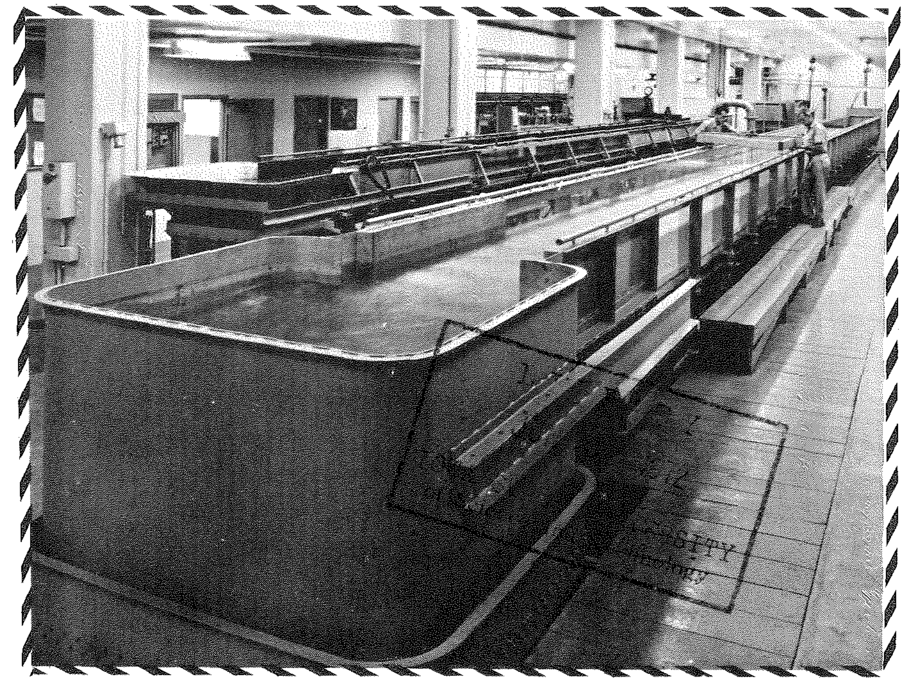
UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

WATER RESOURCES DIVISION

AIDS IN DESIGNING LABORATORY FLUMES



By

Garnett P. Williams

Open-file report

Washington, D. C.

1971

Cover: California Institute of Technology 130-foot flume (foreground) and 60-foot flume (Cal. Tech photo).

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SYMBOLS

A	cross-sectional flow area, in ft^2
C_d	coefficient of discharge used in determining water discharge by various flow meters, dimensionless
D	mean flow depth, in ft
H	height of upstream water surface above weir crest, in ft
HP	pump horsepower
K	coefficient needed to determine local head losses, dimensionless
L	distance along a boundary, parallel to flow (e.g. length of pipeline), in ft
Q	water discharge, in ft^3/sec
Q_{max}	maximum water discharge, in ft^3/sec
V	mean flow velocity, in ft/sec
V_o	free-stream velocity (outside the boundary layer), in ft/sec
W	flume width, in ft
d	inside pipe diameter, in ft
f	Darcy-Weisbach friction factor, dimensionless
g	acceleration due to gravity, in ft/sec^2
m	experimental coefficient for discharge over a weir, dimensionless
x	downstream distance needed for full development of a turbulent boundary layer, in ft
ΔH	total head (sum of static head and head losses), in ft
Δh	elevation difference between high pressure and low pressure in a differential manometer, in ft
Δz	static head (vertical elevation difference between two interconnected water surfaces), in ft
δ	thickness (height) of turbulent boundary layer, in ft
ν	kinematic viscosity of water, in ft^2/sec

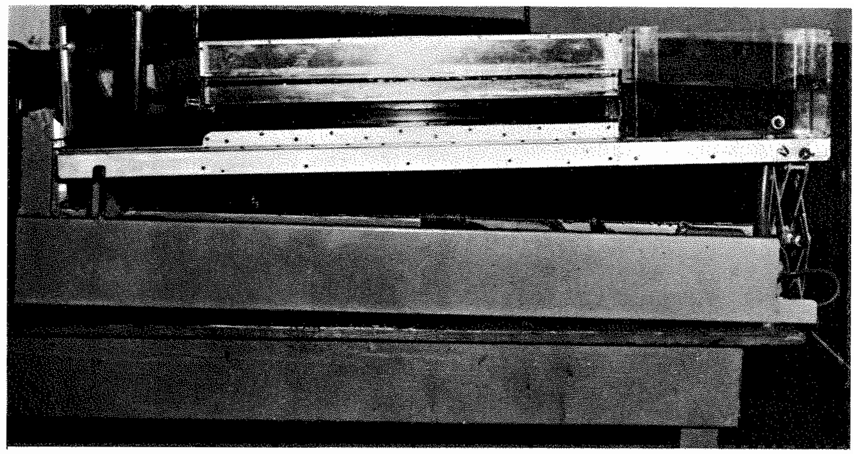
INTRODUCTION AND ACKNOWLEDGMENTS

The upsurge of interest in our environment has caused research and instruction in the flow of water along open channels to become increasingly popular in universities and institutes. This, in turn, has brought a greater demand for properly-designed laboratory flumes. Whatever the reason for your interest, designing and building the flume will take a little preparation. You may choose a pattern exactly like a previous design, or you may follow the more time-consuming method of studying several existing flumes and combine the most desirable features of each.

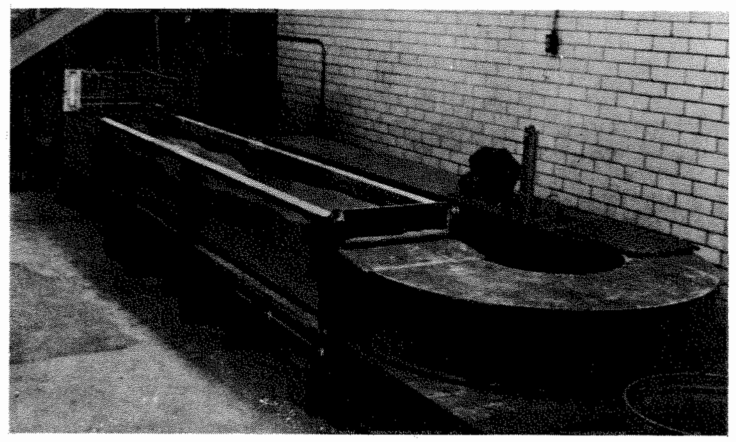
The main purpose of this manual is to bring to your attention various techniques of design and construction. Advantages and disadvantages of each will be pointed out. You will thereby get some scope and choice of the different ways of building a flume and will be able to avoid many of the costly mistakes other people have made. Even if you intend to buy a flume ready made rather than build one, the manual will help you determine the desirable features in view of your particular purposes and will provide some understanding of the reasons for these features.

The basic ingredients of a system are the test channel (flume), water or whatever fluid is to be used, a pump, piping, various tanks, and possibly sediment (for sediment-transport studies). Figure 1 shows some examples.

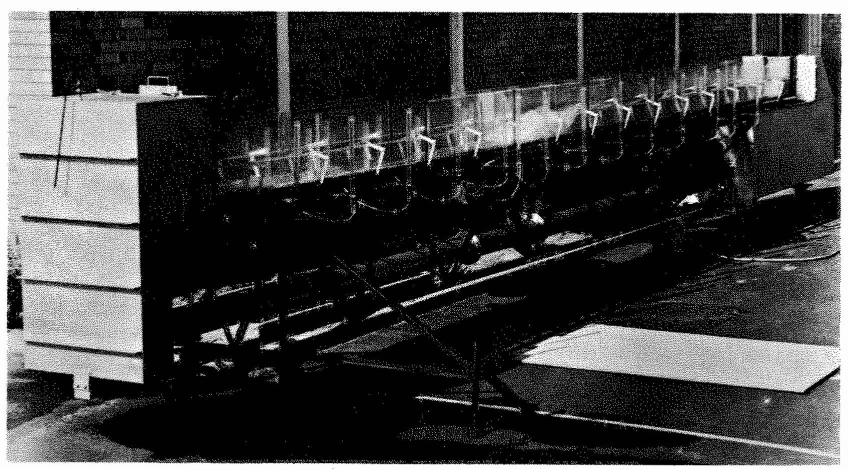
Before deciding on a final design it will be worthwhile visiting laboratories and investigating in detail many of the suggestions given



A. Small table-model demonstration flume built at Georgia Tech for the U.S. Geological Survey.

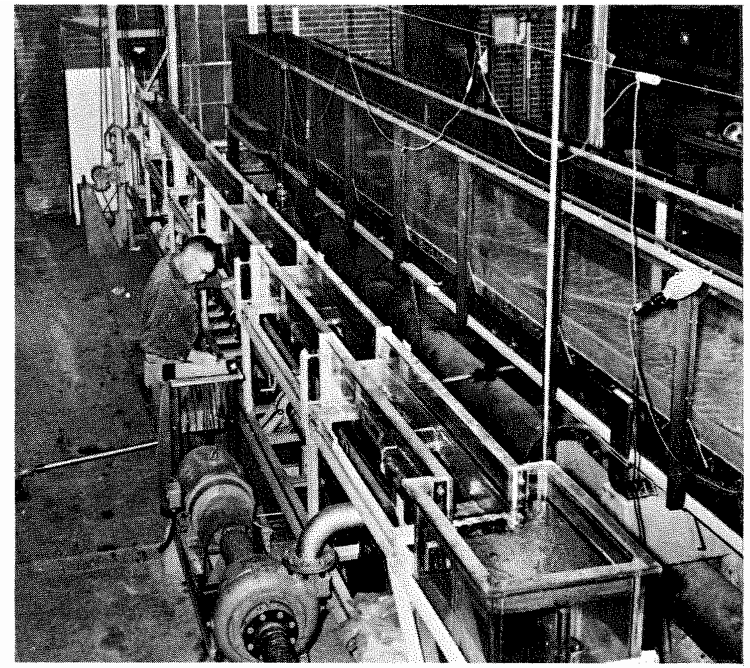


B. Amherst College 15-foot demonstration flume (Amherst photo).



C. University of Western Australia portable plastic flume (U.W.A. photo).

Figure 1.--Examples of laboratory flumes.



D. U.S. Geological Survey 30-foot plastic flume, here photographed in the Colorado State University laboratory.

E. California Institute of Technology 130-foot flume (foreground) and 60-foot flume (behind) (Cal Tech photo).

Figure 1, continued.

in these pages. New materials, instruments and techniques are being developed at a rapid rate.

The text in a few places includes names of companies and of special products. Mention of these names does not necessarily imply endorsement by the U.S. Government.

A word of apology may be in order in regard to the style and content of this manual. Many readers undoubtedly will be quite experienced and competent in designing a flume. Others, however, especially those not trained in hydraulic engineering, will be novices. I hope that those who are already knowledgeable will not be offended that much of the text is written in the second person and that a certain amount of detailed instruction is included. A proficient flume engineer probably will not need this booklet, but hopefully the novice, at least, will find many labor-, time- and money-saving suggestions.

Some of the information and description given here comes from scattered articles and testbooks. But much of this manual could not have been written without the cooperation of men experienced in building and using flumes. Everett V. Richardson of Colorado State University and Verne R. Schneider and William W. Emmett, both of the U.S. Geological Survey, have been particularly helpful. My sincere thanks also go to Herman J. Koloseus, John B. Southard, Elton F. Daly, Vito A. Vanoni, Neil L. Coleman, Joe C. Willis, M. R. Carstens, Robert P. Apmann, R. Silvester, R. H. B. Hebbert, John O. Normann, Emmett M. Laursen, James E. Glover, M. Gordon Wolman, A. L. Lembeck, Ralph Asmus, Bryce M. Hand, Barrie C. McDonald, Hubert J. Tracy, Alvin G. Anderson, Dale Harris, Jacob Davidian, Homer Bates, R. F. Aked, H. A. Einstein and George F. Smoot.

THE PURPOSE OF A FLUME

As a preliminary step you should be certain of the purpose of the proposed flume. Most people are concerned with one of three purposes: to demonstrate flow and/or sediment-transport phenomena, to teach students to make flow measurements of various sorts, or to carry out basic research. Francis (1966) gives an interesting discussion of the first two of these goals.

Size and expense will vary tremendously, depending mainly on which of these three purposes you have in mind. Those just listed are in order of increasing cost, size and difficulty of operation. In other words, flumes intended only for demonstration purposes will be much smaller, cheaper and easier to operate than those to be used for basic research.

For research some people advocate designing only for the immediate research project. The flume can then be dismantled upon completion of the project. This approach, though perhaps feasible in certain cases such as model studies, probably will not be practical for most institutions. The more common approach is to build a well-designed permanent flume to serve a variety of research problems.

The most important measurements you will want to make in research studies are the volume rate of water flow (discharge), water depth, the slopes of the bed and water surface, and, for sediment-transport studies, the volume or weight rate at which sediment moves. Some of these variables, such as water discharge, can always be controlled. Others, such as sediment-transport rate, can be controlled only in certain types of flumes. Many other features, such as mean velocity and water temperature, should also be recorded. It would be easy to make a long list of possibly-relevant variables, but those mentioned in this paragraph are the ones to keep in mind in designing.

FLUME TYPES: RECIRCULATING VERSUS NONRECIRCULATING FLUMES

A good way to begin planning your flume is to decide on the type you will have. This manual discusses sediment-transport flumes as well as rigid-bed channels, and we're going to classify flumes into two major types (recirculating and nonrecirculating) according to the method of introducing sediment into the test section. Either of these types can of course be used without sediment.

In recirculating flumes (fig. 2) the sediment always stays within the system, passing through the pump with the water and being pumped up into the test channel[1]. The second major flume type is the nonrecirculating flume, shown in figure 3. In this type the sediment is introduced by some external feed system at the upstream end of the flume and is trapped at the downstream end just after the water and sediment leave the test channel. Some laboratories that use nonrecirculating flumes are the U.S. Waterways Experiment Station (Vicksburg, Miss.), St. Anthony Falls, (Minneaplois, Minn.), and the U.S. Geological Survey (Washington, D.C.). The rate of sediment infeed is directly controllable and usually constant in nonrecirculating flumes,

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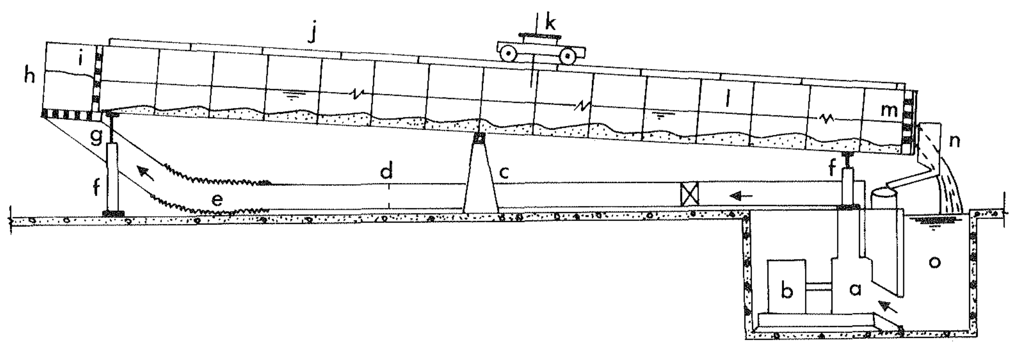
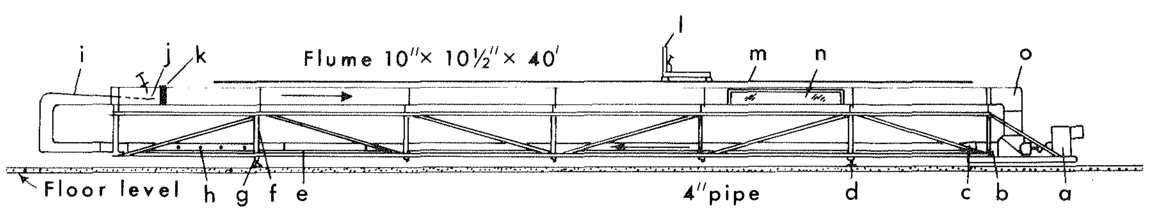
[1]Some people think of a recirculating flume as one in which the <u>water</u> recirculates (always stays in the system), as contrasted to situations where the water flows in from an outside source (river or reservoir), is routed through the flume and back out into the river. The laboratories at St. Anthony Falls (Minneapolis) and Utah State University (Logan) have flumes of the latter sort.



A. Free-overfall recirculating flume (Colorado State University).

a. Pump b. Motor c. Center support d. Orifice e. Flexible rubber connection f. Jacks g. Manifold diffuser h. Headbox i. Baffles and screens j. Rails k. Instrument carriage l. Flume (2×2.5 × 60 ft) m. Tailgate n. "Total-load" sediment sampler o. Tailbox



B. Closed-circuit recirculating flume (California Institute of Technology).

a. Vari-drive motor b. Pump c. Venturi meter d. Fixed pivot support e. Transparent section of return line f. Slope gage g. Adjustable support h. Four 1,000-watt heaters i. Transition section j. Diffuser k. Damping screens l. Instrument carriage m. Rails n. Observation window o. Pump well (tailbox)

Figure 2.--Recirculating flumes.

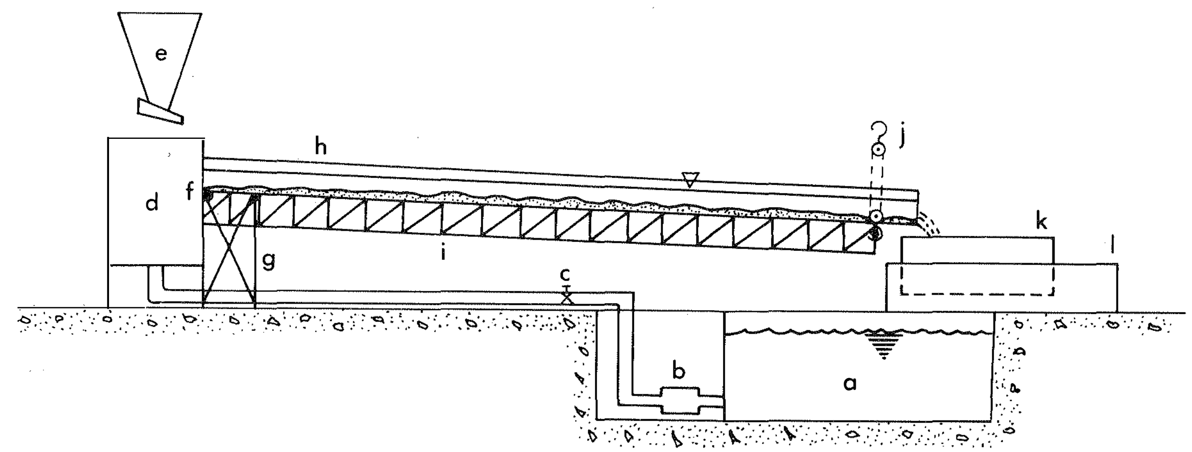


Figure 3.--Nonrecirculating flume. Not drawn to scale. Sediment-weighing system not shown. a. sump b. pump c. control valve for water discharge d. head tank e. sediment infeed device f. pivot g. pivot stand h. test channel i. truss j. chain hoist for tilting the test channel k. sediment collection box l. return channel.

whereas with recirculating flumes the infeed rate depends on the rate at which sediment leaves the downstream end.

Recirculating flumes fall into two subdivisions: The free-overfall or open type (fig. 2A) and the tailbox or closed type (fig. 2B).

In the free-overfall type the water and sediment spill off the downstream end of the flume and fall through the air into a tailbox below, which acts as a sump. A tailgate regulates the uniformity of flow depth for subcritical flows. Colorado State University (Fort Collins) uses this type.

The second and more common kind of recirculating flume is the tailbox or closed-circuit type. Here no spilling occurs, i.e. the tailbox is attached to the flume test section and the water surface in the tailbox is usually on the same level as the water at the end of the test section. From the tailbox the water and sediment are pumped directly back to the head of the flume. In these closed-circuit flumes the volume of water in the test channel usually remains constant, i.e. the flow depth in the test section depends only on the amount of water in the system rather than on the water discharge, slope and other factors. California Institute of Technology (Pasadena), the U.S. Department of Agriculture (Oxford, Miss.), the Iowa Institute of Hydraulic Research (Iowa City) and Colorado State University are some of the many laboratories using this kind.

Both recirculating and nonrecirculating flumes can be used for rigid boundary studies as well as for sediment studies. Therefore, in your design you may as well plan on using sediment at some time in the future even though you may have no immediate plans for studying sediment-transport phenomena.

With careful design a recirculating flume can be turned into a nonrecirculating flume, and vice versa, as far as sediment studies are concerned. For example, by installing an upstream sand-feed machine in a recirculating flume, and a trap at the downstream end, you have a nonrecirculating flume. Or, by removing the sediment-trap, putting the pump intake at the bottom of the sump, and making a few changes in the sump and piping (discussed later), a nonrecirculating flume can become a free-overfall recirculating flume. In the latter case the pump must be of the type that can pump sand as well as water. Hence to convert the types the initial design must anticipate the change.

For purposes of demonstration and instruction the best type of flume is the closed-circuit recirculating kind. These take up the least laboratory space and are the easiest to operate. They also cost less than nonrecirculating flumes.

There is no consensus as to which kind is best for basic research. Recirculating flumes are more popular in the USA today, but in foreign laboratories nonrecirculating flumes seem to be more common, at least for sediment studies. Let's look at the advantages and disadvantages of these two major types.

The advantages of recirculating flumes are:

1. The required laboratory space, total cost and construction time are less. This is because you won't need such items as a sediment-infeed device, large sediment trap, big scale for weighing large amounts of sediment and constant-head tank. (The latter is optional with nonrecirculating flumes.) With the closed type of recirculating flume you also avoid a sump or large tailbox and the associated extra piping.

2. They are easier to operate in sediment-transport studies, mainly because the flume handles the sediment at all times. Particularly when using large quantities of sediment in the experiments, you will be happy to let the flume system do the job of transporting the sediment from the downstream end back up to the head of the channel and feeding it into the water stream.
3. Greater sediment transport rates can sometimes be attained, because the restrictions of maximum infeed capability of the feeding device and the capacity of the trap which collects all the sediment are absent.

Nonrecirculating flumes have certain advantages for sediment-transport research:

1. You can usually measure the sediment-transport rate much more precisely because the total amount of sediment in movement is always trapped continuously. (In recirculating flumes catchment of the total load usually is not practical because an amount equal to that being removed from the system should simultaneously be fed back in to maintain the established equilibrium; to get around this problem small but hopefully representative samples from a portion of the flow cross-section commonly are taken in recirculating flumes. This sampling introduces more error into the sediment-transport measurement.)
2. You usually have a direct control over the rate of sediment movement. This is because you govern the rate of infeed, and the typical experiment is one in which sediment infeed rate = transport rate = output rate. Thus the sediment transport rate can be studied as an independent variable.

3. The sediment-transport rate can be recorded continuously and compared to the infeed rate as an aid in determining whether equilibrium conditions exist in the test channel.
4. You can study larger particles. In recirculating flumes the maximum particle size you can investigate is restricted by the openings in the pump impeller, the size of the sediment sampler and the strength of the pump. (Usually the pump cannot push large particles up the vertical section of the return conduit at the head of the flume.) The only restriction in nonrecirculating systems is the size capacity of the infeed device.
5. Sediment entering the head of the flume can be more thoroughly mixed in regard to sizes, shapes and densities. Some preferential sorting may occur with recirculating flumes, either in the test channel or in the return piping (see fig. 2). Hence the particles entering the test channel may not be as well mixed as the original stock material.

These five advantages do not apply to very fine sands (say grain diameters of about 0.1 mm) because it's practically impossible to trap all of this fine sediment at the downstream end. (The particles stay suspended and flow out with the water.) For such fine material, however, a nonrecirculating flume can be operated as a free-overfall recirculating flume (Guy, Rathbun and Richardson, 1967).

While we are comparing flume types let's compare the good and bad features of the two kinds of recirculating flume. The free-overfall recirculating flume has the following advantages over the closed-circuit type:

1. Easier and probably more accurate sediment sampling (in the overfall).
2. Variable depth in the test channel, due to the possibility of storing water in the tailbox (sump). Changing the water depth is possible with closed recirculating flumes by adding or withdrawing water while the flume is operating, but this is more complicated.
3. Better control of the water depth in the downstream region of the test channel, by means of the tailgate. This helps bring about equilibrium sooner, which is a convenience in research projects.
4. Easier design of the flume, because you don't have to design the flume structure to hold or somehow articulate with the tailbox.

Free-overfall recirculating flumes have several disadvantages, all of which you avoid in a closed-circuit type.

1. The plunging of the water into the tailbox aerates the flow of water. This aeration can cause errors in reading instruments such as manometers.
2. The air entrained in the tailbox water may reach the pump and cause the pump to operate in surges or even to lose its prime completely. Baffles in the tailbox can prevent this, as explained in a later chapter.
3. The tailbox is larger and more complex than in closed recirculating flumes. A minor consideration is that when using sediment in the flume you need a little more sediment with free-overfall flumes because some storage occurs in the sump.

Summing up, in regard to recirculating flumes the free-overfall type is probably better for sediment-transport research, due to the easier and more accurate sediment sampling. For other purposes, such as demonstration or the study of turbulence and other fluid-flow phenomena, the closed type is better.

Summary

The type of flume you choose can depend on several factors -- space, cost, purpose of flume and help available for performing experiments. Recirculating flumes take up less space and cost less. They are also easier to operate; frequently one man can do everything alone, and this is not always true with nonrecirculating flumes. Consequently for purposes of demonstration or instruction a closed-circuit recirculating flume is best. Nonrecirculating flumes offer more accuracy and flexibility in sediment-transport research.

Among the two types of recirculating flumes, the closed-circuit type is best for research projects which require detailed flow measurements and for demonstration, whereas the free-overfall type is preferable for sediment-transport research because of the better sediment-sampling opportunities.

FLUME DIMENSIONS

The second step in designing a flume is to decide on its size. Mainly this means the length, width and depth of the test channel.

Depth

The depth of the test section includes the maximum water depth to be carried, the thickness of a sediment bed and some extra wall space along the top to prevent water from splashing out. We'll discuss wall details in another chapter; right now you need only decide on the maximum water depth you want the flume to carry.

Flumes to be used only to demonstrate hydraulic principles won't need water depths greater than about 0.5 ft. Those intended for basic research will yield more valuable results if a wide range of flow depths can be obtained. Most of the present laboratory flumes, partly for reasons of practicality, cannot accommodate depths greater than about one foot and often cannot hold more than 0.5 foot. You should plan on a maximum water depth of at least one foot. If you have a laboratory about 100 ft. long or more, plan on two or three feet.

Width

Flumes for demonstration and instruction purposes need not be wider than about one foot, and a width of 0.5 ft is quite adequate.

Many flumes used for basic research are less than two or three feet wide; most, however, are at least one foot wide. But if you

intend to do research, try to make the channel at least four or five feet wide. You can always insert narrower temporary channels within the permanent walls.

Having made this recommendation it is only fair to warn you that conducting experiments in a flume five feet wide can often be a job for at least two men.

Why should the walls be far apart? Firstly because wider channels for a given depth are much more common in nature. Secondly, if the walls are close together they retard a large portion of the flow cross-section, and this retardation can influence the experimental results in various ways. Available data (Chow, 1959, p. 169; Williams, 1970) suggest that to avoid sidewall effects the channel width should be at least 3 to 5 times the water depth. For smooth, rigid boundaries the required width/depth ratio may be even greater (Cruff, 1965). Finally, you may wish to conduct experiments where a stream meanders in alluvium. If so, you won't want to restrict the path of the meandering stream.

Length

Again the demonstration or instruction flume can be small. A length of 5-10 feet usually suffices.

No such easy rule of thumb can be given for basic research flumes. There is in fact quite a range of opinions on the desirable length of a research flume, but most people think 80 feet is a minimum acceptable length unless the flume is being built for just one specific study. Some phenomena, such as roll waves, may not appear in flumes shorter than about 80 feet. Although ripple and delta formation, to cite two examples, can be studied in flumes only 20 to 30 feet long, such short lengths will greatly restrict the range of research problems you can investigate. Actually, the maximum water depth, rather than a rule-of-thumb, should determine the length, as explained in the following paragraphs.

Let's discuss the determination of the channel length in terms of three zones - the entrance region, the "working section" and the exit region.

Entrance region

The water must travel some distance down the channel before the velocity, turbulence and sediment distribution adjust to the channel shape, size and roughness, i.e., before the boundary layer is fully developed. (The boundary layer is the zone near the bed where the flow velocity increases with height. The boundary-layer thickness is the vertical distance from the bed to where the velocity no longer increases with height.) The boundary-layer thickness is relatively small at the very entrance of the channel and increases with distance downstream. Eventually - when it reaches the free surface - it stops increasing and becomes constant.

For a given channel the required downstream distance for full development of the boundary layer can be determined by velocity measurements (see, for example, Einstein and Chien, 1955, pp. 13-15). But in our case the only available tool is a formula which gives an approximate answer. The formula applies only to hydraulically-smooth boundaries, but this puts you on the safe side because for rougher boundaries the required distance is less. The standard equation (Albertson, Barton and Simons, 1960, p. 242) is

$$\frac{\delta}{x} = \frac{0.38}{\left(\frac{V_o x}{\nu}\right)^{0.20}} \qquad (1)$$

where δ is thickness of turbulent boundary layer (equal to mean depth D for this purpose), x is distance from start of channel needed for full development of the boundary layer, V_o is the free stream velocity outside the boundary layer and ν is kinematic viscosity. V_o in this context is the velocity at the water surface and for practical purposes is about 1.2 times the mean flow velocity.

Figure 4 shows the required distance x for various flow depths and mean velocities (V), using the above equation. To use figure 4 you'll need your maximum flow depth and an estimate of the fastest mean velocity you'll ever use. Most flumes can't get mean velocities greater than about seven feet per second (if that) at the deeper depths, but this is usually due to inadequate pumping capacity. To assure a wide range of flow conditions plan on a maximum mean velocity of 10 feet per second at the maximum flow depth. (Several reviewers of this text believe velocities as fast as 7 ft/sec are rarely needed in flume studies. You'll have to estimate the maximum flow conditions you will ever want to study.)

According to the above equation the boundary layer over a smooth surface needs about 105 feet to become fully-developed for a water depth of one foot and a mean velocity of 10 feet per second. For a depth of 0.2 foot and a mean velocity of 10 feet per second the boundary layer theoretically becomes fully-developed in about 14 feet.

Now, if you are absolutely certain that you will <u>never</u> study sediment transport, then the first step in deciding on the flume length is to estimate the distance needed for boundary-layer development. For this purpose use figure 4 with your maximum water depth and mean velocity.

If there is any chance at all that you'll study sediment transport some day, you'll need to consider another factor when estimating the length of this entrance region: the sediment entering the test

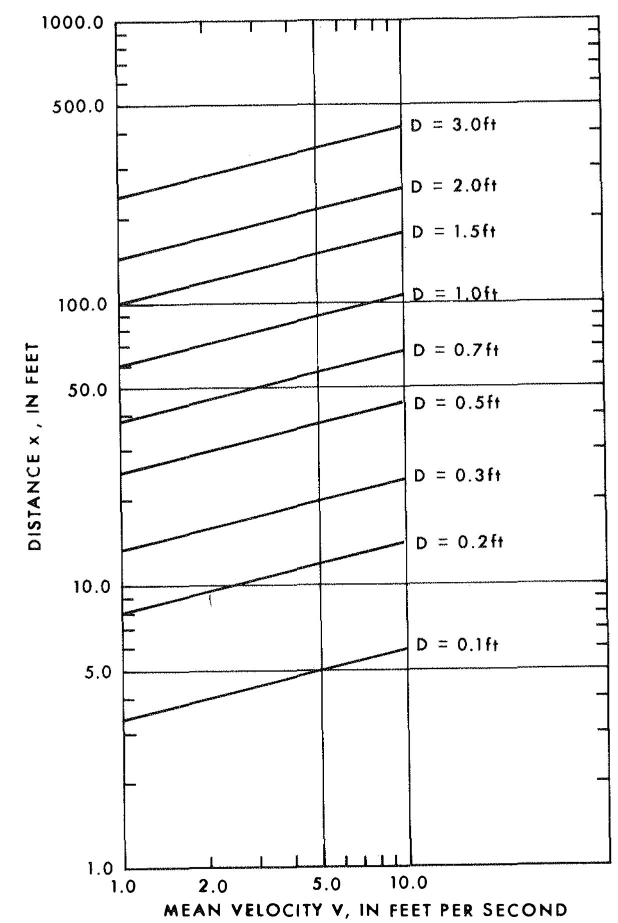


Figure 4.--Distance (x) needed for full development of a turbulent boundary layer over a smooth, flat surface, for various flow depths.

channel is not distributed according to the channel flow pattern. For example, with recirculating flumes the suspended-sediment distribution at the channel inlet is mainly a function of the pump, piping and headbox characteristics. With nonrecirculating flumes the sediment distribution at the channel entrance depends on the headbox and sediment-infeed peculiarities. Only after travelling some distance downstream does the sediment become distributed vertically and laterally according to the channel flow characteristics, so that meaningful measurements become possible.

As a crude rule-of-thumb the distance needed for the sediment in the flume to rid itself of the headbox influence and other undesirable entrance effects would be the distance that your smallest grains would need to fall from the water surface to the bed (Willis, 1969). This distance is easy to estimate. Figure 5 gives an approximate fall velocity for a given grain size. The mean stream velocity tells the approximate downstream distance that a particle travels each second. These two velocities therefore give a crude idea of how far a grain falls vertically for a given horizontal distance. For example, suppose V = 5 ft/sec, D = 1 foot and the smallest grain size is 0.1 mm. The fall velocity is about 0.03 ft/sec. So the grain moves about five feet downstream for every 0.03 foot of descent. For a one-foot depth the grain would fall from the water surface to the bed in about 170 feet of travel. With grains 0.1 mm in diameter there would be a lot of sediment in suspension, and you could expect that the suspended-sediment profile would need about 170 feet to develop, for those flow conditions.

Figure 6, based on the method just described, gives the approximate

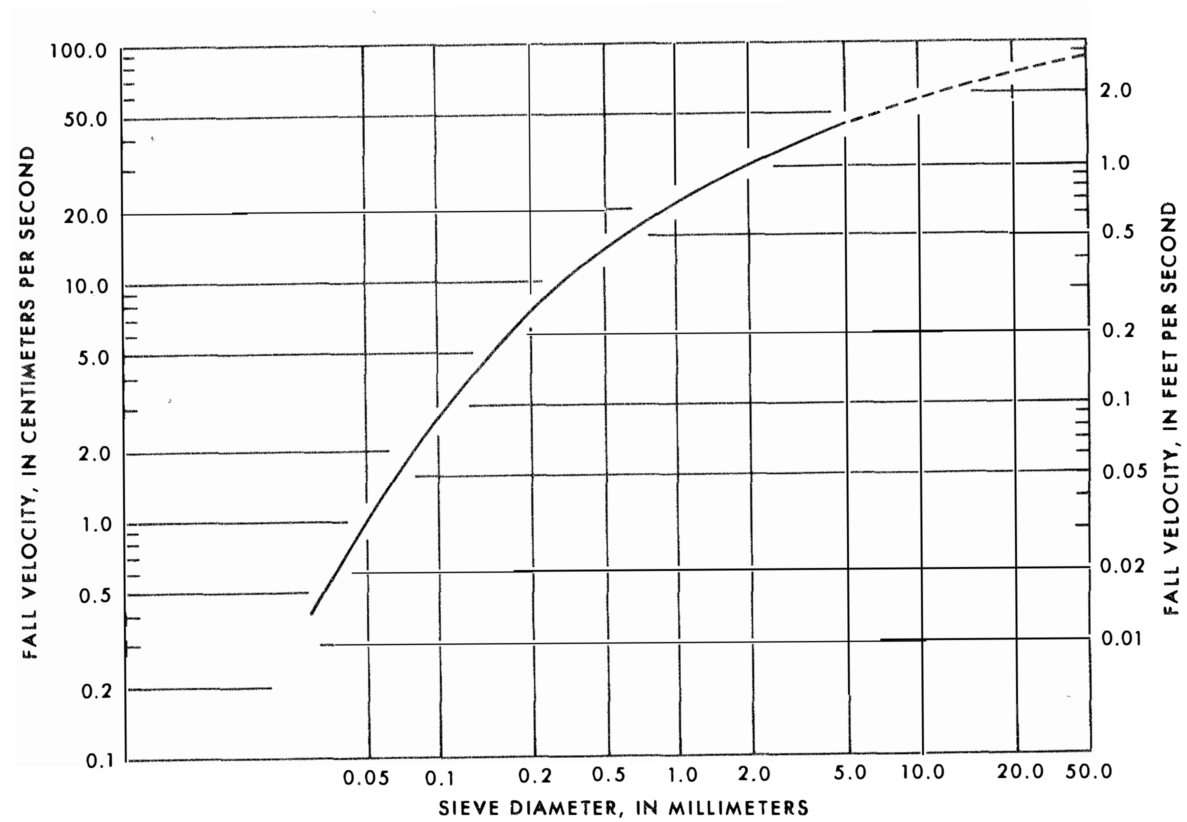


Figure 5.–Approximate settling velocities for natural sediment grains in water (from Subcom. on Sedimentation, Inter-Agency Water Resources Council, 1957, p. 36).

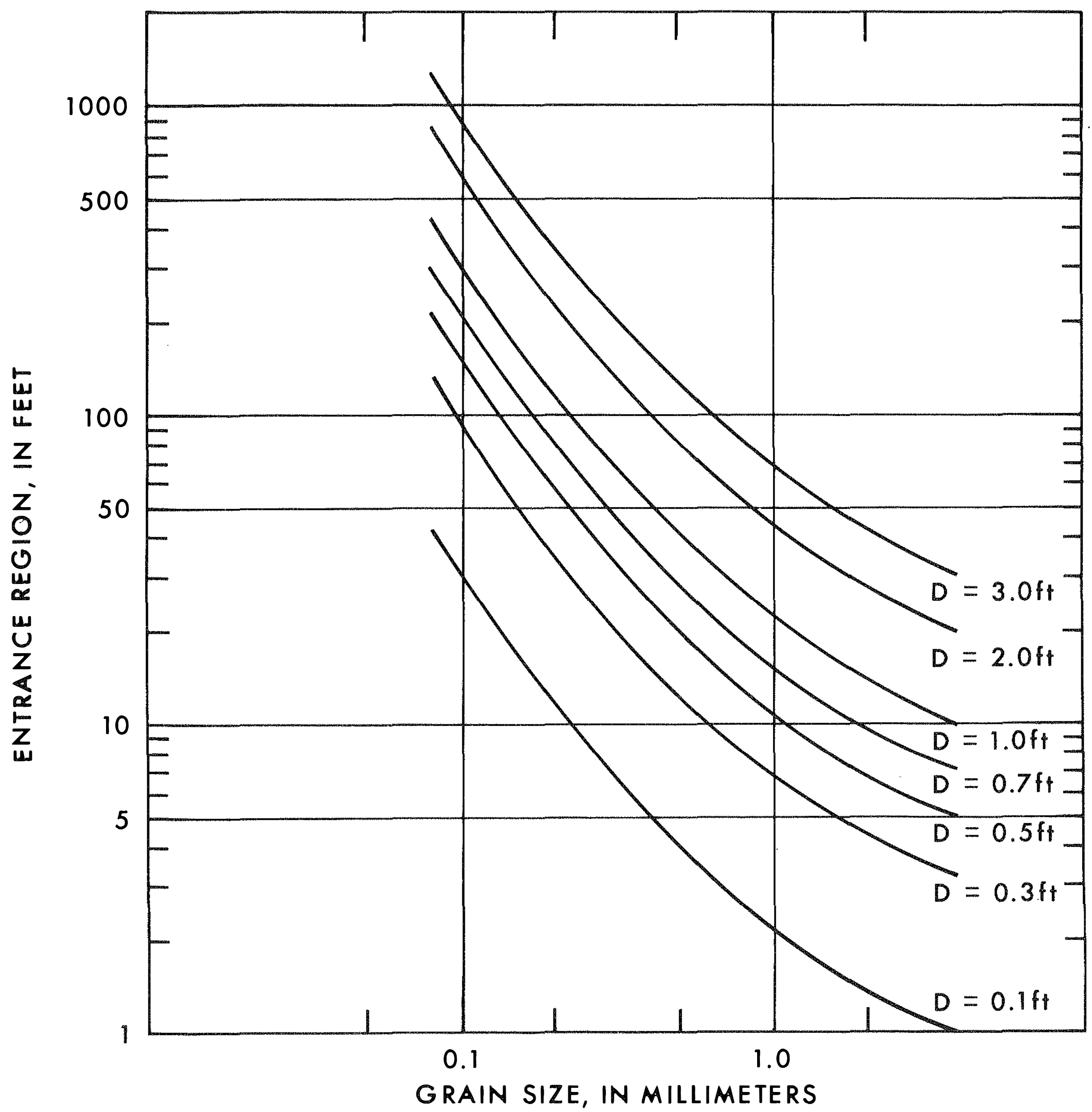


Figure 6.–Approximate length of flume entrance region for suspended-sediment studies, or distance needed for grains to fall a vertical distance D in a mean flow velocity of ten feet per second.

length of the entrance region for various flow depths and grain diameters, taking V = 10 ft/sec. Using such a fast mean velocity should put you on the safe side because you'll only rarely have such a velocity. But an important rule throughout this manual is to <u>over-design</u> (plan on more than your initial estimate) if possible.

