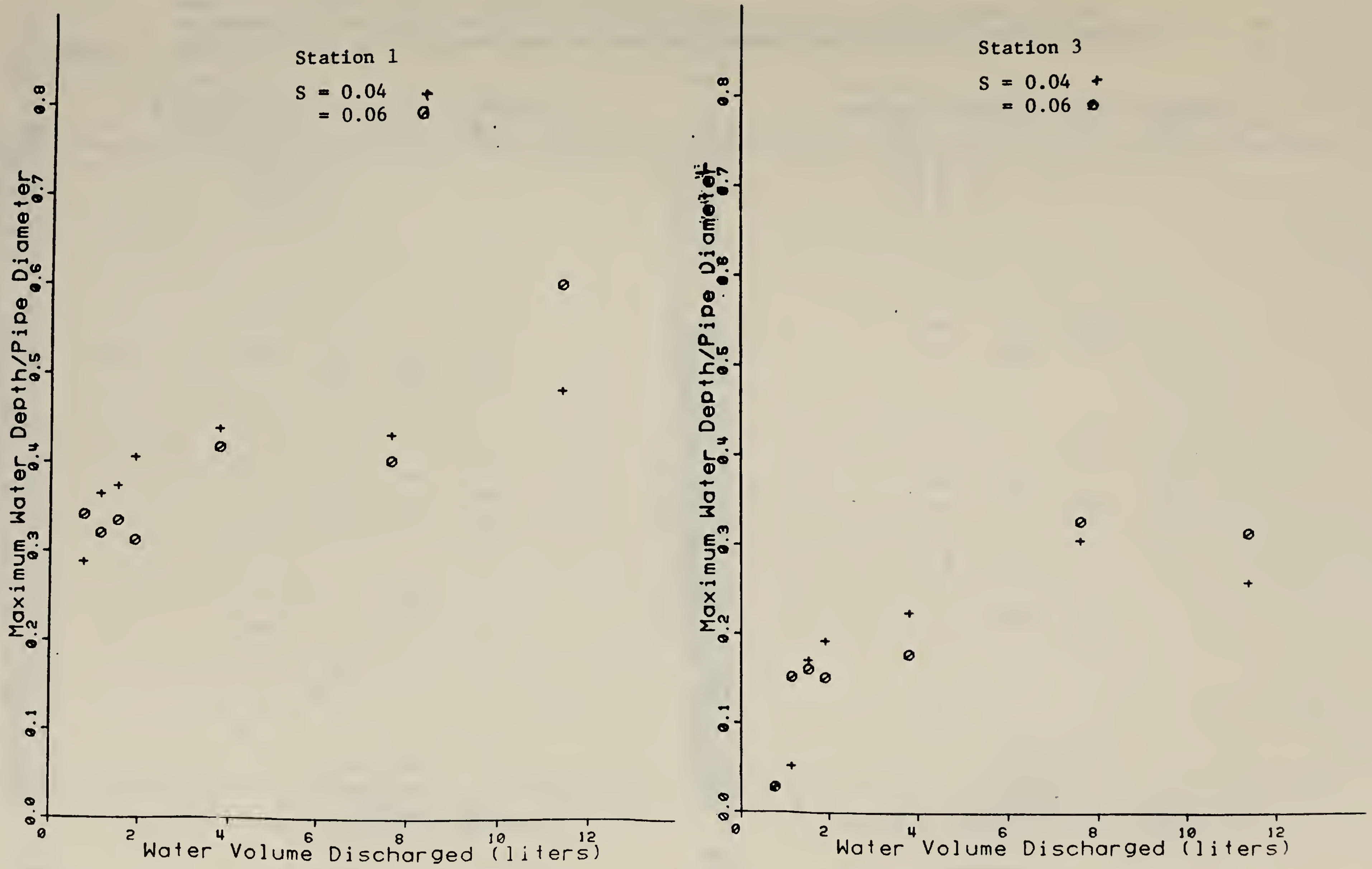


Figure 32. The peak value of non-dimensional stream depth versus V_w at measuring stations 1 and 3, at drain slopes of 0.04 and 0.06, and with a 3.8 by 7.6 cm solid in the drain.

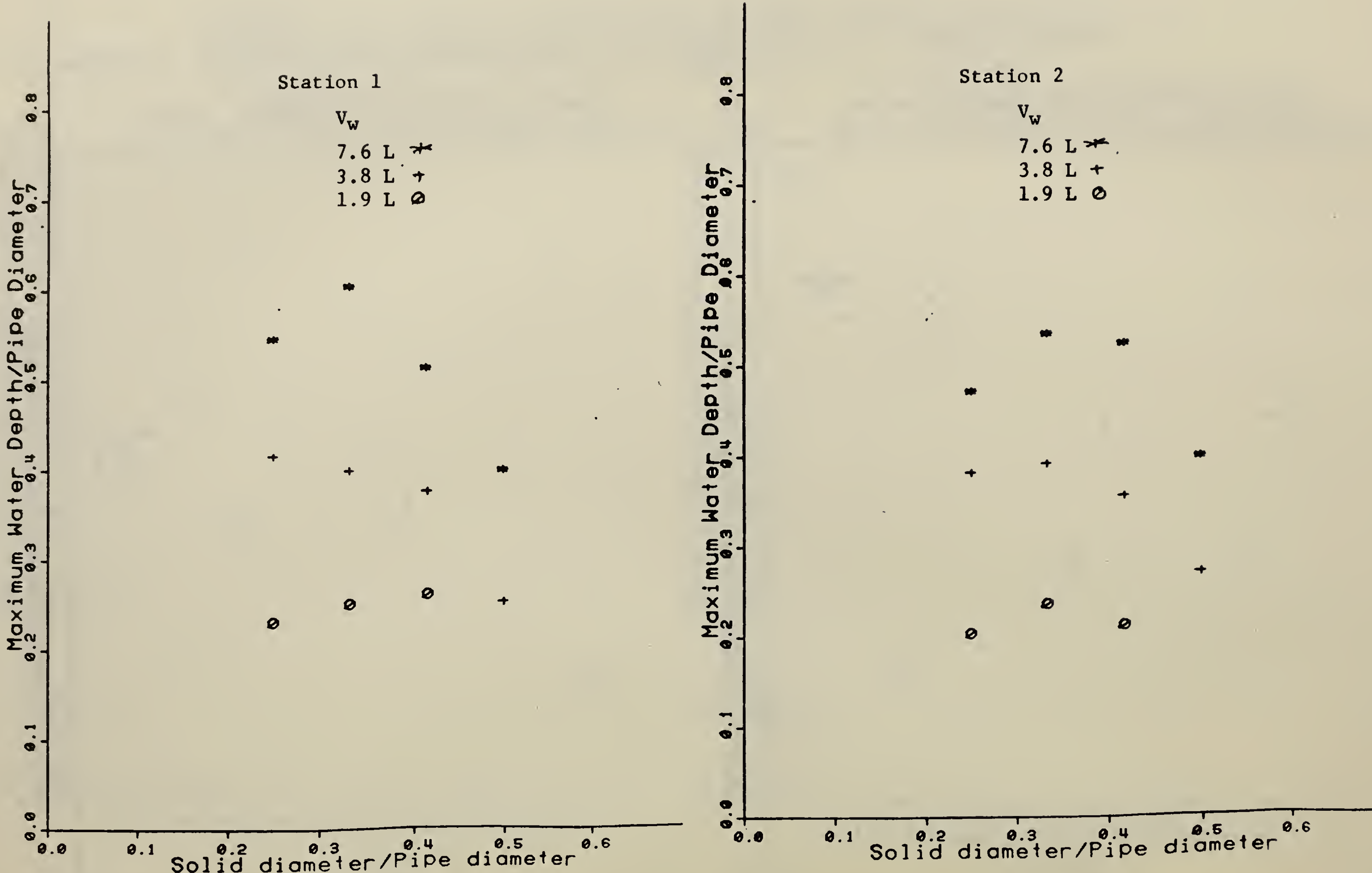


Figure 33. The peak value of non-dimensional stream depth versus non-dimensional solid diameter at measuring stations 1 and 2, for 2.5 cm long solids, at a drain slope of 0.04, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

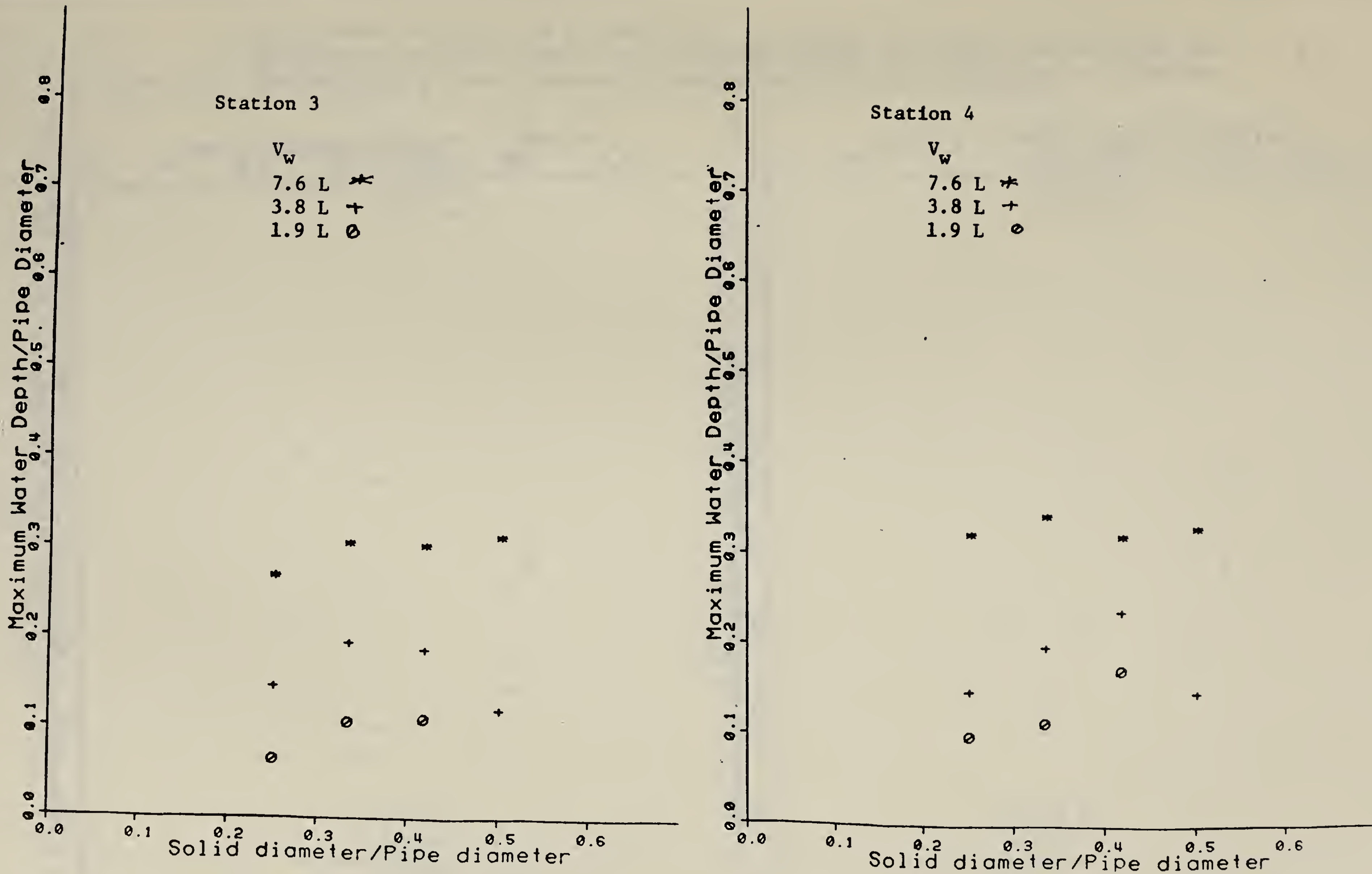
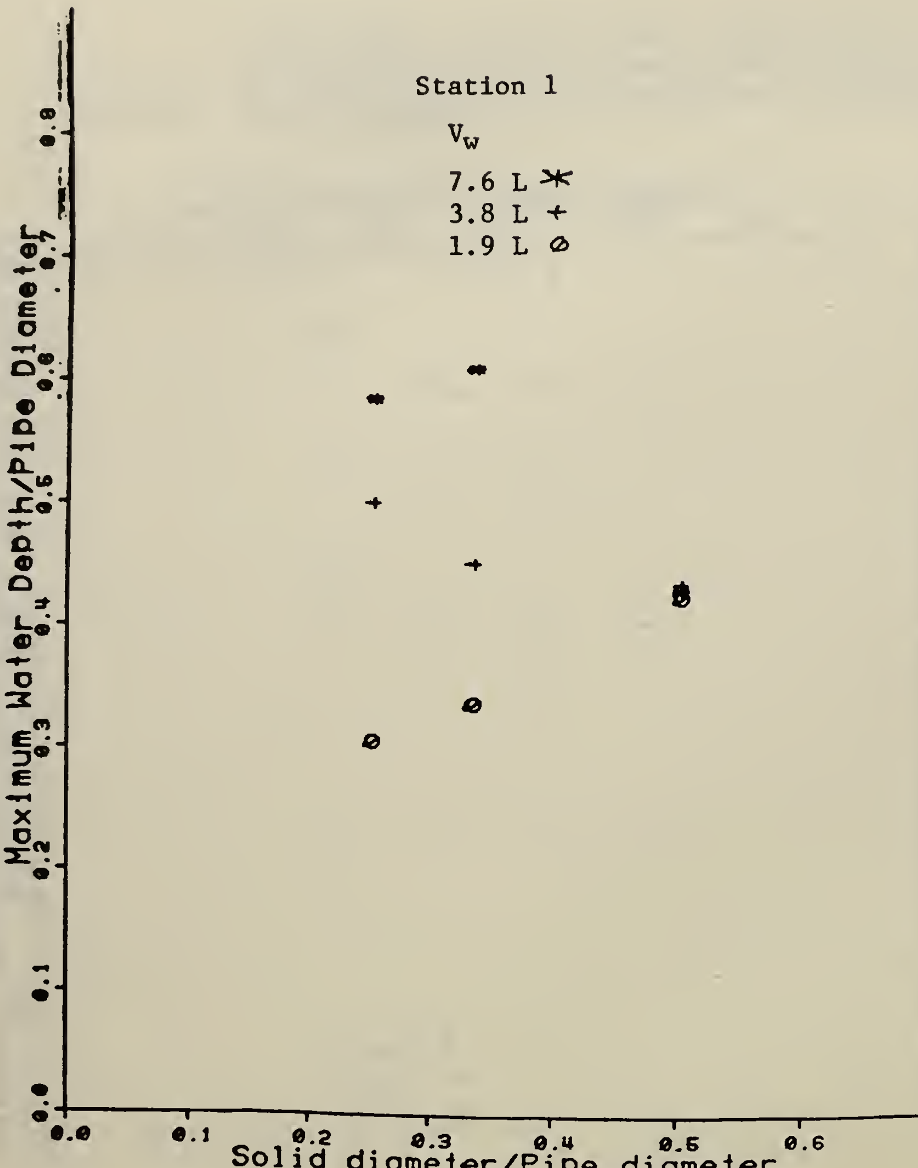


Figure 34. The peak value of non-dimensional stream depth versus non-dimensional solid diameter at measuring stations 3 and 4 for 2.5 cm long solids, at a drain slope of 0.04, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.



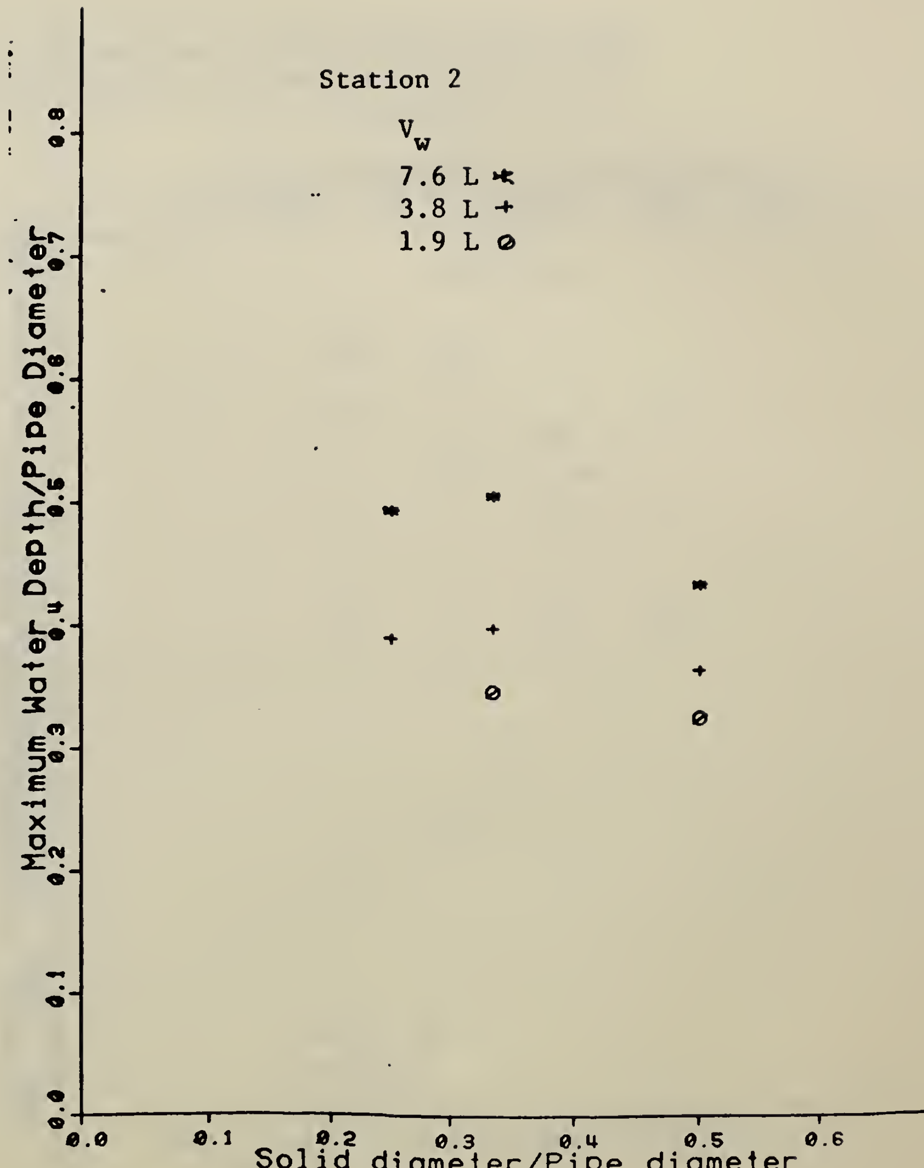


Figure 35. The peak value of non-dimensional stream depth versus non-dimensional solid diameter at measuring stations 1 and 2 for 7.6 cm long solids, at a drain slope of 0.04, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