So to estimate the length of your entrance region use either figure 4 or figure 6, whichever gives the <u>longer</u> distance. Use a grain diameter of 0.1 mm in this estimate.

Lest figure 6 be too discouraging note that many suspended-sediment studies can be made at mean velocities of five or even three feet per second. This means your entrance region would be only one half or one third as long, respectively, as indicated by figure 6, for the same depth. But you can see that shortening the entrance region severely limits the range of conditions you can study. In general, the length of the entrance region for sediment studies is about equal to the water discharge per unit channel width divided by the fall velocity of the sediment (Willis, 1969).

One trick to reduce the length of the entrance region is to roughen the bed at the head of the channel. Wire screen, sandpaper or emery cloth glued to the flume floor are useful for this purpose. Baffles, described in another chapter, also help. Brooks (1954) found that using screens as baffles at the head of the test section as compared to no screens or baffles at all, significantly reduced the distance needed for the water depth and sand-bed thickness to become constant. For one pair of runs in a 40-foot closed recirculating flume the introduction of screens saved about 12 feet, in effect increasing the test section by 12 feet.

Working section

In some studies you may need measurements at only one single station in fully-developed flow, but for many projects (e.g. sediment-transport studies) you'll want a reach of channel. So looking to possible future research, plan on a working section of flume after the entrance region. Nobody knows how long the working section ought to be but it definitely increases with water depth. This is because with greater depths the water surface irregularities are much higher so that you need a longer reach to get an accurate slope measurement. As a minimum rule of thumb make this section about 40 feet long for a depth of 0.3 foot and add about 10 feet for every additional 0.2 foot of water depth. Thus, for a depth of one foot the working section would be about 75 feet long. If you have the space available, increase this estimate of the working section by about 20 percent. Remember that all of this is in addition to the entrance region.

Thus, the second step in determining the flume length is to add a liberal distance for the working section on to the distance estimated for the entrance zone.

Exit region

Finally, at the downstream end of the flume several feet will not be usable due to exit conditions. This exit region varies with the flow depth, the mean velocity and for certain flow conditions with the tailgate setting. The exit distance is longest at values of $V/\sqrt{gD} \ll 1$ (where g = acceleration due to gravity), i.e. subcritical flows

characterized by slow velocities and deep depths. Good tailgate control can shorten the distance considerably. Generally the exit region will vary from about four feet (flumes ≤ one foot wide and water depths ≤ 0.5 foot) to about 20 feet for very long, wide flumes.

The above considerations show that longer flumes will yield much more reliable data than short ones. Good research can be done in short flumes, but the trend, over the many years that people have been building research flumes, has been toward greater length. Whereas early flumes commonly were 20-50 feet long, modern laboratory flumes are often 50-200 feet long or more. The hydraulics laboratory of Kyoto University has an outdoor tilting flume 491 feet (150 meters) long. <u>Many</u> investigators have lamented that their flumes are too short, but no one engaged in research has yet complained that his flume is too long!

Obviously there are practical limitations on flume length. Often the size of the building or room which houses the flume restricts the length. Secondly, the possible range of attainable slopes decreases as the flume becomes longer. Another major factor is cost: the cost of the flume system increases radically with the flume size. ("Size" in this sense includes all of the integral parts of the flume system — test-section dimensions, pumping capacity, etc., as in figs. 2 and 3.) And a possible consideration, too, is that flumes longer than about 100 feet and/or wider than about five feet are not easy for one man to operate. This is particularly true of nonrecirculating flumes. Rouse (1961) states that costs and difficulties of operation increase about as the cube of the size.

Thus, a research flume probably should be from 100 to 300 feet long or more, depending mainly on the water depth. But you may have to compromise between desired flume size, available space, funds, and possibly ease of operation. If you are restricted by space, be sure to make the flume as long as possible anyway.

Summary

Decide on the length, width and maximum water depth of a research flume by following these steps:

1. Choose a maximum water depth first. Aim for at least one foot, preferably more.
2. Make the width at least four or five times the maximum water depth.
3. Determine the length by adding the entrance, working and exit regions, as follows:
   a. Find the entrance region from figure 4 or figure 6, using whichever estimate is longer.
   b. Make the working section at least 40 feet long for a maximum water depth of 0.3 foot, and add about 10 feet for every additional 0.2 foot of water depth. Increase this estimate by 20 percent if at all possible.
   c. Allow about 4-20 feet for exit conditions, depending mainly on the maximum water depth.

Costs and laboratory space are the two most common restrictions on the size of research flumes. Regardless of the width and water depth try to make the flume at least 100 feet long, and preferably much longer. As flumes become smaller they depart further and further from field situations.

MAXIMUM DISCHARGE

The details of most of the remaining parts of the flume system depend on the maximum water discharge which the flume test section can carry. So step number three in flume design is to determine this maximum discharge (Q_{max}).

You can compute a value for Q_{max} with the continuity equation

$$Q = VDW \qquad (2)$$

where Q = discharge and W = channel width. Use V = 10 feet per second, your channel width W and maximum water depth D as selected in the previous chapter.

Many laboratories have been restricted in their experiments because they could not get high enough discharges at large widths and depths. It is a good idea to choose as Q_{max} a discharge slightly greater than that just computed. (On the other hand, if you are certain that your interests will be restricted to low flow rates use a slower mean velocity, such as 5 or 7 ft/sec, in the computation.)

Now we can move on to the design of the flume itself.

CHANNEL FEATURES

Having decided the important general questions of flume type, size, and maximum discharge, you can think about some specific details. Let's begin with the test-channel.

Flume test-channels usually are rectangular in cross-section, though they can be made in many cross-sectional shapes. The channel proper (see figs. 2 and 3) consists of the floor, along with its supporting structure, and the sidewalls. For research flumes a rail is fixed on or near the top of each sidewall so that instrument-bearing carriages can ride along the channel. Finally, a sluice gate at the head of the flume and, with the exception of closed-circuit recirculating flumes, some sort of downstream tailgate will be needed to help you get a uniform water depth along the channel. These gates are discussed in the chapter entitled "Aids in Obtaining Uniform Flow."

Walls

Materials

Flume sidewalls are made of glass, plastic, steel plate, wood, aluminum plate, steel or aluminum channels, and concrete, or a combination of these materials.

Demonstration and instruction flumes of course should have transparent walls (glass or clear plastic) so that people can see the flow phenomena from the side as well as from the top.

It is equally important that research flumes have at least some, and preferably all, sidewall sections transparent. For positioning and observing the behavior of instruments, for measuring sediment bed-form features and for many other reasons it is a tremendous advantage to be able to see into the stream from a side view. People whose flumes do not have transparent wall sections say they wish they had them. Here, then, is where you can benefit from the experience of others. Make the sidewalls of glass or clear plastic unless this becomes prohibitively expensive.

Glass makes a good, rigid sidewall and has been used successfully on a number of flumes. It has the important advantages of forming a very plane and very smooth surface and of not scratching too easily. However, it does have several disadvantages: (1) it breaks more easily than other materials and can in fact shatter enough to present a real hazard to anyone in the vicinity; (2) it is not machinable; and (3) it requires a heavier supporting framework (greater expense) due to its weight. Rouse (1961) states that glass tends to become weaker with age in an unpredictable way. Robert P. Apmann of the State University of New York (SUNY) at Buffalo reports that Dow-Corning Silastic Rubber caulk, together with plastic swimming pool tape, is very effective in patching cracks in glass.

Plastic is rapidly becoming the most popular material for transparent sidewalls. Plastic is easily cut, drilled and threaded. It doesn't crack or break as readily as glass, either. A major drawback with plastic is that it deforms more readily than glass under pressure or heat, so you'll need thicker walls or smaller panels than with glass. Another disadvantage of plastic is that it scratches more easily than other materials, but this usually is not enough to inhibit observation. Wiping plastic with chloroform may restore the transparency. With age plastics tend to craze or develop a myriad of thin cracks which cannot be polished out.

Avoid placing plastic sections in direct sunshine or next to any heat source. One plastic sidewall was nearly ruined on one occasion when a flood light for picture-taking was placed within a few inches of the wall. The damage was worsened by the fact that the flume held cold water at the time. As a matter of fact the same general rule applies to glass and aluminum; in one instance a glass flume showed some warping due to the sun shining on the side of the building, even though the flume was about eight feet from the wall of the building. To be safe do not place <u>any</u> flume in direct sunshine or close to a source of heat. The only possible materials which might deform only slightly in sunshine are steel and concrete.

Steel plate comes in stainless, stainless clad and regular varieties. The former is about 20 times as expensive as regular steel but saves you the considerable trouble of periodic scraping and repainting. However, finishes such as epoxy can be applied to regular steel plate and will make the surface almost as durable as stainless steel.

Aluminum sidewalls are light in weight and are machinable. However, there are three disadvantages to aluminum sidewalls: they are opaque, they are temperature-sensitive and they corrode. (The hydroxyl ions in the water react with the aluminum to form aluminum hydroxide. This whitish material is then eroded, leaving a pitted and corroded surface.) Coat aluminum sidewalls every one or two years with epoxy or a polyester resin, to prevent the corrosion.

For shallow depths (half a foot or less) the walls of some flumes consist of a steel or aluminum channel with the large flat face on the channel interior. The only major advantage of this type of sidewall is that it's easier to mount. It has the severe disadvantages of being opaque and restricting you to the study of shallow flow depths.

Concrete has occasionally been used, especially in earlier European flumes (see Freeman, 1929); however, concrete cannot be easily drilled or otherwise machined, is not transparent, may develop cracks, is more awkward to mount and has a surface which is rougher than is generally desirable.

Dimensions

Make the channel sidewalls about 0.5 foot higher than the maximum expected water elevation. The latter height will equal the maximum flow depth plus the thickness of the sand bed. For basic research the thickness of the sand bed should be about 0.7 of the maximum flow depth (an empirical rule of thumb for very rough or irregular water and bed surfaces). The wall height for sediment studies should therefore be about 1.7 D + 0.5 foot. The extra 0.5 foot along the top will help prevent a rough water surface from splashing over the sides of the flume. High walls are especially important if you want to convert the flume to a wave tank someday.

The thickness of the sidewalls depends not only on the strength of the material but also on the distance between wall supports and on the amount of deflection you are willing to put up with. The thicker the material, the smaller the deflection. For their plate-glass sidewalls the Iowa Institute of Hydraulic Research uses thicknesses of $\frac{1}{4}$ inch for a one-foot water depth, $\frac{1}{2}$ inch for a two-foot depth and 3/4 inch for a three-foot depth (Rouse, 1961). Plastic sidewalls 3/8 inch thick have been used satisfactorily at Colorado State University for walls $2\frac{1}{2}$ feet high, with vertical supports every four feet. However, a safer rule of thumb is to use thicknesses of 3/4 inch for wall heights less than two feet and one inch for higher walls, with vertical supports every four feet. These thicknesses help reduce warping and make it easier to tap and thread holes in the wall.

For a given wall thickness plate glass costs about three times as much, per square foot, as plastic (Plexiglas). 3/4 inch plastic costs about the same, per square foot, as $\frac{1}{2}$ inch-thick plate glass.

Rolled steel and aluminum side panels usually are $\frac{1}{4}$ inch thick. For depths greater than about two feet a 3/8-inch thickness is enough.

Mounting

(a) Joints. Daly (1965) and Rouse (1961) explain methods of mounting plate glass in flume walls. Figure 7 shows Daly's recommendations,

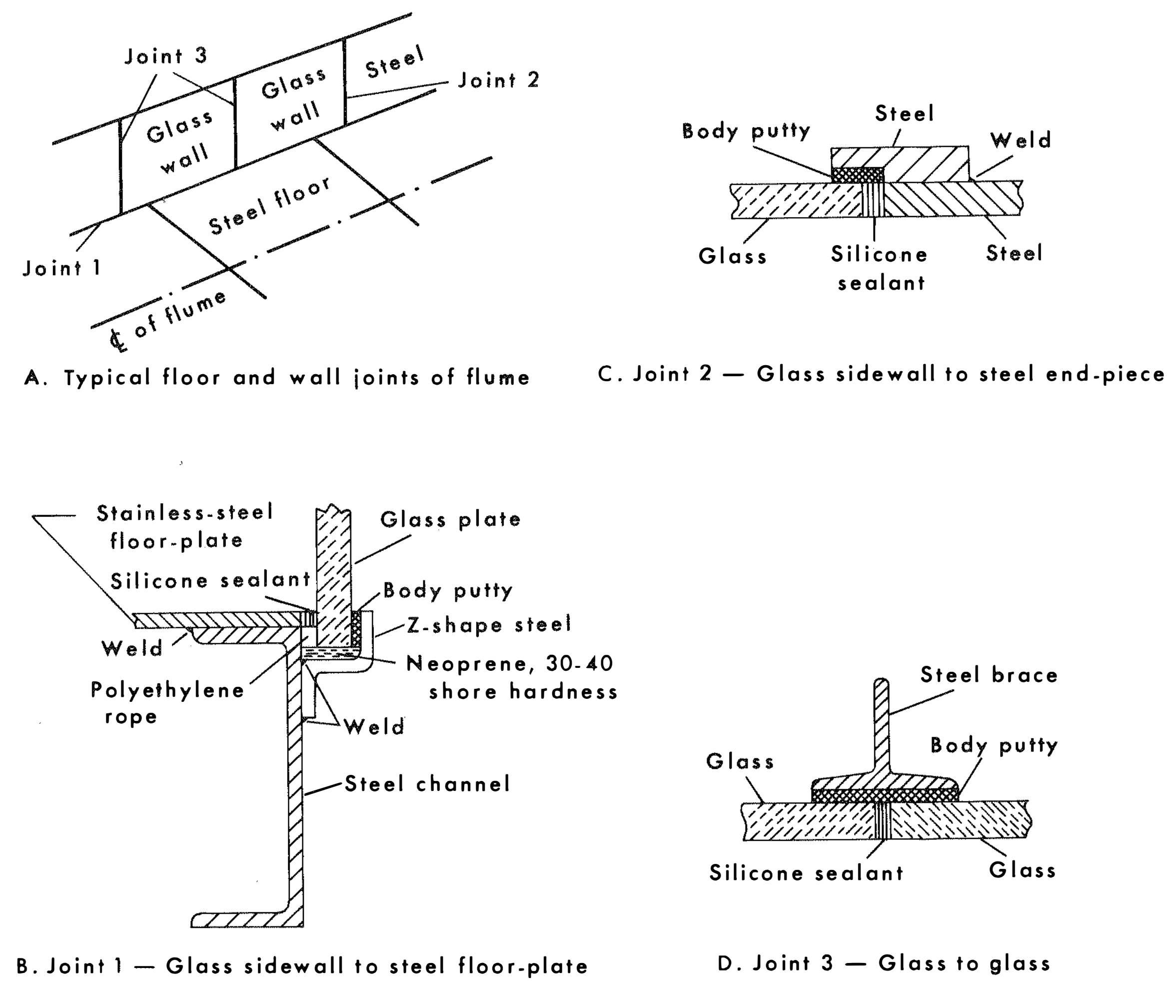


Figure 7.-- Mounting glass in flume sidewall (after Daly, 1965).

and his important paper (Civil Engineering, June, 1965) is so pertinent and useful that it is reprinted here in its entirety:

"Mounting plate glass in sides of flumes and tanks[1]

by Elton F. Daly

Laboratory and Shop Supervisor, W. M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Pasadena, Calif.

"A common problem in hydraulic laboratories is that of mounting glass plates in the walls of flumes and tanks and sealing them to prevent leaks. A simple but effective method has been developed over a period of years in the hydraulic laboratories of the California Institute of Technology (C.I.T.). The most recent facility in which glass windows were used is the 130-ft-long tilting flume completed in 1964 in the W. M. Keck Laboratory of Hydraulics and Water Resources at C.I.T. with the aid of a grant from the National Science Foundation. In this flume 44 panels of glass 26 in. high by 60 in. long were mounted in the sides and sealed with only two minor leaks.

"The vertical section through a lower edge of the flume in fig. 7B shows the method of mounting and sealing the glass. The Z-shaped support permits the glass to extend below the bottom plate of the flume so that the seal does not block the line of sight at the bottom of the flume. The rigid structure shown is important to the success of this method of mounting the glass. It minimizes deflections and movement between

[1]Figures refer to figure in present text.

the glass and the structure, thus reducing stresses in the glass and movement in the seals.

"First phase—mounting

The glass is first set in place on a piece of neoprene strip lying in the bottom of the Z-shape formed from 3/16-in. steel plate, which has been welded to the standard rolled structural channel. The neoprene strip serves to support the glass by a fairly uniform pressure and avoids overstressing it. The glass panel is then positioned in the channel by using small wooden wedges inserted on each side at the bottom and by wedging on the outside and clamping at the top. By the use of wedges the glass panel can be positioned to any degree of accuracy required.

"In this flume, the panels were set with the aid of a piano wire stretched from one end of the structure to the other. When the glass was finally positioned, spaces were left between the glass and the steel structure. Experience indicates that these spaces should be no less than 3/16 in., or even $\frac{1}{4}$ in., in width. In the present case the spaces were only 1/8 in. wide and were found to be too narrow. Because such a small width was allowed, it was necessary to align the steel structure of the flume much more precisely than would otherwise have been necessary, thus adding to the cost without improving the end result.

"The space on the outside—or dry side—of the glass is filled with body putty, a material commonly used in the repair of automobile bodies and which is available from many different manufacturers. It can best be described as a two-part system composed of a putty-like material that remains soft and pliable until the second part, or catalyst, is added. This causes the putty to polymerize and become hard with very good adhesion. The amount of time to work the material, or the "pot life" after the two parts have been mixed, varies from 20 min. to over one hour, depending on temperature and the amount of catalyst used. This is a convenient material because it can be applied easily with an ordinary putty knife.

"Since this material has very good adhesion, the glass should be waxed where it comes in contact with the putty to reduce adhesion and facilitate removal of the glass panel when necessary. Any good paste wax of the kind normally used to polish automobiles will do. Care should be taken not to get wax on any surface except that which is to be in contact with the putty.

"The glass is thus fully supported laterally by the body putty on the outside and by wood wedges and clamps on the inside. This completes the first phase of the mounting procedure.

"Second phase—sealing

"The second phase, or sealing operation, is done in the space on the inside—or wet side—of the glass panel. The depth of the inner and outer spaces can vary but in this case a depth of $1\frac{1}{4}$ in. was used. This was a good depth for supporting the outside but deeper than needed to make a good seal. To reduce the amount of sealant needed, the lower part of the space was filled with a polyethylene rope material to within 3/8 in. of the finished flume floor or bottom, as shown in Fig. 7B. This rope was 3/8 in. square and was squeezed into the inner space with a

thick-bladed putty knife so as to provide a base for the sealant.

"The sealant used is a silicone-rubber material available at most industrial paint supply houses and is used commonly to seal steel sash. It comes in polyethylene throw-away containers to fit ordinary hand-calking guns or it can be applied by power (air) operated guns. When it comes out of the tube it is similar to toothpaste in appearance. It air cures in several hours and is completely cured in 24 hours.

"On some surfaces this sealant requires a primer to insure good adhesion. The primer is easily applied with a brush as it has the clearness of water and the same consistency. In the present flume it was necessary for the surface of the seal to be smooth and flush with the steel bottom. To achieve this a strip of masking tape was put on both sides of the area to be sealed and a putty knife was drawn along the joint to remove all excess sealant, thus leaving a smooth flat surface. The masking tape was removed while the sealant was still soft. Care should be used in pulling it away from the joint so as not to roughen the surface. Since the silicone sealant shrinks slightly when it sets, a slight excess of material must be added if an absolutely flat surface is required.

"Other joints used on the flume are shown in Fig. 7A. A vertical joint, glass to steel, is made as shown in Fig. 7C. A joint of glass to glass is made by having a section of steel T- or I-shape supporting both ends of the glass panels, Fig. 7D. In both of these joints the body putty is used to fill the outer space and the sealing is again done from the inside with the silicone sealant. The ends of the panels are spaced approximately $\frac{1}{4}$ in. apart, leaving a space for the seal that will be $\frac{1}{4}$ in. wide and equal in depth to the thickness of the glass panels. A steel-to-steel butt joint is also easily made as shown in Fig. 15. This joint was made with the sealant in preference to butt welding in order to avoid the distortion of the bottom resulting from welding.

"Principles summarized

"The principles of making successful seals on glass windows may be summarized as follows:

"Glass should not be in contact with steel, and the mounting compounds should be flexible enough to allow a slight deflection of the steel structure without overstressing the glass.

"Two different kinds of material are required: one for structural support (on the outside), and one for sealing (on the inside)."

In general glass should not be in direct contact with any rigid members (other glass or steel) or it may crack, for example when it expands slightly due to heat. Leave at least a 3/16-inch gap for this purpose. Also, the sealants (discussed below) should be flexible enough for the flume test section to bend slightly without overstressing the glass.

It is very important to mount plastic sidewalls in such a way that the walls can expand and contract. This expansion and contraction is negligible over short distances such as a foot or so, but it becomes more and more important over greater distances, i.e. in a downstream

direction as the flume gets longer. Figure on about $\frac{1}{2}$ to one inch variation over a distance of 30 feet. (For standard 8-foot lengths this calls for an expansion gap of 1/8-1/4 inch at each longitudinal joint.) A more precise estimate can be obtained by using the expected temperature change and the coefficients of linear thermal expansion provided by plastic manufacturers. Any holes drilled through plastic for bolts or screws should be extra large, due to the expansion and contraction.

To allow for the expansion and contraction do not anchor the plastic sidewalls to any support with screws. Instead use bolts with oversized holes filled with putty. In fact do not have a plastic test channel rigidly attached to any metal. Instead merely rest the whole flume test section on top of supports such that the test section can move upstream or downstream. Where the test section joins the tailbox on closed recirculating flumes insert a seal of rubber-tubing (about $\frac{1}{2}$-inch diameter tubing when uncompressed). Also on these flumes if the plastic tailbox and plastic headbox sit in some sort of angle-iron framework you should use spring-loaded attachments between these boxes and their metal frameworks (Colorado State University). In this manner the metal frameworks stay fixed in place but the plastic flume can expand or contract as the temperature changes.

Where plastic test sections join metal tailboxes and headboxes be sure to make similar allowances for expansion and contraction. For example, the Perspex (Plexiglas) test channel on the University of Western Australia flume is clamped at the ends of the channel, and these connections are unclamped when the flume is not in operation.

Use a solvent such as ethylene dichloride to attach a plastic sidewall to a plastic floorpiece (fig. 8A). (This same solvent, with perhaps some ground-up plastic particles mixed in if you need more viscosity, is good for repairing cracks in plastic.) Manufacturers are continually producing better cements, solvents and sealants, and it is very worthwhile consulting two or three manufacturers before starting on the flume, to see what new products are available.

For the vertical joint between two adjacent plastic sidewalls (Fig. 9) (and for the horizontal joint between two floor sections) the first step is to fix a bar or angle-iron to the end of each section. These bars can be glued or bolted to the wall or floor section. One bar should overlap the crack between the two floor pieces or wall pieces to provide support for a pliable sealant. Fig. 8B shows one of various possible ways to do this. To connect the two sections simply bolt these bars of flanges together (pre-drill the holes). A pliable caulking compound will suffice as a sealer if you have made a generous allowance for expansion and contraction at the upstream and downstream ends of the flume. Another good sealer for this purpose is ordinary rubber surgical tubing, say $\frac{1}{4}$- or 1/8-inch diameter.

Silvester (1966) describes in detail a flume with plastic sidewalls in which the sidewalls are hinged along the base to permit trapezoidal in addition to rectangular cross-sections. The sidewalls are kept watertight along the base by a strip of flexible plastic. Figure 10, taken from Silvester's paper, shows the main features.

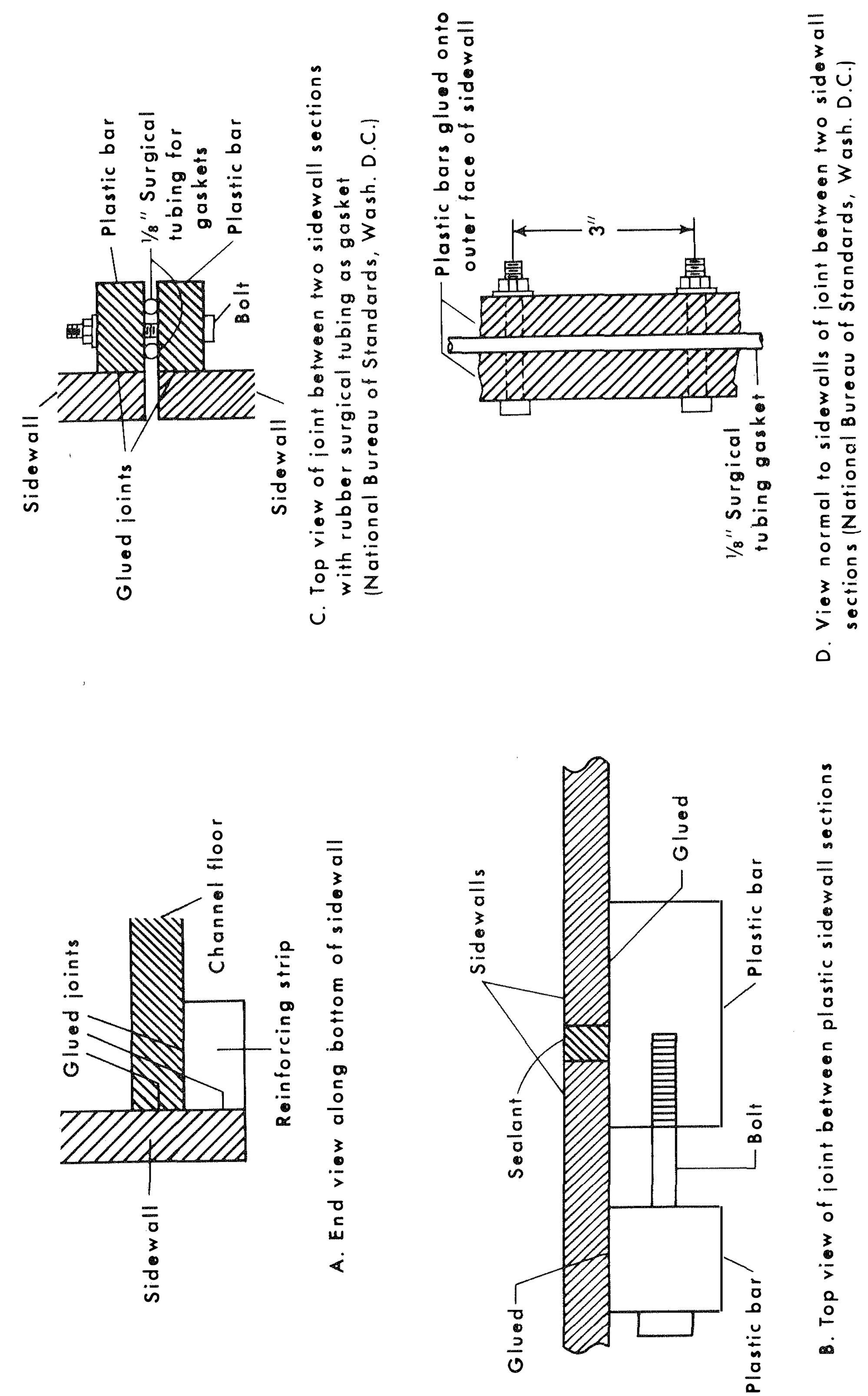
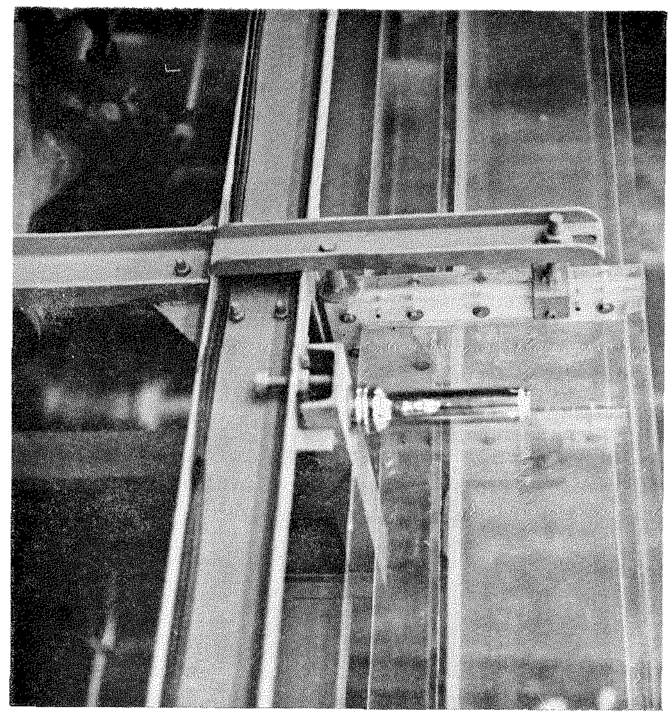
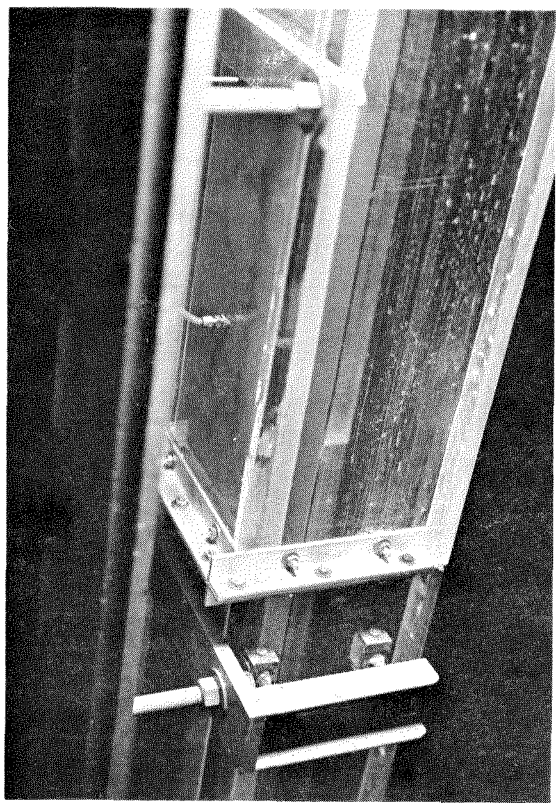


Figure 8.--Details of plastic sidewalls.



A. USGS 30-foot plastic flume at Washington, D.C.



B. USGS 30-foot plastic flume at Colorado State Univ., showing sidewall and part of floor.

Figure 9.--Joint between plastic sidewalls.

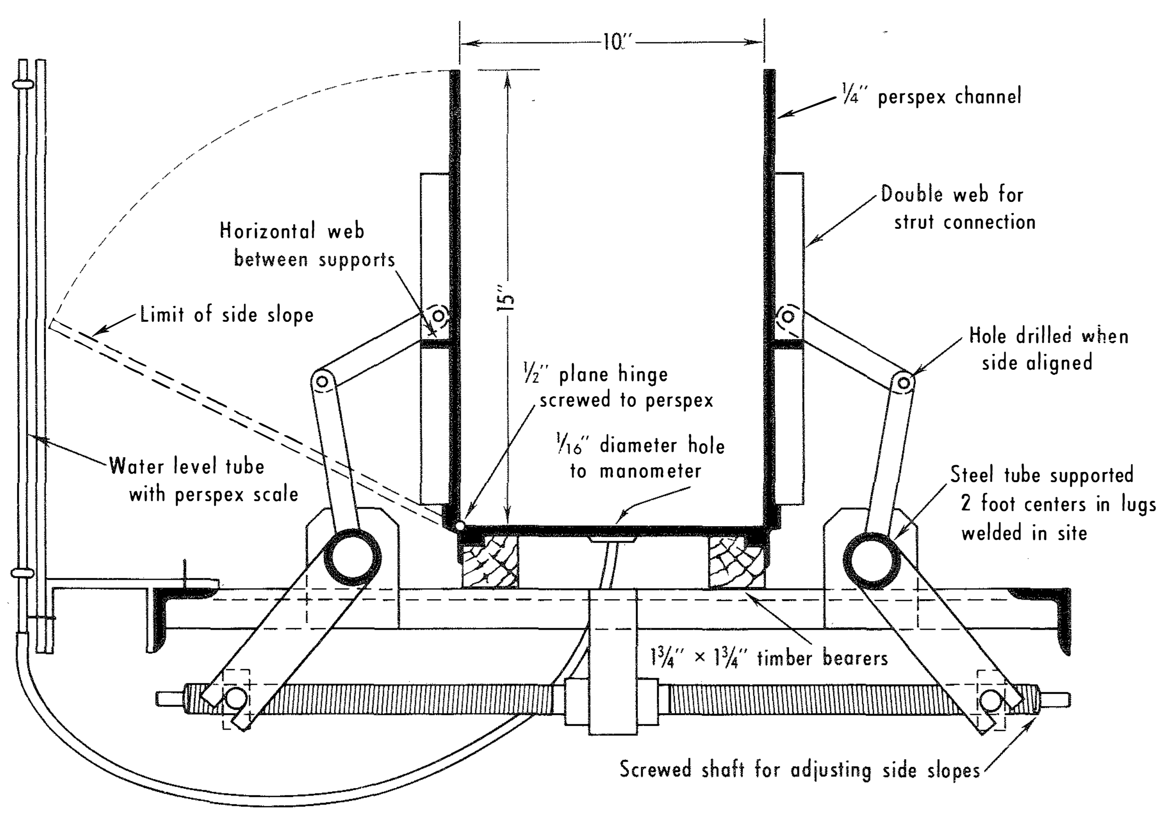


Figure 10.--Details of sidewall slope-adjustment in 32-foot plastic flume at the University of Western Australia (from Silvester, 1966).

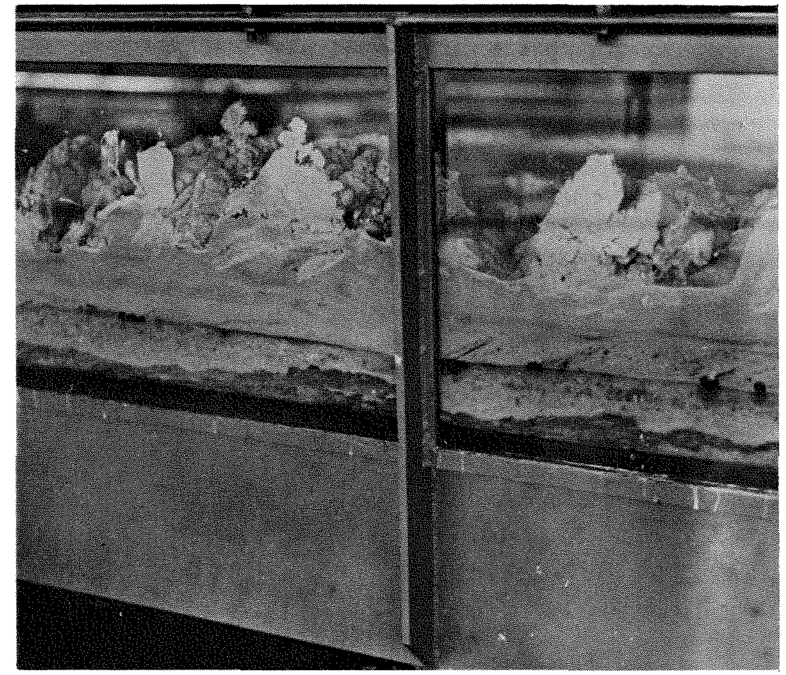
Mount aluminum sidewalls much the same as glass, because these aluminum plates will expand and contract. Hence, two adjacent aluminum pieces should not be in direct contact with one another. This applies to wall-to-wall joints, wall-to-floor joints, and floor-to-floor joints. Use sealers of the sort mentioned below or surgical tubing.

Steel panels can be mounted by spot-welding or bolting an angle-iron flange to the end of each panel and then bolting adjacent panel sections together. A steel sidewall can be fixed to a steel floorpiece using the same principle, except that only the sidewall needs an angle-iron flange in this case. For wall-to-floor joints space the bolts about every six inches to reduce the number of leaks.

As a general rule the inner face of the sidewalls should be as smooth as possible to avoid disturbing by projections or depressions. Also, for some research projects you may need hydrodynamically-smooth sidewalls. The inner face of opaque flume sidewalls is often painted to obtain a smoother finish.

(b) Alignment and bracing. Figure 11 shows typical methods of bracing flume sidewalls. The braces are usually spaced at about four-foot intervals. They should not be joined to one another across the open channel because this would inhibit the downstream movement of instruments.

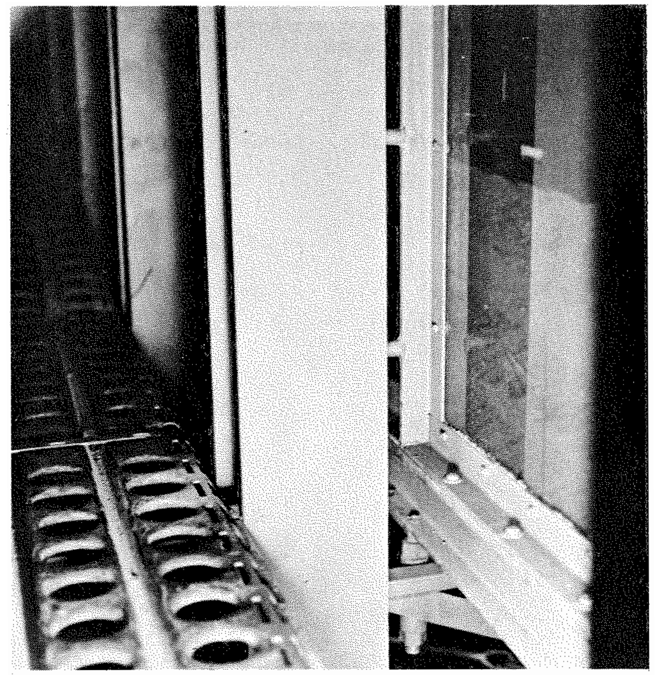
The pressure of the water may cause the walls to deflect outward to a significant extent, especially at the joints. Consequently the braces on many flume sidewalls are adjustable so they can be aligned very closely.



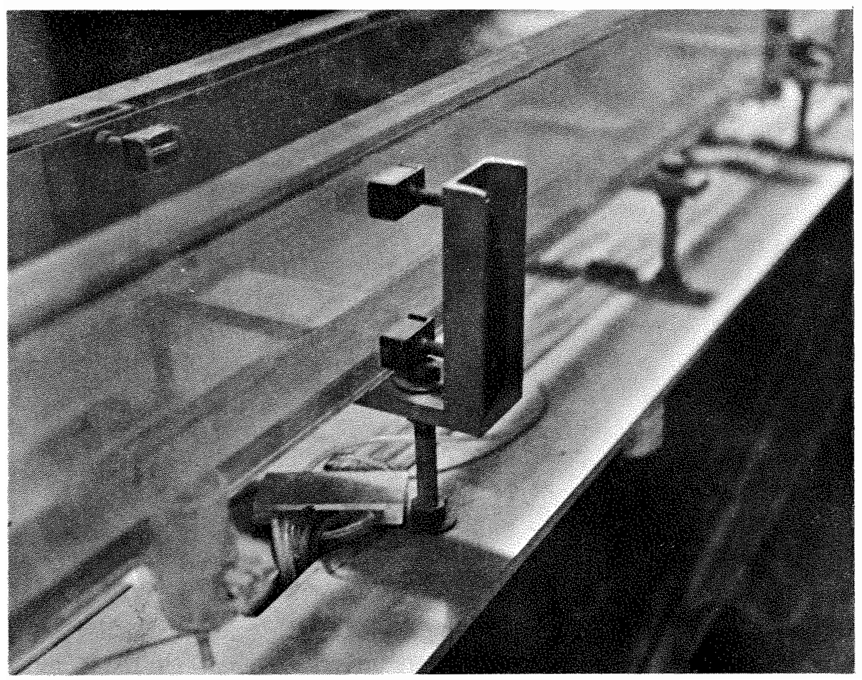
A. Iowa 90-foot sediment flume.