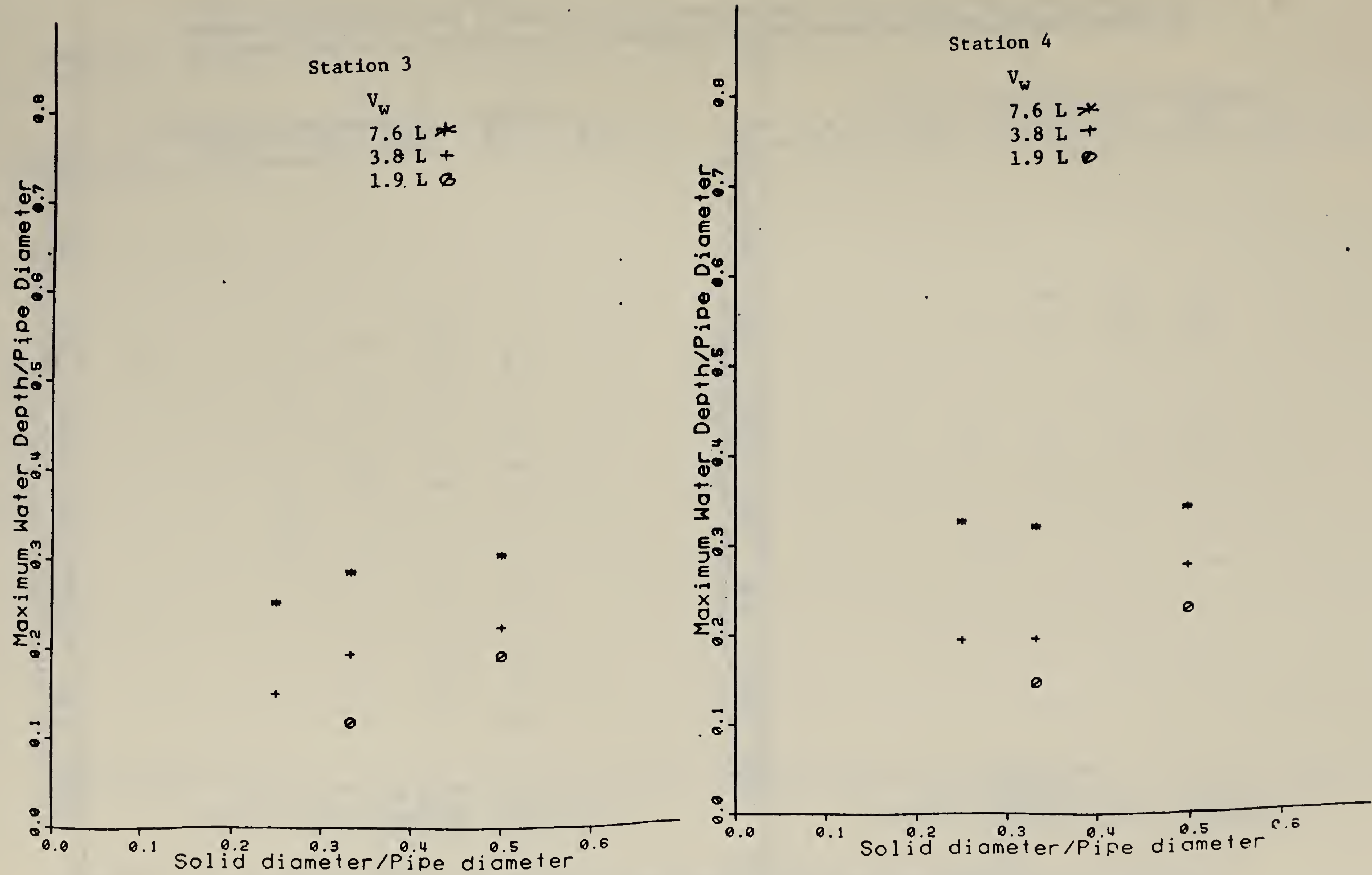


Figure 36. The peak value of non-dimensional stream depth versus non-dimensional solid diameter at measuring stations 3 and 4 for 7.6 cm long solids, at a drain slope of 0.04, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

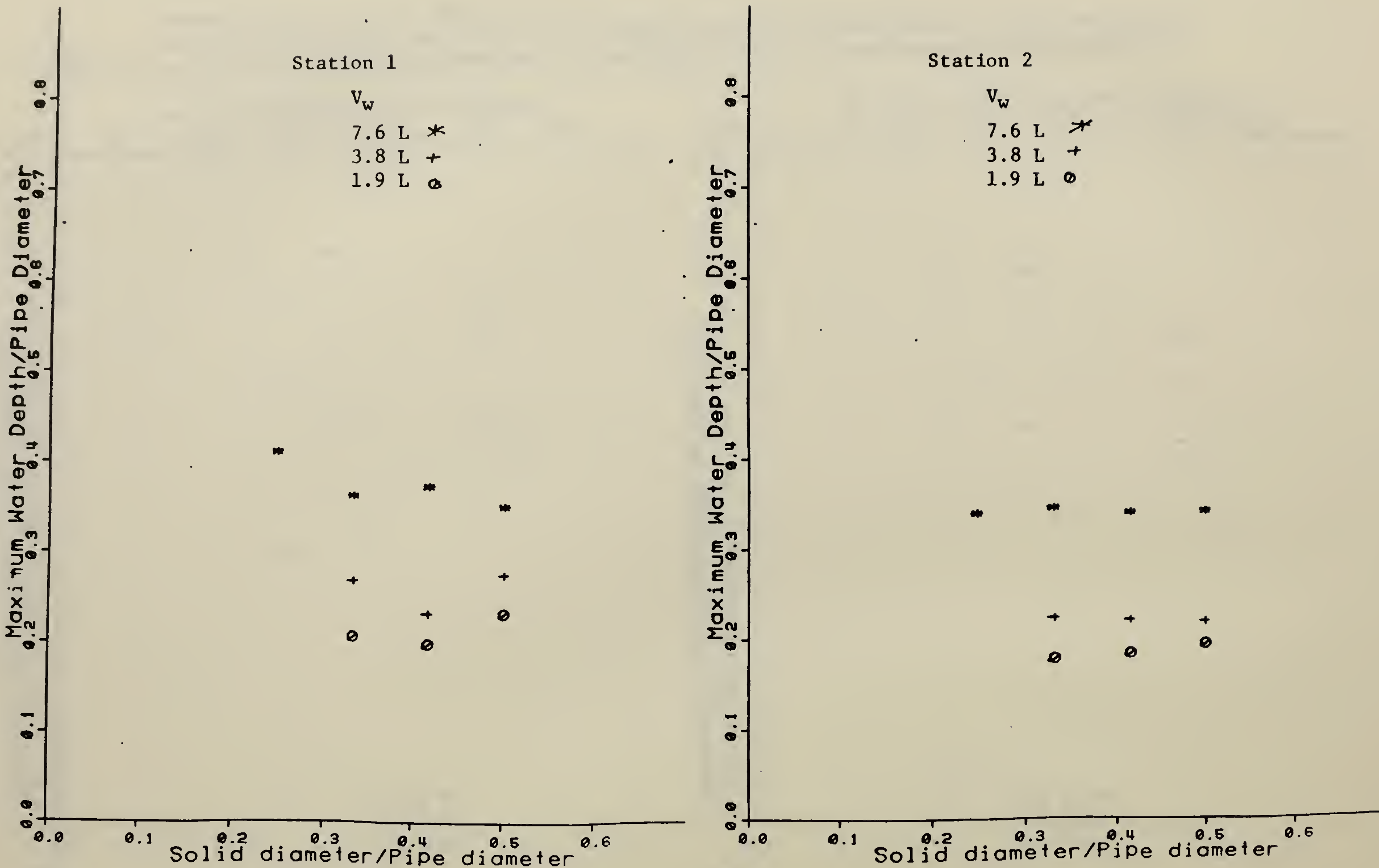


Figure 37. The peak value of non-dimensional stream depth versus non-dimensional solid diameter at measuring stations 1 and 3 for 2.5 cm long solids, at a drain slope of 0.06, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