B. Georgia Tech 80-foot flume.

Figure 11.–Arrangements for supporting and aligning flume sidewalls. Except for part A all methods use a threaded bolt.

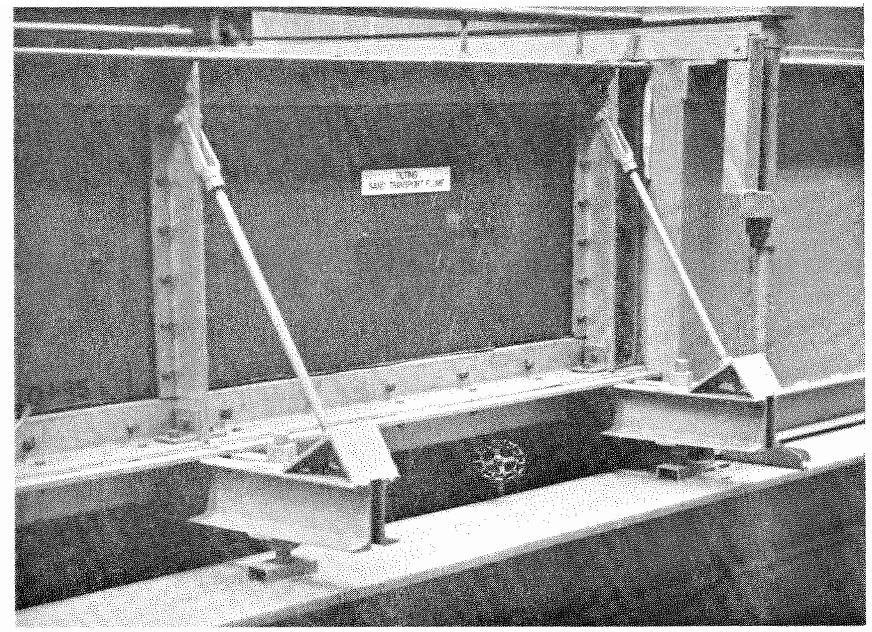


C. Colorado State Univ. 200-foot flume.

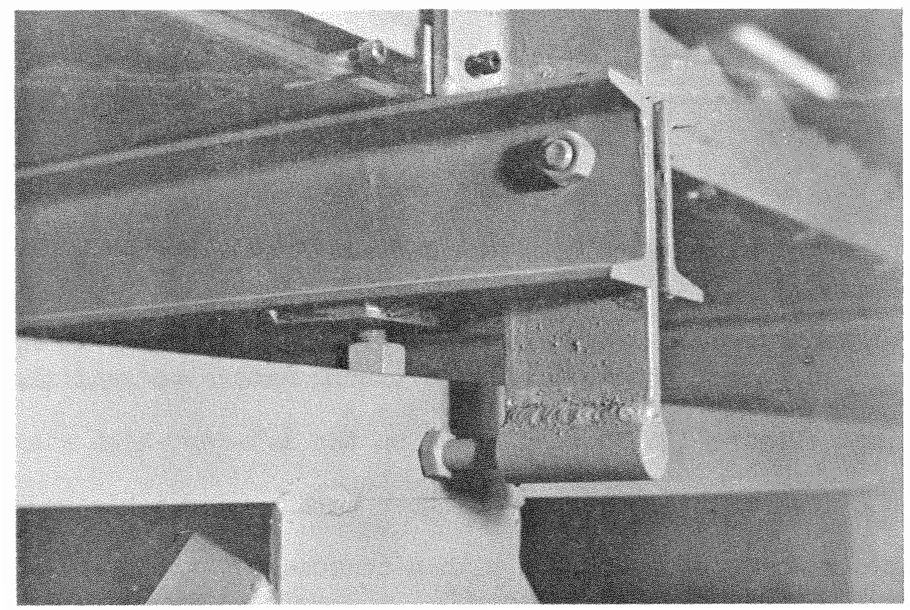


D. USGS plastic flume at Colorado State Univ. Bolt through upper plastic block to allow for flume expansion is visible in brace on far side of flume.

Figure 11, continued.



E. U.S. Department of Agriculture (USDA) 100-foot flume.



F. 36-foot flume at Dept. of Earth and Planetary Sciences, Massachusetts Institute of Technology. Turning the lower horizontal bolt pushes in or lets out the upper part of the wall brace.

Figure 11, continued.

Flumes which expand and contract need braces that permit the sidewalls to move longitudinally. Figures 9 and 12 show the excellent way in which this is done on the Colorado State University 30-foot plastic flume. Each brace uses a small plastic block, about 2 inches long x 1 inch x 1 inch, with a $\frac{1}{4}$-inch-diameter hole drilled through the middle of the block. A bolt fits inside this hole and is rigidly attached at each end to a metal brace. One face of the plastic block is glued to the flume sidewall so that the block rides longitudinally on the bolt as the flume expands and contracts.

Instead of special braces outside the walls you can adjust the wall alignment by means of crossed turnbuckles and/or horizontal threaded rods with nuts, between two longitudinal I-beams under the flume floor (fig. 13). The flume walls for this purpose must form a rigid structure with the I-beam truss, so that pushing on the bottom of an I-beam moves the whole flume sidewall. The Colorado State University 60-foot flume uses both of these methods. In addition to aiding in wall alignment this method also helps keep the I-beams from warping.

A vertical steel brace, such as a tee-piece or structural channel, welded in place, probably will be strong enough to keep the walls from bowing. Figure 11A shows a brace on the 1.5-foot-high glass sidewalls of the Iowa tilting flume. In other words, adjustable wall supports probably won't be necessary with a reasonably strong brace such as the one shown in fig. 11A. With strong-enough braces you can probably align glass sidewalls by using different amounts of sealer, as required, on the inner and outer wall faces (California Institute Technology 130-foot flume).

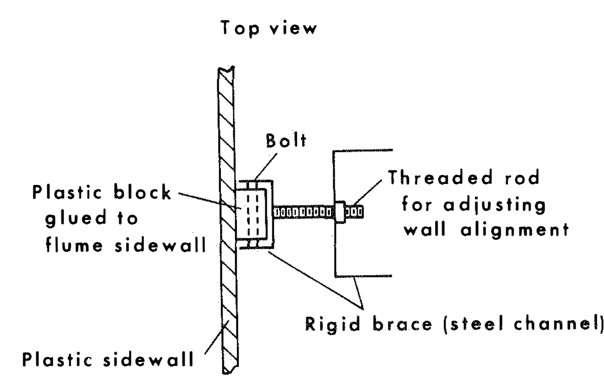


Figure 12.--Sidewall brace to allow for flume expansion and contraction (Colorado State Univ. 30-foot plastic flume).

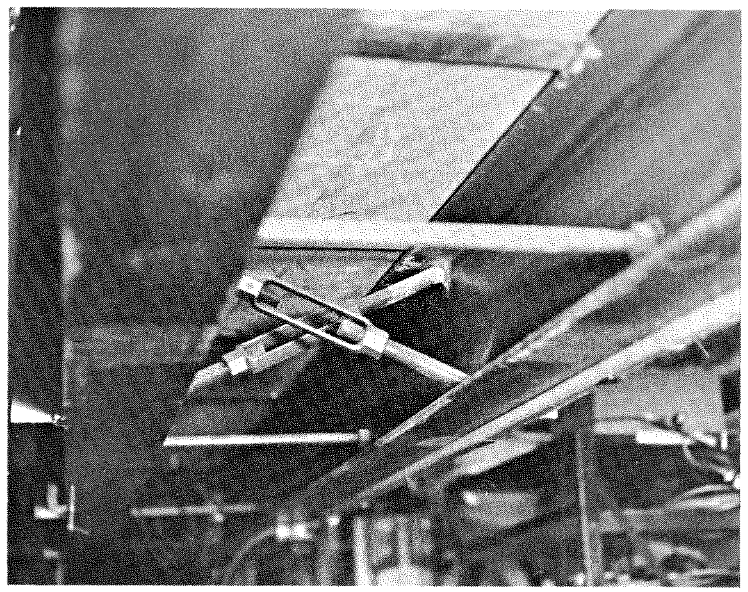


Figure 13.--Turnbuckles and horizontal rods under a flume floor for aligning the channel sidewalls (Colorado State Univ. 60-foot flume).

A thin wire (piano wire) stretched along the flume makes a good guide for wall alignment.

Glue a measuring tape along the top of one sidewall, from the channel entrance to the downstream end of the channel, to indicate distance downstream.

(c) Sealing. All joints must be sealed watertight. Currently there are at least five very good sealants in use on flumes. Many of them not only seal, they also fix materials in place quite effectively. In no special order of preference these products are:

(1) Dow-Corning Silastic #732 RTV adhesive sealant

(2) General Electric RTV 108 silicone-rubber sealant

(3) Dow-Corning #780 building sealant

(4) Dow-Corning #781 building sealant

(5) TRAVACO Laboratories' "Caulk-Tex" epoxy caulking compound.

The above sealants usually are available from marine supply stores or plastics dealers. Many other sealants have been used successfully but those listed above are relatively easy to apply, efficient and not hard to obtain. When purchasing the sealant mention the purpose and the kind of surface involved.

Be sure to lay down a liberal bead of sealant when putting the flume together, in order to insure a good seal. Leaks are much harder to stop later on.

Rails

Both instruction and research flumes need some provision for instrument-bearing carriages to move along the channel. In most cases these carriages ride on rails which are fixed to the tops of the flume sidewalls (fig. 2). But in rare instances the rails are supported independently from the flume structure, so that they remain perfectly horizontal regardless of the tilt of the flume (St. Anthony Falls). This method has the distinct advantage of eliminating the measurement of the flume slope in determining the absolute water-surface slope (and sand-bed slope, for sediment studies). (If the rails tilt with the flume, the flume slope and water-surface slope relative to the rails must both be measured.) A second advantage is that any sag or deflection of the flume test section does not affect the alignment of the rails.

Independent supporting of the rails may be impractical when the flume is at steep slopes or for very long flumes because any instrument riding on the rails might be too high above the bed at the downstream end. If you adopt this method, be sure that the flume bed elevation at the downstream end can still be measured when the flume is at its steepest slope.

Rails not connected to the flume can be supported from the laboratory ceiling or the floor. They can be adjacent to the top edges of the flume sidewalls or they can be overhead.

The usual method of placing the rails on top of the sidewalls insures that instruments will always be within easy reach of the bed but necessitates an additional measurement (that of the flume rails, i.e. the flume itself) to get the water surface slope.

The rail itself is usually of metal and can be made of any pieces that are available in long straight sections. Get a stainless or non-

corrosive material (stainless steel is common) and you'll avoid a lot of rust problems. Brass and aluminum have been used but are a bit soft for this purpose. One-inch diameter steel rods work quite well. For plastic sidewalls with very evenly-aligned top edges the top edge of the wall itself can serve as a rail. However, the alignment should be checked frequently in this case, as plastic is not very stable dimensionally.

Rails should be mounted in such a way that they can be leveled. For this purpose the top edge of the flume sidewall must have a solid metal lip or protruding edge, such as an angle iron or structural channel, if the rail is to be mounted on the sidewall. Figure 14 shows two popular arrangements, both of which use threaded rods and nuts equally spaced at 1-2 foot intervals along the flume.

Adjust the rails by first setting the flume test section (flume floor) horizontal. The reference datum for this purpose can be (a) the horizontal line of sight through a transit or engineer's level or (b) the surface of a pool of still water, obtained by blocking the downstream end and filling the test section. The still-water surface probably is the best datum, as this further assures that the levelling will be done under conditions as close to experimental conditions as possible. The pooled water can be used to establish the horizontal position of both the flume floor and the rails. The floor will be horizontal when the water depths are equal along the entire test section. (Depths usually are measured with a point gage, described later in the manual.) After the test section (flume floor) is horizontal,

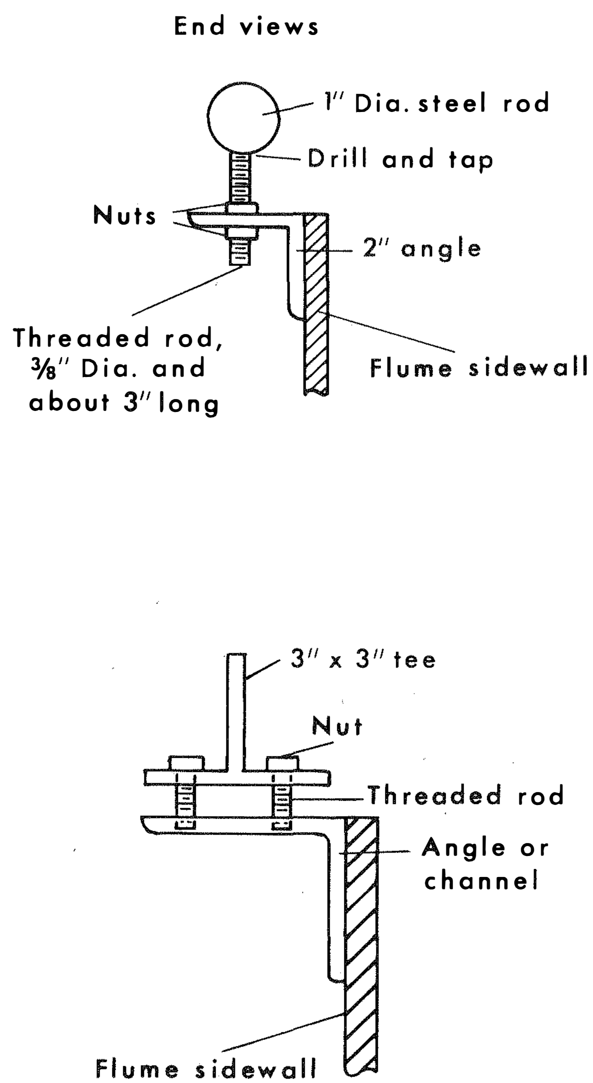


Figure 14.--Two methods of mounting rails on flume sidewalls.

level the rails by drawing each threaded rod down or up as needed, so that the rail becomes parallel with the flume floor and water surface. First get the four corners of the two rails on the same level, then systematically adjust all the other threaded rods. The rails must be horizontal (preferably to within $\pm$ 0.003 foot), mutually parallel and on the same elevation.

<u>Floor</u>

The same materials just discussed for sidewalls can also be used for the flume floor. Stainless steel, $\frac{1}{4}$ inch thick, is by far the most common, probably because transparency is not as important as durability and machinability for the floor. (Floor transparency can, however, be very useful in some studies, such as the investigation of sedimentary structures.) Aluminum, plastic and plywood, in no special order, follow steel in popularity. Note that these are all machinable. Plywood is by far the cheapest and will last several years if painted, epoxied or fiberglassed. Sometimes the availability of certain materials on surplus will influence your choice.

Rust primers to be applied to metals should be tested before being applied to the flume. Not all of them can be recommended for surfaces (metal or wood) which will be in contact with water. A good paint for plywood is AQUAPON, made by Pittsburgh Paint and Glass Industries.

To join adjacent sections of a steel floor use the method which Daly (1965) proposed (fig. 15). For plastic use the method described earlier in the sidewall discussion. Figure 7D, taken from Daly (1965), shows the joint between two glass sections. With aluminum a pliable or

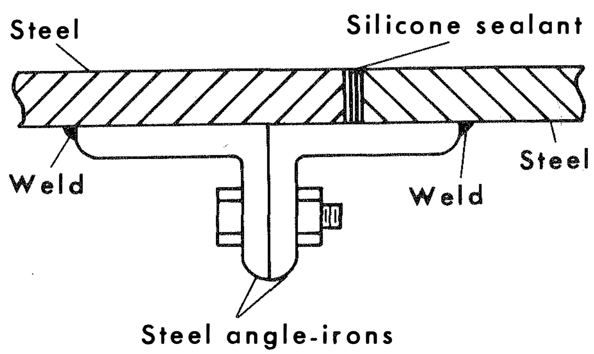


Figure 15.--Joint between steel floor sections (after Daly, 1965).

surgical-tube seal is a good idea, as this will allow for expansion and contraction without flexing.

On the subject of the test-section floor, a flume at the University of California at Berkeley has an excellent method of removing the sediment from recirculating flumes. At the downstream end of the test section the flume floor contains a hopper which spans the full channel width. During the experiments a removable lid covers the hopper. To take the sand out of the flume they remove the hopper lid and slowly pump the sediment-water mixture through the flume, so that the sediment settles into the hopper. Opening a drain at the bottom of the hopper then flushes the sand and some water out of the flume by gravity and into a small tank. A method of this sort is a lot easier than removing the sand manually. (A tee and extra valve in the pipeline underneath the flume also provide a good outlet for sand and/or water.) (To remove the sand manually from recirculating flumes fill the flume with water as deep as practical and run the pump at high speed. This flushes the sand out of the return line, where velocities are fast, and deposits it in the test section where the deep water lowers the flow velocity.)

<u>Truss</u>

A flume truss, although a key component, may present no problem at all to an engineer. On the other hand, non-engineers probably will need varying degrees of assistance with this important feature.

Therefore, with all due apologies to professional engineers, this section is written under the assumption that some readers have had little or no experience with trusses.

The discussion here will treat only the support (truss or beam) of the flume test section; supports between the laboratory floor and the truss, beam or flume bottom, such as pivot points and jacks, will be discussed in another chapter. You'll have to choose the number and locations of pivot points and jacks in conjunction with the planning of the truss details. In most cases you'll want the smallest practical number of jacks or similar supports, for simplicity in tilting the flume. The truss therefore must be quite rigid and designed specifically with your deflection tolerances in mind.

Demonstration flumes often are small enough to sit on a table in the laboratory or classroom, and for such small flumes you won't need any special support under the flume floor. Otherwise, use a single I-beam, channel or a lightweight and simplified version of the trusses discussed below. Deflection usually is not too important in demonstration flumes, as they are usually small enough to produce the desired flow phenomena in spite of a little deflection.

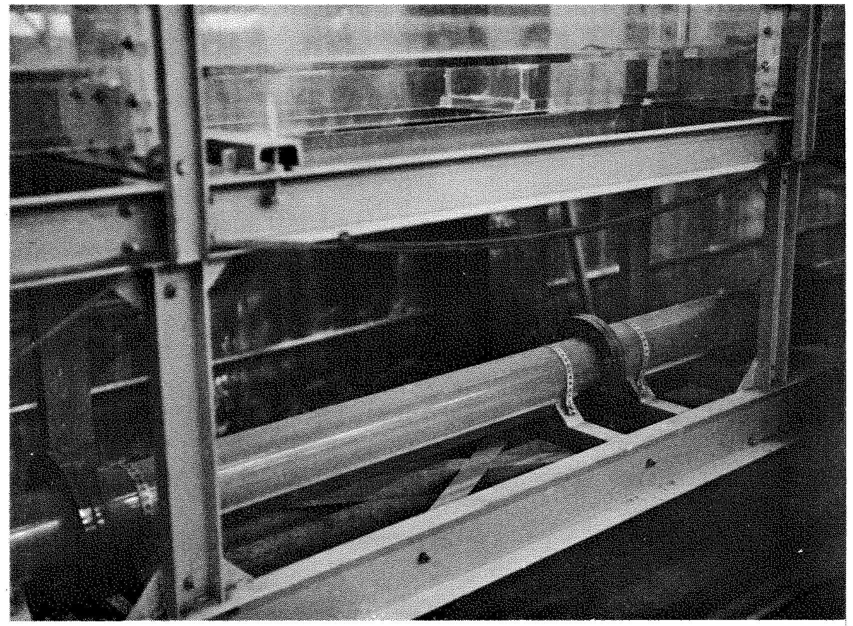
The truss or beam of research and instruction flumes must be rigid enough to minimize any floor sag when the flume is filled with water and sediment. Such deflection not only disrupts a straight flume floor, it also distorts the alignment of the sidewalls and rails. Vertical deflection should be no more than 0.003 foot, and

0.001 foot is a worthy goal. The design, in other words, should strive to keep deflections between supports small under the maximum expected load. Thus the truss or beam must be very rigid and oversized compared to the expected load and to a conventional design.

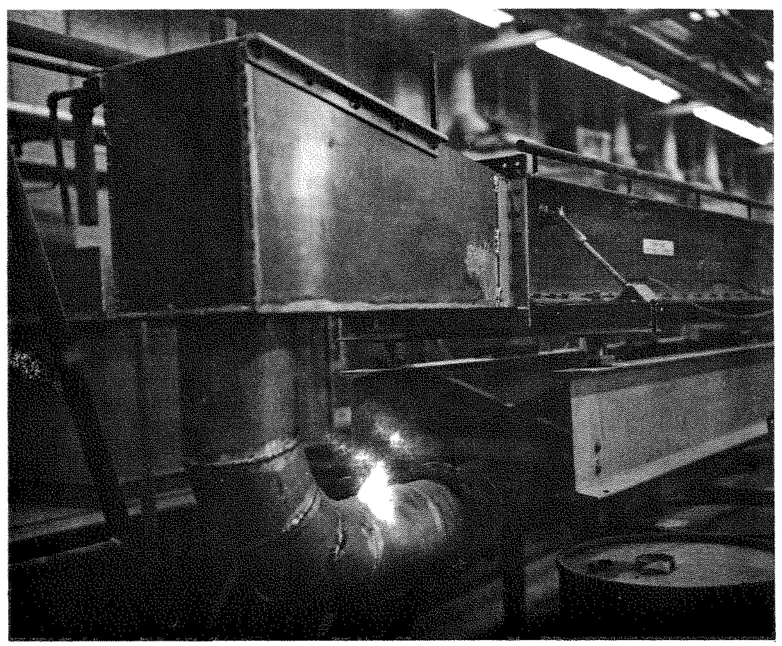
Another factor which can influence the strength of the truss is that it may have to support the pipe (and water) going to the flume headbox. That is, you may decide to keep this pipe independent of the flume structure or you may rest it directly on the flume truss. We'll discuss this possibility in the chapter on pipes.

The two most popular types of truss are (1) two heavy steel I-beams or channel irons (one below each side of the flume) in a longitudinal direction, with small structural channels or angle-irons as cross-braces connecting the I-beams (figures 13 and 16) and (2) an ordinary bridge-type truss of angle-irons and other small structural pieces (fig. 16F). Many flumes have trusses which don't fall into either of these categories.

The two advantages of the steel I-beam are simplicity in construction and shallower depth. The lesser depth lets you tilt the flume to a steeper slope. This is particularly valuable with research flumes.

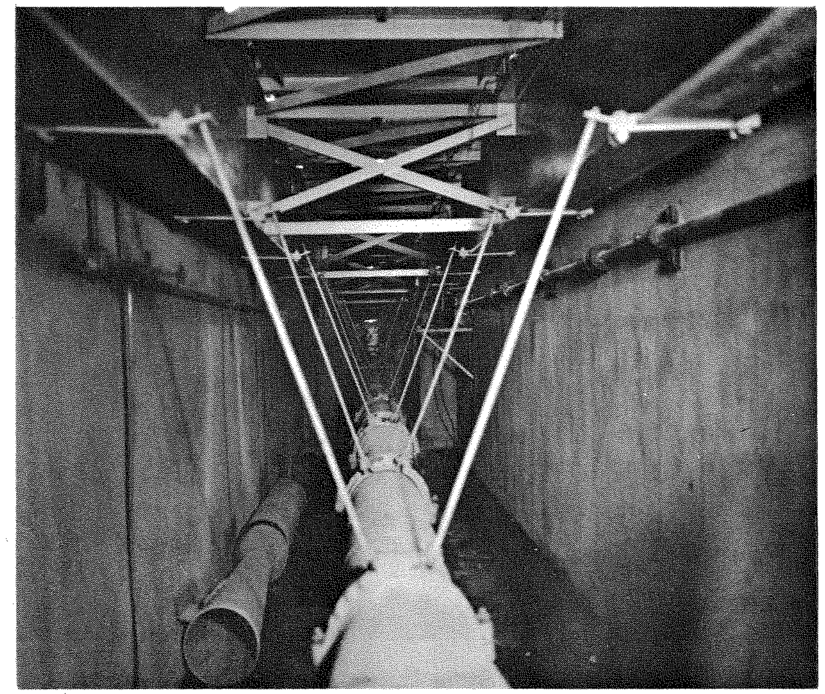


A. USGS 30-foot plastic flume.



B. USDA 50-foot flume.

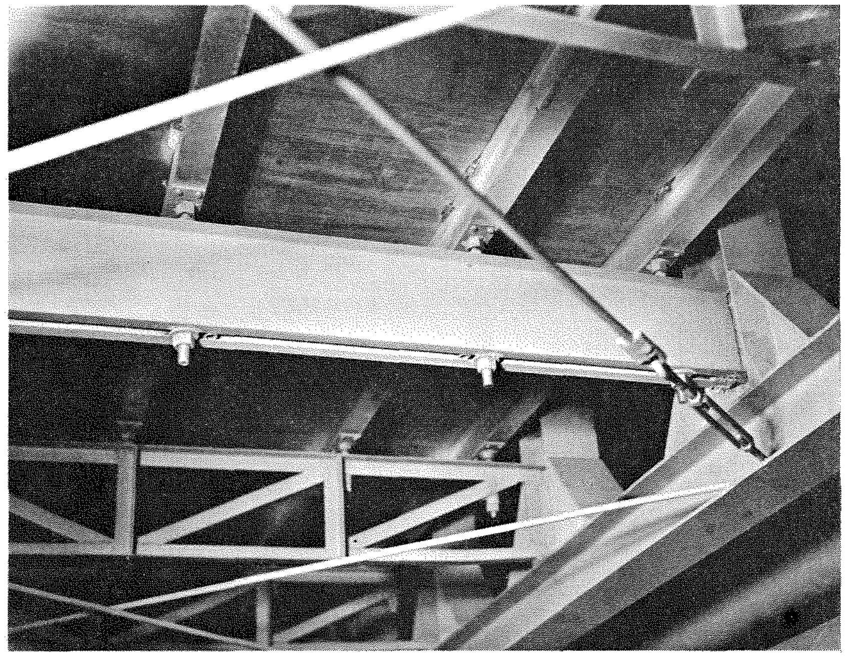
Figure 16.--Examples of flume trusses.



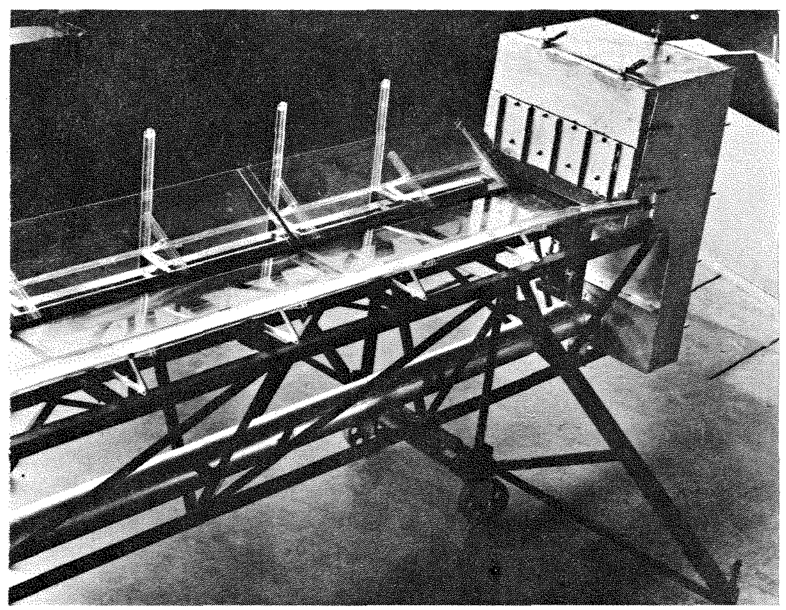
C. USDA 100-foot flume.

D. Iowa 85-foot glass flume.

Figure 16, continued.



E. Colorado State Univ. 200-foot flume.



F. Univ. Western Australia 32-foot perspex flume (U.W.A. photo).

Figure 16, continued.

Trusses, on the other hand, can be made at least as strong as (if not stronger than) I-beams and involve much less metal. A truss therefore weighs much less but generally is about twice as deep as an I-beam. The depth of a bridge-type truss should be at least 1/10 the distance between the underneath supports. The extra work in making a truss means that the labor cost is higher, but this may be offset by the lesser expense for the materials. The truss depth would not restrict the flume slope if you could install a pit or trench under the flume, and this may or may not be feasible for your situation. Another advantage to such a trench is that the flume can be placed at a convenient working height.

The size of the I-beam depends mainly on the distance between supports and the total weight to be borne per foot of channel length. Finding the total weight per foot of channel length involves adding the weights of the test-section walls and floor, the water in the channel using the maximum depth, the sediment (figure this as about 62 pounds per cubic foot when immersed in water) and any extra steel members such as rails, channels for floor leveling (discussed below), cross-braces connecting the I-beams, etc.

An I-beam gets stronger as it gets deeper but unless you put a trench under the flume a deep I-beam may limit the flume slope. (The USDA 100-ft flume at Oxford and the California Institute of Technology 130-foot flume are each supported by two I-beams, about 2.5 feet deep; a trench underlies each of these flumes.) When you have determined the number and location of supporting points (next chapter) and the weight to be borne per foot of channel length, call up a steel company. Tell the company representative you need two I-beams (to be placed side-by-side) and give him the load and deflection tolerance. He can quickly tell you the required size and cost of the I-beams. It is also a good idea to consult an engineer.

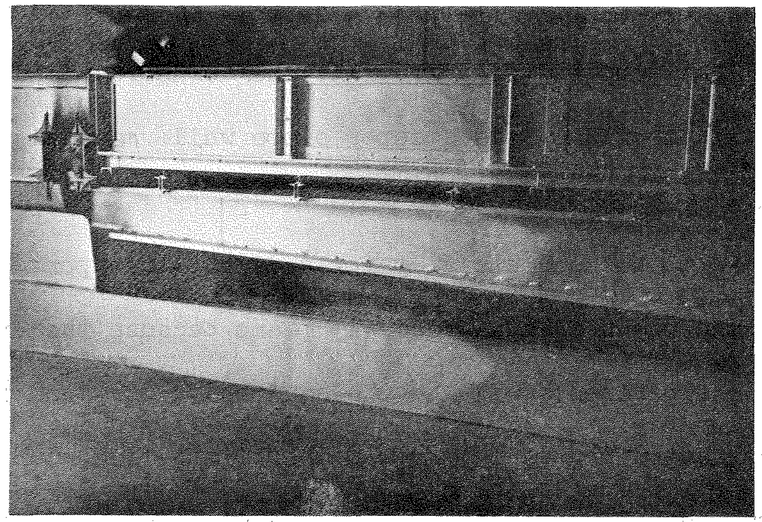
In the particular case of selecting I-beams be cautious about overdesigning. Big steel I-beams can weigh many tons. Some laboratory floors and foundations cannot support extremely heavy weights, and very heavy I-beams with the load they must carry could add up to enough weight to cause the floor to settle or fail. This has happened. So make sure the floor and the earth beneath the building are reasonably reliable for heavy weights. Pads, piles or caissons can be used if the floor is too weak to support the flume. Even if the floor will support the load, pads might be worthwhile to spread out the load. In such case find the position of the major structural elements within the floor, to spread the load over several of these elements.

Bridge-type trusses usually consist of angle-iron members. To get the required size of angle-iron you'll need the same weight information mentioned above in the I-beam discussion. In addition, you'll need a truss analysis. (This is a computation of the tension and compression on the various members.) The steel company may have this truss analysis already worked out for the common type of truss you'll need, so call up a steel company and ask.

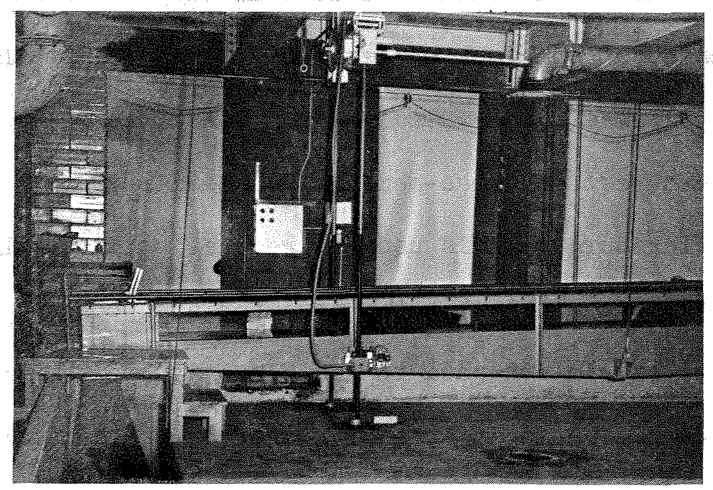
If the flume has some central support (jack or pivot) then either the truss or beam can be tapered such that the truss depth decreases away from the support (fig. 17). At the downstream end this enables you to tilt the flume to a steeper slope while maintaining structural strength.

Flumes to be used strictly for sediment-transport studies need not have floors which are precisely plane because the effective floor during the experiments will be the sand bed. For such flumes the floor can rest directly on cross-members (fig. 16A, 16B) such as structural channels (3- or 4-inch width of large face) or angle irons. Usually these pieces are spaced about $1\frac{1}{2}$ to 3 feet apart. Place the channels upside down and at each end bolt them to the truss to level the floor laterally. This same support method is common with flumes about one foot or less in width and less than about 30 feet long. If the flume sidewalls consist of structural channels, the floor can rest on cross-members welded directly to the sidewalls (USWES at Vicksburg). This usually reduces still further the depth you can study but eliminates the need for a supporting framework.

A level bubble attached to the flume at or near one end of the test section can serve as an approximate check that the flume is level laterally.



A. Georgia Tech 80-foot flume (Georgia Tech photo).



B. Iowa 85-foot flume.

Figure 17.--Tapered beams at downstream end of flume, to obtain steeper slopes.

The support structure of many research flumes provides for areal adjustment of the floor level. This is because the truss and hence the floor bend to varying extents under the weight of the truss and the water in the flume. The floor can be very accurately leveled by means of threaded rods (say $\frac{1}{2}$ or 3/4 inches in diameter) and nuts. For this purpose each horizontal member that bridges the top of the support framework should consist of a heavy angle iron or two structural channels (fig. 16). The truss must be about 1-2 feet wider than the test channel. From here on you can proceed in any of several ways:

1. Use only two threaded rods for each horizontal cross-piece of the truss. Fix each rod to the longitudinal member of the truss as shown in figure 16A and 16B. The rod fits vertically between each channel pair. Bolt the floor directly onto the horizontal cross-pieces so that adjustment of the nuts alters the floor elevation.
2. Mount two threaded rods to the longitudinal and cross-members of the truss as in (1) but on the cross-piece use 2-5 additional rods, as desired, equally spaced across the flume width. At Georgia Institute of Technology "the (five) rods project to a height of about 3 inches above the top of the channels which extend the length of the flume. The flume floor is bolted directly to the car channels." (Tracy and Lester, 1961). With

this arrangement the floor can be drawn down or pushed up as needed. Figure 16E shows a similar arrangement on the Colorado State University 200-ft flume.

3. Same as (2) but do not bolt the flume onto the car channels. This method is necessary with glass flume floors, as at Iowa (fig. 16D). Iowa's flume has rods rather than car channels.

Variations of the above methods may also be feasible, as long as you use the threaded rod principle. Iowa has tried and does not recommend applying a thin (say ½-inch) layer of cement to the top surface of the flume floor to obtain a plane surface.

Aluminum can be used rather than steel for the flume truss. Aluminum is lighter in weight, but materials cost more and construction is a little more expensive because of the need for helium-arc welding.

Summary

Make the flume sidewalls out of glass or clear plastic so that you can see everything going on below the water surface. The walls should be about ½ foot higher than the maximum expected water elevation (= 1.7 D + 0.5 foot for sediment studies). The sealant space between adjacent glass panels and along the base of a glass panel should be about 3/16 of an inch as a safety factor against expansion. Use glue rather than screws to anchor the base of plastic sidewalls, because fixing the walls with screws causes cracking. The cardinal rule in working with plastic, glass or aluminum is to allow for expansion and contraction. Brace the sidewalls at least every four

feet and leave some provision for additional braces (say 2-foot intervals) in case these prove necessary.

Rails can be fixed to the top of each sidewall or can be mounted horizontally on a structure that does not touch the flume. Use threaded rods and nuts to support the rails for precise leveling.

Stainless steel is probably the best material for the flume floor, but ordinary steel, plywood, aluminum, plastic and glass are also common.

The intended use of the flume and the acceptable tolerance of deflection may influence both the choice of materials and the design of the flume. For example, wood can swell a bit, and steel may warp slightly in the vicinity of a weld. No material is ideal or perfect. Hence you should keep in mind the various characteristics of each material. You may also want to consider the abilities of the personnel who will help in the construction and the availability of materials on surplus.

The supports for the flume test section usually consist either of (1) two heavy I-beams connected by small structural channels or angle irons or (2) small structural pieces in the form of an ordinary bridge-type truss. Many flumes have an arrangement that permits adjustment of the floor elevation by means of threaded rods and nuts.

Never place a flume in direct sunlight or close to a heat source.

SLOPE ADJUSTMENT

Deciding how to vary the flume slope is step five. Now why should you want to adjust the flume slope, anyway?

To begin with, there is a wide range of slopes in Nature, and many flow phenomena are very much influenced by the slope. For uniform flow (constant depth with distance downstream) and rigid boundaries you would be limited to just one slope with a non-tiltable flume. This would be undesirable for any kind of flume, regardless of what the flume is used for.

Secondly, in sediment-transport studies the sediment stabilizes at a certain slope. This sand-bed slope in flumes nearly always changes with the flow and transport conditions. By tilting the flume to the approximate probable stable slope right at the start you can save many days or even weeks of valuable time which otherwise would be taken up waiting for the water and sediment to change the slope. Furthermore, if the equilibrium slope differs greatly from the flume slope a large wedge of sediment necessarily will build up in the test section. Such a wedge reduces the cross-sectional area of the test section and thus may curtail the range of flow conditions which you can investigate. Also, a much larger quantity of stock sediment will be needed because so much sediment is stored in the wedge.

The worst situation for fixed boundary flow is a non-tiltable horizontal flume. In this case uniform flow is impossible, i.e. the water depth must continually decrease in the downstream direction.

So build your flume in such a way that you can change its slope. The available slope range should be from horizontal to at least 5 percent. If the flume is too long to permit a 5 percent slope try for a slope as steep as possible. About two or three percent is common on present flumes.

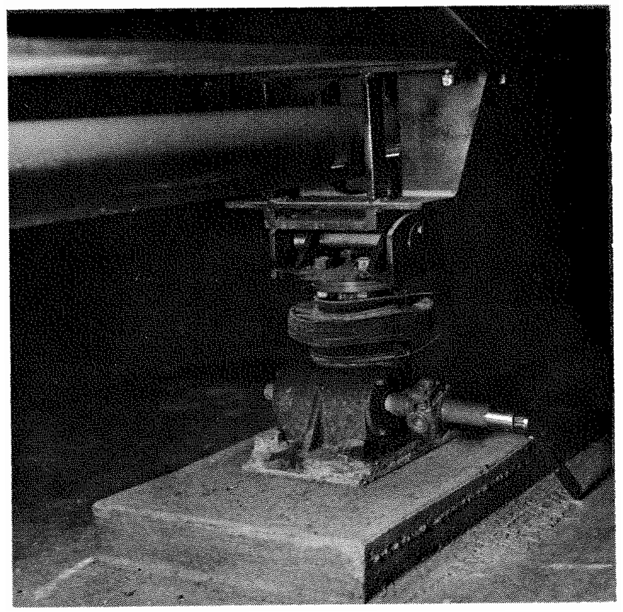
Two methods of getting more slope to the flume are (1) dig a trench in the laboratory floor under the downstream half (or even all) of the test section (e.g. USDA at Oxford; USWES) and (2) taper the supporting truss at the downstream end of the flume so that the depth of the truss decreases with distance downstream (fig. 17).

Methods of tilting the flume

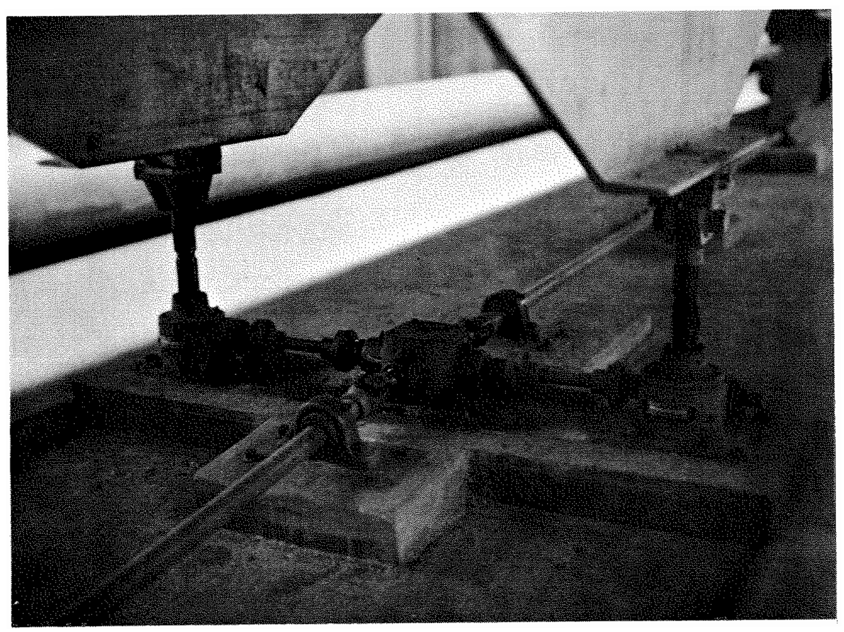
Here are four good ways to change the flume slope:

1. Screw jacks (fig. 18). Probably the most popular method of tilting a large research flume is to support it on one or more screw jacks. The flume rests on a fixed pivot, usually located about halfway along the test section (U. of California at Berkeley; USDA at Oxford; Georgia Tech; many others) but in some cases located near one end of the flume (Colorado State University and others).

   In flumes about two feet wide or more each jacking station usually has a pair of jacks - one under each side of the flume. Flumes narrower than about two feet only need one jack per station.

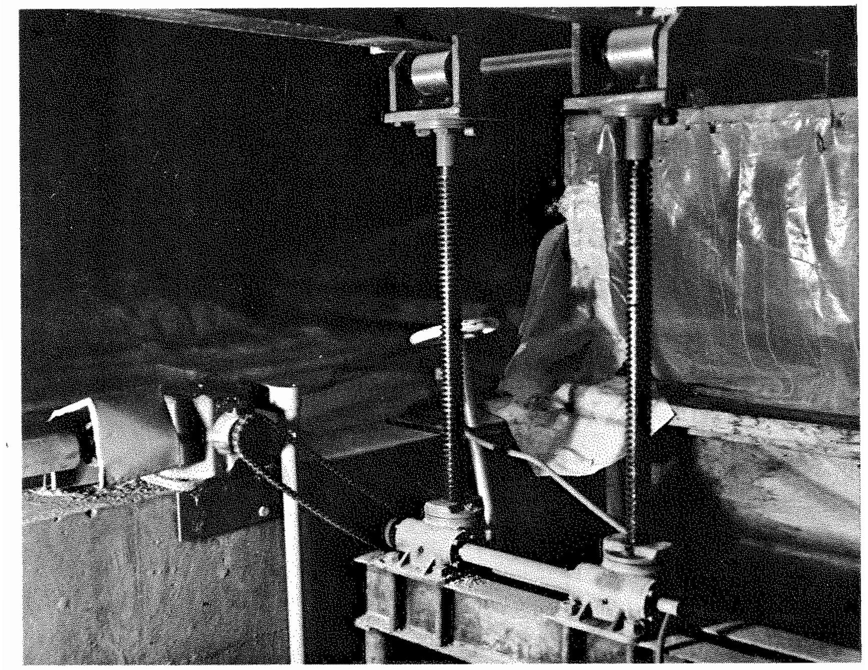


A. USGS 30-foot plastic flume at Colorado State Univ.

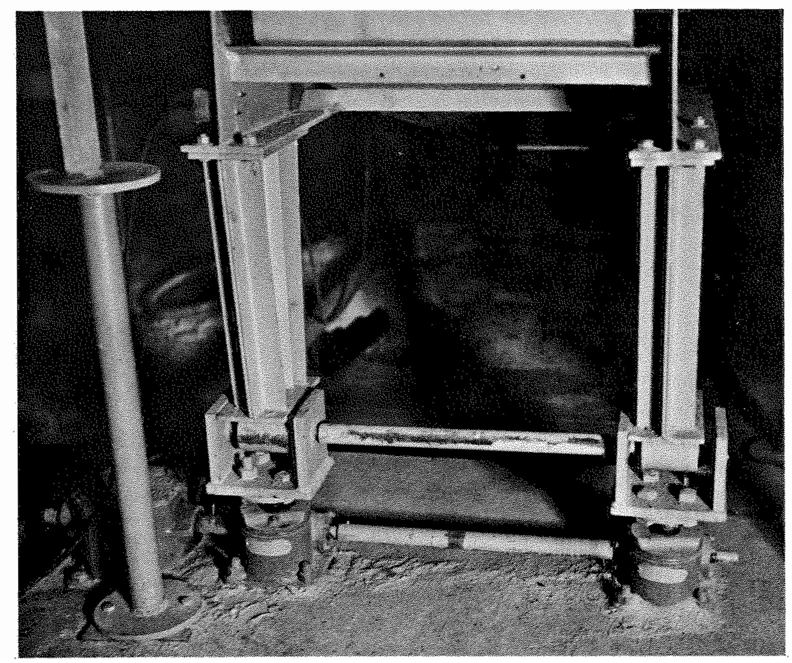


B. USWES 75-foot flume.

Figure 18.--Screw-jack arrangements for tilting a flume.

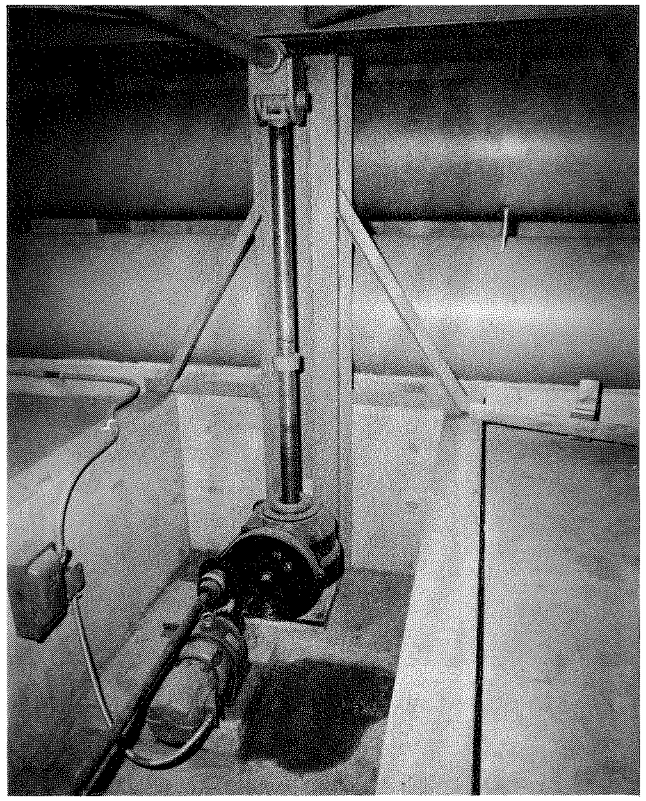


C. Colorado State Univ. 60-foot flume (downstream end).

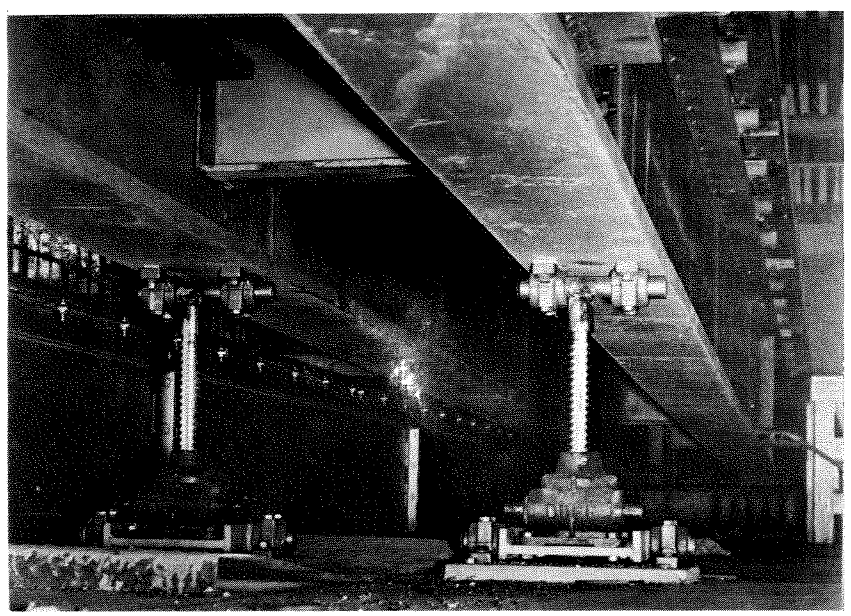


D. Colorado State Univ. 60-foot flume (upstream end).

Figure 18, continued.

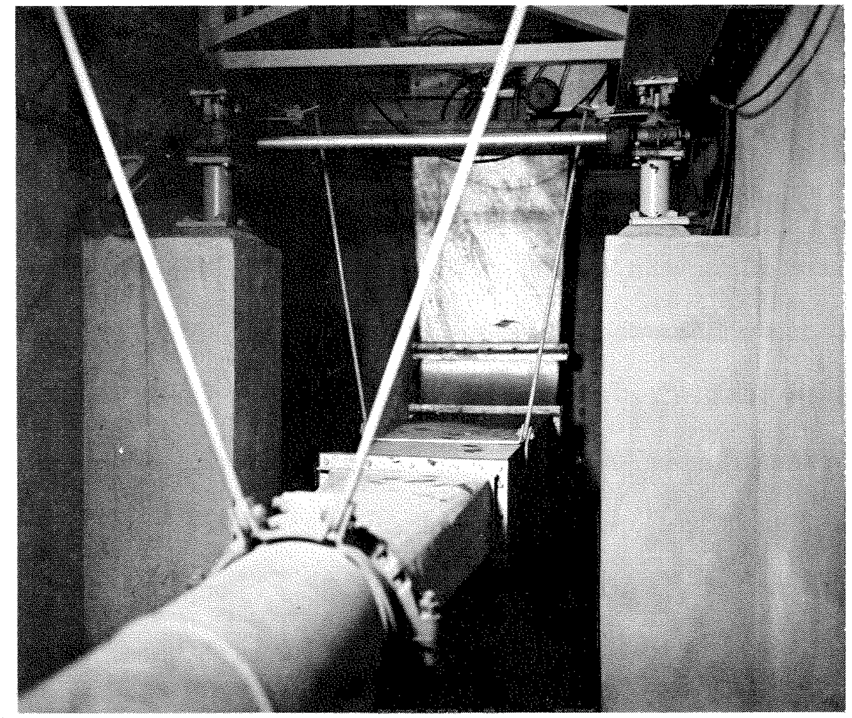


E. Colorado State Univ. 200-foot flume.

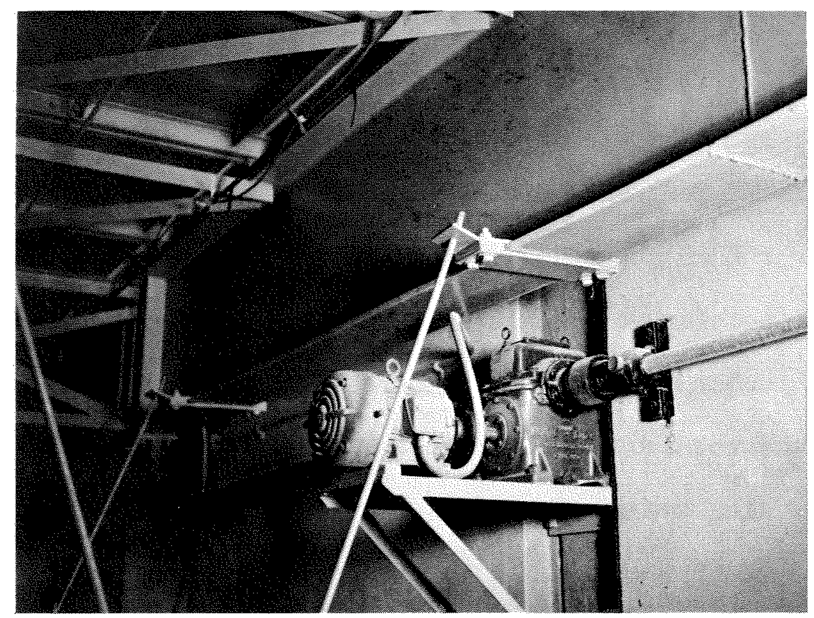


F. Georgia Tech 80-foot flume, during construction (Georgia Tech photo).

Figure 18, continued.



G. USDA 100-foot flume, upstream end.



H. USDA 100-foot flume: motor and rod connections for tilting device.

Figure 18, continued.

One word of caution: flumes with one jack per station have a tendency to tip, so some sort of brace to prevent tipping and sidesway is advisable (fig. 20B).

The supports (jacks and possibly a pivot) can be located anywhere along the flume. One common arrangement, placing the fulcrum at one end of the flume and the tilting device at the other end, gives little or no displacement at the fulcrum end and requires a minimum number of jacks. A disadvantage, however, is that you get maximum truss span and hence maximum deflection. Another common arrangement is with the pivot halfway along the test section and two jacking stations equidistant from the pivot near the ends of the test section. This reduces the deflection but gives some displacement at each end of the test section. There are many variations of these and other arrangements, in regard to the locations of the supporting points.

The average laboratory research flume has a support at least every 75 feet and usually at 30-40 foot intervals. Hence for flumes longer than about 150 feet at most, you'll have to have three or more jacking stations even with the pivot serving as one support. The number of supports of course depends on the truss strength and on the tolerable deflection.

With two or more jacking stations all jacks must act in unison. For example, with the flume pivoted in the middle and jacks at each end, the jacks at one end must go up at the same time and rate that

those at the other end go down. From one point of view this is not too hard to arrange, but it can pose some practical difficulties depending on how you try to do it. Problems encountered in tilting the flume with two or more jacks have caused considerable extra work and loss of time for a number of people. Their ready advice on this subject condenses to the following strongly-recommended rules:

(1) Keep the number of jacks to a minimum (i.e. one is best);

(2) Do not try to operate the jacks individually - instead connect them so that a single control such as <u>one</u> motor or <u>one</u> cranking mechanism operates them all simultaneously;

(3) Interconnect the jacks electrically or with a rod- and gear-box system rather than by means of wires, chains- and sprockets or any other method.

There is no gearing problem with just one jacking station or with two jacking stations equidistant from the pivot. Figure 19 shows a typical arrangement with the pivot about halfway along the flume test section.

With two jacking stations not equidistant from the pivot or with more than two jacking stations a minor gearing problem arises because for a given slope change the displacement varies at different jacking stations. The necessary rise or fall at any station increases with distance from the pivot. The proportional drive needed for such situations is accomplished by having different gears on the various jacks or by electrically controlling the speed at which the jacks operate.

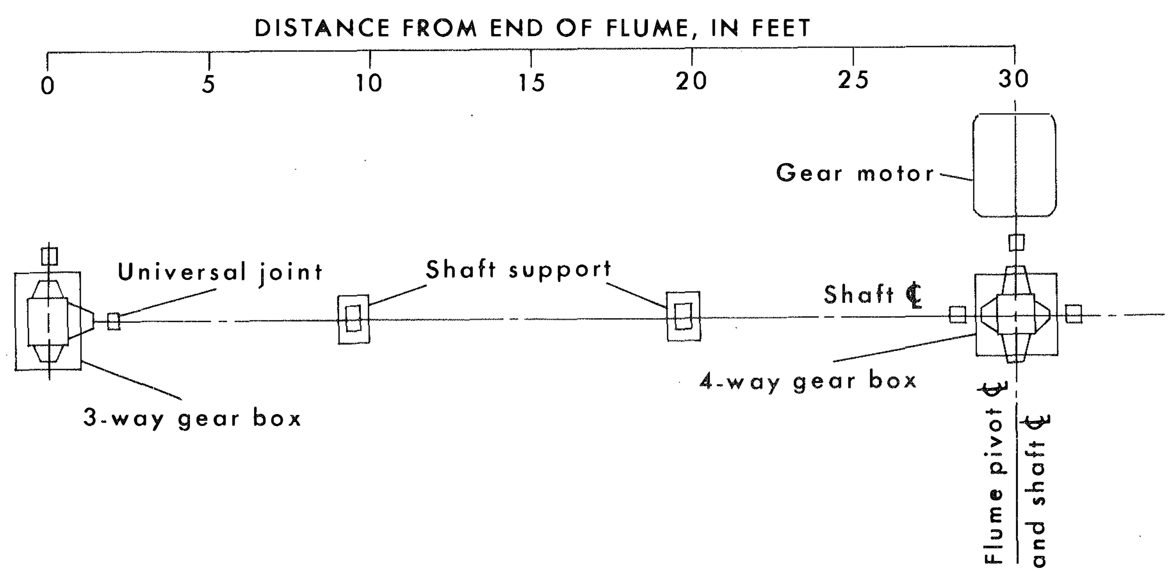


Figure 19.--Components of gear system for tilting a flume by means of screw jacks (upstream half of Colorado State Univ. 60-foot flume).

Regardless of how many jacking stations you have, the best policy by far is to contact a jack company (e.g. Duff-Norton; Joyce-Cridland; Armco) and explain your needs. Frequently the jack company has a design already developed which will apply to your situation. Hence they can give you more accurate advice in much less the time, as part of their normal service.

For interconnecting the gears on the jacks the rod or shaft diameter can be as little as 3/4-inch for flumes less than about 40 ft long but should be thicker (up to five inches in diameter) for heavier loads (larger flumes). Shafts ought to be supported with pillow blocks at least at 10-foot intervals to prevent whipping of the shaft. Cut the shaft lengths to fit as a final step, after the jacks and gear boxes are in place. By making the shafts equal in length you minimize the stress and/or torque on the shafts, jacks and flume truss.

The size of the jacks will be governed by the required vertical movement and by the total weight to be carried (truss, water, test section, etc.). For research flumes screw-jacks ranging from two to ten tons in capacity are common. Jacks should be greatly overdesigned in order to minimize the errors in flume alignment and slope that can occur gradually due to wear on the threads of the jacks. Again, be sure to contact one or more jack companies and explain your needs in detail, to make sure you get the right size jack.

For flumes that are not more than four or five feet above the floor level the jack housing probably will have to extend down into the laboratory floor in order to take full advantage of the maximum rise of the jacks. This depends in part on the headbox and tailbox dimensions and on other features not yet discussed.

On larger flumes (greater than about 50 feet long) the simplest and most popular method is to have a single motor operate the entire screw-jack system. The 200-foot flume at Colorado State University has four motors - one for each pair of screw jacks. The motor speeds are adjusted in proportion to the distance of the jack-station from the pivot, which is at the head of the test section. All of the motors are electrically connected to a central control button so that operating this single button tilts the flume. Safety switches are provided so that either (a) all motors operate together or (b) no motors operate unless an override is pushed.

For flumes less than about 40 or 50 feet long a hand-crank works just as well as a motor and reduces the cost of the flume. The University of California at Berkeley has a good example.

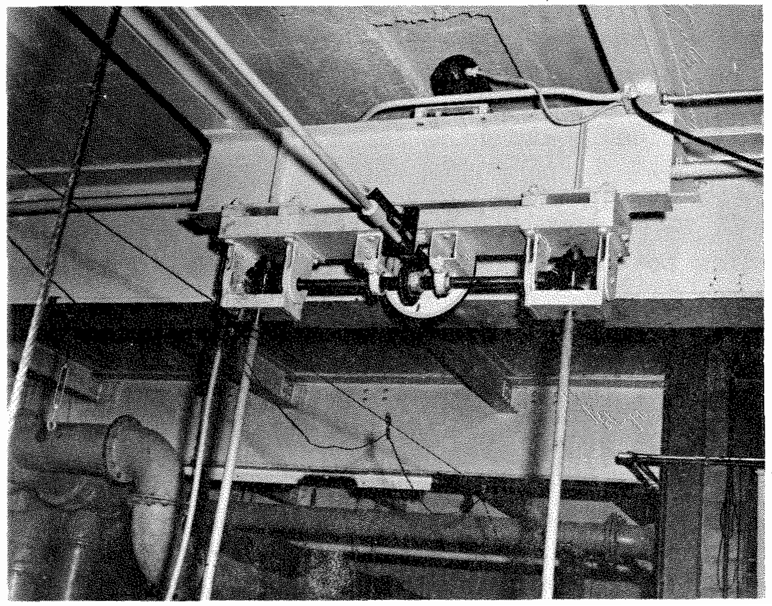
Each jack has to be mounted in one of two ways: (a) with rotatable connections at both the top and bottom, so that the jack can tilt slightly as the flume tilts. The 130-foot California Institute of Technology flume uses ball and socket joints for this purpose. (b) With a roller on the top so that the jack always remains vertical but supports the flume at a point further from the pivot as the flume slope steepens. Colorado State University (fig. 18C) uses this method. Make some provision to keep the truss from shifting laterally (fig. 18 and 20B).

You'll have to be careful to keep the grooves of the screws clean and well lubricated.

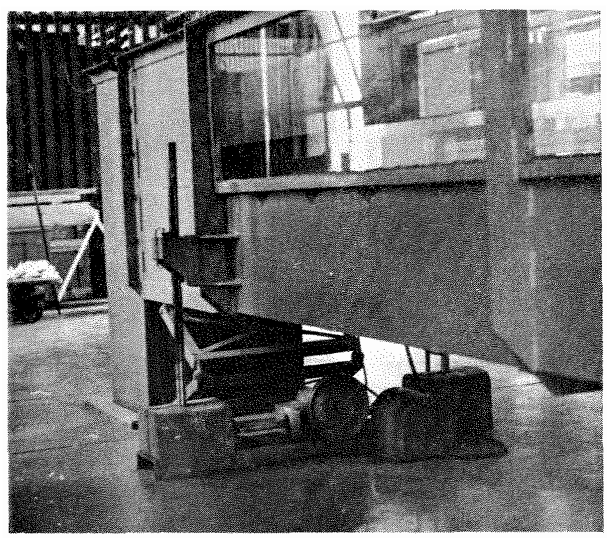
2. Rotating threaded rods. A second method of tilting the flume is to use vertically-oriented large screws or threaded rods which merely rotate in place, allowing the flume to ride up or down according to the direction of rod rotation. The threaded shafts can hang from a strong framework above the flume (fig. 20A) or they can rest on the floor or other foundation (University Western Australia; Iowa) (fig. 20B).

   This system can be used with flumes of any size, and the shaft can be rotated by a motor or by hand. The threaded posts actually are only approximately vertical, as they tilt slightly as the flume slope changes. Be sure to provide for this tilt in the mechanical support. Again, you'll have to keep the grooves of the screws clean. And don't forget to include a limit switch (discussed below) to prevent the flume from moving too far up or down.

3. Chain hoists (fig. 21). Two ordinary chain hoists on opposite sides of the channel at one end of the flume serve quite well for changing the flume slope (USGS, Washington, D. C.). The chain hoists must hang from a strong cross-beam. This simple method works only for flumes less than about 50-75 feet long because flumes longer than this need intermediate support, and this would be rather complicated with chain hoists. The pivot has to be at or near the other end of the flume to minimize the vertical displacement there. At the chain-hoist end of the flume use a level-bubble or some other means to insure that the flume stays level laterally.



A. Iowa 85-foot glass flume. The test section, just below the picture, hangs on the two rods.



B. Iowa 24-foot flume, showing the motor arrangement which rotates the threaded rods. The folding brace between the flume and the laboratory floor prevents flume sidesway.

Figure 20.--Tilting of flume using threaded rods.

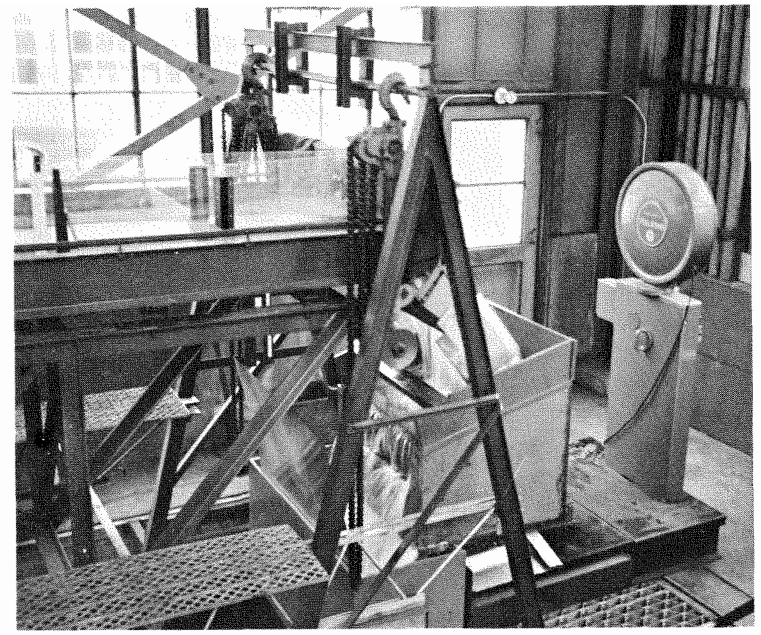


Figure 21.--Chain hoists for changing flume slope (USGS 52-foot flume, Washington, D.C.).

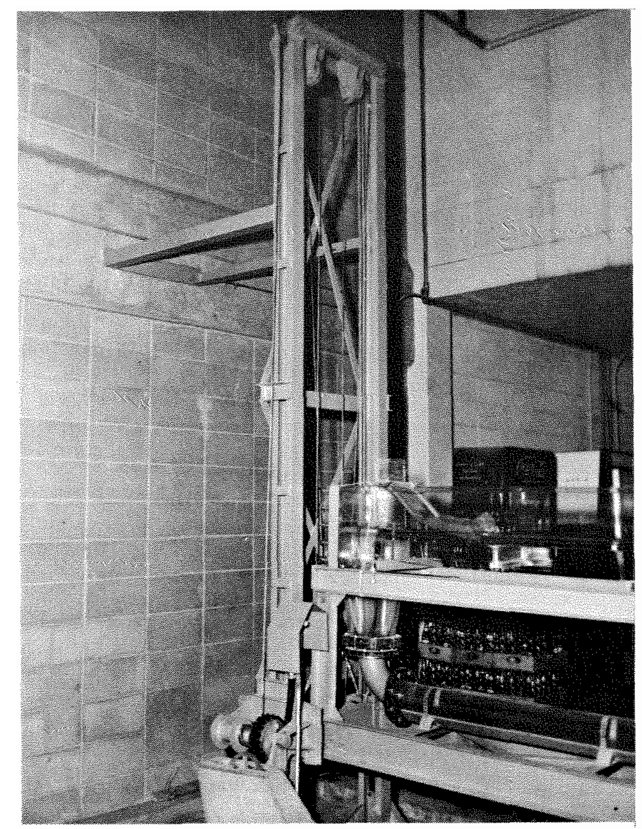


Figure 22.--Block and tackle arrangement for tilting a flume (USGS plastic flume). Photo shows upstream end of flume.

4. Block and tackle. A fourth possibility is to hang the flume at one end with a block and tackle system. As with the chain hoist method this can be used only with shorter flumes. The pivot must be at or near the opposite end and must travel horizontally parallel to the laboratory floor in addition to rotating.

Figure 22 shows the block and tackle arrangement used on the U.S. Geological Survey's 30-foot plastic flume. The $\frac{1}{4}$-inch steel cable is taken up or played out by a motor and revolving drum.

The tilting methods listed above are only the most common. Many other methods may be feasible. For example, on smaller flumes a hydraulic oil device might be used. Colorado State University has a tilting rig built from the hoist of an old fork lift.

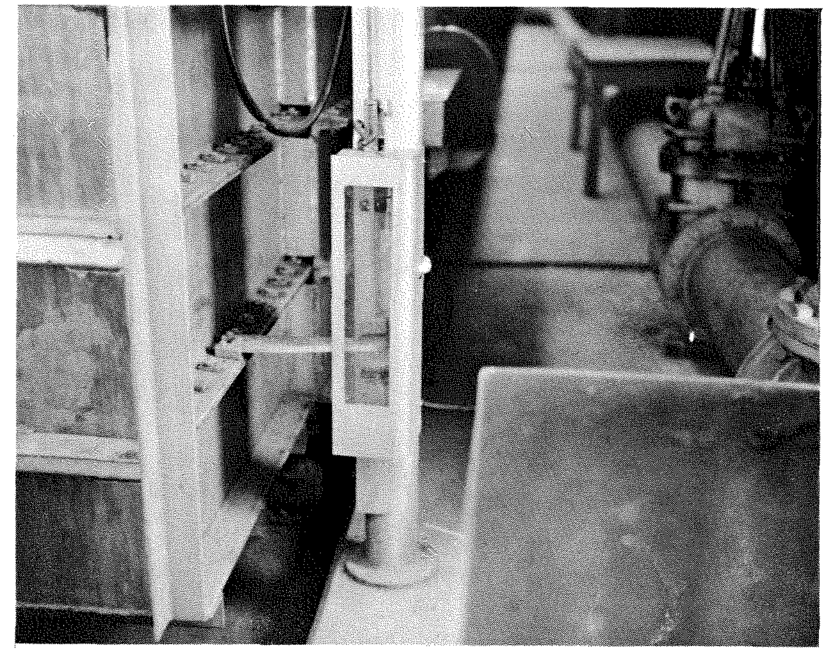
Regardless of how you tilt the flume it's a good idea to have some sort of safety control which limits the maximum and minimum slope (fig. 23). Otherwise damage may occur at the upstream or downstream end by inadvertently operating the tilting mechanism too long. A limit switch makes a good safety control. Be sure the switch is rated to handle the volt-ampere characteristics of the system (overdesign!).

Pivot

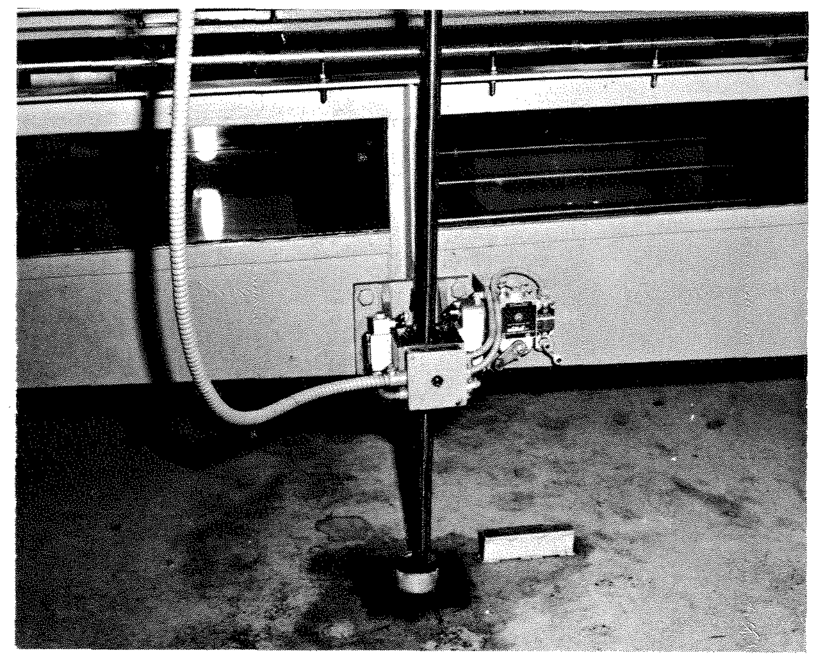
Location

The pivot (fig. 24) can be at the upstream end, downstream end or anywhere along the test section, depending in part on the type and size of the flume.

On small flumes the pivot can be anyplace - even attached to the headbox or tailbox.

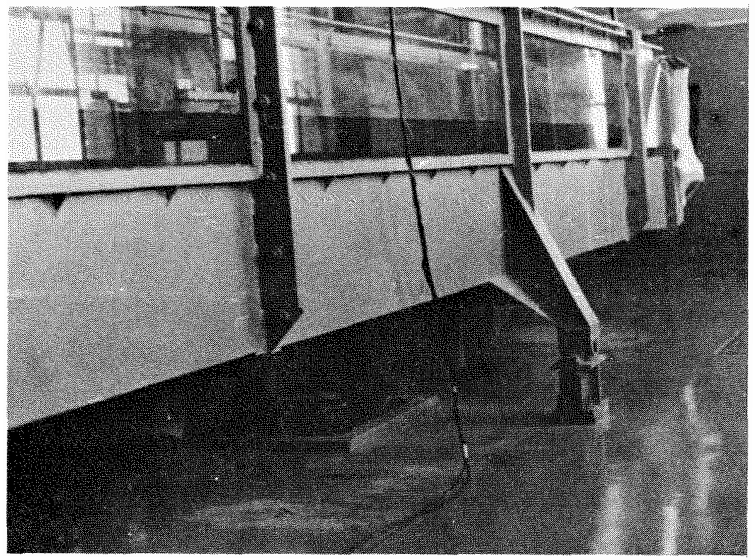


A. USWES 75-foot flume. Switch is adjustable in height and can regulate the maximum or minimum flume tilt.

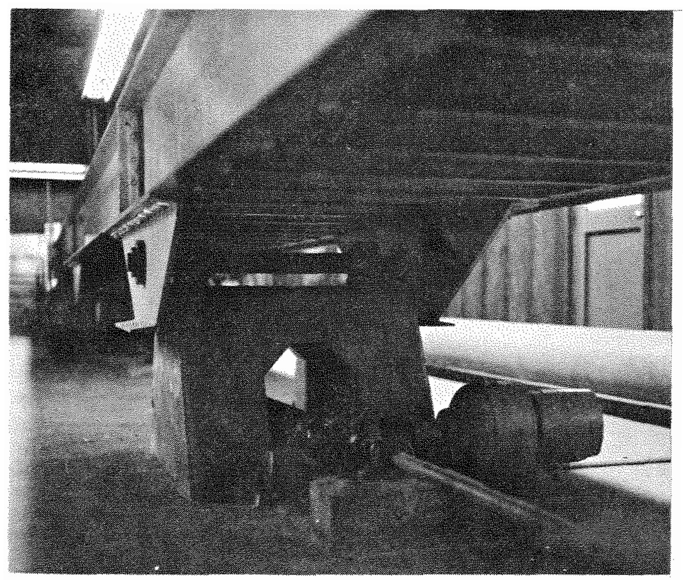


B. Iowa 85-foot glass flume.

Figure 23.--Automatic shut-off switches to limit flume tilt.

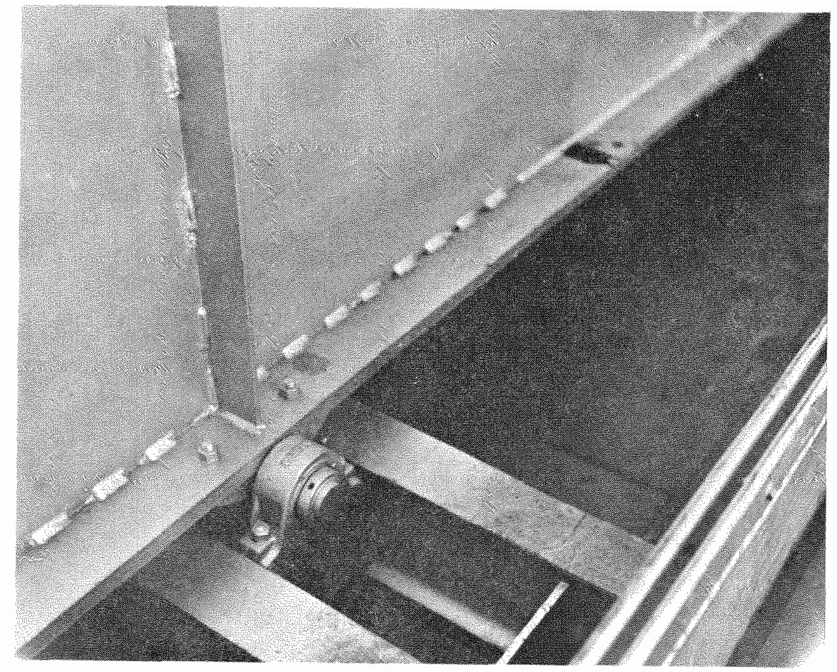


A. Iowa 24-foot flume.

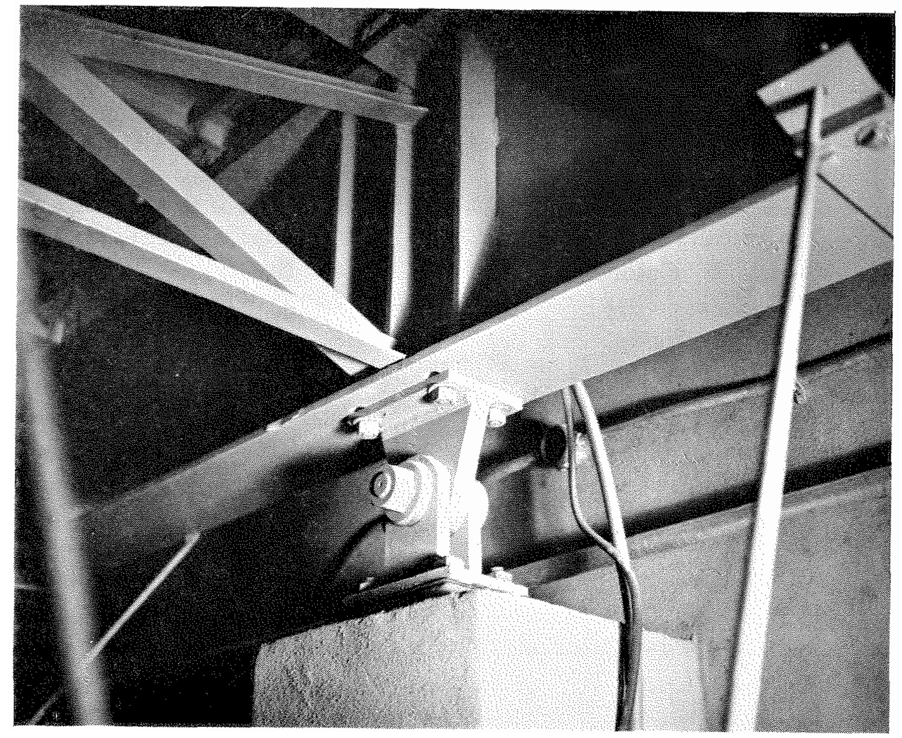


B. USWES 75-foot flume.

Figure 24.--Typical pivots for tilting a flume.

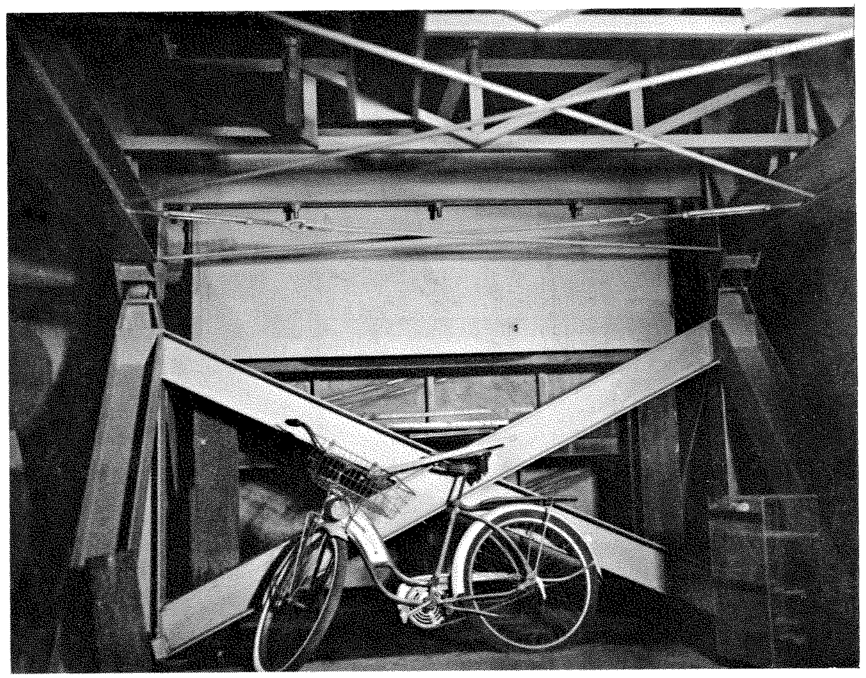


C. Georgia Tech 80-foot flume.



D. USDA 100-foot flume.

Figure 24, continued.