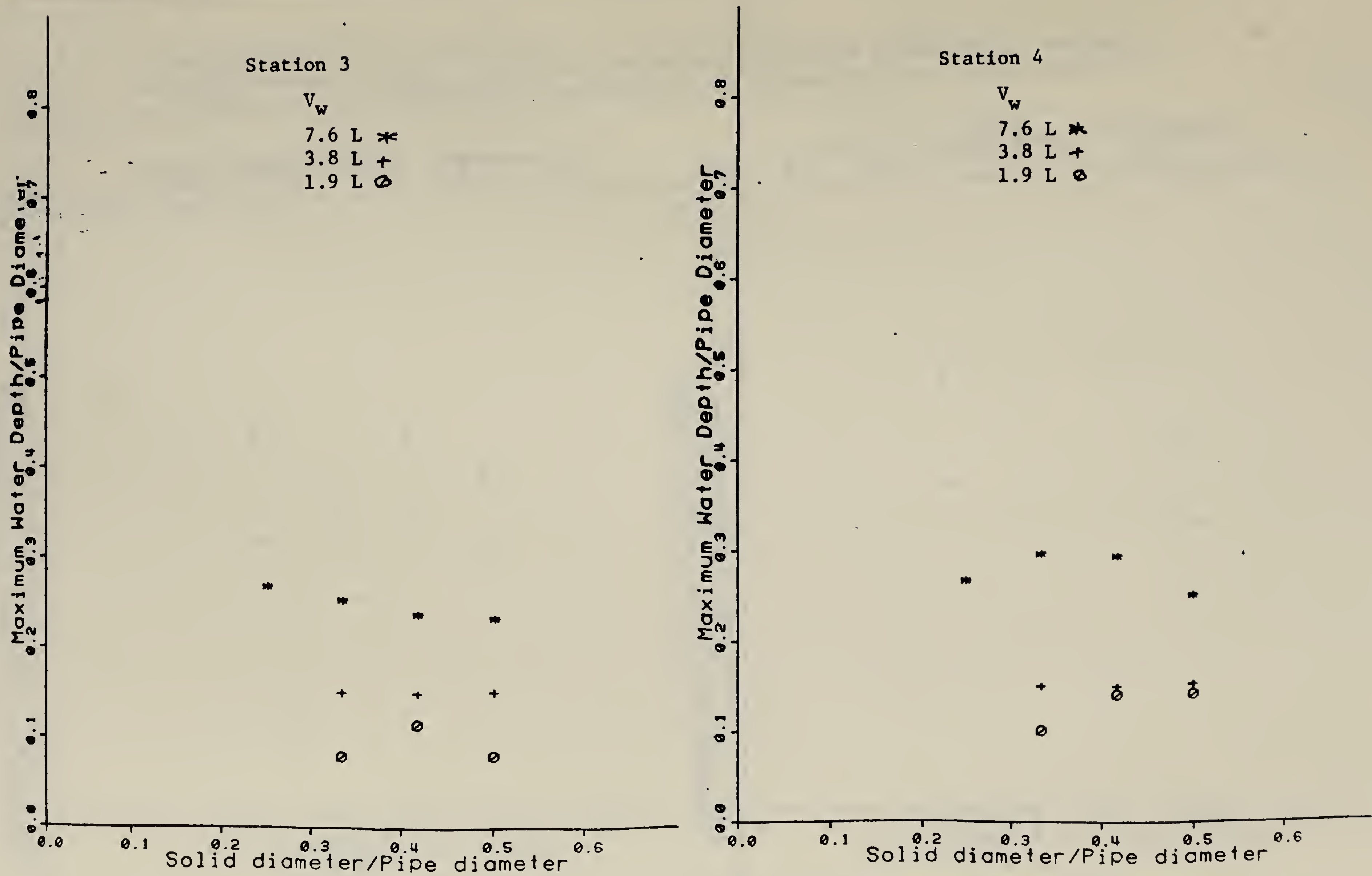


Figure 38. The peak value of non-dimensional stream depth versus non-dimensional solid diameter at measuring stations 3 and 4 for 2.5 cm long solids, at a drain slope of 0.06, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

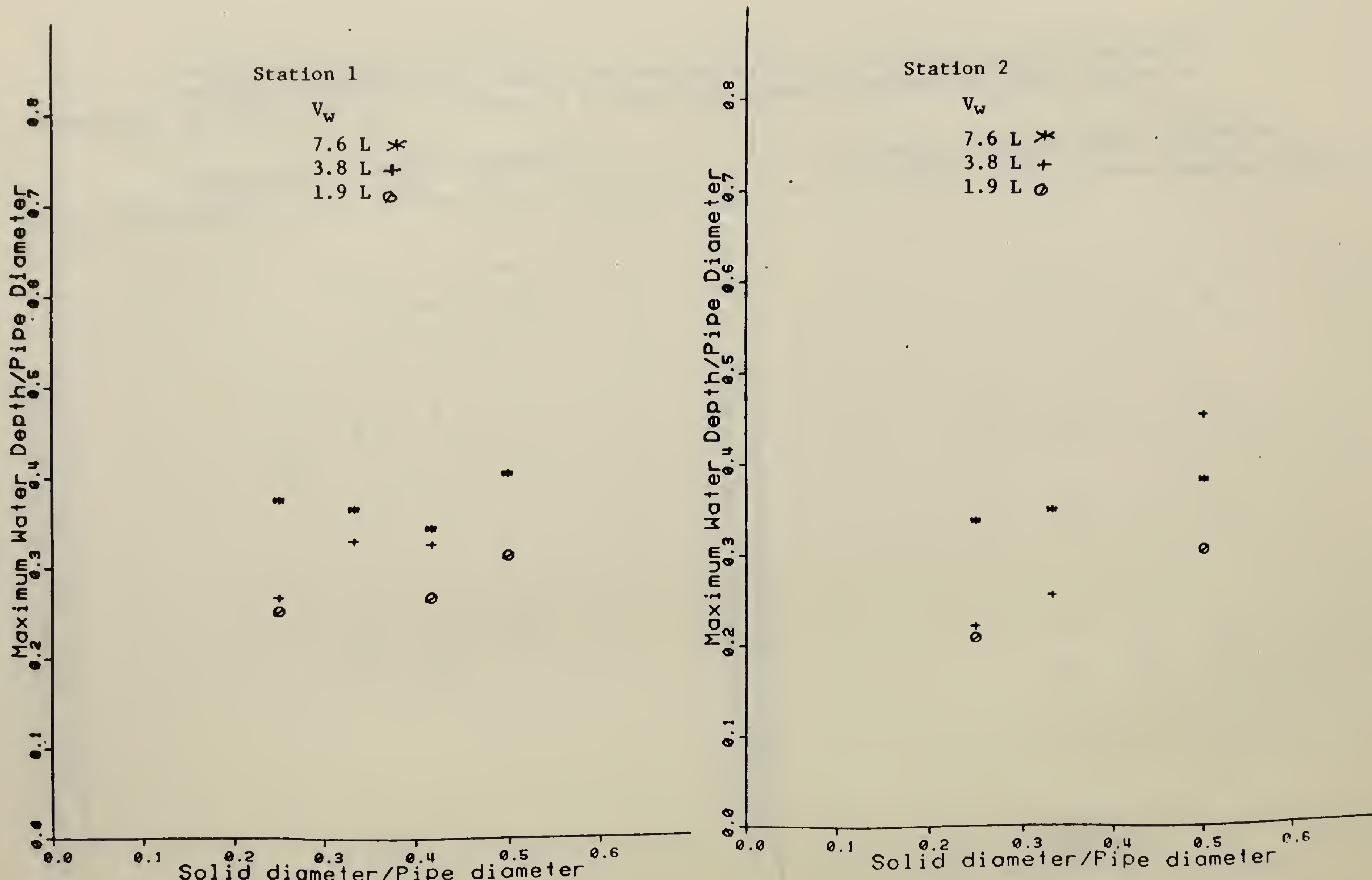


Figure 39. The peak value of non-dimensional stream depth versus non-dimensional solid diameter at measuring stations 1 and 2 for 7.6 cm long solids, at a drain slope of 0.06, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

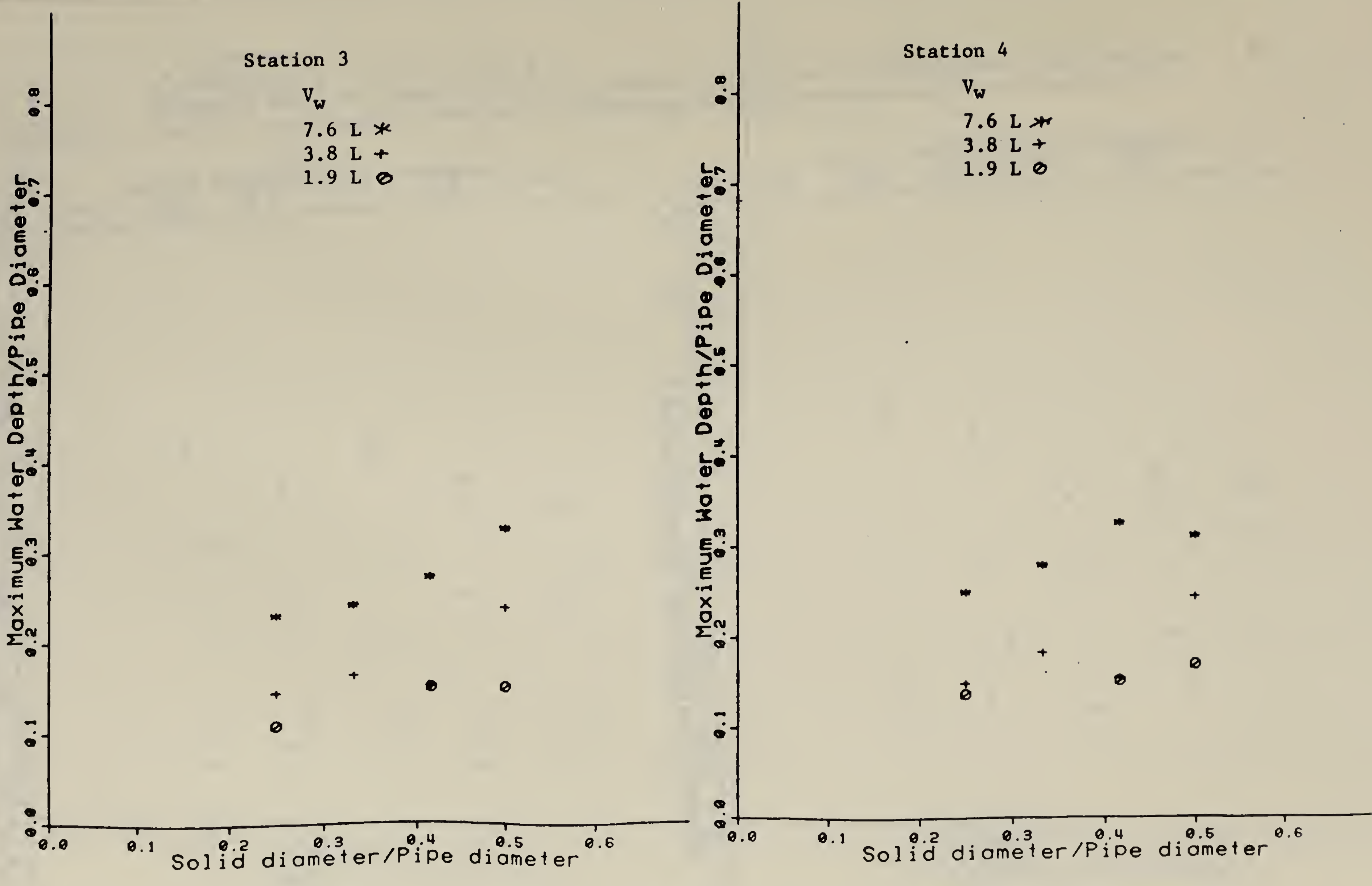


Figure 40. The peak value of non-dimensional stream depth versus non-dimensional solid diameter at measuring stations 3 and 4 for 7.6 cm long solids, at a drain slope of 0.06, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

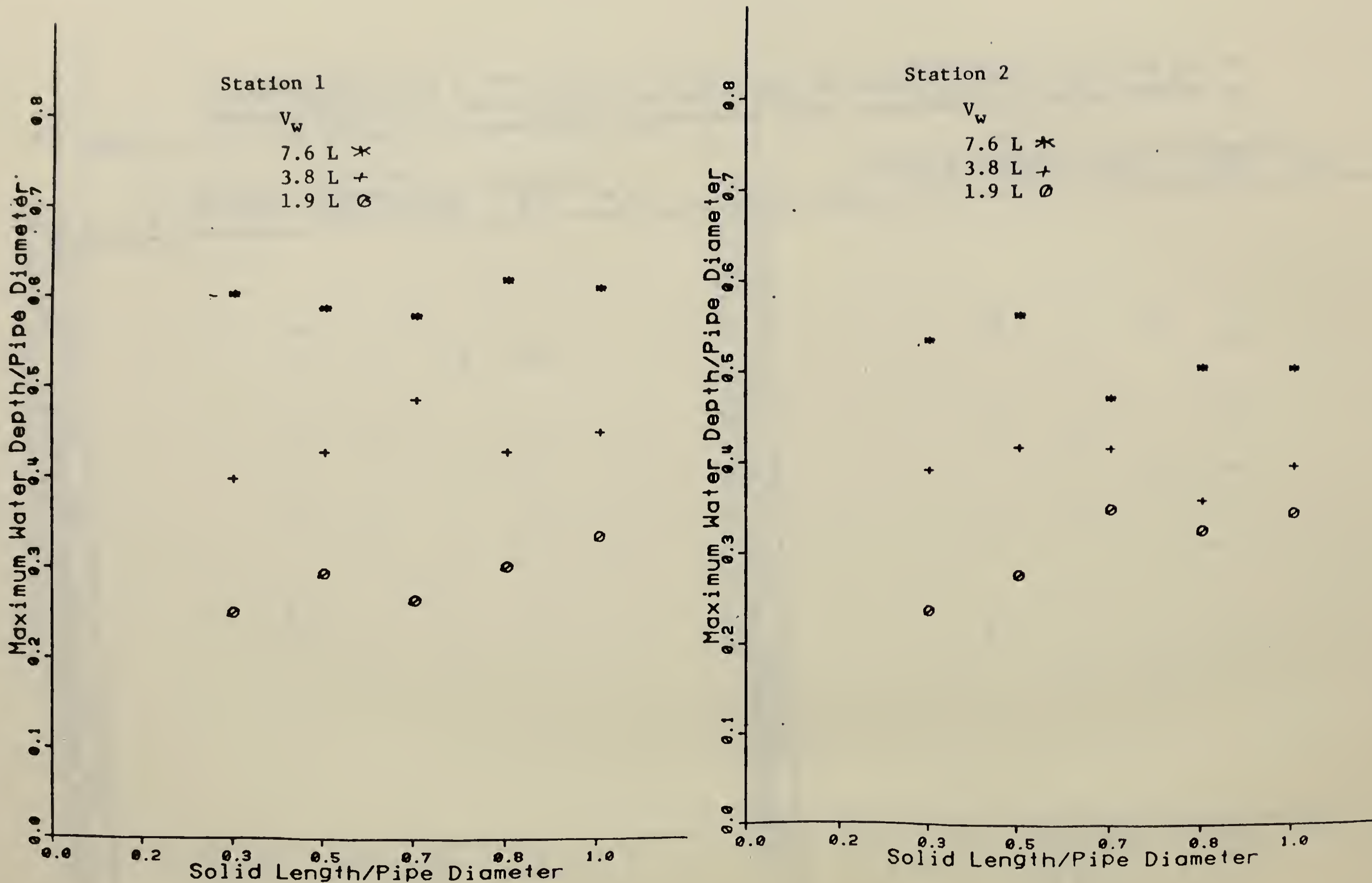


Figure 41. The peak value of non-dimensional stream depth versus non-dimensional solid length at measuring stations 1 and 2 for 2.5 cm diameter solids, at a drain slope of 0.04, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