E. Colorado State Univ. 200-foot flume.

Figure 24, continued.

For research flumes the pivot is usually somewhere between the start and end of the test section, i.e. it is not ordinarily attached to the head tank or tailbox. This is because you reduce construction and flow-measurement problems by keeping at least one of these tanks approximately fixed in position.

By placing the pivot as far as possible from the slope-changing device (screw jack, chain hoist or whatever) you get a more sensitive control over the flume slope.

With nonrecirculating flumes and with free-overfall recirculating flumes any vertical displacement at the downstream end will be unimportant because the water is just going to plunge into a tank or channel anyway. Hence with these flumes you may as well place the pivot close to the upstream end. This provides more constant flow conditions as the water goes from supply line to headbox to flume. It also provides more constant sediment-infeed conditions with some feed systems. (We'll discuss flow conditions in the headbox and infeed conditions later in the manual.)

For the closed-circuit type of recirculating flume the pivot can be anywhere along the test section.

Height

The elevation of the pivot relative to the laboratory floor and the height of any other underneath supports depend on the length of the flume and the dimensions of the head tank and tailbox. It also depends on whether you want a trench under the flume (e.g. fig. 16C). Hence you'll have to wait until you've determined all of these features before deciding on the height of the pivot.

Construction details

Figures 18 and 24 show some typical pivots, all of which are simple and sturdy.

The pivot for a flume tilted by a block and tackle system must be a traveling pivot, as shown in fig. 25.

If you pivot the flume near one end you may need some sort of bracing near the other end to prevent any lateral sway of the test section. Two types of braces for this purpose are vertical posts on each side of the flume test section (fig. 18E) and a folding brace between the laboratory floor and the underneath side of the truss (fig. 20B).

Summary

Make the flume tiltable so that you won't suffer from the severe restriction of a limited or fixed bed slope. The flume can be tilted by screw-jacks, threaded posts, chain hoists or block and tackle arrangements. Use screw jacks or threaded posts to tilt the flume if the flume is longer than about 50 feet. Be sure to keep the number of jacks to a minimum and to interconnect them with shafts and gears such that a single motor or hand-crank operates all the jacks simultaneously.

Pivot the flume at or near the upstream end of the test channel if you have a large flume of the nonrecirculating or free-overfall recirculating variety. For closed recirculating flumes the location of the pivot is not too important, unless the tailbox is not rigidly connected to the channel, as explained in the chapter on tanks and auxiliary channels.

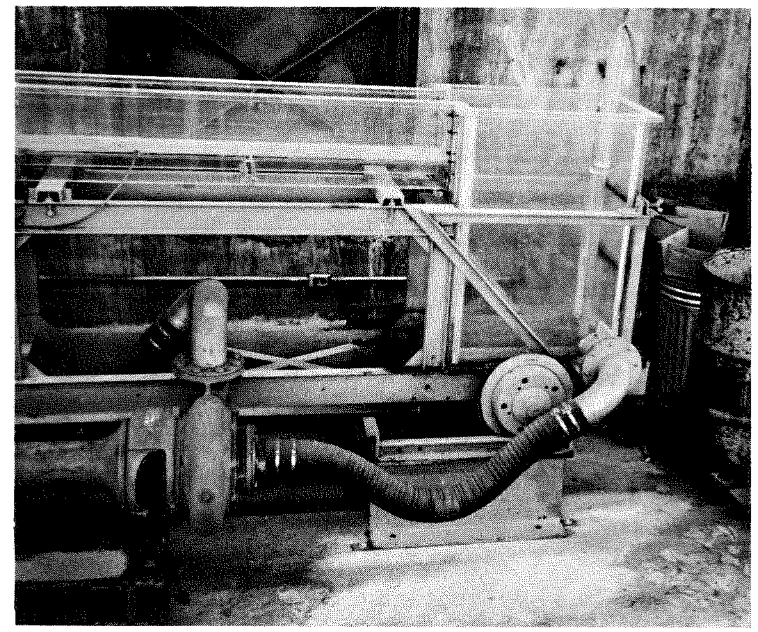


Figure 25.--Traveling pivot for flumes which are tilted by a block-and-tackle (USGS 30-foot plastic flume, Washington, D.C.).

SEDIMENT INFEED

By this time you have some ideas about the test channel, truss and tilting methods. For flumes which may some day be used for sediment studies, step number six is to decide how to feed in the sediment at the head of the test channel. (In recirculating flumes the water and pump do the feeding for you. Hence you can skip this chapter if you have chosen a recirculating flume.)

The requirements for a sediment-infeed mechanism are (1) the infeed rate must be constant, (2) the infeed rate must be measurable, (3) you must be able to feed very large as well as very small particles and (4) a wide range of feed rates, preferably variable by a factor of 1,000, should be obtainable.

There are two general methods commonly used to feed sediment into the water stream. In the first method particles drop into the water from above the channel. The second approach is to introduce particles directly onto the channel bed from a submerged elevator (rising platform). Let's look first at the advantages and disadvantages of each system.

The advantages of the "drop-in" feed method are:

1. Duration of run is not limited by the volume capacity of the infeed device. Hence an experiment can continue for as long as you desire, depending on the amount of sand you have.
2. Faster sediment-transport rates can be studied compared to the elevator feed system, for reasons explained below.

The main disadvantages of the drop-in feed system are:

1. Sediment must be nearly or completely dry or it won't flow at a constant rate (with the possible exception of gravel-sized particles).
2. Fine sand particles at fast water velocities may not settle to the bed for a considerable distance downstream, unless you use some method to overcome this.
3. The infeed device must be tended periodically during a run, to check on the infeed rate and to keep the machine supplied with sand.

The chief advantages of the elevator feed system are:

1. Sediment need not be dried prior to being loaded into the apparatus.
2. Smaller quantities of sediment are needed owing to the restricted volume capacity of the infeed system.
3. The infeed system does not have to be tended during the run.
4. No supplementary devices are needed to ensure that sediment is introduced evenly across the full channel width or to ensure that grains are not carried too far downstream before reaching the bed.

Disadvantages of this rising-platform feed method include:

1. The limited sediment supply (volume of elevator) severely restricts the range of experiments. For fast infeed rates the sediment supply is depleted before you can make the necessary experimental measurements. You are therefore limited to studying slower transport rates.

2. Construction is more complicated, mainly due to the problem of making the junction between the rising platform and the wall of the enclosing tank "sediment-tight."

Theoretically, voltage fluctuations and the decreasing load on the electrical drive system for the elevator could cause variations in the feed rate (Rathbun, Guy and Richardson, 1969); however, no one has ever mentioned having this difficulty. If such a problem arises a voltage regulator probably can solve it.

Drop-in method

By way of introduction to methods of feeding in the sediment from above the channel, it seems necessary to mention that feeding sediment by hand is much too imprecise for any scientific experiment. Some sort of mechanical regulation of the feed rate is indispensable.

Maximum feed rate

Choose the maximum feed rate (maximum sediment-transport rate) to be investigated before deciding on any details of the feeding mechanism. If laboratory experiments are to approach some of the conditions which exist in Nature, we must be able to study transport rates greater than those which have been investigated so far. Keep this thought in mind when designing not only the sediment infeed system but the other flume features as well.

A good maximum feed rate (sediment-transport rate) is about 20,000 pounds (dry weight) per hour per foot of channel width. Faster rates would be even better, so try to overdesign if possible.

Devices large enough to feed at a very fast rate may not be suitable for extremely slow infeed rates in very narrow channels (less than about 0.5 ft.). But you can easily set up a small and inexpensive mechanism for the latter conditions. (Uppsala Univ. has a good machine, described below, for slow feed rates.) Most people have found themselves restricted at fast transport rates rather than at very slow rates.

Supply hopper

Any arrangment for feeding the sediment from above the channel must include a supply hopper. The essential requirement of this hopper is that it must be large. A small hopper is worthless for fast feed rates. Furthermore, a large hopper will allow you to concentrate on the experimental measurements rather than devoting a lot of time to tending the sediment supply. Make the volume of the supply hopper at least 20 cubic feet for flume channels less than about four feet wide. For fast transport rates an even larger hopper probably will be needed.

Take a few moments to compute the time needed to empty a supply hopper of known volume, for several rates of sediment feed. (Figure on each cubic foot of dry sand weighing about 100 pounds. Remember, too, that transport rates are reckoned per foot of channel width, so multiply the transport rate per foot width by the channel width to get the feed rate.) The purpose of this computation is to give you an estimate of how frequently the supply hopper will need refilling, especially at fast feed rates.

Granular material often won't flow out of hoppers at a constant rate. Two articles which deal with this problem and which ought to be read before you build a hopper are the papers by Jenike (1954) and Lee (1960). Rather than building your own hopper you probably will be better off buying one. Companies that produce sand-feed machines also produce hoppers.

The hopper will be located above the flume channel, so the top edge of the hopper unavoidably will be rather high off the ground. You will need some sort of mechanical conveyor, such as an overhead crane, screw conveyor or tilted conveyor belt, to carry the sediment up into the hopper from the level of the laboratory floor (fig. 26). The only possible exception would be for short and very narrow flumes (less than about six inches wide) where the material can be carried up by hand. An overhead crane is an extremely useful tool to have in a laboratory.

Keeping the sediment at approximately a constant level in the hopper will help produce a constant feed rate to the flume. The U.S. Geological Survey group at Colorado State University accomplished this by fixing a large secondary storage bin above the hopper. They deposited the sediment in this storage bin, and from the bin the sand flowed by gravity through a tube into the hopper. The sand in the hopper stays about at the level of the tube outlet.

Feeding devices

There are various possible devices to regulate the feed rate of the sediment as it comes out of the hopper. One way of feeding the

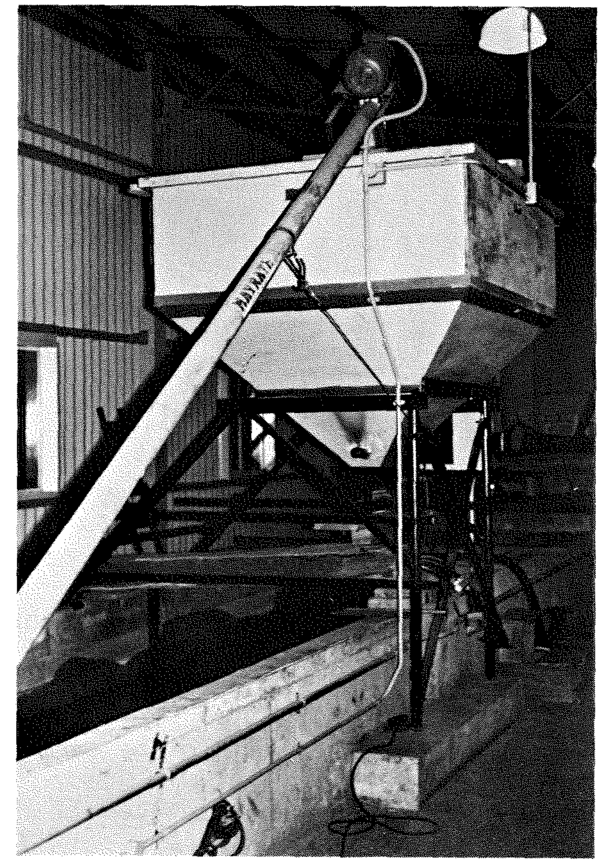


Figure 26.--One of the drop-in feed systems used at the Hydraulics Research Station, Wallingford, England.

sediment into the stream is by means of a vibrating trough just under the hopper outlet. In fact, commerical feeding machines (Syntron Co., Homer City, Penna. - fig. 27) are available which use this technique. Material from the hopper falls onto the feeder trough. The hopper is suspended within a framework by cables, and a lever near the bottom of the hopper tilts the hopper by degrees to vary the size of the gap between the hopper outlet and the trough just below. (Varying the diameter of the hopper outlet would accomplish the same thing.) A rheostat governs the rate of trough vibration. The rate at which particles fall off the end of the trough (feed rate) is regulated mainly by the rheostat but also by the size of the gap between hopper outlet and trough and by the inclination of the trough.

The attractive features of this machine are that it comes to you already built, hopper and all, and is easy to install. However, several people who have used it for sediment-transport studies report that the feed rate can be erratic (gradually changes, often in some unpredictable way). This may or may not be surmountable by keeping the sediment in the hopper at a constant level. But in any case the feed rate from a machine of this sort needs frequent or even constant checking during an experiment.

The Delft Hydraulics Labora.ory at De Voorst, Netherlands uses a variation of this method in which a vibrating screen takes the place of the trough. The distance between the hopper and the screen and the angle of the screen determine the feed rate.

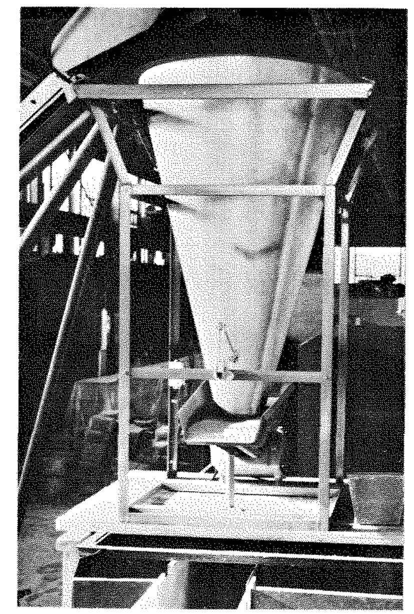


Figure 27.--Commercial hopper and vibrating trough sand feeder (USGS, Washington, D.C.).

The Hydraulics Research Station at Wallingford, England recommends a commercially-produced machine called Vibra-Screw (Totowa, N. J., USA) for feeding sediment. With this device the vibrating hopper leads into a horizontal tube which houses a rotating screw. The rotation of the screw pushes the sediment through the tube and out the far end, so that the sediment drops into the flume at a constant rate. The Hydraulics Research Station uses this feeder a great deal and finds that the feed rate is constant to within ± 2 percent. However, they point out that they have used it only with material of a fairly uniform size and say they have no experience of the machine's performance when handling material with a widely-distributed particle size range.

This machine has been modified by the Hydraulics Research Station by fitting a control system to permit the feed rate to be programmed either as a function of time or some other variable such as rate of water flow.

Another way of feeding the sediment from the hopper outlet is by means of a small conveyor belt (Callander, 1966; Leopold and Wolman, 1957). The rate at which particles drop off the end of the belt can be governed by the rate at which the belt travels, the diameter of the hopper outlet and the clearance between the bottom of the hopper and the belt. This type of machine also is available commercially (e.g. Vibra-Screw, Inc., Totowa, N. J., USA).

A third possible method uses a rotating wheel with equally-spaced notches or compartments, similar to a water wheel. Material from the hopper falls into the compartments or grooves on the wheel and is then

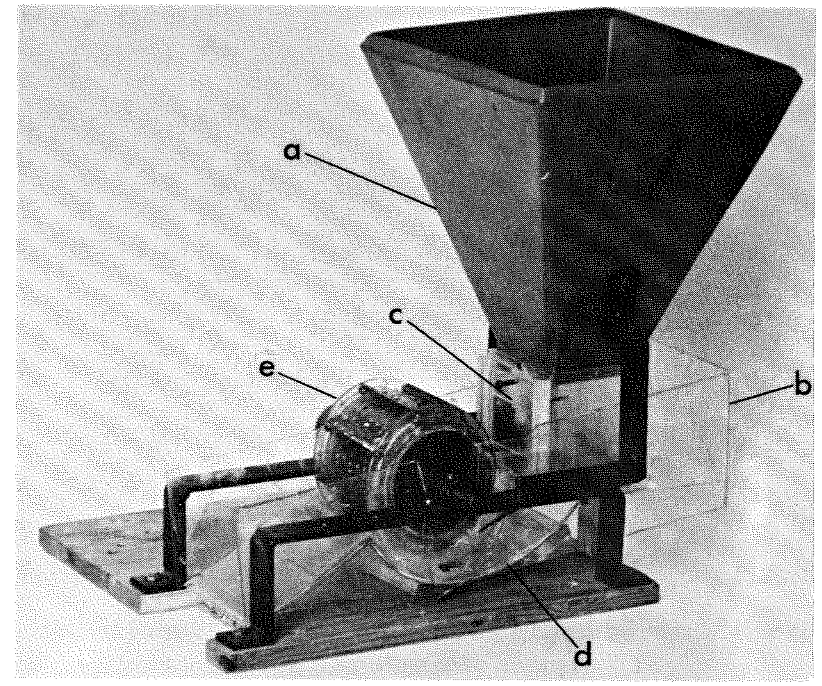
dumped into the stream as the wheel revolves. The feed rate is governed mainly by the rate at which a variable-speed motor turns the wheel and is also influenced by the size of the compartments and the size of the hopper outlet. G. K. Gilbert proposed this general infeed method in 1914 (1914, p. 241) but did not have a chance to use it because it was conceived only near the end of his investigation. The revolving wheel in his plan was a drum having a uniformly-roughened surface. Gilbert suggested a variable space between the bottom tip of the hopper and the drum.

H. A. Einstein (personal commun., 1968) while at Zurich successfully used a similar wheel arrangement, with some refinements added. In Einstein's apparatus the wheel, about two feet in diameter, had equally-spaced compartments of curved cross-sectional outline. The outlet size of a steep-walled hopper could be adjusted horizontally and vertically. The gap between the lower tip of the hopper and the revolving wheel had to be at least twice the diameter of the largest particle. Einstein used gravel-sized particles and found that he could feed these wet by sprinkling water onto the top surface of the gravel in the hopper.

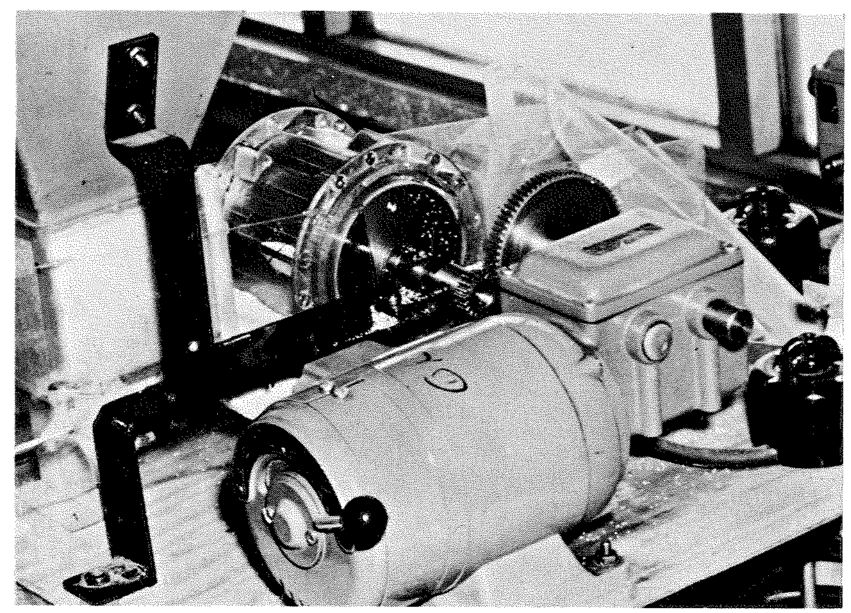
The Hydraulics Research Station at Wallingford, England has used essentially this same feed method. In their case the equally-spaced notches in the revolving drum were rectangular from a side view. Two rubber flaps hung from the opposite ends of the hopper outlet to keep the surface of the rotating drum brushed free of sediment.

The latest variation of this general feed method is at the Dept. of Physical Geography, Univ. of Uppsala. They have been interested in very slow feed rates - 5 to 800 grams per minute. In principle the chief difference between earlier models and the Uppsala device is that in the latter the sediment gets onto the rotating drum by being scooped up from underneath the drum, rather than falling onto the drum from above. The supply hopper is above and behind the rotating drum (fig. 28) and feeds sediment to a plastic box. The gravity flow of sediment continues from this box into a curved plastic trough located directly under the rotating drum. Exchangeable scoops of any specified width and depth are attached to the drum. As the drum rotates the scoops fill with sand from the trough below and dump the sand just after they reach their highest position. Removal of sediment from the trough brings in new material from the plastic box. A sliding panel on the outlet wall of this box is adjusted to insure that too much material does not enter the trough. Feed rate is governed by number and size of scoops, an electrical motor with a reduction transmission and step-less R.P.M variator and gear wheels between transmission and drum.

If the flume channel is considerably wider or narrower than the feeding implement (trough, belt, etc.), you will have to put in some sort of guides so that the sediment will enter the stream at about equally-spaced stations across the channel. A couple of deflecting surfaces (thin sheet metal or plywood, for example) often can be arranged to do this. Another possibility is to direct the sediment from



A. General view. a. supply hopper b. plastic box c. adjustable sliding panel d. sediment trough e. rotating drum (diameter and width 11 cm.).



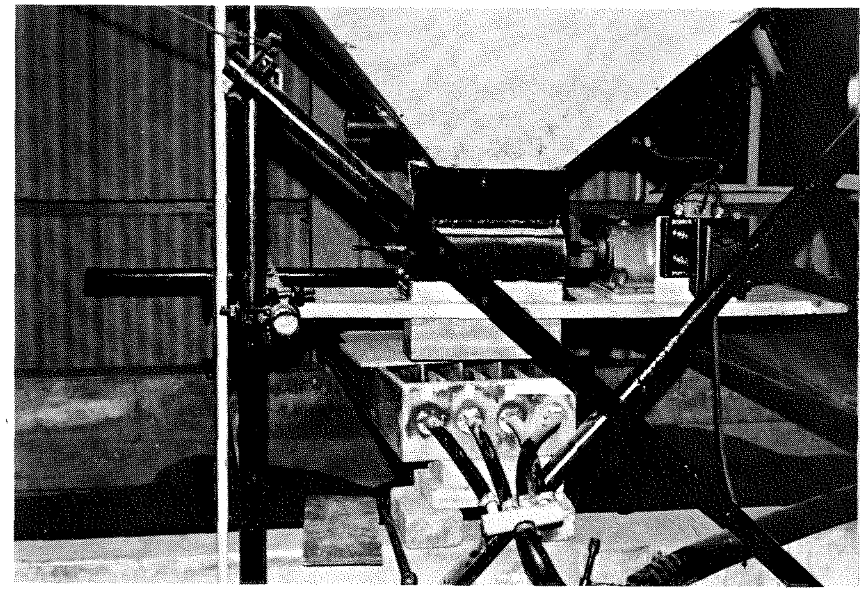
B. Close-up view of motor, transmission, gears and revolving drum.

Figure 28.--Hopper and rotating drum feed apparatus at the Dept. of Physical Geography, Univ. of Uppsala, Sweden (Univ. Uppsala photos).

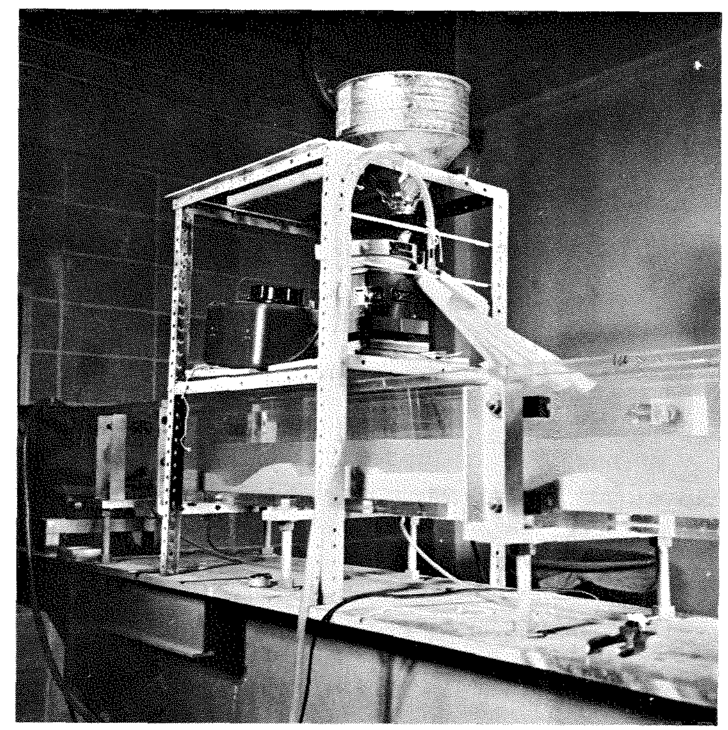
the feeding device into a general compartment from which tubes or troughs carry the sediment to the various release locations. If it is inconvenient to fix such tubes or troughs at a rather steep angle then a small amount of water can wash the sediment down each conduit (fig. 29). You will have to measure this discharge if it makes up a significant part of the discharge in the test channel. It may, on the other hand, be a negligible amount, or it may be procured in some manner from the flume water as part of the measured flume discharge.

Drop the sediment into the water as far upstream as possible. The sooner it settles to the bed, the better.

One bothersome disadvantage of the drop-in feed method is that you will have to pay attention to the moisture content of the grains. Gravel and larger particles can be fed wet or dry. Coarse sand must be dry or only slightly (and homogeneously) damp. Medium sand and smaller grains will have to be completely dry. If particles are not dried to the extent described, they will not flow out of the supply hopper at a constant rate. Indeed, they may not flow out at all. The commercial hopper and trough machine has tried (unsuccessfully, in my opinion) to overcome this by putting a vibrator on the hopper in an effort to obtain uniform packing and a steady flow rate. Washing the damp sediment out of the hopper with a steady trickle of water may help in obtaining a uniform feed rate. Drying the sediment probably will not be a major problem, however, if space is available.



A. Hydraulics Research Station, Wallingford, England device. Note also the revolving drum and lower part of supply hopper.



B. Arrangement used by USGS at Colorado State Univ.

Figure 29.--Washing sand into the stream by means of troughs and tubes.

Sediment drained until water stops dripping noticeably will easily dry in a day or two under normal laboratory temperatures and humidities, if spread on a floor to a thickness of 1-2 inches. Heating units or fans of course would hasten the process.

You will always have to set a desired rate of infeed by trial and error, regardless of whether the sediment is dry or partly moist. This is easy to do. Approximate settings for various feed rates can serve as permanent guides, as long as the moisture content of the sediment doesn't change radically. Then a few quick trials will give you the feed rate you want.

Several people have experienced difficulty with dropped particles of sand floating on or near the stream surface due to attached air bubbles or to surface tension. Callander (1966) solved this problem by having the grains blown down a special duct and off a deflector with sufficient speed that they penetrated the water surface and then sank. The Univ. of Uppsala's solution was to route the feeding channel to a vertical pipe which extended down into the water and to spray the particles with water in this pipe. Iowa used this same system but with several tubes rather than just one. The use of tubes or pipes has the additional advantage, with fin. sediment at least, of introducing the particles closer to the stream bed so that they do not drift too far downstream before reaching the bed.

Extremely fine particles (<0.1 mm) may be transported largely in suspension regardless of how they are introduced.

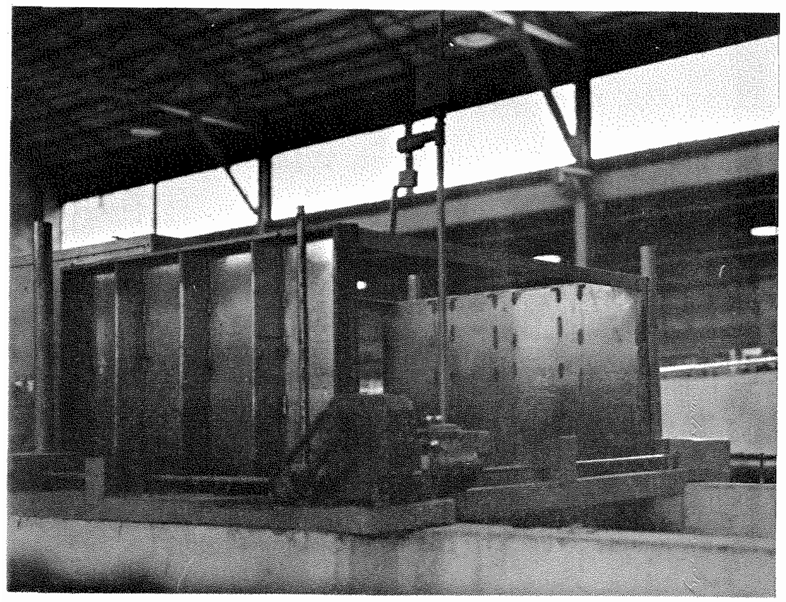
If you adopt the drop-in feed system put a false (second) floor over the first few feet of the test channel, i.e. over the reach where no sand accumulates. Roughen this floor with tacks, screen or the like. This false floor has several purposes: (1) the sand bed builds up sooner (i.e. further upstream than it would without the false floor); (2) the boundary layer becomes fully developed closer to the channel entrance: (3) during the experiments, observing the downstream end of the false floor can reveal scour or fill, an indication that the sand bed is decreasing or increasing its slope.

The height of the secondary floor above the permanent channel floor should be equal to the depth of the sand bed in the upstream end of the test section. The floor should extend downstream to a point just further than the point of impact of the grains hitting the bed, unless this distance is unfeasible. A plywood board will suffice.

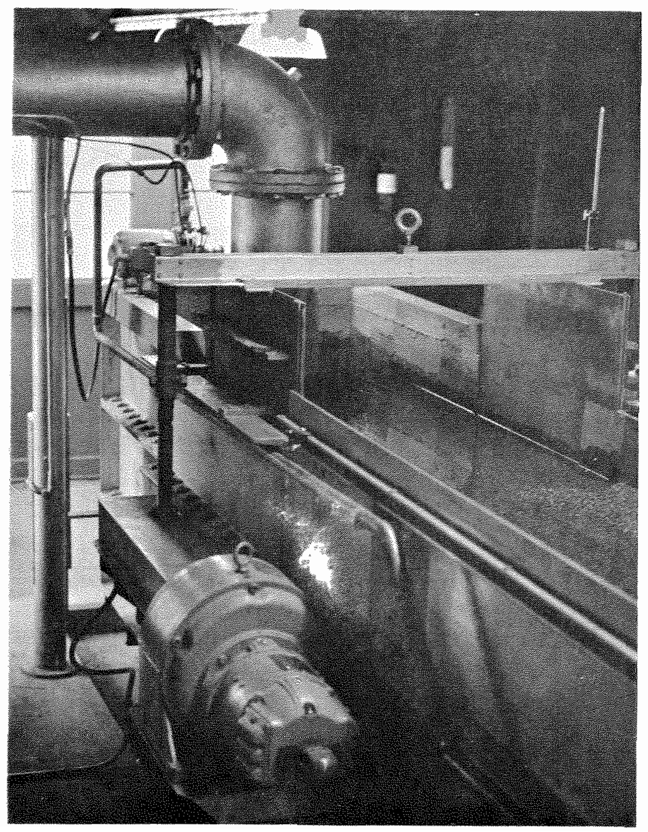
Rising-platform method

For the rising-platform method you need an elevator and an enclosing tank, located directly between the stilling tank (headbox) and the test section. Sediment is loaded into the elevator, up to the level of the test bed. The elevator, consisting of a floor and two sidewalls, rises at a constant rate, enabling the flowing water to scour off the sediment and carry it into the adjoining test section (fig. 30).

When the rising floor gets up to the channel level the sediment

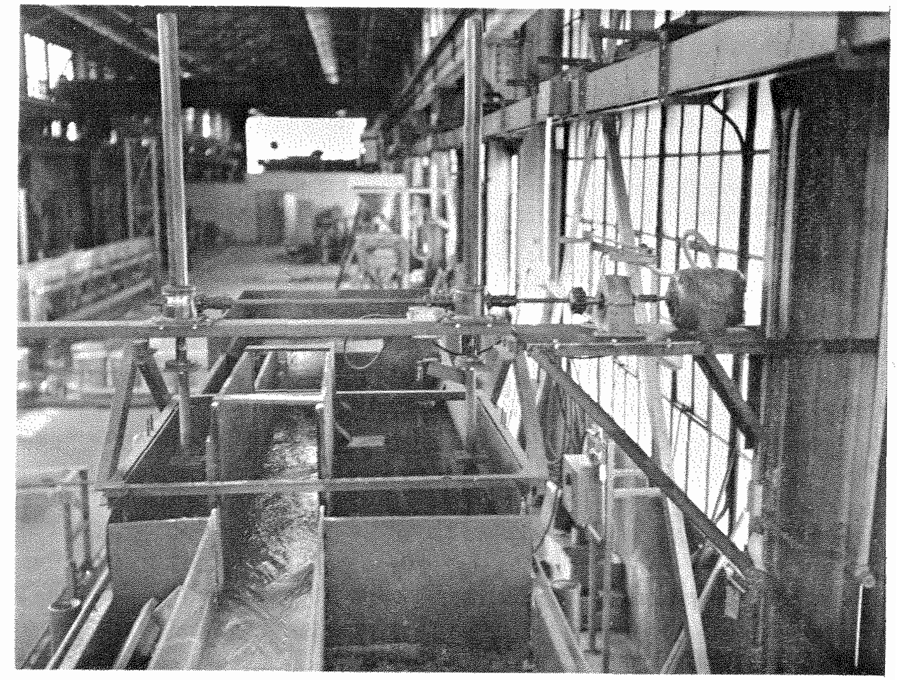


A. Iowa scour flume.



B. USWES 75-foot flume.

Figure 30.--Elevator-type sand feeds.



C. USGS 52-foot flume.

Figure 30, continued.

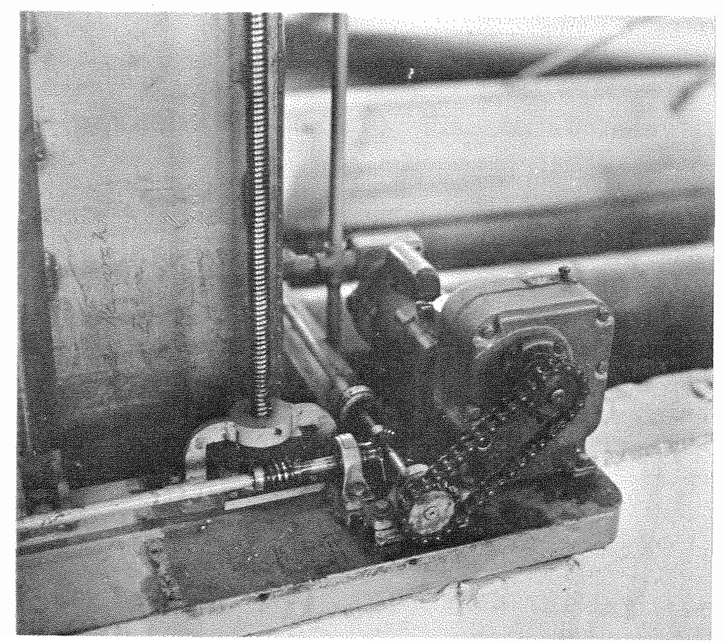


Figure 31.--Motor and system of interconnecting screw jacks on elevator sand feed, Iowa scour flume.

supply of course is exhausted, and the run will have to be temporarily or permanently stopped.

The platform usually is elevated by means of a variable-speed motor, screw jacks and various reduction gears. Although it is possible to elevate a platform with single-acting hydraulic cylinders, lowering them back down to the starting position is awkward and difficult.

Two screw jacks, one on each side of the channel, are ordinarily enough to ensure that the floor does not tilt significantly during its rise (USWES at Vicksburg; USGS at Washington, D.C.; St. Anthony Falls). To keep the floor precisely horizontal or with large elevators you can use four screw jacks - one regulating each corner of the platform (Iowa). The Delft laboratory at de Voorst uses a hydraulic lift on a flume 10 feet wide.

Dimensions

The rising platform can be of any shape - circular, rectangular, etc. A rectangular shape is most common and simplifies construction problems, especially when temporary narrower channels may be installed in the future.

The weight or volume of sediment fed into the test section per unit time depends on the length and width of the false bottom and the rate of its rise. It also depends on the density of packing of the sand within the elevator, and this may vary from sand to sand. The platform width must be the same as the flume test section. Consequently, the infeed rate can be varied only by changing the length of the platform or the rate at which the platform ascends.

The downstream length of the elevator usually does not exceed four feet, in most existing laboratory flumes. Elevators longer than about four feet are a little more complicated (they probably need four jacks instead of two) and more expensive. With an elevator four feet long you will probably be able to study sediment-transport rates up to about 0.5 pounds (immersed weight) per second per foot width. For a given rate of floor rise this figure depends in part on the depth of the infeed bin, because even at extremely fast transport rates you'll need at least a half hour to make a run. (Runs at slow transport rates can take many days.) Plan on at least three feet of platform rise.

Construction

(a) Jack and motor details. There are two possible orientations for the screw jacks. One arrangement is with the jacks in a normal position beside the tank walls so that the platform is pushed upward (fig. 30B). The alternative is to invert the jacks so that they draw the floor upward (fig. 30A, 30C). With the latter arrangement, used by Iowa and the USGS (Washington, D. C.), the jack housing points toward the laboratory ceiling so that longer jacks can be used. This provides a greater sediment-infeed capacity.

The advantage of greater infeed capacity with inverted screw jacks does not apply if the flume pivot is between the entrance of the test channel and the adjoining elevator infeed section, because the elevator section then remains fixed (does not tilt with the flume). Thus the jacks could be normally oriented and the jack housing conceivably could extend into the laboratory floor. If the elevator feed section tilts along with the test channel (USWES), then the complete jacking system including the motor must be attached to the infeed tank.

Interconnect the screw jacks with rods and couplings so that the jacks rise in unison (fig. 31). The rate of rise is governed mainly by a variable speed control on the motor and can be further regulated by inserting various gears between the motor and jacks. If the very slowest rate of rise is still too fast for extremely slow feed rates install a precision potentiometer and an interrupter for intermittent elevating (USWES). The potentiometer controls the voltage going to the motor and can be set for any desired time periods - 30 seconds on and 30 seconds off, or whatever. E. M. Laursen when at Iowa also used the principle of intermittent elevating and found that the overall sediment feed process was just as good as with the motor running steadily.