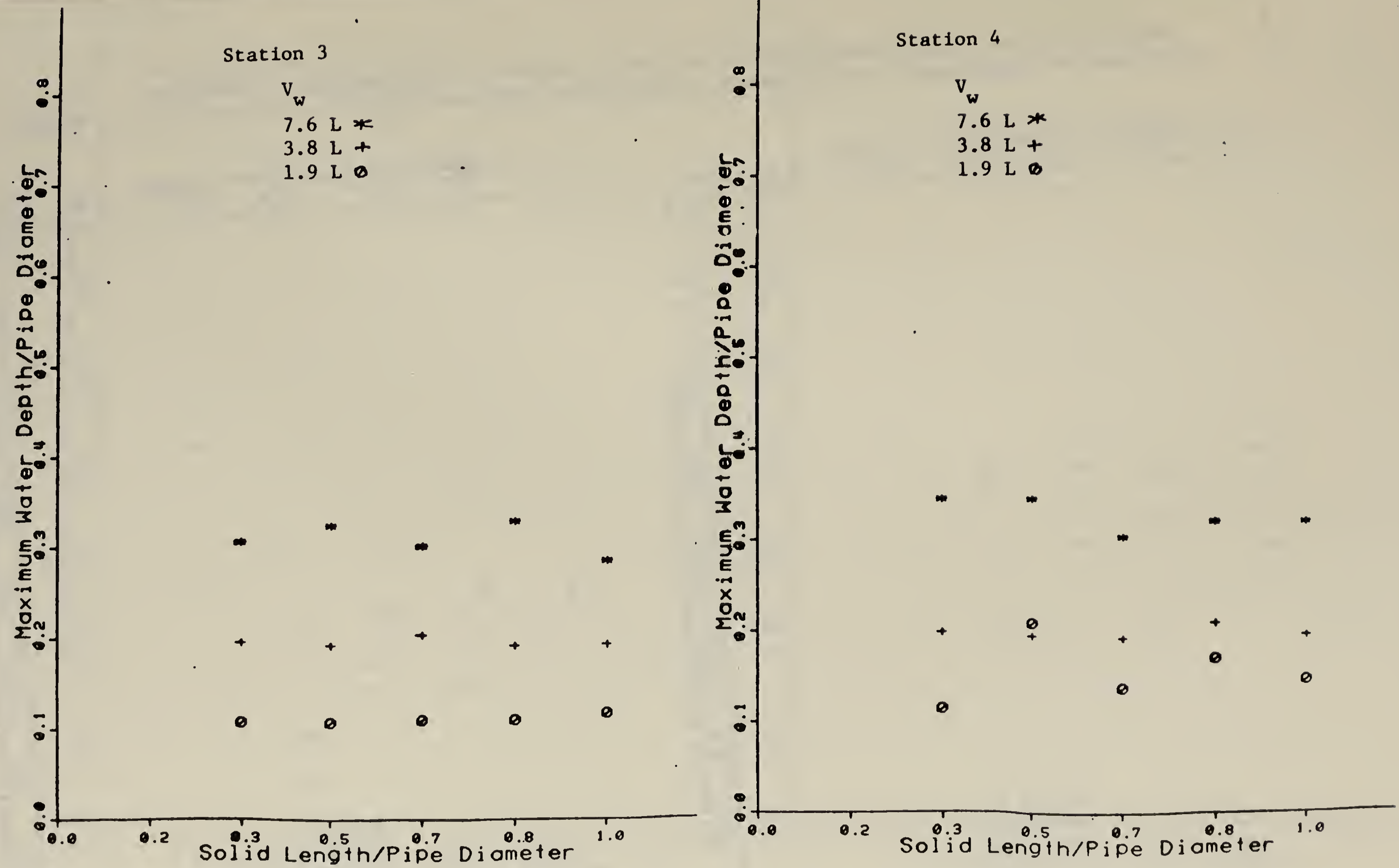


Figure 42. The peak value of non-dimensional stream depth versus non-dimensional solid length at measuring stations 3 and 4 for 2.5 cm diameter solids, at a drain slope of 0.04, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

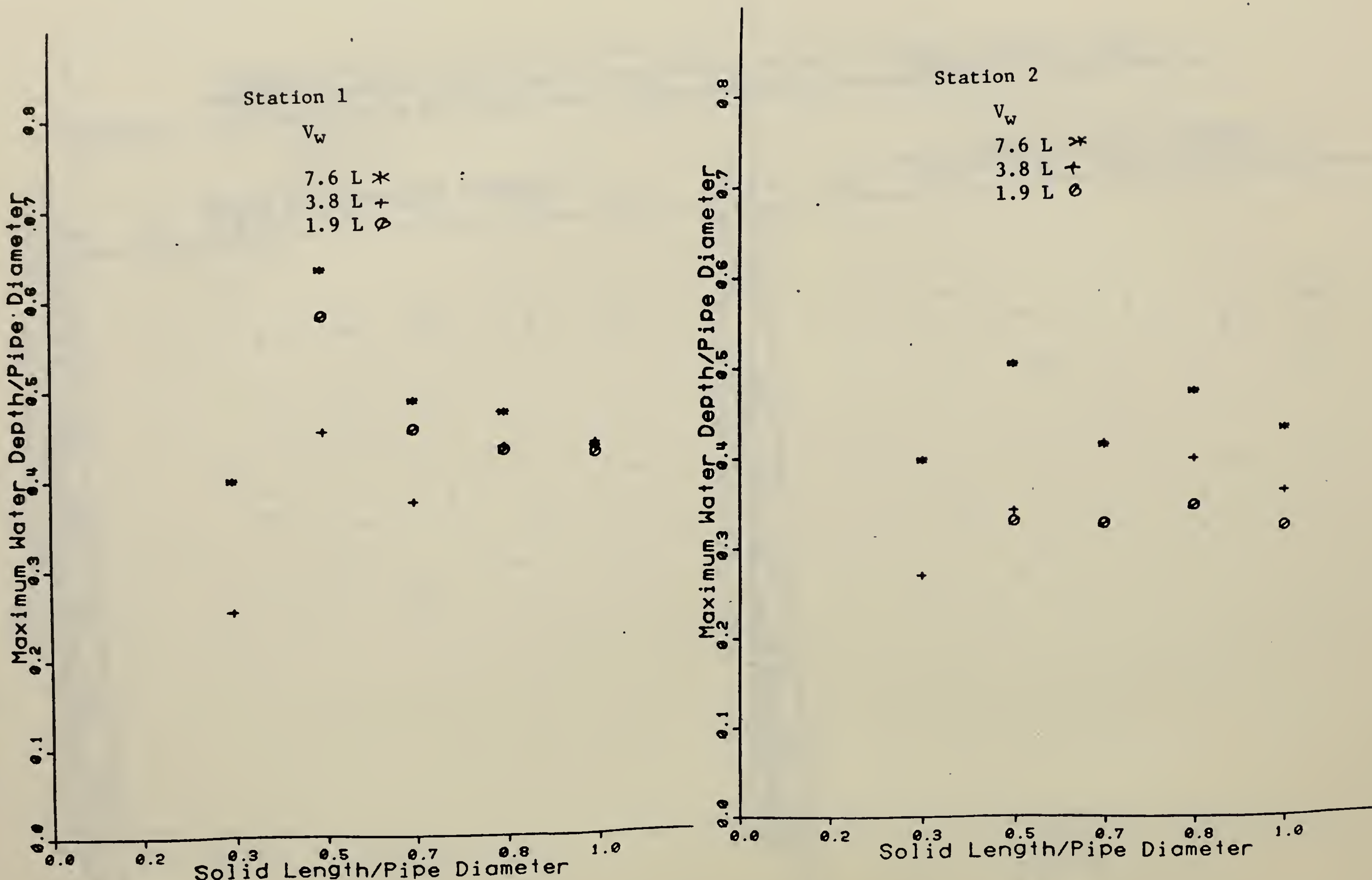


Figure 43. The peak value of non-dimensional stream versus non-dimensional solid length at measuring stations 1 and 2 for 3.8 cm diameter solids, at a drain slope of 0.06, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

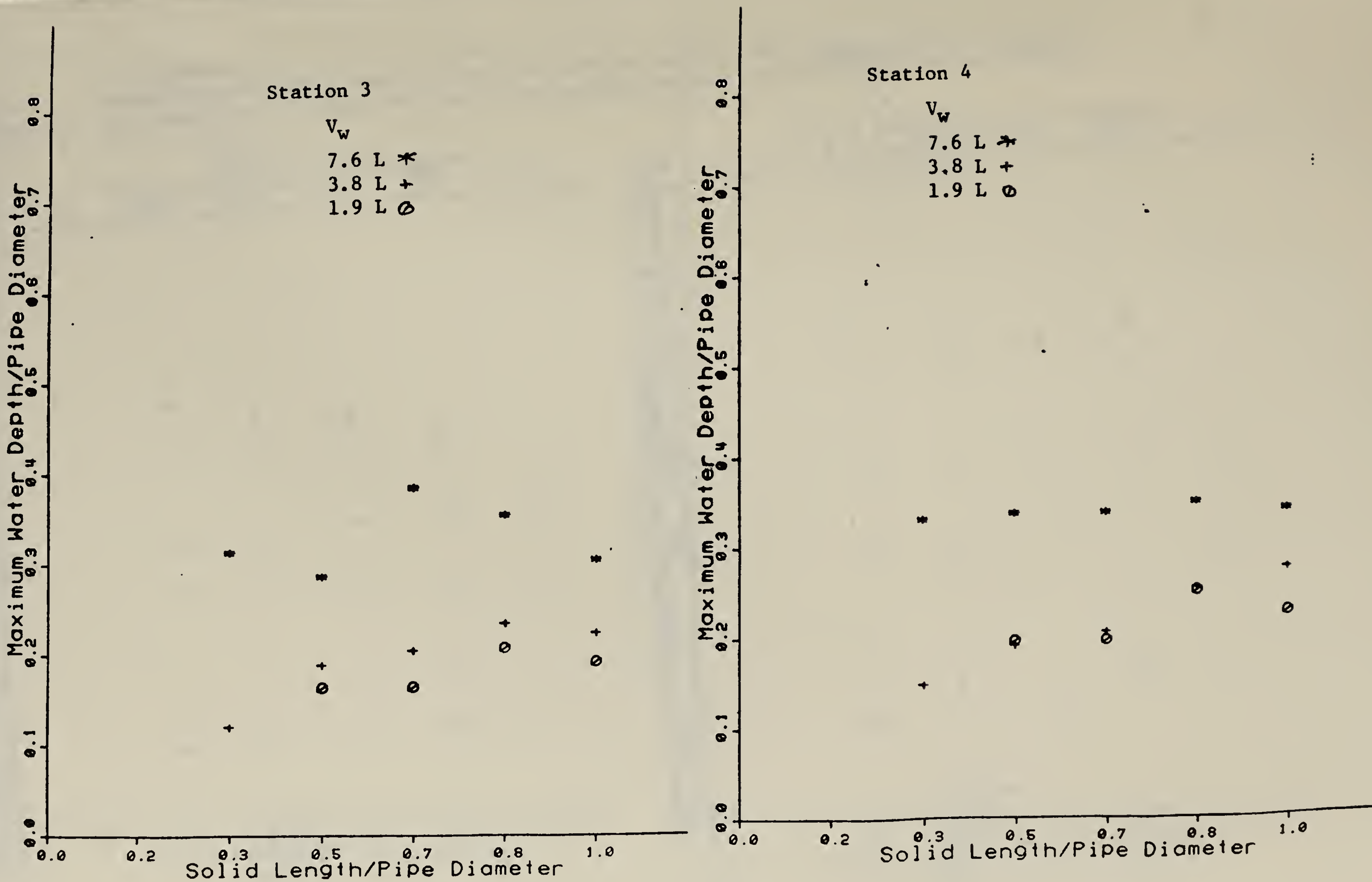


Figure 44. The peak value of non-dimensional stream depth versus non-dimensional solid length at measuring stations 3 and 4 for 3.8 cm diameter solids, at a drain slope of 0.06, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

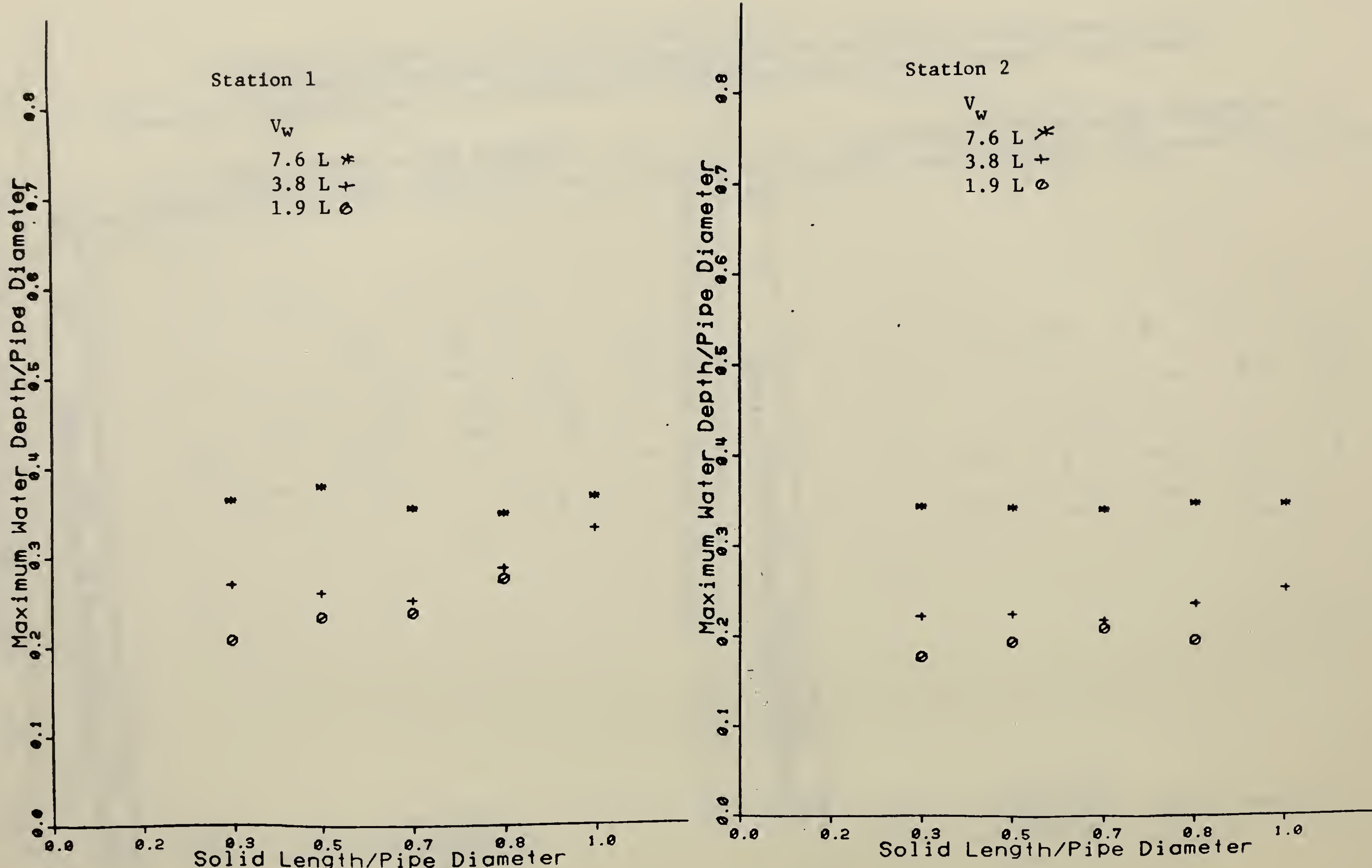


Figure 45. The peak value of non-dimensional stream depth versus non-dimensional solid length at measuring stations 1 and 2 for 2.5 cm diameter solids, at a drain slope of 0.06, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

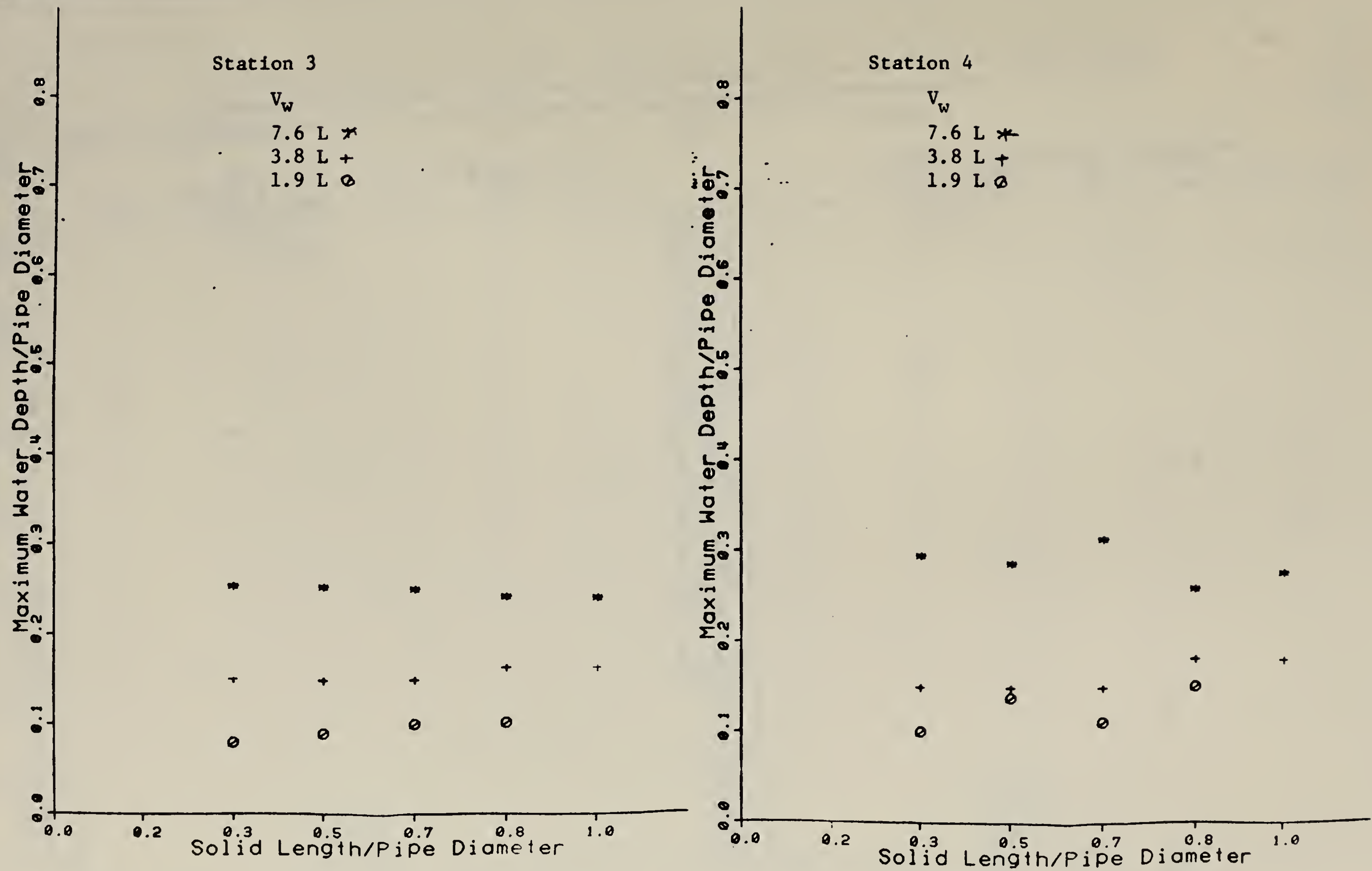


Figure 46. The peak value of non-dimensional stream depth versus non-dimensional solid length at measuring stations 3 and 4 for 2.5 cm diameter solids, at a drain slope of 0.06, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