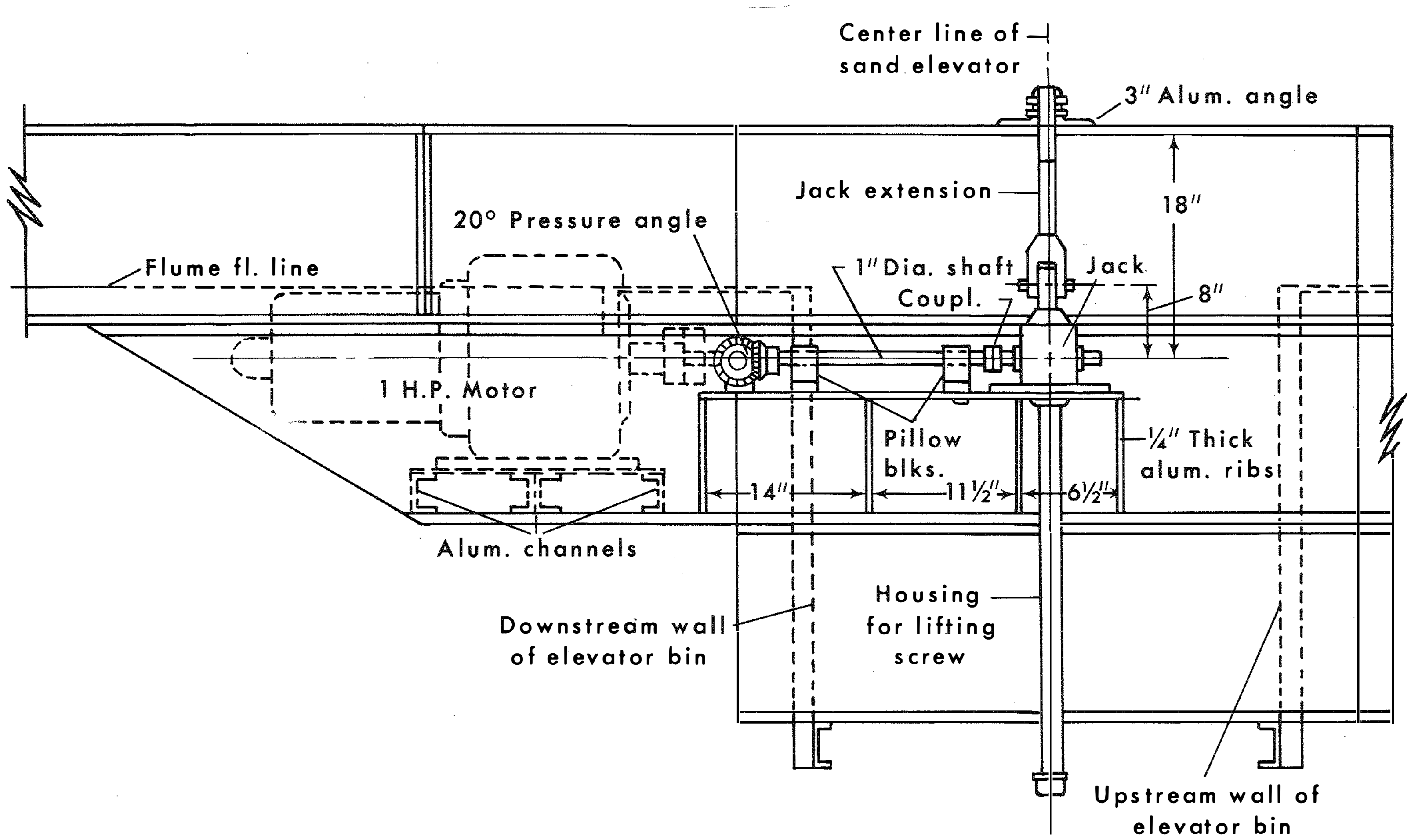
Motors used for elevator infeeds are usually in the range of $\frac{1}{2}$ to 1 H. P.

Sometimes the line voltage in a building can change slightly, for example at the end of a normal work day. This could in turn affect the infeed rate. One flume-specialist mentioned the desirability of a voltage regulator to guard against this potential problem; another laboratory, however, did not think this was necessary.

You'll also need automatic shut-off switches at the top and bottom of the elevator's range. These can be ordinary push-button switches in a fixed location, activated by a small foot attached to the elevator. Figures 30A and 30C show two examples.

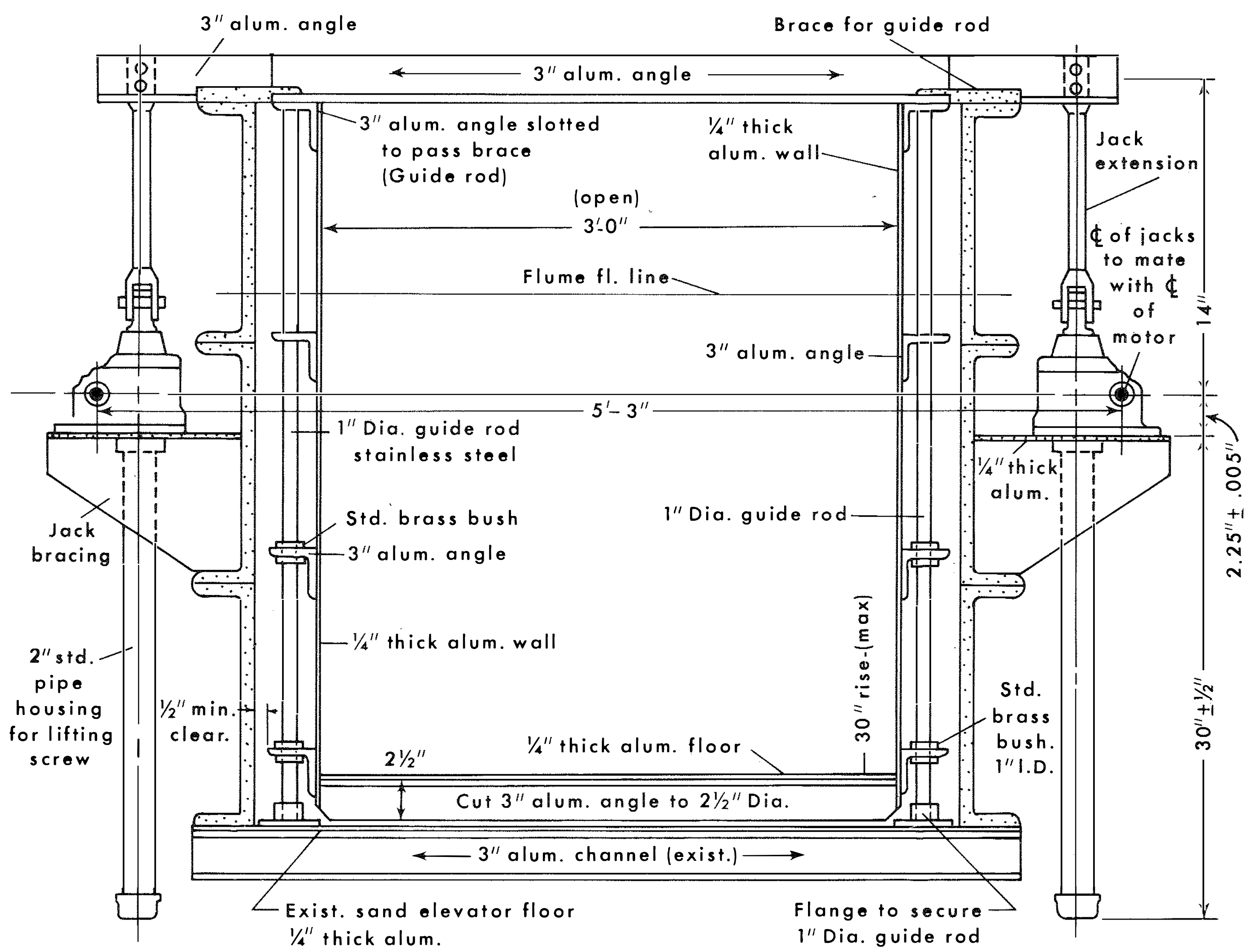
(b) Platform. The rising platform should be of steel or aluminum since it will always be immersed in water. Stainless steel saves you the trouble of repainting once or more per year but is about 20 times as expensive as regular steel. A plate thickness of $\frac{1}{4}$ inch is common.

Reinforce the platform on the underneath side with structural channels or angle braces (fig. 32). By keeping the platform as plane as possible you relieve stress on the jacks and shafting and you reduce the chances of sediment leakage along the upstream and downstream edges of the elevator.



A. Side view.

Figure 32.–Elevator sand feed, USWES, Vicksburg, Miss.



B. End view looking downstream.

Figure 32, continued.

Preventing sediment leakage is probably the main problem with an elevator infeed. Leakage can occur along the vertical edges of the elevator sidewalls as well as along the upstream and downstream horizontal edges of the floor. There is usually no trouble with coarse sand and gravel; however, fine sand requires a particularly efficient seal. Aside from the nature of the seal itself, discussed below, you can reduce the likelihood of sand leakage by (1) making the walls of the enclosing tank very straight and rigid, (2) fitting the elevator snugly inside the enclosing tank ($\frac{1}{2}$ inch clearance at most), and (3) making sure that the platform stays perpendicular to the enclosing walls as it rises.

Welding angle-irons or other structural pieces to the upstream and downstream exterior walls of the enclosing tank helps keep these tank walls plane. Another way of keeping these walls plane is to mount them in concrete, as in the Iowa non-tilting "scour flume."

There are several ways of keeping the platform perpendicular to the sidewalls during its rise. Both Iowa and the USWES have particularly good ways of doing this. At Iowa the exterior of the elevator sidewall has three equally-spaced vertical braces, welded on (fig. 30A). These are V-shaped, with the point of the V outward. The tip of each brace rubs against a small roller which is fixed to the top of the enclosing tank. Both sidewalls have similar arrangements. The four screw jacks, rather than two, also help. The USWES elevator has guide rods (two for each of the two sidewalls) fixed rigidly to the inside of the enclosing tank (fig. 32B). Each rod fits into several slotted braces attached at vertical intervals to the outside of the elevator wall.

The seals on elevators used in the USA consist of rubber strips (St. Anthony Falls; USWES; USGS; SUNY at Buffalo) or of sponge-rubber held by thin metal strips (Iowa). Rubber strips should be about $\frac{1}{4}$ inch thick, and along the horizontal edges of the rising floor they should deflect upward. The SUNY at Buffalo elevator has an efficient sheet-rubber seal with the rubber fastened to the underneath side of the platform. The rubber curls upward along the edge of the platform and is pressed tightly against the enclosing wall (glass, in their case). In the corners and in places where pieces of rubber had to be lapped or joined Tygon or rubber tubing was fixed between the platform edge and the rubber sheet. Dow-Corning Silastic Rubber caulk helped stop any corner leakage, on the elevator. Figure 33 shows the efficient sponge and metal-strip seal used at Iowa. Leather is not effective as a sealer.

With the width and length of the elevator compartment fixed, the rate at which the elevator rises determines the sand-feed rate. One way of measuring the feed rate is to calibrate the speed control on the motor to find the rate of platform rise that corresponds to each dial setting for the variable-speed motor drive. A second and better method is to attach a counter to one of the screws or rods, to get the number of turns (Iowa). This can then be calibrated with distance of platform rise. But the most precise way of determining the sediment feed rate is to directly measure the vertical distance of platform rise over a timed interval.

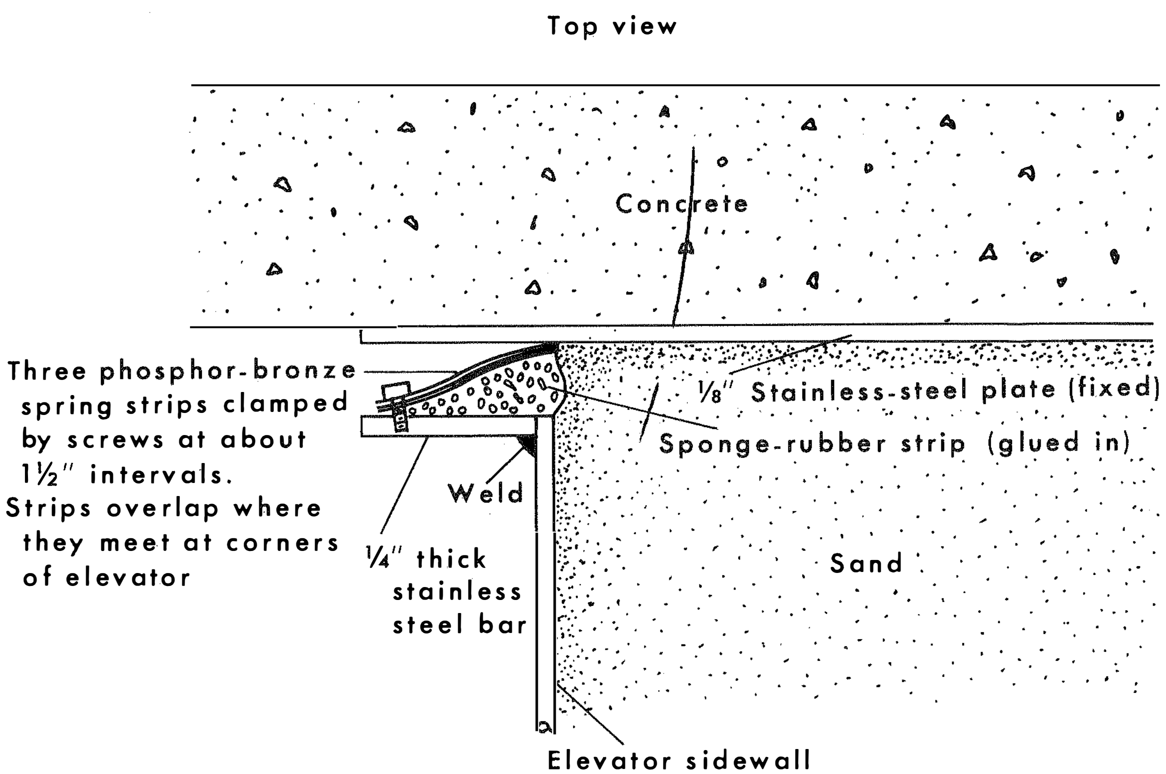


Figure 33.--Seal along vertical edges of sand-feed elevator, Iowa scour flume. Same type of seal is used along horizontal edges.

The USWES flume has a good arrangement for measuring this platform rise. The bottom tip of an ordinary point gage is fixed vertically to the top of the enclosing tank's sidewall. The housing and vernier portion of the point gage are attached to the top of the elevator and travel upward with the elevator. At any given moment you can thus read the elevation of the platform relative to the fixed datum (top of enclosing tank).

(c) Enclosing tank. Make the watertight enclosing tank out of metal plates, $\frac{1}{4}$ inch thick.

The tank dimensions depend on the flume width, the length of the elevator floor and the length of the screw jacks. (Actually you may decide on the length of the screw jacks and the tank depth at the same time.) The tank width will be equal to the flume width plus the space needed for guide rods or jack extensions (see figs. 30B and 32B). The length of the tank will be the length of the rising platform plus the clearance at each end, i.e. platform length plus about one inch. The tank depth need be only a few inches greater than the depth of the elevator (fig. 32).

It is important that all four tank walls be plane. Structural channels or angle braces fixed to the outside face of the wall will accomplish this.

It is worthwhile to have a removable panel near the bottom of one of the tank walls, say a sidewall, for access to the interior. (You may, for example, want to clean out any sand that may have leaked down.) Be sure to make this panel large enough for a man's shoulders to pass through. You might also consider making part or all of this panel transparent to help check for sand leakage.

Install a small faucet in the floor of the tank to empty the water.

Summary

The two methods for feeding sand into a flume are to (1) drop the grains from above the stream or (2) elevate the particles from below the channel bed so that the stream scours them. Both methods are popular.

The drop-in method requires a large hopper; otherwise you lose one of the big advantages of this infeed method, namely, the ability to study fast sediment-transport rates. The sediment can be fed by screw systems, by vibrating troughs or screens, by endless belts or by revolving wheels. With the possible exception of gravel the grains will have to be dried in order to get a steady feed rate.

Once the initial construction is completed the elevator infeed is much easier to operate. However, the limited sediment supply prevents you from studying fast sediment-transport rates. The elevator platform can be drawn up by inverted screw jacks or pushed up by screw jacks oriented normally. For given platform dimensions the sediment-infeed rate mainly depends on the rate at which the platform rises. This in turn is governed by the motor speed and by reduction gears between the motor and jacks. Three aids to prevent sand leakage, in addition to a firm and pliable seal, are (1) keep the walls of the enclosing tank plane and rigid, (2) fit the elevator snugly inside the enclosing tank, and (3) make sure the rising platform always stays perpendicular to the enclosing walls.

SEDIMENT TRAPPING AND WEIGHING

Step number seven concerns the collection of sediment and the measurement of sediment-transport rates. Sediment collection must be discussed at this point, at least for nonrecirculating flumes, because the size and location (elevation) of the collection box can influence the elevation of the headtank (if fixed in position) and the route of the piping at the head of the flume (see fig. 3).

The most accurate way to measure the sediment-transport rate is to collect all of the discharged sediment particles for a timed period. This is easily done in nonrecirculating flumes by using a large container at the downstream end of the flume; sand accumulates in the bottom of the container while the water escapes over the top.

Recirculating flumes don't have any collection box as such (fig. 2). Special sampling methods are used instead, and we'll discuss these methods near the end of this chapter. (You can turn to that discussion right now if you have chosen a recirculating flume, as the next section here deals with trapping the total sediment load.)

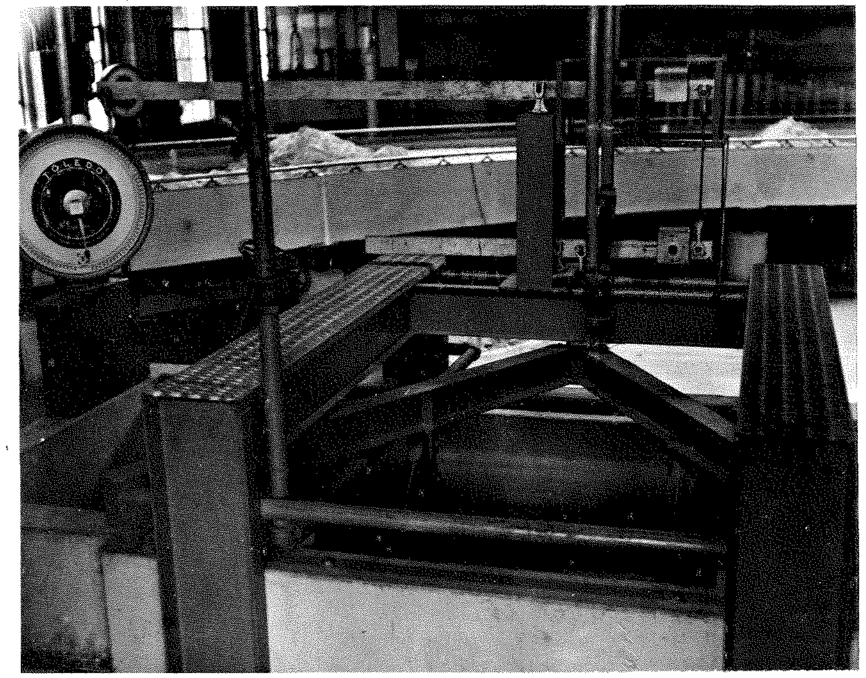
Trap location

The two most common locations for the trap used to catch the total sediment load at the downstream end are:

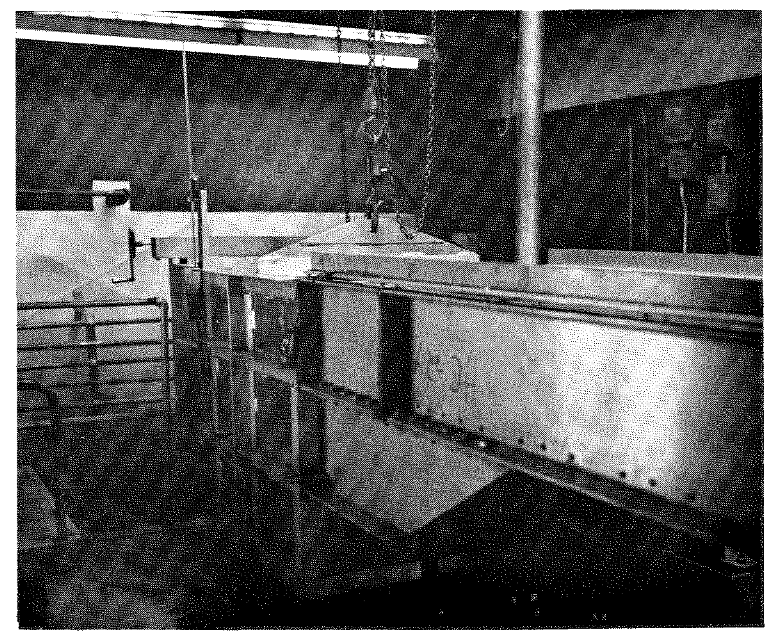
1. Upstream from the tailgate so that the test section and collection box have a common, continuous water surface. Flumes at Iowa, Vicksburg (USWES) and St. Anthony Falls have this arrangement (fig. 34).
2. Downstream from the tailgate, i.e. below the downstream tip of the flume. Figure 35 (USGS in Washington, D. C.) shows two examples.

The main advantage in placing the trap upstream from the tailgate is that the continuous water surface eliminates the turbulence and downward force which otherwise occur as the water and sand enter the trap. You therefore get a much steadier and hence more accurate weight reading. A minor advantage is that you don't need any special means of checking on the water level in the trap, as explained below.

Putting the trap downstream from the tailgate has a number of advantages, especially for tilting flumes. Firstly, you are less restricted in regard to the size of the collection box. Secondly, you may not have to build a special enclosing tank. Thirdly, for tiltable flumes you avoid the construction work of including this extra enclosing tank into the rigid structure of the test channel. A fourth and major advantage is that instead of just one overflow wall you have three or four trap walls available for water overflow. This is a big help in getting the sand to settle in the box. Fifth, screens can be used around the top of the collection box to help trap the sediment. (Such screens can't be used when the trap is upstream

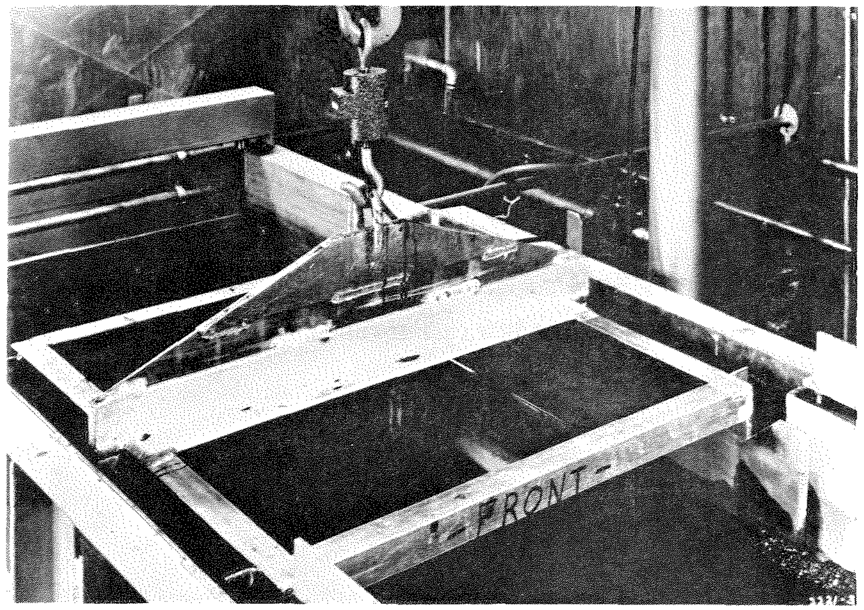


A. Iowa scour flume.



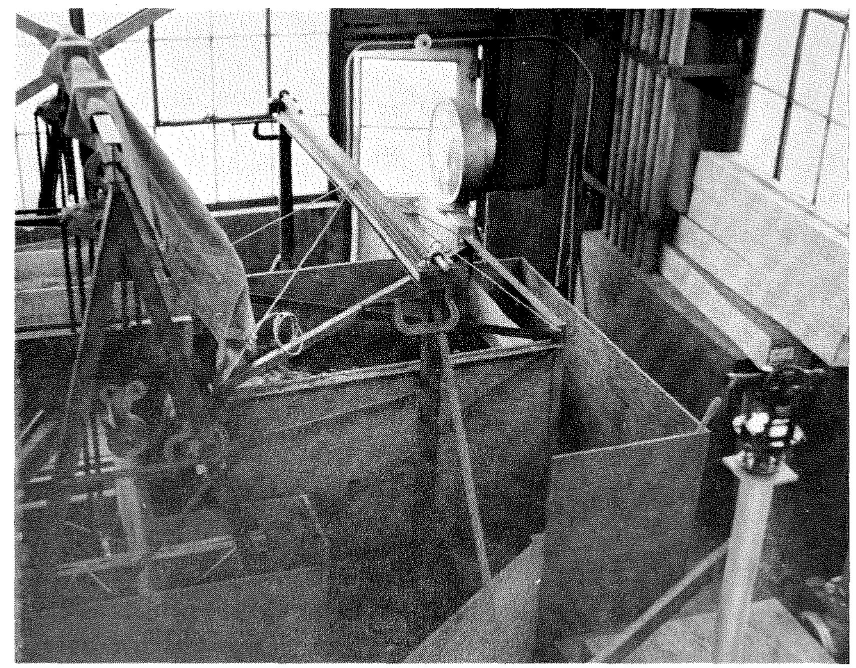
B. USWES 75-foot flume.

Figure 34.--Total-load sand traps located upstream from the flume tailgate.

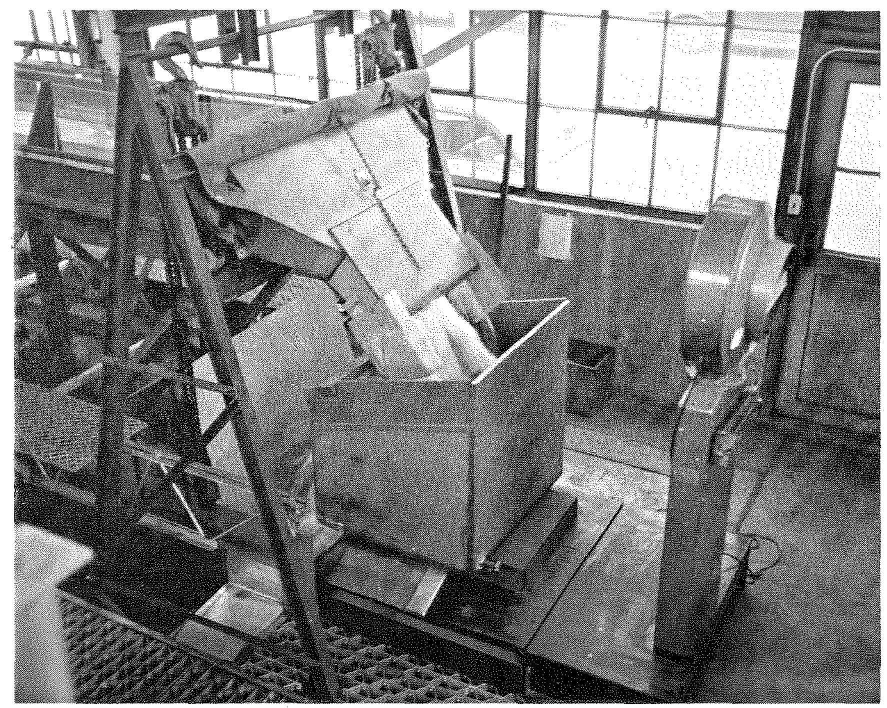


C. USWES 75-foot flume (USWES photo).

Figure 34, continued.



A. Suspended trap, with scale off to one side.



B. Collection box resting directly on scale platform.

Figure 35.--Total-load sediment traps below the downstream end of the flume (USGS, Washington, D.C.).

from the tailgate because they would affect the level of the water surface, i.e. the depth of flow in the flume.) Also, you can usually tilt the flume to steeper slopes, compared to situations where the enclosing tank is rigidly included in the structure of the test channel. Finally, you have much easier access to the interior and exterior of the trap.

Trap size

Just as the sediment infeed should be capable of providing fast sediment-transport rates, so also should the downstream collection box be LARGE. There are two reasons for this: finer particles tend to move with the water and don't settle out in small boxes, and at fast sediment-transport rates a small box fills up much more quickly. The inability to measure fast sediment-transport rates, where large quantities of sediment are moved in short time periods, has severely limited most studies done in nonrecirculating flumes. Moreover, you get a reliable sediment-transport measurement only by waiting for at least several bed forms (e.g. ripples or dunes) to migrate into the collection box. Thus if the trap is too small you simply won't be able to study fast transport rates. (One possible alternative, not always practical, is to use several collection boxes, as discussed below.) Even at intermediate transport rates you may have to stop a run because the box fills up before you can take all the experimental measurements. Many people have had these unfortunate

experiences with small sand traps, and here again you can benefit from their experience. So make the box big. Now, how big?

First, compute a rough estimate of the maximum rate at which sediment will accumulate in the collection box. This you can do from a knowledge of the maximum flume width and a maximum sediment-transport rate. For example, suppose the maximum rate to be run is three pounds per second per foot of channel width (a worthwhile goal) and the flume is four feet wide. For these conditions sediment will enter the collection box at the rate of 12 pounds per second or 720 pounds per minute. Sand weighs about 100 pounds per cubic foot, so the box will collect about 7.2 cubic feet of sand each minute. A run takes at least 30 minutes at very fast transport rates. Hence for this example you'll get a total of about 216 cubic feet of sediment during the run. You can see that a large container will be needed.

Next, remember that only the lower 75 percent of the box will be available for sediment collecting; in the upper region water will be flowing out and several inches of water depth will be useful as protection against scour. So increase the estimated maximum sediment volume by at least 25 percent. This gives a general figure for the desirable volume of the collection box.

A rule-of-thumb for flumes using an elevator infeed is to make the trap volume a little greater than the volume of the elevator. However, you may switch to the drop-in feed method at some time in the future, so this is not always a reliable criterion.

The depth of the collection box may have to be restricted lest the upstream end of the flume be too high in the air when the flume is at its maximum slope. If possible, though, make the box at least three feet deep.

With the trap depth somewhat restricted, the width and length of the box have to provide much of the required volume.

The length of the box should be at least six feet to allow for settling and distribution of the sediment. You may need a longer box, say 10 feet long, if (1) the water and sediment entering the box cannot be directed downward rather than directly toward the box outlet (the further the point of entry from the exit, the better); (2) you are using sand-sized grains rather than larger grains (more settling distance required as grain size decreases); and (3) the flume width is greater than about three or four feet (more sediment involved).

Make the width of the trap at least equal to, and certainly for narrow flumes greater than, the flume width. A wide trap gives a larger cross-sectional flow area and hence a slower mean velocity, so that the grains settle out quicker.

At slow transport rates several small containers conceivably could be used, rather than one large container. One possible arrangement is to have these smaller containers ride on wheels or rails so that they can quickly be moved into position to catch sediment (Gilbert, 1914). Or, the boxes might remain in place and a diverter or spout on the end of the flume can direct the flow into each box in turn. Both

arrangements, though, mean extra work during the run. And you'll be very busy anyway during runs that involve large quantities of sediment. Also a smaller container causes a lot of turbulence which is undesirable for in-place weighing. In most cases you save a lot of trouble by having a single very large container.

Weighing

Weighing in-place versus weighing elsewhere.

The rate of sediment transport (weight of sediment collected per unit time) can be determined directly if you make some provision to weigh the collecting box and its contents in place. Otherwise you have to either remove the trapped sediment (possibly with the collecting box) and weigh the sediment elsewhere or resort to one of the less-accurate special sampling methods described later. Both weighing in-place and weighing elsewhere have been used successfully, but the best system is to periodically weigh the material in place, as it accumulates. This automatically provides a continuous record of sediment-transport rates (weight in box is plotted as a function of time). Such a record is a valuable aid in determining whether equilibrium conditions have been obtained in the test section (sediment input = sediment output). Weighing the trapped sediment elsewhere is more time-consuming and laborious, sometimes requires extra construction and traps to catch or segregate the sediment leaving the flume while a collected amount is being removed, and presents difficulties in getting a continuous record of sediment-transport rates.

By weighing the trapped sediment in-place, under water, you get what is known as the immersed or submerged weight. This weight is really more appropriate than dry weight (weight of dry sand in air) in describing sediment-transport rates because the phenomenon of sediment transportation takes place in the present case wholly within the water. Immersed weight implies a displacement of water equal in volume to the volume of the sediment being weighed. In order for this equal displacement to occur the water level in the collection box must remain constant. (Methods of maintaining and checking this water level are discussed below.) Knowing the specific gravity of the sediment (e.g. 2.65) and the specific gravity of water (1.00), the immersed weight of such material is equal to $\frac{2.65 - 1.00}{2.65}$ x dry weight = 0.624 x dry weight. Thus immersed weight can easily be converted to dry weight and vice versa.

With most in-place weighing arrangements the collection box hangs by cables or chains. If the trap is located downstream from the tail gate, you can choose between suspending the trap and placing it directly on a scale. The latter method is simpler from the construction point of view. On the other hand, by suspending the box you gain more area around the top edge of the box for water overflow so that the grains settle more readily. Furthermore, you can use a smaller-capacity weighing device (the force pressing on the weighing device is less, for the same trap weight). Either arrangement may be feasible for your circumstances.

If the box rests directly on a scale platform, you'll have to keep the platform from being flooded with water. Two aids in accomplishing this are (1) a waterproof cover over the scale platform and (2) protective walls bordering those sides of the scale platform where water overflows from the box.

Weighing devices

Most nonrecirculating flumes use a standard platform scale to weigh the trapped sediment. The scale may sit directly under the collection box or it may sit off to one side of the trap (fig. 35).

With a suspended trap a strain gage (Moore, 1960) can be used (fig. 34B and 34C). The strain gage on the USWES flume at Vicksburg is a Baldwin SR-4 load cell with a 1,000-lb. capacity. The gage records electrically, directly onto a graph, which can be accurately read to $\pm$ five pounds (estimated to half of this or $\pm 2\frac{1}{2}$ pounds). The gage is easily removed (slipped off the chain hook) when not needed.

Callander (1966) weighed the trapped sediment in-place with a precalibrated lever and fulcrum system. Selected weights hung from one end of the lever. When sand had accumulated over a timed period in an amount proportional to the hung weight, the lever shifted position. An alarm bell triggered by the lever signaled this shift of the lever's position.

An alarm bell can also be used on a regular beam scale. However, alarm bell techniques are poor, or at best offer no advantage, when sediment collects at slow rates. The triggering lever or scale beam shifts position so very slowly and irregularly that an unacceptable amount of subjectivity is introduced in deciding when the bell is firmly ringing. The same problem arises in judging the lever's position by eye.

If the weighing device is directly to one side of a suspended collection box then the weight reading is reduced by a factor proportional to the horizontal distance from the point of suspension to the weighing device. You'll therefore need a calibration between the weight in the trap and the value indicated by the weighing device, to get the constant of proportionality.

When purchasing a scale or strain gage be sure to take into account the maximum possible weight (box filled with immersed sand) of the collection box, along with the location of the box relative to the weighing device. Then increase your initial estimate of the required capacity by a factor of about 1.5.

Scales with a dial face are easier to work with than beam scales on which weights are shifted.

Suspended traps

Figures 34 and 35A show some arrangements for suspending a sediment trap. All of these cases have a very strong cross-beam arrangement, i.e. one which can support the maximum trap weight without bending. Steel I-beams or channels are probably best for this.

The shorter the beam, the less likelihood of its bending. Iowa in fact uses two beams rather than one, as fig. 34A shows. This is more stable in addition to being less likely to bend.

Because the Iowa "scour flume" (non-tilting) is on the level of the laboratory floor they were able to use low concrete walls to support the cross-beams (fig. 34A). Their collection box fits into a pit in the laboratory floor. Originally the scale sat on the floor adjacent to the collection box but later, in order to get more floor space, they placed the scale on top of the tailbox wall and arranged an intricate lever system (fig. 34A).

In many cases designed for in-place weighing the bottom of the sediment trap is above the level of the laboratory floor. The cross-beam is then too high above the laboratory floor to make a tailbox-wall-support feasible, and some sort of vertical steel supports, ceiling support or both become necessary. The USWES (fig. 36) has a heavy steel I-beam fastened to the ceiling, supported by a vertical pipe on each side of the collection box.

With the USGS arrangement (fig. 35A) the support at one end of the cross-beam stands on the laboratory floor while the support holding the other end of the cross-beam presses directly onto the scale platform. In frameworks of this sort the vertical support resting on the scale platform must not be too tall; it will tend to

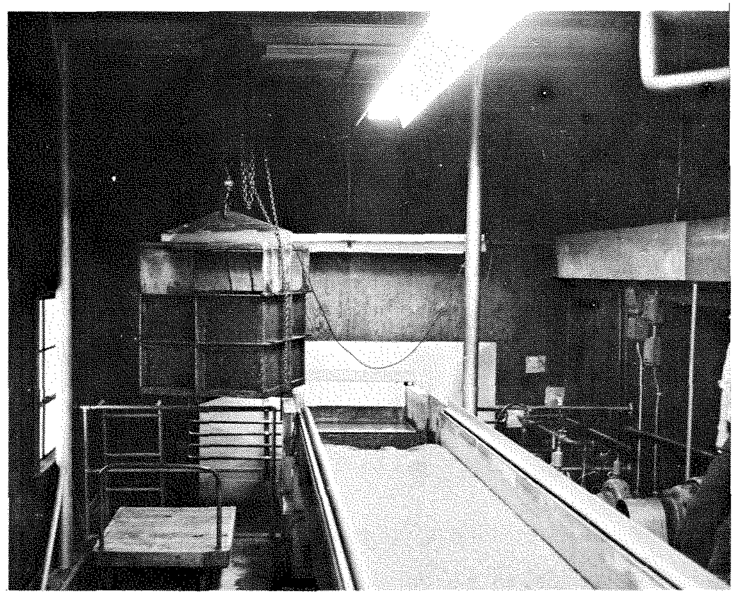


Figure 36.--USWES sediment trap on the 75-foot flume, showing method of removing trap with chain hoist.

become unstable if it is more than about 6-8 feet high, even with diagonal braces leading to a base-plate. Make all connections between cross-beam and vertical supports with pillow blocks.

Be very careful to prevent suspended traps from swinging or tilting. If the box tilts the water level changes instead of remaining constant, and you get an erroneous weight reading. This is particularly apt to occur when sediment slowly accumulates on one side of the box, in which case the gradual tilting may not be noticeable by eye. Stabilize the box with eight small braces - one touching or almost touching each of the four lower and the four upper box corners. These braces can take the form of rollers which create a minimum of friction and do not hamper the vertical movement of the box. Braces of this sort will eliminate any tilting or swaying of the collection box.

<u>Several traps</u>

If you want to use more than one collection box instead of a single large container, several arrangements are possible:

1. Place all the boxes side-by-side on a scale platform, for in-place weighing, and divert the flow to a particular box as needed;
2. Have the boxes on wheels, replace a box as it fills up and weigh the sediment elsewhere (Gilbert, 1914);
3. Suspend several boxes from a cross beam and either shift each box in turn into a position to catch sediment, or divert the flow.

These methods are all rather awkward compared to using a single large container and are not very popular.

Construction of trap

Materials and interior.

Plywood (3/4 inch), steel (1/4 inch) and aluminum (1/4 inch) are common materials for the trap walls and floor. The metals of course last longer but are much more expensive. Steel, being heavier, may require a stronger (more expensive) weighing device, unless you remove the sediment and weigh it without the trap. The Delft Hydraulics Laboratory (de Voorst) uses the latter method - at various time intervals they pump the sand from the trap (a large pit) to a weighing tank. Finally, a lighter box is easier to handle.

The collection box must be supported by a strong framework of angle-irons or structural channels (fig. 36). Be sure to make the floor particularly strong if the box is to be suspended. In general a suspended box must be stronger than one which sits on a scale platform. Keep the number of braces across the top of the box to a minimum as they will interfere with the removal of sediment, except for cases where the sand is removed by pumping.

With boxes longer than about four feet, as your trap ought to be, you get a greater capacity for sand storage within the box by subdividing the box into several compartments. This way the compartment furthest upstream fills with sediment before sediment

begins to accumulate in the next compartment, and so on. (The alternate possibility is for you to periodically redistribute the trapped sand with a shovel, but this is not always practical, especially at faster transport rates.) Make the dividing walls for these compartments out of stainless screens with mesh openings just smaller than the finest sediment grain. This permits some water to pass through the partitions. Plywood partitions will suffice only for slower sediment-transport rates (lower water velocities through the collection box); at high water velocities most of the grains flow over the tops of such solid barriers along with the water. In any case make the partitions easily removable, mainly to simplify and expedite the removal of the collected sediment (USGS).

For sand traps included as an integral part of the flume test section, attached a hinged metal lip along the upstream top edge of the tank which houses the trap. The hinged lip should extend over the full flume width and should cover the upstream edge of the collection box. The purpose of this guard lip is to make sure all grains roll into the trap rather than falling into the space between the trap and the enclosing tank (USWES).

Overflow conditions

The general principle in regard to the overflow of water from the collection box is to provide as much overflow area as possible. This lowers the velocity of the escaping water so that all sediment particles tend to settle in the box.

If the trap is within the flume test section, you are automatically restricted to just one overflow wall - the downstream wall of the trap. So with faster water velocities and/or smaller sand grains you'll have more problems trapping the sand if the collection box is part of the flume test channel.

By placing the trap on a scale platform beyond the downstream tip of the flume at least three overflow walls become available. And if the box is not submerged and hangs beyond the flume, you can use all four walls. By suspending the trap you don't have to worry about protecting the scale platform from the water. And the extra overflow area is a definite help at high water discharges.

The traps shown in figure 35 are not good traps from the point of view of overflow area, and both were altered after the pictures were taken to accommodate higher discharges. (The trap resting on the scale - fig. 35B - had a volume of about 9 cubic feet and proved to be much too small, in addition.)

Install rust-proof screening on the tops of all available overflow walls, on traps located beyond the end of the test channel. The Tyler Co. of Mentor, Ohio, provides screen of various meshes. The size of the screen openings of course should be just smaller than the finest sediment particle. Brace the screen along each of its four edges. At least two of the screens should be easily removable to facilitate sand retrieval and access to the interior of the box.

Much of the entering water will flow out over the downstream wall which faces the flow direction.

Keep the principle of overdesigning firmly in mind when planning the collection box. This applies to box capacity and to screened overflow area. As a rule-of-thumb, allow at least three square feet of screened overflow area for each cubic foot per second of water discharge. The volume capacity of the box for sand containment, as determined by the approximate method of calculation explained above, should not be reduced to provide the needed overflow space.

For suspended traps not submerged within an enclosing tank, leave a foot or more of space underneath the floor of the trap, to make sure the escaping water doesn't buoy up the trap.

Water level in trap

For in-place weighing the water level in or above the trap must remain constant in order to get the true weight of the immersed sediment. Once you have arranged to keep the box from swinging or tilting, the constant water level in the box can be checked by installing a piezometer tube into the wall of the box. (Piezometers are open tubes which indicate water level. They are described in more detail in another section.) Cover the piezometer opening in the box with fine-mesh screening. Use flexible tubing in case the box shifts position. Transparent plastic tubing is good because you can also check for air bubbles in the line. Mount the open end of the tube and an adjacent scale in a convenient location.

Such a piezometer check will be very worthwhile and often is vital. Reason: even if the box doesn't tilt, sediment particles frequently clog the interstices of the guard screens at the overflow regions and cause the water level to rise in the box. You'll probably have to brush the screens every so often during a run.

For traps included in the flume test section you probably can get by without this special piezometer, though it may well be worthwhile anyway. A simple tap through the wall of the enclosing tank would probably suffice.

With some flumes (e.g. University of Auckland) where the collection box is suspended beyond the end of the flume, the water level in the trap is kept constant by submerging the trap inside a larger tank. The overflow wall of this larger enclosing tank keeps the water at a constant level well above the collection box (Callander, 1966). This could also dampen the turbulence and impact-force as the water and sand enter the sediment trap.

Turbulence in the sediment trap

A lot of turbulence and entrained air can occur when the water and sediment plunge through the air and into the collection box. Also, the force of impact causes a little more fluctuation in the weight readings, in the case of in-place weighing. At lower discharges this is not too significant but at high discharges it can affect the weight reading. (The amount of entrained air can vary as sand piles up in the box.) To reduce or nullify this potential problem use several baffles to break up the incoming flow. The

section on "Stilling Tanks" gives examples of baffles. Strong wire screens facing the incoming flow work well. The force on the weighing device is less if you support the baffles independently of the collection box. Baffles also distribute the escaping water more evenly over the various overflow walls and so are definitely worthwhile for in-place weighing.

Removal of water

The sediment naturally can be recovered much more easily if water is first removed from the box. For this purpose put a small trap door on the outside of one wall, near the floor of the box. Cover this opening on the inner face of the collection box wall with a rust-proof screen, fine enough to stop any sand grains. Sheet-rubber gaskets will make the trap door essentially leak-proof. A small amount of constant water leakage will not introduce any error in weight readings, if the box and contents are weighed in-place with water continuously flowing over the top of the box.

Removing the sediment

When the collection box has filled up with sediment there are several ways to empty the box. Simplest of all is to leave the box in place and either shovel (USGS) or pump the sand out of the box (Iowa, Delft Hydraulics Lab., SUNY at Buffalo). Instead you can use a chain hoist (USWES) or crane to lift the trap out of its position (fig. 36).

Special sampling methods

The term "special sampling methods" as used here will refer to methods which sample only part of the cross-sectional flow area, regardless of the duration of the sampling period. These methods have to be used when there is no better system available (recirculating flumes), but the inability to trap sediment over the full cross-sectional flow area is a serious disadvantage. For example, in regard to the movement of sand along the flume test section Einstein and Chien (1955, p. 15) reported that "at low concentrations the sediment tends to move in longitudinal strips each of which keeps swinging sidewise in a very unsteady manner. In these runs the measuring instruments are in one instant hit by a strip of heavily concentrated sediment-water mixture, and yet in another instant they are completely out in the clear." Note that to obtain an accurate sample under these conditions the sampling time must be long.

Some possible devices for trapping or measuring the sediment concentration of segments of the flow are:

1. An opening in the channel floor (Gilbert, 1914).
2. A basket-type trap placed on the stream bed (Subcommittee on Sedimentation, 1963).
3. Special hand-held samplers used in the flume test section to trap some of the suspended sediment.
4. Sensors which measure the concentration of suspended solids on the principle of X-ray or light attenuation.

5. Quick-closing valves which trap a slug of the water-sediment mixture in the return pipeline of recirculating flumes.
6. Open tubes or slots through which sediment and water are routed to a container outside the flume.

The first two of these methods trap only the bedload in the test channel and are not always very efficient or practical. Very few people use them in flumes. In Europe, where the basket-type traps were developed, engineers do use such traps in natural rivers.

An example of a special hand sampler is the DH-48, described in the Catalog of Instruments and Reports for Fluvial Sediment Investigations, Federal Inter-Agency Sedimentation Project (Subcommittee on Sedimentation, 1966). This consists of a streamlined aluminum case containing a pint milk bottle which you lower and raise at a selected vertical in the flume test section. These samplers, too, are rarely used in flume studies. E. V. Richardson of Colorado State University (written communication) suggests that this sampler can be used effectively at the downstream end of the flume. Placing a sill on the bed across the full channel width allows the sampler to traverse the entire flow depth, thus trapping both bedload and suspended load.

Sensors (for an example, see Bhattacharya, et al., 1969) unfortunately are still not well-enough developed to be reliable, in spite of continuing efforts. Some people use them anyway, in natural streams. A reliable sensor could measure just the suspended load in the flume test section or the total load in a vertical section of the return conduit.

The quick-closing valve method for measuring total load in recirculating flumes requires a special section in the return pipe: the pipe splits into two parallel conduits for a distance of several feet before merging again into a single pipe. At any given time one section is fully open, the other closed. Valves at the ends of each section open and close in unison to trap the sediment and water in one section at the same instant that the other section opens to maintain the flow continuity. The trapped sediment and water give the sediment concentration in weight of sediment per unit volume of water. Multiplying this by the water discharge gives the rate of sediment transport in weight of sediment per unit time.

Straub, et al. (1958) tried this trapping system in a vertical pipe section but found that (1) the sand particles prevented the valves from closing water-tightly and (2) sediment movement through the system was unsteady, so the instantaneous samples were not reproducible. The U.S. Geological Survey at Colorado State University also used this method at one time. Results were reasonably reproducible but there was some difficulty removing the full sample from the pipe.

Nearly all recirculating flumes depend on open tubes or slots to trap samples of the water-sediment mixture. The principle is to catch samples which accurately represent the water-sediment flow rates but which are negligibly small compared to the total amount of water and sediment contained in the flume system. Removing too much of the water and/or sediment interrupts the established equilibrium: for example, the depth in the test section will decrease and the slope may increase.

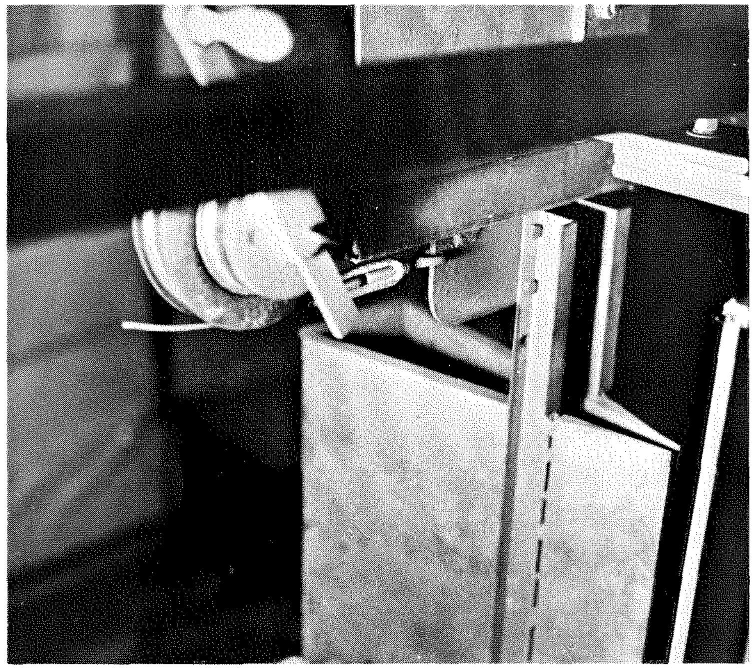
In practice the amount of sediment removed is usually not large enough to require immediate replacement. In large flumes the same is true for the water. You can easily compute the amount of water which can be removed before the flow depth in the test section begins to decrease significantly.

The simplest of these sampling methods is the vertical slot, so let's discuss that first.

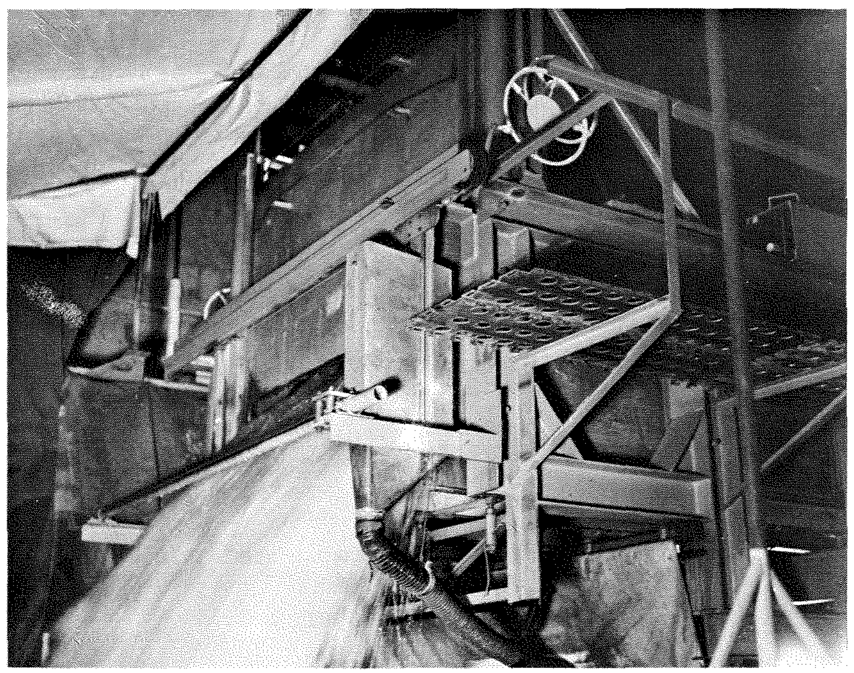
Vertical-slot samplers

Free-overfall recirculating flumes have an ideal sampling location: the downstream tip where the water and sediment sail off the end of the flume structure. The sampling job is merely to divert a representative fraction or column of the flow (including the full flow depth) into a container. Thus the sampler basically consists of three sheets of rigid metal welded together so that the only side-opening is a narrow vertical slot which faces the flow. From the bottom of the sampler a tube carries the water and sediment to the container. The height of the sampler must be a little greater than the maximum flow depth which the flume can accommodate. Figure 37 shows the slot samplers used at Colorado State University.

The sampler at Colorado State University rides on guide rails at the top and bottom, and it travels systematically back and forth across the entire flume width by means of a cable and pulley. This is hand-operated, although it could be motor-operated.

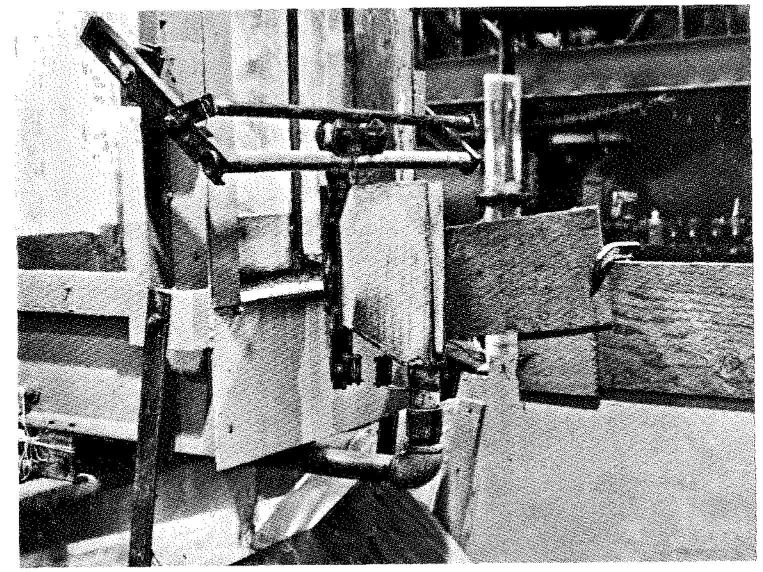


A. Close-up view of sampler used on 200-foot flume.



B. Side view of sampler used on 200-foot flume.

Figure 37.--Vertical-slot type samplers used at Colorado State Univ.



C. Sampler on 60-foot flume.

Figure 37, continued.

A transparent tube leading from sampler to container would show any sediment being stored within the tube.

Slot samplers theoretically can also be used on closed recirculating flumes. The Department of Earth and Planetary Sciences at Massachusetts Institute of Technology is presently testing such a sampling method at the downstream end of the test section. Preliminary trials are with the sampler in a fixed position rather than traveling back and forth. The water withdrawn is routed continuously back to the flume.

The sediment transport rate, in lbs/sec, is the product of the water discharge in ft^3/sec and the sediment concentration, in pounds of sediment per cubic foot of water-sediment mixture. Measuring any two of these factors gives the third. Water discharge is always measured, so you also have to measure either the sediment transport rate or the sediment concentration. A slot-type sampler can be used for either of these. For sediment transport rate per flume width you simply collect sediment over a measured time interval, translate this into pounds per second and multiply by a factor equal to the flume width divided by the slot width. (This assumes that the slot sample is a mean value for the full flume width, an assumption true only if the sampler traverses the full flume width.) To measure sediment concentration, on the other hand, you need the volume of the water-sediment sample and the weight of sediment collected. In either case, therefore, the trapped sediment must be weighed. The other measurement depends on convenience - either time the sampling period and compute sediment transport rate (lbs/sec) or measure the volume of water-sediment mixture and compute mean sediment concentration (lbs/ft^3).

To get the volume of the water-sediment sample you can either take a limited sample and measure the volume directly or monitor the rate of withdrawal, as explained below. Regardless of the sampling and measuring method any water withdrawn from closed recirculating flumes must be simultaneously replaced with an equal amount, to keep the flow depth in the test section from decreasing.

Two easy ways for directly measuring the volume of the water-sediment mixture are:

1. Use a container having a known volume, say a one-liter bottle, and simply sample until the container is filled (California Institute of Technology).
2. Use a container in which the volume can be easily and quickly measured. One example would be a container such as a graduated cylinder which has marks indicating volume. Another method, especially suitable for large samples, is to mount a point-gage on top of the container (fig. 38) and pre-calibrate the point-gage reading to the volume in the container (Colorado State University). With either of these methods you get a more accurate measurement by making the container tall and narrow.

A third possible method is to sample any amount, remove the sediment and weigh the water.

At least two laboratories, the USDA at Oxford, Miss. and the St. Anthony Falls lab, monitor the flow rate through the sampling tube and then send the water back to the flume after retaining the sediment. These laboratories use open-tube samplers, but the method

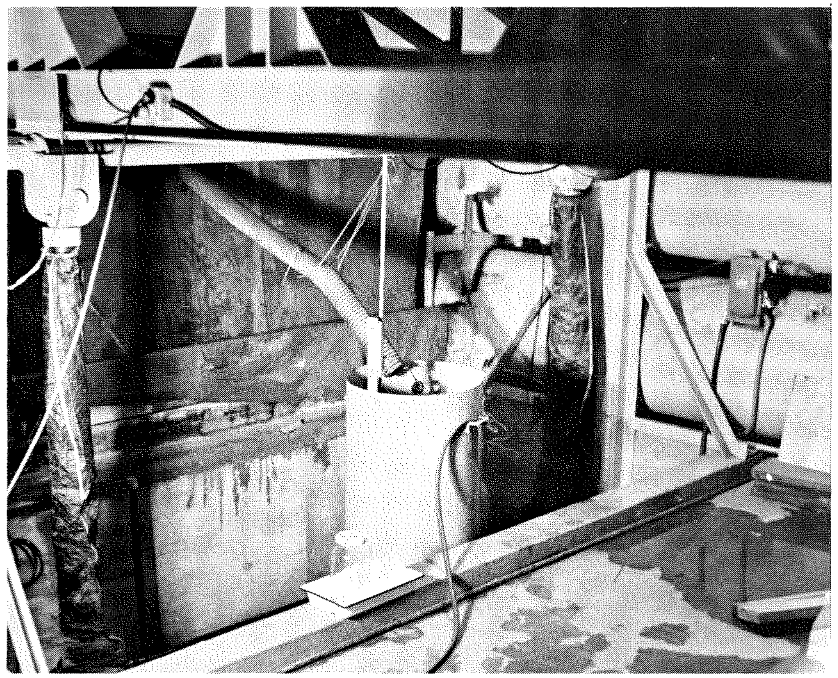


Figure 38.--Container with point gage for determining volume of water-sediment sample (Colorado State Univ. 200-foot flume).

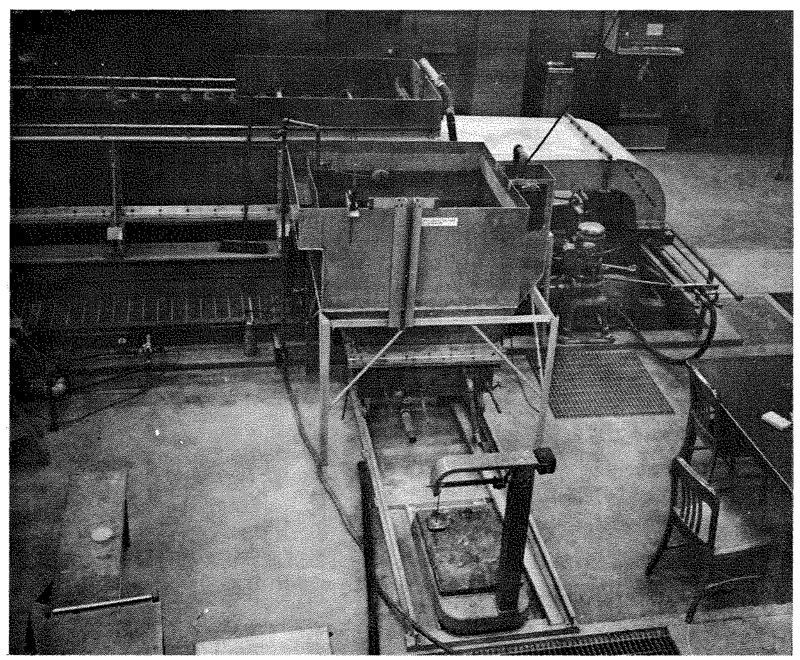


Figure 39.--Overall view of the upstream end of the USDA 100-foot flume, showing the sediment sampling, collecting and weighing arrangement.

is equally valid with slot samplers. The total volume of water sampled is found by multiplying the measured discharge through the sampling line by the total time of sampling.

At the USDA laboratory the water-sediment sample enters a large tank (fig. 39), where the sediment settles to the bottom while the water escapes over one of the tank walls. The escaping water is pumped directly back into the flume. Both the length and width of the tank are about four feet, with the overflow area being large enough such that the settling velocity of the smallest sediment particle exceeds the mean flow velocity through the tank.

At St. Anthony Falls each of four sampling tubes connects to a Venturi meter (discussed later) and manometer to measure the flow rate. The water-sediment mixture then flows through sieves which retain the sediment, and the water goes back into the flume (Straub, et al., 1958).

Most people, since they deal with small quantities of sediment, dry the trapped sediment before weighing it. For larger quantities of sediment you can get the weight easier and quicker by weighing the sediment under water, as explained earlier. At the USDA (Oxford) laboratory they merely unbolt a special bottom section from their hopper-like settling tank and wheel this section by rail to a nearby scale for weighing (fig. 39). They recommend some sort of clamping arrangement for easily and quickly removing the sediment box from below the settling tank, rather than the somewhat tedious bolting assembly they have at present. An in-place weighing arrangement of the sort described earlier in this chapter would avoid this minor problem.

Open tubes

The open-tube method is the system ordinarily used to measure sediment-transport rate in closed-circuit recirculating flumes. Samples of the water-sediment mixture are withdrawn through one or more tubes and are routed into a container for analysis. Sampling usually takes place where the flow travels vertically, at either end of the flume, because the sediment presumably is more evenly-distributed across the flow cross-section in these vertical zones. For special studies, such as the determination of suspended load, people use tube-type samplers in the flume test-section.

One complicating factor is that in order for the sediment-water mixture to enter the tube at a representative rate the velocity at the sampler inlet must be adjusted to equal the velocity of the general stream at the sampling point (Subcommittee of Sedimentation; Report No. 5, 1941 and Report T, 1966).

The main components of a typical sampling-tube apparatus (fig. 40) are a metal sampling tube (often brass), flexible tubing to convey the sample, a container waste bucket and sometimes a small pump (say 1/3 H. P.). (The pump begins withdrawing the water and sediment from the flume into the waste bucket in cases where you are withdrawing the sample in an upward direction. Otherwise the sample probably will flow through the tube by itself, by a siphoning action.) After the adjustment of the inlet velocity the discharge end of the flexible tubing is switched from the waste bucket to the sample container.

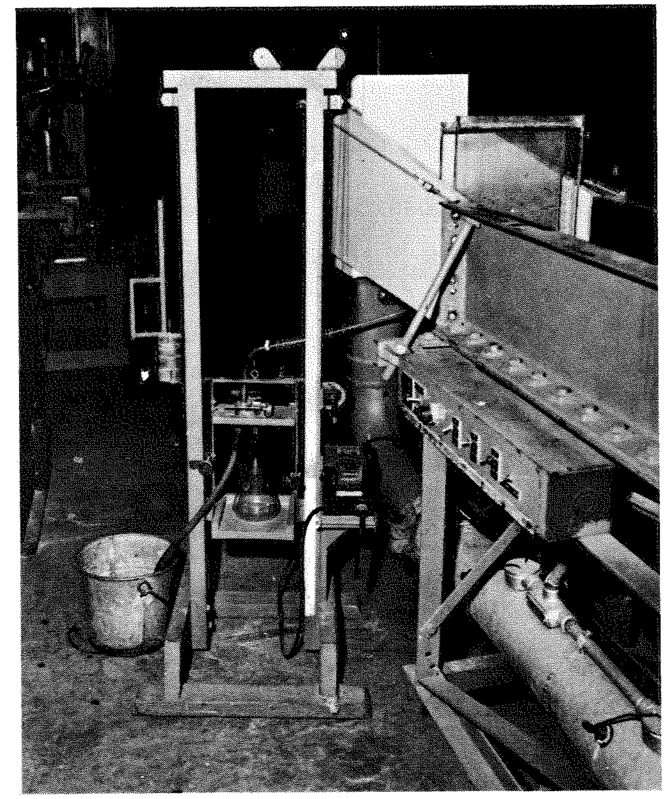


Figure 40.--Sampling-tube apparatus used at California Inst. Tech. (Cal Tech photo).

The quantities normally determined are the volume of sample withdrawn and the weight of the trapped sediment. In some cases timing the sampling period might be easier than getting the volume of the sample. Multiplying the representative transport rate by a factor equal to $\frac{\text{total area of conduit}}{\text{area of sampler inlet}}$ would then give the total transport rate.

There is no ideal location within the flume system for these tube samplers. In general you'll want a location where the sediment is distributed as uniformly as possible over the cross-sectional flow area. This is most likely to occur in a vertical section. Various locations have been tried on the same flume and on different flumes in the same laboratory. The trend today is toward sampling in the vertical section near the head of the flume, to keep the sampling away from the pump (the latter is usually just below the downstream end of the flume). The California Institute Technology flumes often have screens or baffles about 1-3 feet upstream from the sampling point in an attempt to distribute the sediment more uniformly. One possible sampling location within a pipeline (horizontal or vertical) is at an orifice plate (a discharge-measuring device with an opening slightly smaller than the inside pipe diameter, placed perpendicular to the flow). The flow disturbance at this location usually distributes the sediment more evenly.

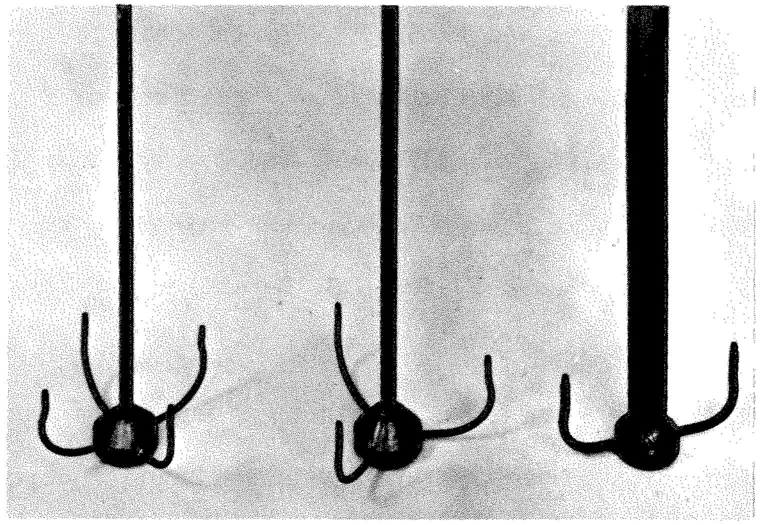
The sampling tube itself is usually of brass or something of comparable hardness. The diameter of the inlet should be at least twice the <u>long axis</u> (<u>length</u>) of the largest sediment grains. Inlet diameters commonly range approximately from 0.13 to 0.31 inches. Bevelling the tube wall at the tip of the tube reduces the flow disruption.

Figure 41 shows some typical samplers used at California Institute of Technology (Vanoni and Brooks, 1957) in their 60-ft flume (sampling done in vertical section at <u>downstream</u> end of flume).

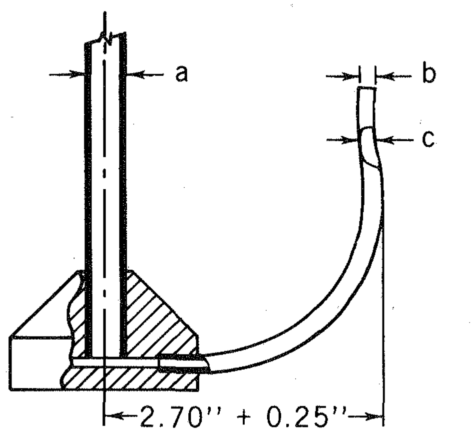
There is really no need to make the opening circular; construction is just a little easier because the material comes this way. The sampler opening used by the U.S. Department of Agriculture (Oxford, Miss.) is fan-shaped.

Although the sampler inlet of course must face into the flow, the configuration of the rest of the metal portion depends on where you withdraw the sample from the flume. The whole tube can be straight (University of California at Berkeley) if you withdraw upward at the head of the flume; or, bent 90° for lateral withdrawal such as on the California Institute of Technology 40-foot and 130-foot flumes; or, curved (fig. 41), as in sampling where the flow is downward, such as at the downstream end of the flume.

People often assume that the stream velocity at the location of the sampler inlet is the mean flow velocity in the section. They get this velocity by dividing the general discharge of the flume by the cross-sectional flow area of the return section at the sampling location. With this approach there will be some error if the tube inlet gets too close to the wall of the return section. Roughening this wall induces turbulence and makes the velocity more uniform across the whole cross-section. The USDA at Oxford uses one-inch angle-irons on the inside wall of the return conduit for this purpose.



A. View of 'total-load' samplers. Flow is downward at sampling point. (Cat Tech photo)



Sampler	Dimensions			No. of inlets
	a (in)	b (in)	c (in)	
A	0.305	0.136	0.089	4
B	0.353	0.129	0.129	3
C	0.416	0.136	0.194	2
—	0.188	0.312	0.188	1*
*No manifold - simple bent tube				

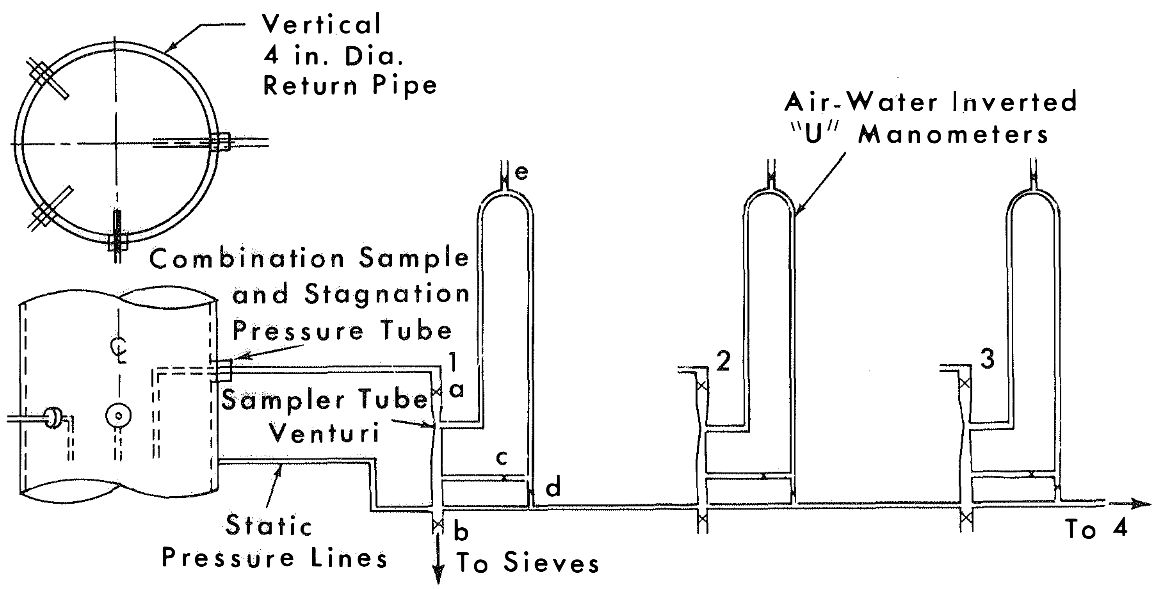
B. Diagram and dimensions of typical samplers.

Figure 41.--California Inst. Tech. sampling tubes (from Vanoni and Brooks, 1957).

An alternative to this mean-velocity assumption is to actually measure the velocity at the sampler inlet. The sampler itself can be used for this purpose, and figure 42 shows the way Straub, et. al. (1958) did this at the St. Anthony Falls Hydraulic Lab. The sampling tube on the California Institute of Technology 130-foot flume is also equipped to measure such point-velocities.

Once the flow through the sampler has started, the velocity at the inlet has to be kept equal to the stream velocity at the region of the sampler. At the California Institute of Technology and the University of California at Berkeley they accomplish this by simply changing the elevation of the siphon outlet. This method involves a trial and error process of finding the correct outlet elevation. The first step is to measure or assume the stream velocity at the sampling point. By knowing the area of the sampler inlet and by using the mean stream velocity as the velocity through the sampling tube you can compute the desirable discharge through the sampling tube. This discharge (volume of flow per unit time) tells you the desirable time needed to fill your container, since you already know the container's volume. Then it's a matter of trying different outlet elevations until you get the container filled in the right amount of time.

The St. Anthony Falls arrangement (fig. 42) uses a valve or petcock together with a manometer to regulate the inlet velocity. The USDA at Oxford withdraws the samples by means of a pump, and they regulate the motor speed on this pump to get the desired inlet velocity.



"With valves "b" and "c" closed and "a" and "d" open, the system measured the dynamic pressure or velocity head. Then valves "a" and "d" were closed and valves "b" and "c" were opened. With valve "a" acting as the control, the system operated as a sampler with the Venturi manometer indicating the flow rate. Calibration curves for each Venturi manometer gave the required manometer deflection for any desired velocity at the sample tube tip." (Straub, et al., 1958).

Figure 42.--Four-tube 'total-load' sampler devised at St. Anthony Falls Hydraulic Laboratory (from Straub, et al., 1958).

The latter is taken as the mean flow velocity in the cross-section of the return conduit, at the general sampling location. A manometer and volumetrically-calibrated orifice plate (discussed in another chapter) within the sampling line give the discharge through the sampling tube, and dividing this discharge by the area of the sampler inlet gives the velocity through the inlet.

The sediment concentration and water velocities very probably will not be uniformly distributed over the flow cross-section. In this case you get the most accurate estimate of total sediment concentration by sampling at various points within the cross-section. At each point measure the sediment concentration and the water velocity. The product of these two factors gives the weight of sediment in a unit cross-sectional flow area per unit time, assuming that the sediment grains travel at the same rate as the water. Repeating at other points and integrating over the whole cross-sectional flow area of the conduit then gives the total sediment concentration. Although this method is most accurate, it is rarely used. Nearly everyone moves the sampler during the sampling period and tries to trap a mean concentration.

You can keep the sampling tube in a fixed location only if you have made extensive preliminary tests to make sure that (1) the chosen location represents average conditions of sediment concentration for the existing flow conditions or (2) the shape of the concentration profile stays constant for all flow conditions so that the total concentration can be obtained by integrating over the whole cross-section after measuring the concentration at one point.

Since most people move the sampler, systematically or otherwise, to different points within the cross-section during the sampling period, you'll want to design the sampler such that you can shift the sampler inlet to various known locations within the cross-section. Here are some ways to do this:

1. Use a manifold-type sampler having several inlets which connect to a single main tube, as shown in fig. 41 (California Institute of Technology).
2. Orient a straight sampling tube vertically, inserting it through a lid on the headbox of the flume. Fix the tube in a special movable circular section on this lid, so that rotating the circular lid-section moves the sampling tube to different locations within the cross-sectional flow area below (University of California at Berkeley).
3. Use a single tube, bent to a 90° turn, which can move back and forth across the flow area in a single plane (California Institute of Technology - see Kennedy, 1961).
4. Do the same but with two or more tubes so that two or more planes can be sampled (St. Anthony Falls - fig. 42).
5. Sample from a single tube, bent to a 90° turn, which passes through a ball and socket assembly such that the tube can swing in a horizontal plane back and forth across the cross-sectional flow area (California Institute of Technology - see fig. 43).

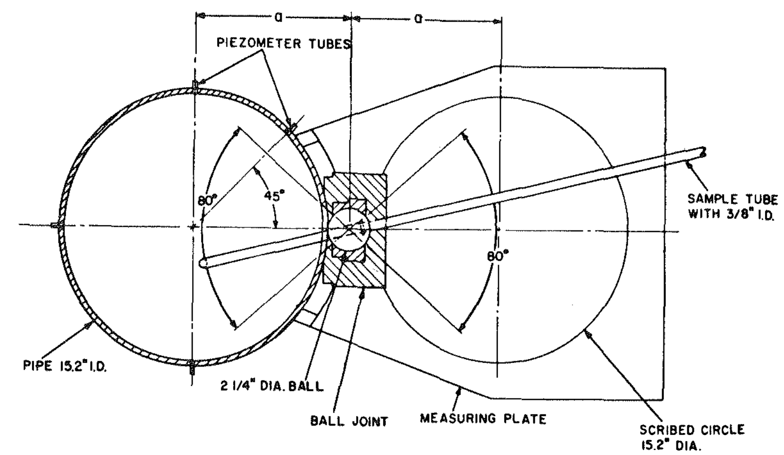
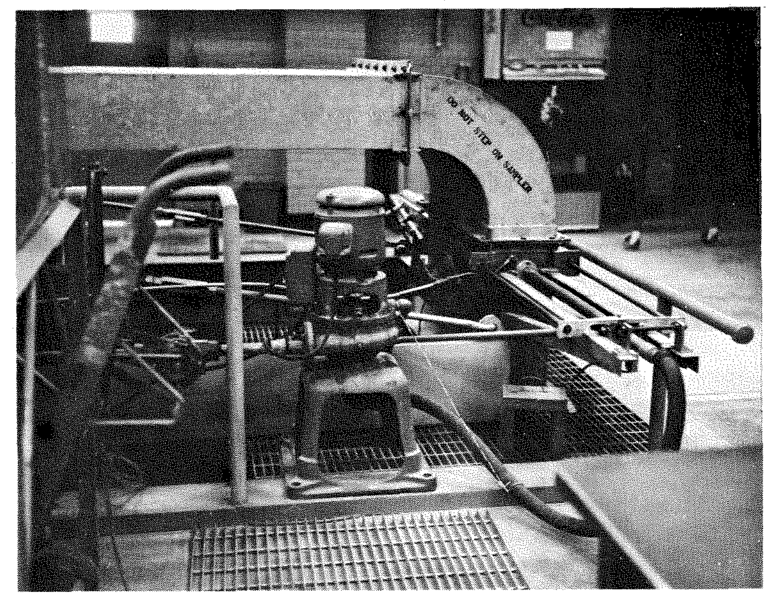


Figure 43.--Sampler and positioning plate used in the California Inst. Tech. 130-foot flume (from Hwang, 1965).

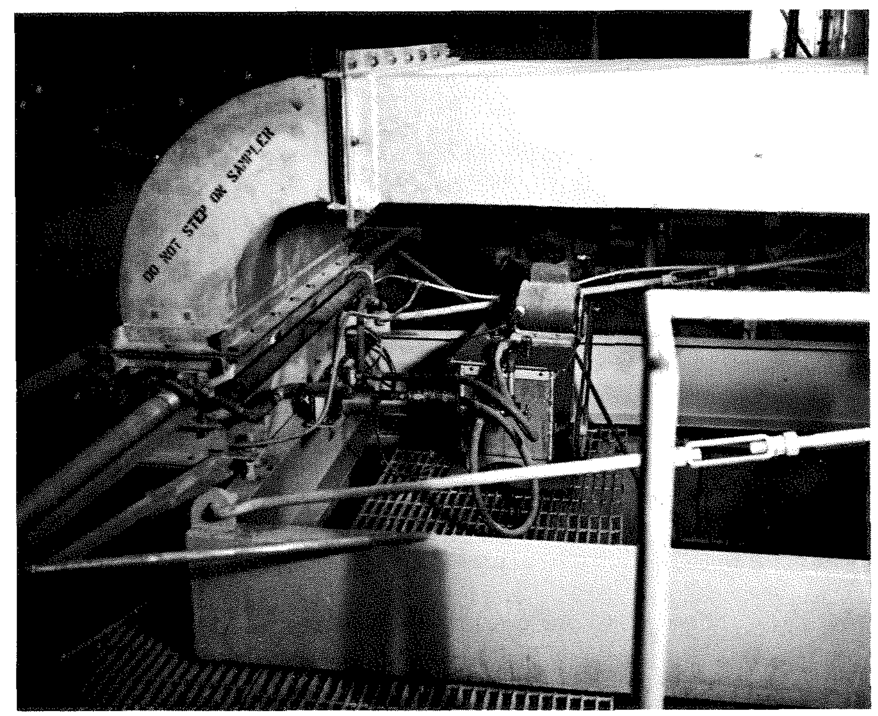
6. Insert permanent rails across the interior of the return conduit and mount a traveling sampling nozzle on these rails. The sampler could be hand-operated or motor-driven. The USDA at Oxford, Miss. uses such a sampler with a hydraulic-drive mechanism (fig. 44), permitting continuous sampling for the full duration of the experiment (usually four hours or more).

Flexible tubing has to carry the sample from the metal sampling tube to a container or waste bucket. This flexible tubing should be transparent so that you can see whether any of the trapped sediment is settling in the line. To prevent such sediment deposition the flow velocity through the tube must be relatively fast at all stations through the line. To maintain fast tube velocities and prevent sediment deposition within the line, keep the tube length short, make the tube diameter small, hold the tube as vertical as possible, minimize the number of bends in the tube and do not include any dead-flow or reduced-velocity spaces in the routing. The smallest feasible tube diameter is about 1/8-inch, whereas the largest diameter should not exceed the area of the sampler inlet.