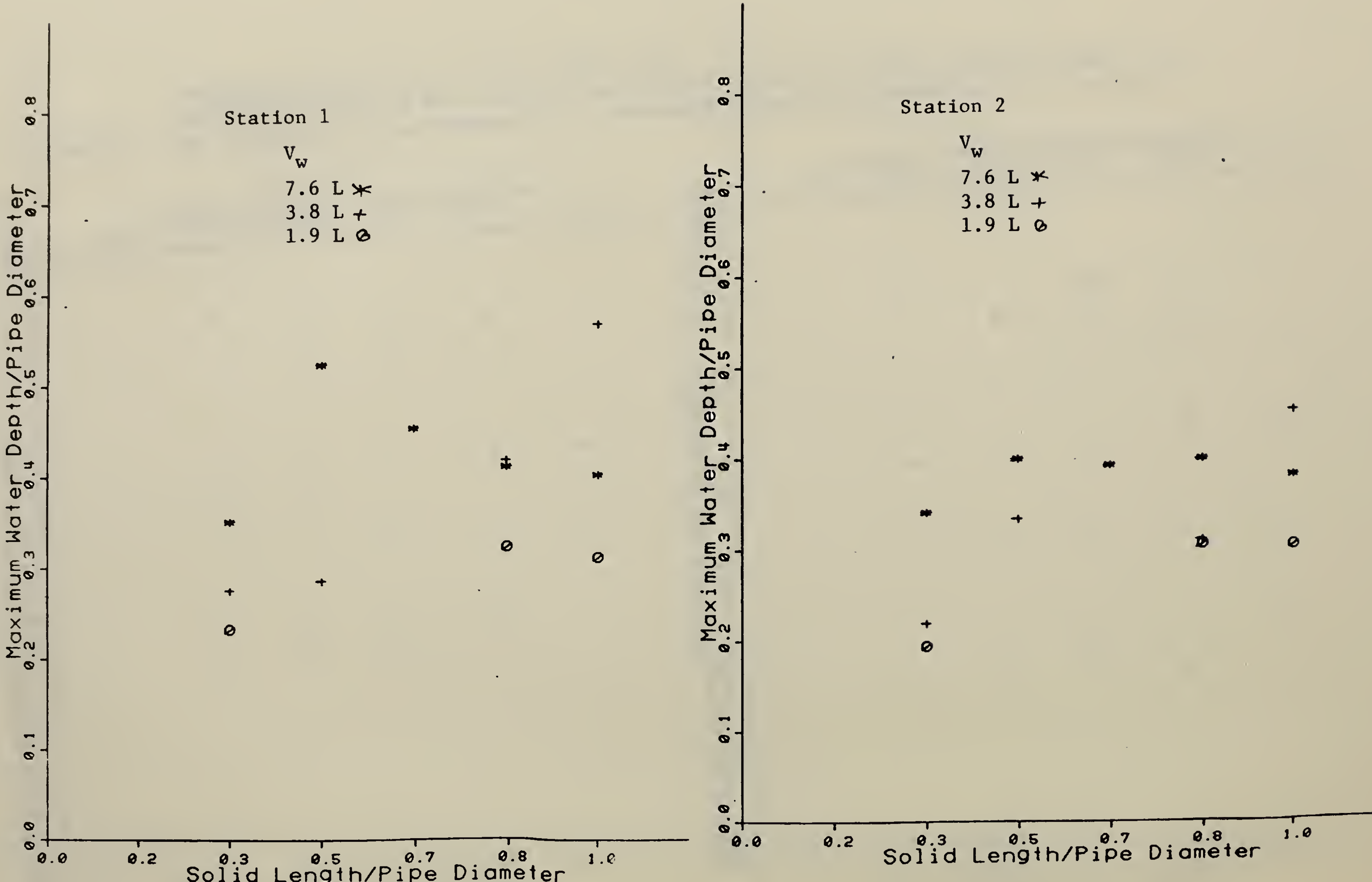


Figure 47. The peak value of non-dimensional stream depth versus non-dimensional solid length at measuring stations 1 and 2 for 3.8 cm diameter solids, at a drain slope of 0.06, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

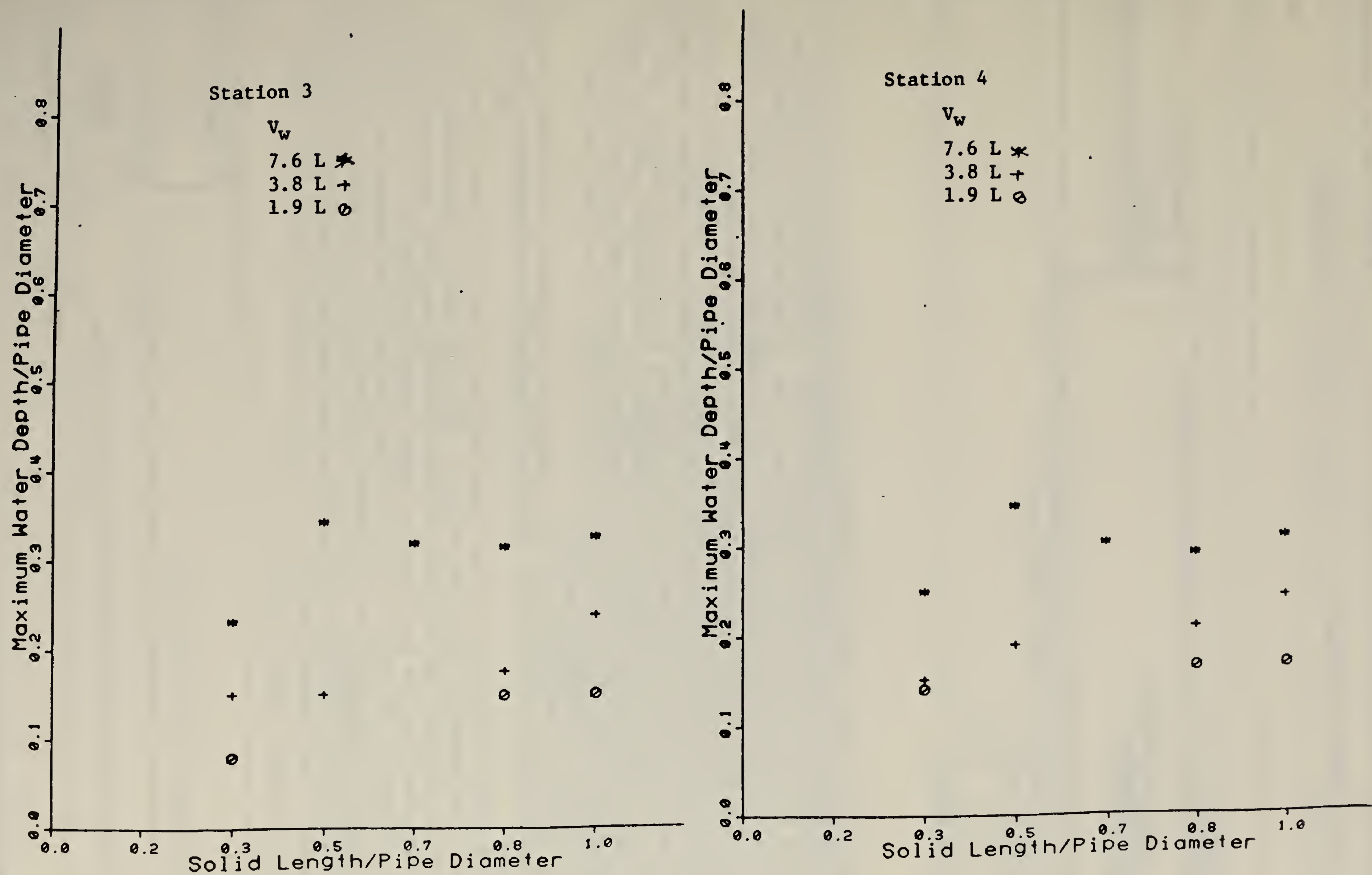


Figure 48. The peak value of non-dimensional stream depth versus non-dimensional solid length at measuring stations 3 and 4 for 3.8 cm diameter solids, at a drain slope of 0.06, and for V_w equal to 1.9 L, 3.8 L, and 7.6 L.

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5. AUTHOR(S)

Bal M. Mahajan

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

A research program to investigate the wastewater solid transport in horizontal drains is under way. The objective of the program is to develop data base and establish correlations for selecting drain pipe diameter, length, and slope for an effective solid waste transport with reduced water usage.

The purposes of this portion of the research program, which is presented here, were: (1) to measure the stream depth histories of unsteady, non-uniform transient, partially-filled pipe flow that ensues when water from a plumbing fixture is discharged into the drain, and (2) to examine the effects of the presence of a cylindrical solid and other relevant variables on the stream depth. The variables selected for the study include: the water volume discharged from the fixture into the drain, drain slope, and the diameter and length of cylindrical solids.

The report contains a description of the experimental apparatus, instrumentation and procedures, and a summary of the stream depth data acquired from experiments in a 7.6 cm diameter drain.

The depth of water stream at any given cross-section of the drain rises rapidly to a peak value and then gradually falls off to zero. The peak value of stream depth at a pipe cross-section decreases as the distance from the drain entrance increases. At a given drain cross-section, the peak value of stream depth increases with an increase in the water volume used, a decrease in the pipe slope, and with the presence of a solid in the drain. The variations in the solid diameter influence the steam depth history more than the variation in its length.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Diameter; drain; flow; history; horizontal; length; partially-filled; pipe; slope; stream-depth; unsteady; volume; water.

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