To withdraw samples from within the flume test section researchers at the Colorado State University laboratory found that the mean velocity through the tube, once the flow moves past the tube inlet, must be about five or six times the fall velocity of the sediment. Lower tube velocities would not lift the sand up the vertical portion of the sampling tube.



A. Pump for withdrawing a water-sediment sample.



B. Mechanism which moves the sampler back and forth inside the return conduit.

Figure 44.–'Total-load' sampler on the USDA 100-flume flume.

California Institute Technology has a two-way swing-spout at the discharge end of the flexible tubing. In one position the swing-spout directs the flow into the collection bottle while in the other position it passes the flow into a waste bucket. The collection bottle and spout rest on a rack which can be moved vertically to get the required head on the siphon (fig. 40).

The duration of sampling varies widely from laboratory to laboratory. In other words nobody is sure about the minimum frequency of duration of sampling which gives accurate sediment concentrations. People who fill up small (say one-liter) bottles may take eight to twelve samples over a half-hour period and average these samples (Kennedy, 1961). Others, such as the USDA at Oxford, sample continuously over the full duration of the run (4-10 hours or longer). Most investigators would agree that "measured" sediment concentrations become more accurate as the sampling period increases. Straub, et al. (1958) found that in their flume two-minute sampling periods gave unreproducible concentrations because of the unsteady sediment flow, and they decided on sampling periods ranging from 15 to 30 minutes.

<u>Summary</u>

For nonrecirculating flumes the best trap location is just below the downstream tip of the flume. A single large collection box is best for measuring the total transported sediment load. Compute a maximum rate of sediment collection for your channel width. Then make the volume of the container at least 1.3 times the maximum volume of sediment you'll collect over a 30-minute period.

Weigh the sediment in-place as it accumulates. To do this the box can be placed on a scale platform or it can hang from a beam with one

beam-support pressing on the scale. Strain gages and other weighing devices may also be feasible.

Screen the upper portion of all available overflow walls of the collection box to prevent sediment from escaping. (If the sediment trap is upstream from the tailgate, you can't use any screening to help catch sediment.) The amount of screening depends on Q_{max}: allow at least 3 sq. ft. of screening for each cubic foot per second of water discharge.

Divide the collection box into two or three compartments with screen partitions. For boxes placed below the downstream tip of the flume use baffles just above or within the box to help dampen any turbulence caused by the incoming flow. Be sure to keep the box from swinging or tilting and to install a piezometer to make sure the water level in the box stays constant.

In recirculating flumes the sediment transport rate has to be estimated by means of special sampling methods. These methods usually involve representative samples of the water-sediment mixture, for which the weight of sediment and either the sampling period or the volume of the sample must be measured.

In free-overfall recirculating flumes you can usually sample the sediment concentration more accurately than in closed recirculating flumes. This is accomplished with slot-type samplers in the nappe at the downstream tip of the flume. Closed recirculating flumes usually depend on open-tube samplers in which the velocity at the sampler inlet must be specially adjusted to equal the free-stream velocity at the sampling point. The best sampling location within the flume system and the best duration or frequency of sampling are pretty much a matter of trial and error, although sampling in the vertical return section near the head of the flume is most popular today.

TANKS AND AUXILIARY CHANNELS

You'll need one or more tanks, regardless of the type of flume. Step number eight is to plan these tanks and for nonrecirculating flumes possibly a return channel (optional). (Pipelines are closely associated with the pump, and we'll take up these features in the next chapter.) Here are the tanks to consider:

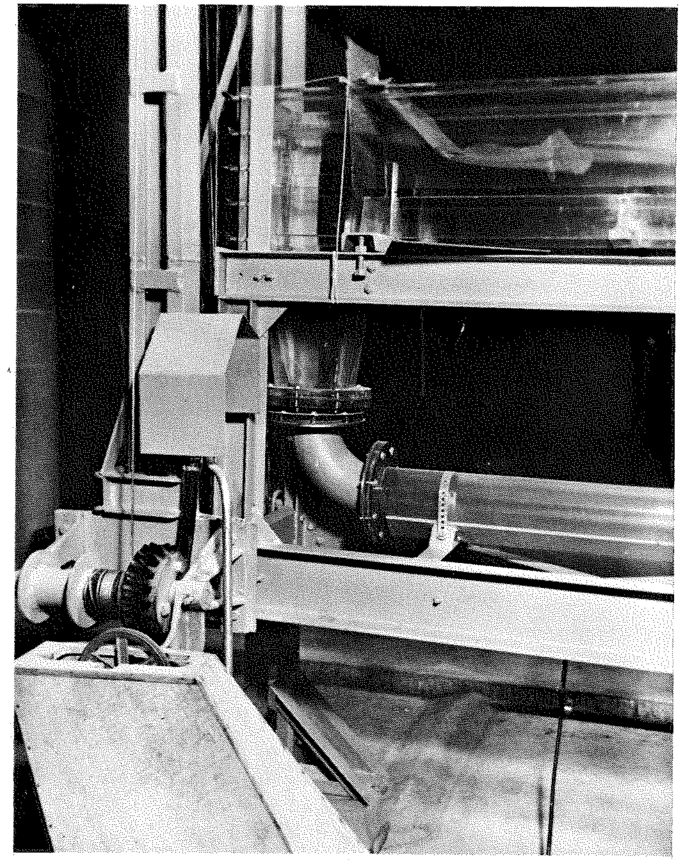
1. Headbox - on all flumes except some closed recirculating flumes.
2. Tailbox - on closed-circuit recirculating flumes.
3. Tailbox - on free-overfall recirculating flumes.
4. Sump - on all nonrecirculating flumes.
5. Constant-head tank - some nonrecirculating flumes (optional).

Stainless steel, stainless-clad mild steel, painted steel and (for small flumes) plexiglas are good building materials for tanks. Plywood, well-painted, epoxied or fiberglassed, also serves quite well for channels. Several people recommend using stainless steel as much as possible for all tanks because of the time and trouble involved in scraping and repainting the non-stainless varieties.

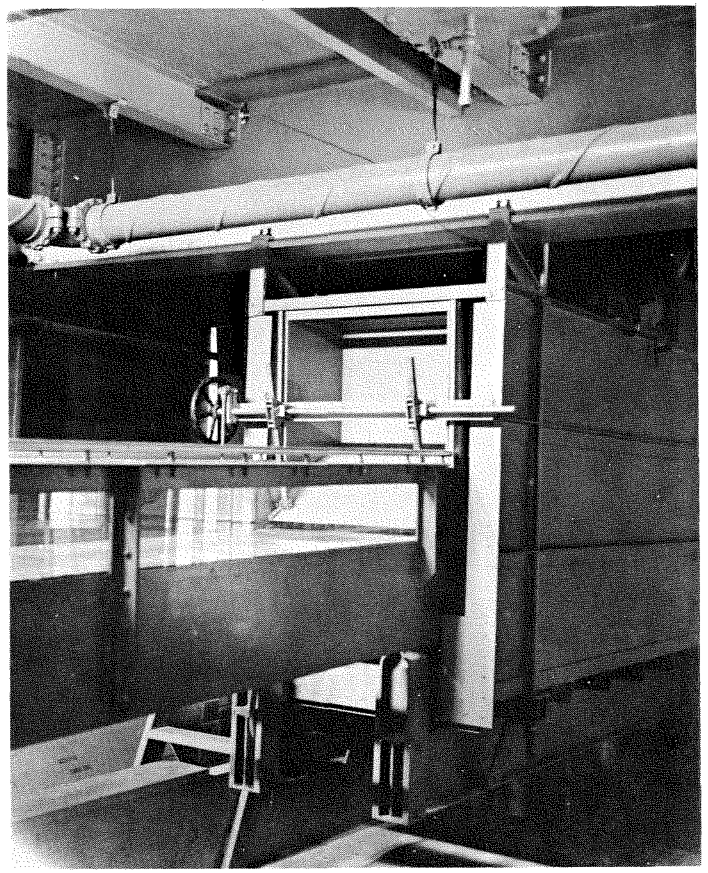
For small tanks you might consider getting an ordinary oil tank, either new or on surplus. Then cut out openings as needed.

Headbox

Most flumes have a tank (headbox) at the upstream end in order to dissipate the jet of water arriving from the supply line and to provide a more quiet and uniformly-distributed flow at the start of the test



A. USGS 30-foot plastic flume.



C. Iowa 85-foot glass flume.

Figure 45, continued.

delete this stilling tank on closed-circuit recirculating flumes and instead to lengthen the return conduit so that the flow travels approximately horizontally directly into the upstream end of the test channel (figs. 39 and 46). You need more laboratory space this way, and there is some question as to whether the possible advantage of horizontal entrance-flow offsets the extra lab space needed.

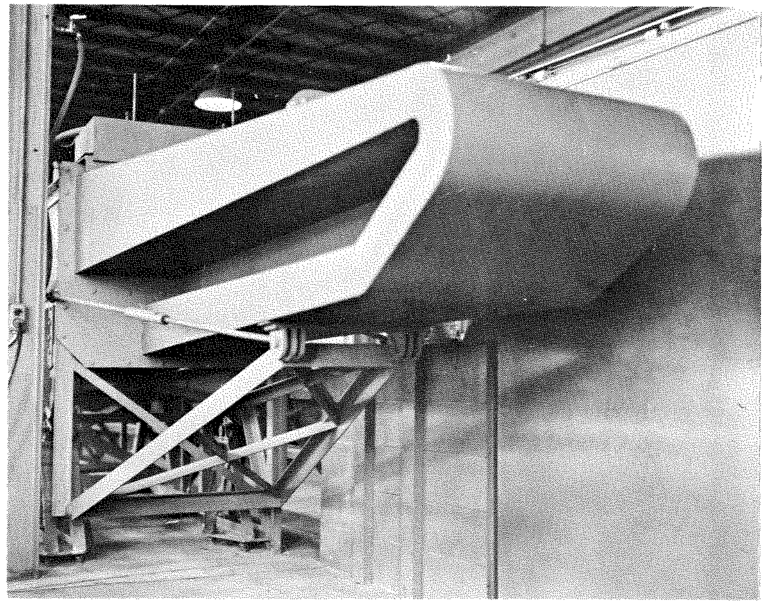
Installing a pipe elbow and guide vanes in place of a headbox very probably will not work if most of the return pipe is below the level of the flume test section. The USDA at Oxford found that the guide vanes caused the water to be thrown into the test channel in a very unacceptable way.

To accomplish its purpose of regulating the arriving flow a headbox should have (1) a large cross-sectional flow area relative to the supply line, so that the velocity through the tank decreases, and (2) baffles to get symmetrical flow across the flume inlet and to eliminate large eddies.

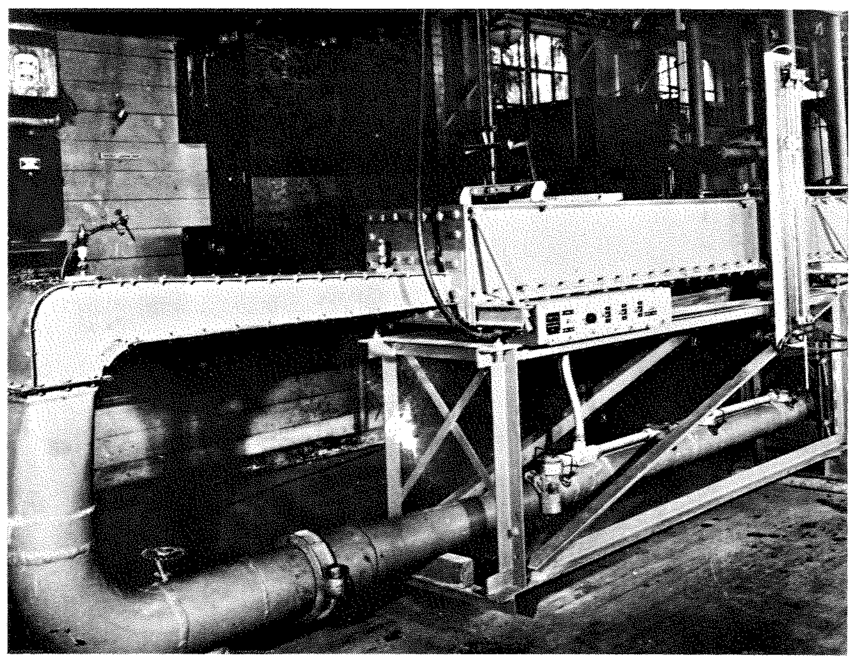
Dimensions

All three tank dimensions - length, width and depth - influence the cross-sectional flow area of the water flowing through the tank. Hence you'll get a more efficient quieting of the flow by making the tank large. Many flume head-tanks are too small in this respect. On the other hand if the headbox on recirculating flumes is too large the mean velocity will not be fast enough to move the sediment.

The width of the tank should be at least equal to the maximum width



A. Iowa 90-foot sediment flume.



B. California Inst. Tech. 40-foot flume (Cal Tech photo).

The length of the tank should be at least two channel widths.

The water surface elevation in this stilling tank depends primarily on the flow conditions (mean water velocity and depth) in the flume test channel. The only way to increase the water depth in the stilling tank is to lower the tank floor, relative to the test section floor. So make the headbox floor several feet below the floor of the flume test section (figs. 45B, 47, and 48).

Generally the water surface in an open headbox will be higher than that in the test section by $\frac{K V^2}{2g}$, where V is the mean velocity in the test section and the coefficient K accounts for the head loss due to entrance baffles and other flow hindrances. With no baffles and with the headbox width equal to the flume width, K = 1. Screens and an abrupt change in flow width can raise the value of K to as much as 2. Thus for a mean velocity in the flume of 10 ft/sec the water level in the stilling tank will be about 1.5 to 3 feet higher than that in the flume. Moreover, under such supercritical flow conditions ($V/\sqrt{gD} > 1$) a sluice gate at the stilling tank outlet is necessary to promote uniform flow, as explained later, and this causes the water to rise even higher in the stilling tank. Consequently, to be on the safe side add another couple of feet to the computed elevation difference $\frac{K V^2}{2g}$ to determine the height of the stilling-tank walls above the maximum water level in the flume.

An easy alternative to building the walls this high is to put a lid on the tank. If you don't take either of these precautions, the water will probably flow over the top of the tank walls when you want fast velocities in the test channel. Colorado State University flumes have

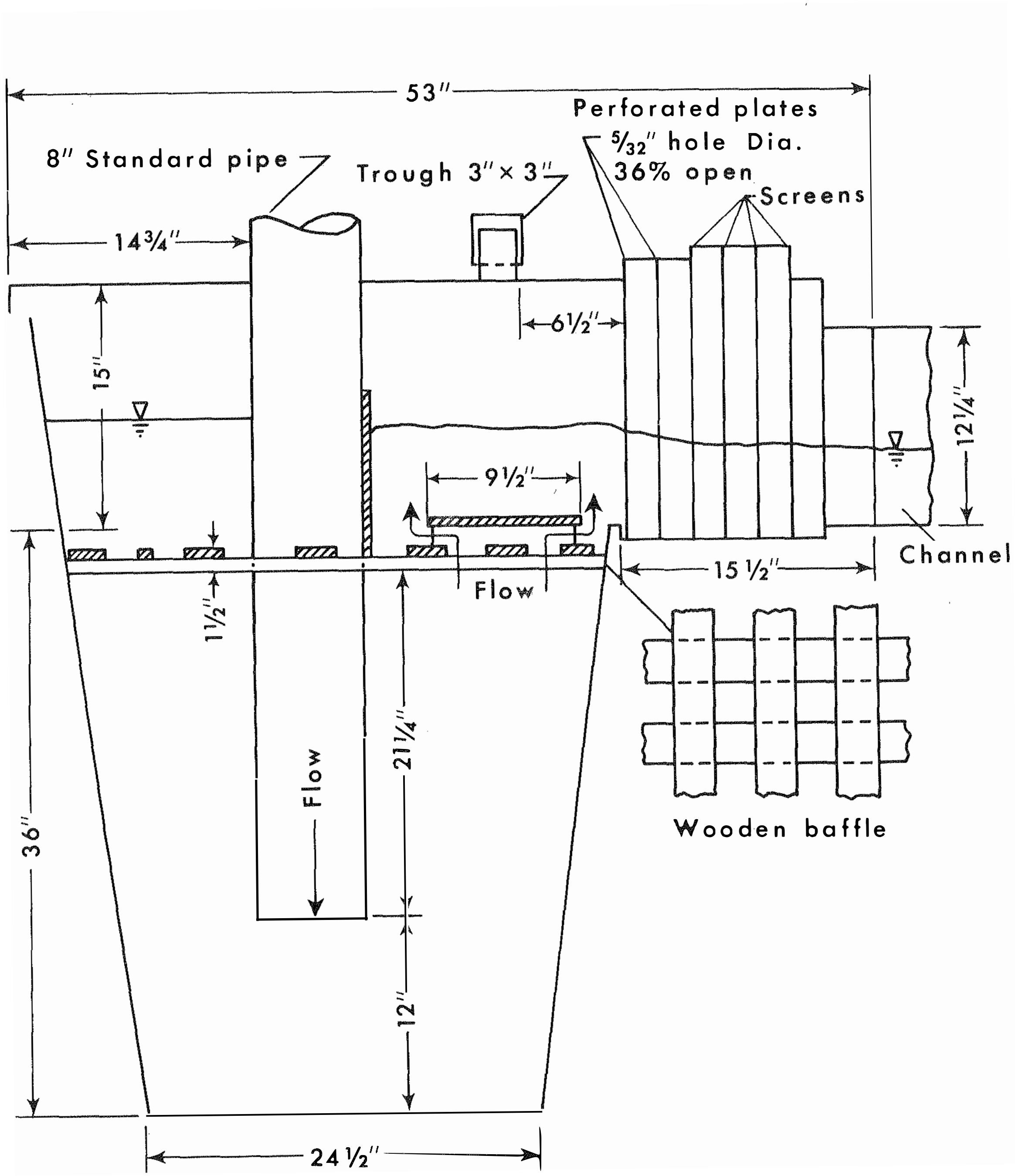


Figure 47.--Headbox on California Inst. Tech. 60-foot closed recirculating flume.

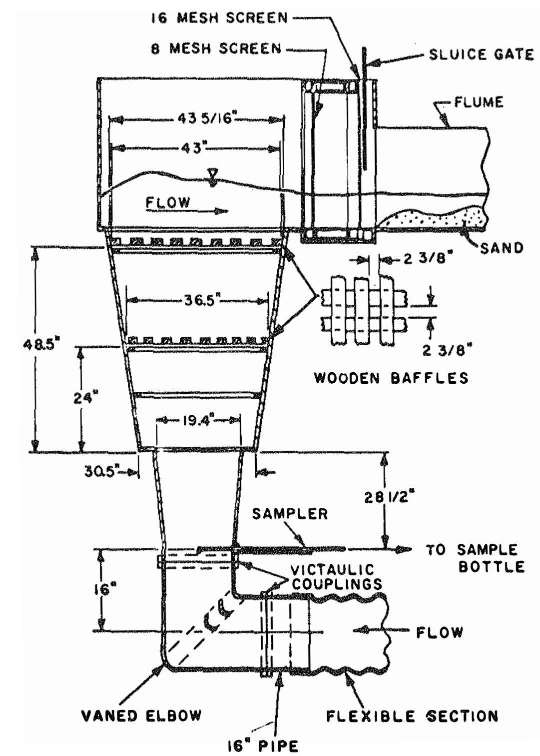


Figure 48.--Headbox on California Inst. Tech. 130-foot closed recirculating flume (from Hwang, 1965).

functioned very well with a lid on a headbox. The lid can be made removable but watertight by the use of silicone high-pressure vacuum grease.

By hinging the headbox lid at the very upstream end of the tank so that the lid height is adjustable you can use this lid to help dampen water-surface irregularities in the headbox and at the test-section entrance (USDA at Oxford).

It is helpful to have a small faucet for draining purposes in or near the floor of the tank.

The headbox dimensions can be reduced if you can devise a way of introducing the flow so that it is evenly-distributed and quiet. For example, the Department of Earth and Planetary Sciences at the Massachusetts Institute of Technology has a closed recirculating flume on which the return line splits into two pipelines (fig. 49). Each line is capped at its downstream end except for a ring of concentric holes in the cap. Many flexible tubes (Lexan, made by General Electric) carry the flow from the capped pipelines to the headbox. The tubes enter the headbox pointing downward, submerged in the water and evenly-distributed over the tank width. Together with other baffling methods in the headbox the system works acceptably and saves space. The disadvantage is the somewhat greater head loss in the pipeline.

Baffling

Baffling in the headbox is important for getting rid of large-

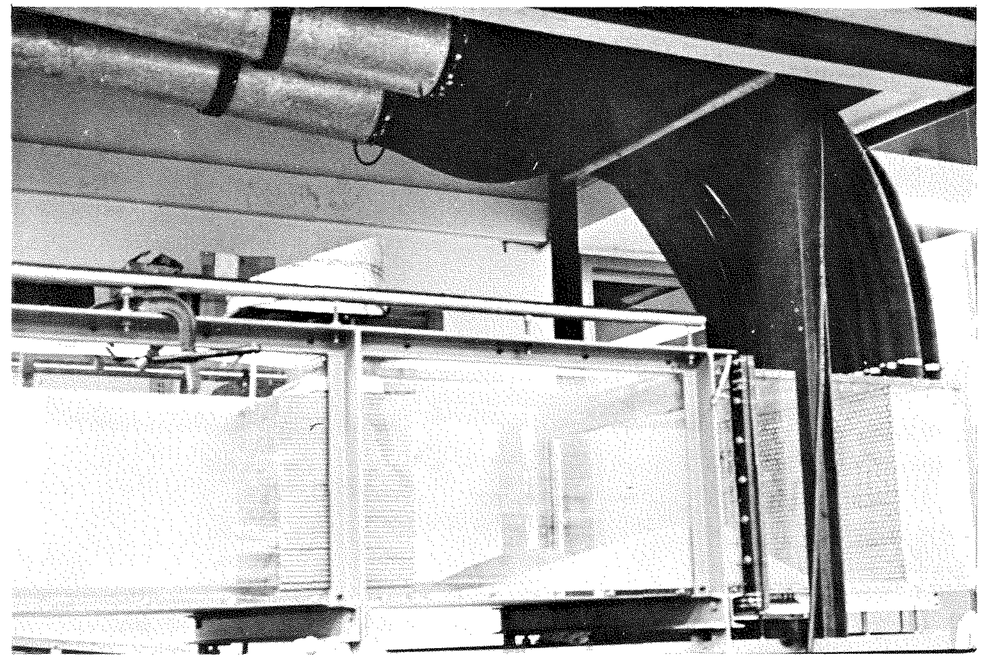


Figure 49.--Groups of tubes in place of return pipe, for a more evenly-distributed flow at headbox entrance (Dept. of Earth and Planetary Sciences, Massachusetts Inst. Tech.). Galvanized pipe, upper left, is capped at top center part of picture except for tube openings. Baffling elements are perforated plate facing flow (far right) and stack of ¼-inch-diameter tubes (center left). (MIT photo)

fence screening, metal screening of different mesh sizes, wood gratings, vanes, weirs, walls extending over parts of the tank interior, wood surface floats (rafts) and stacks of short thin-walled tubes in a honeycomb structure (figs. 47, 48 and 50). Coarse gravel and crushed rock have been used, particularly in the earlier days of flume studies and for clearwater studies. There is some difference of opinion as to the effectiveness of crushed rock. At any rate it is not suitable for recirculating flumes for space reasons.

Many headboxes contain at least two or three kinds and locations of baffling. One example would be a weir downstream from the water inlet and fine mesh screening just before the entrance to the test channel. It is well worthwhile devoting a lot of attention to baffling, as this can greatly reduce the entrance zone in the test section, thus increasing the effective flume length.

Rouse (1961, p. 19) states that screens used as baffles "should have a ratio of open to total area of at least 50 percent; otherwise the jets will coalesce unevenly and thus increase rather than reduce local nonuniformities. Their spacing should be at least eight or ten times the mesh size." You can also help reduce stilling-tank turbulence by (1) expanding the outlet of the supply piping and (2) introducing the water on the center line (length axis) of the tank.

The velocity and sediment distribution at the entrance of the test section are more likely to be evenly distributed if the water flowing through the stilling tank approaches the channel from straight on. If an irregular lateral distribution of velocity does occur in the test

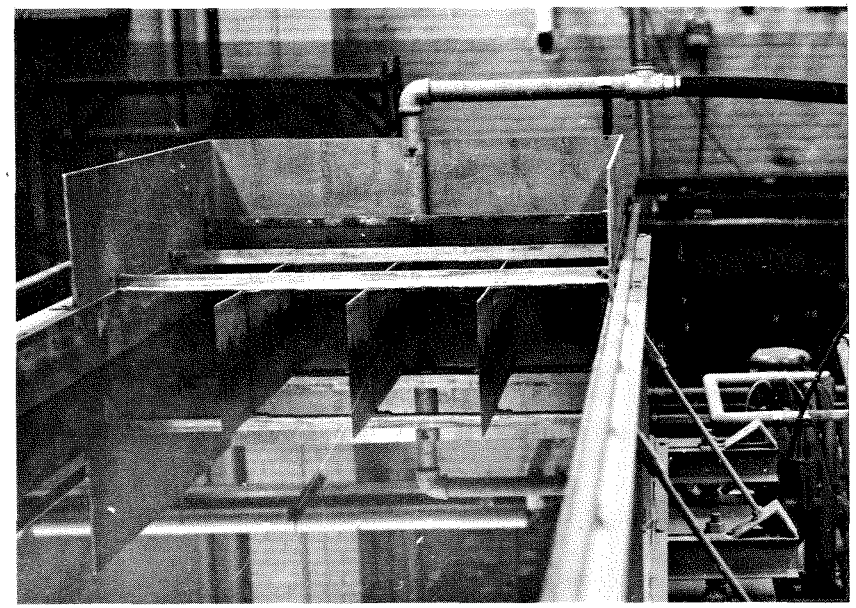


Figure 50.--Baffling at channel entrance, USDA 100-foot flume. Pipe at top of photo brings water back to flume from sediment-sampling apparatus.

entrance, (2) using straightening vanes in the stilling tank near the channel entrance, or (3) completely blocking off a portion of the cross-sectional flow area at the stilling tank outlet. Trial and error methods are necessary to find the best arrangement for correcting an irregular velocity distribution.

Mounting

The stilling tank can be supported in two ways. Firstly, it can remain in a fixed position. Usually this means it is supported by the laboratory floor, although ceiling suspension is possible (Iowa). The second possibility is to fasten the stilling tank rigidly to the flume test section so that the tank moves up or down as you change the flume slope.

Both of these methods are common, and there is no great advantage to either of them. If the tank position remains fixed (floor or ceiling support), you have an easier time designing the flume structure and you don't need such a strong tilting device. Attaching the tank rigidly to the test section provides a little more constant entrance condition at the start of the test section and is easy to mount on small flumes.

If you intend to put the stilling tank in a permanent position, the tank height above the laboratory floor will depend on the elevation of the downstream tip of the flume when the flume is at its steepest slope. This elevation in turn depends on the position of the tailbox or sediment collection box and for closed recirculating flumes on the pump and piping arrangements. Thus you can't decide on the height of a stationary headbox

ding the floor and ceiling, starting at the downstream end and progressing upstream. Draw the flume at its maximum slope and sketch in the stilling tank as one of the last items. If the headbox turns out to be too high, you may have to settle for a lesser maximum slope. This is more apt to occur with nonrecirculating flumes because of the height of the sediment-infeed device.

Keeping the headbox in a fixed position means that the pivot on tilting flumes will have to be at the junction between the headbox and test section (fig. 24E). Make the connection between a fixed headtank and tiltable test section out of a single large piece of sheet rubber (fig.51). The reason for using rubber is that different slopes on the flume produce different amounts of divergence up and down the vertical edges of the headbox-test channel junction. Thus the sheet rubber should extend from the very top of one channel sidewall down to the channel floor, across to the other wall and up to the top of this wall.

Although neglected on many flumes, a streamlined entrance from the headbox into the test section is well worthwhile. This means on the sides in cases where the headtank is wider than the test channel and on the bottom in any case. By thus helping the flow adjust to the test channel you can reduce, sometimes considerably, the length of the entrance region. This streamlining can decrease the coefficient K in $K\frac{V^2}{2g}$ from about 1.8 to 1.4.

For some flume experiments a stream meanders on top of a sand bed. In studies of this sort the water stream can change in width and in location in the flume cross section. You'll need a special entrance piece at

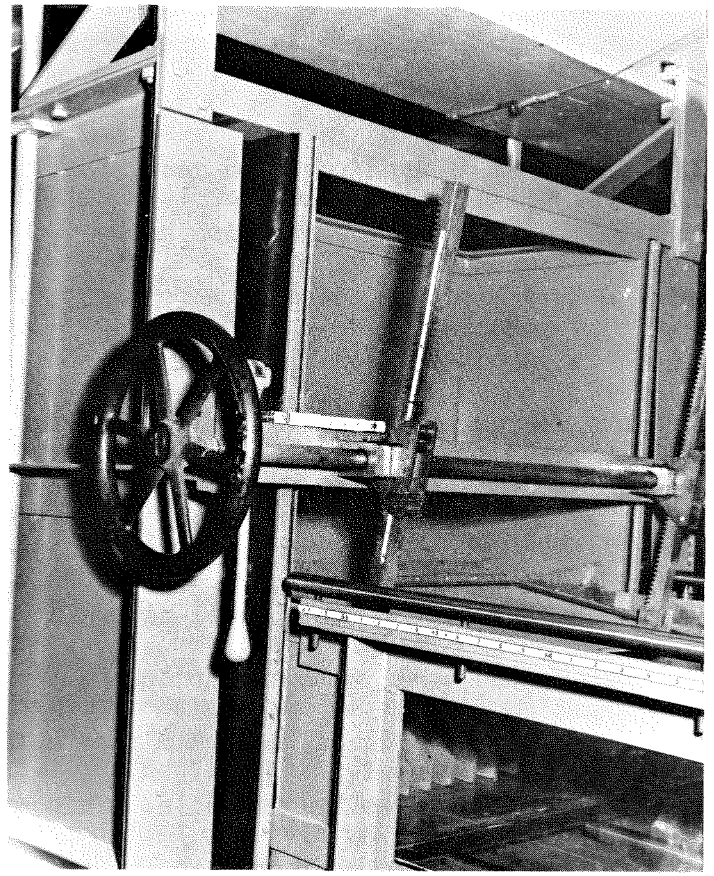


Figure 51.--Sheet-rubber connection between a stationary headtank and tiltable test section (Iowa 85-foot flume). Note the baffling plates for straightening the flow.

must be adjustable so that you can change its width as well as the location of the channel center. There is no standard or common design for such an entrance piece.

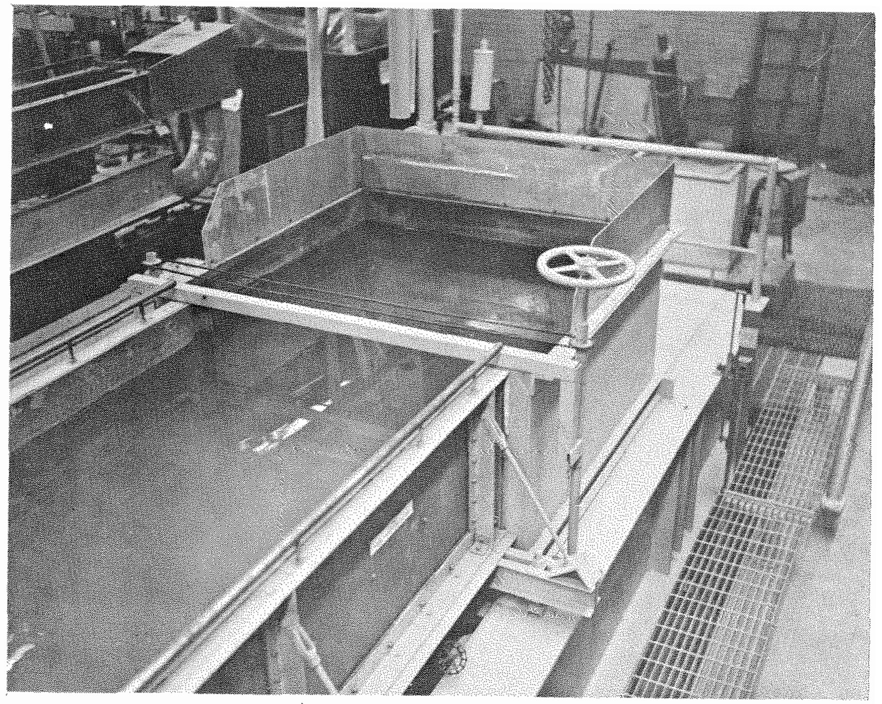
Tailbox (closed recirculating flumes)

Closed-circuit recirculating flumes have a tailbox (fig. 2B) at the downstream end of the test channel except for the rare case where the test channel and return line are all on one level, as with the Amherst demonstration flume (Hand, 1966, fig. 1B). The tailbox is that portion of the flume between the end of the test section and the start of the return pipe. Figures 52 and 25 show some examples.

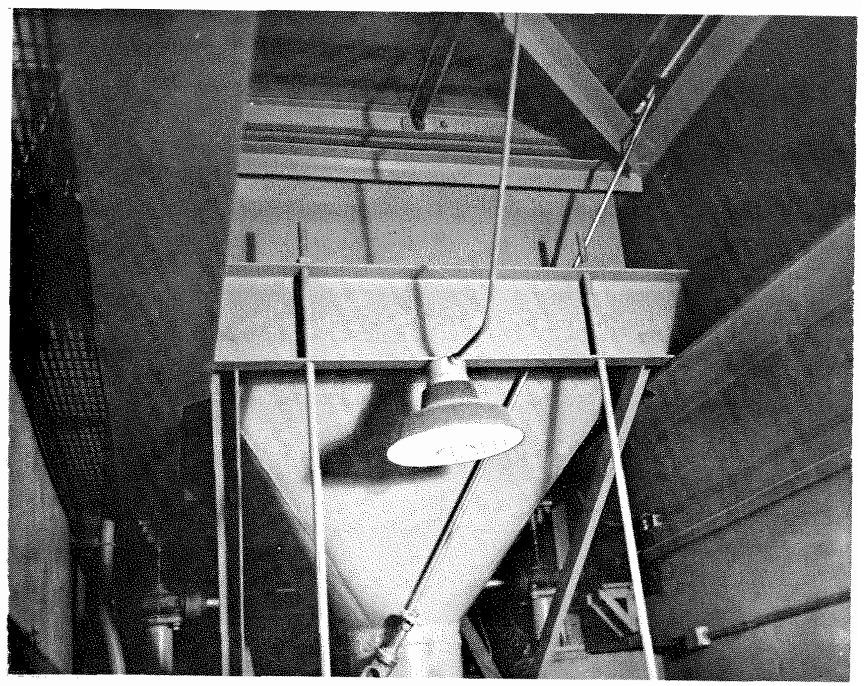
Dimensions and design

The first principle to keep in mind about the tailbox is that it must be deep enough to prevent a vortex and large enough to prevent a complete emptying of the box when flow irregularities occur in the test section. This principle actually applies to both closed and free-overfall recirculating flumes. If air gets down into the conduit the pump will discharge water in intermittent surges. Two design features which help maintain a high water level in the tailbox are:

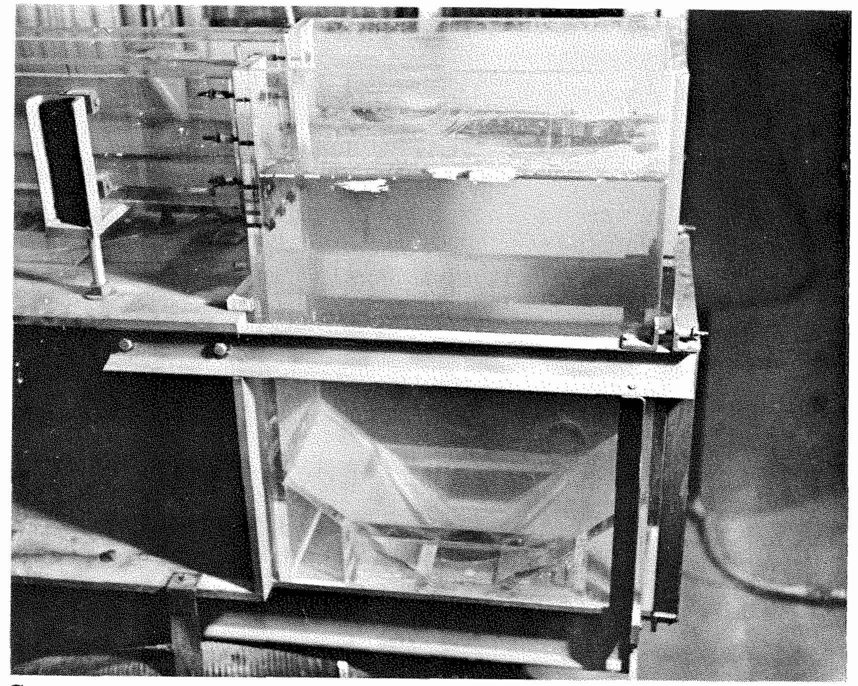
1. A large tank area. The first requirement here is to be sure to make the tank width greater than the flume width. California Institute of Technology finds that a good tailbox width is 1.5-2 times the flume width. This should also be the minimum length and depth of the tailbox.



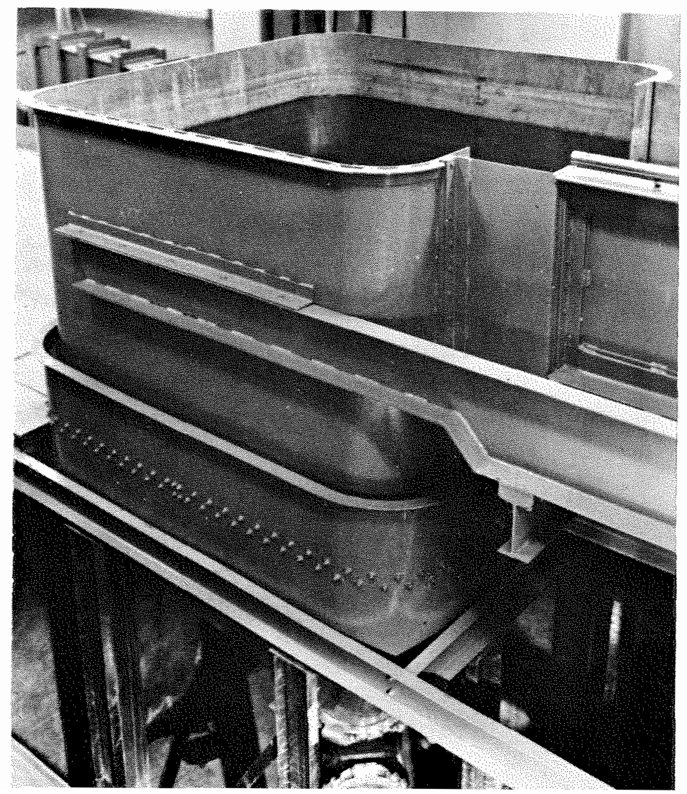
A. Upper part of tailbox on USDA 100-foot flume. See part B of this figure.



B. Lower part of tailbox on USDA 100-foot flume.



C. Tailbox on USGS 30-foot plastic flume at Colorado State Univ.



A third help is to put the pump impeller several feet below the tailbox, as will be discussed in the chapter on pumps.

The second principle in tailbox design is to try to eliminate any sediment storage in the tailbox. (A little sediment accumulation at places other than in the test section is not always a serious disadvantage - it simply means you will need more sand and your experiments will take more time to reach equilibrium.) In designing the tailbox avoid a horizontal floor. Make the walls vertical and/or sloping so that the bottom of the tank is shaped like a hopper leading directly into the return pipe.

Thirdly, with the flume at its maximum slope the tailbox walls must be slightly higher than the flume floor at the test section entrance. Otherwise the water will flow over the top of the tailbox in returning to a horizontal level after you stop the pump, at least for runs involving deep water depths and steep slopes. (If you tilt the flume to a steep slope before filling in the water, prior to starting the pump, you won't even be able to get enough water into the flume, unless the sidewalls are exceptionally high.)

Not all tailboxes have the dimensions and hopper-like design suggested here, but they would function better if they did.

Occasionally water-surface disturbances, probably associated in some way with the tailbox design, may appear in the downstream region of the test section. These can be eliminated by a board, such as a sluice gate (described later), placed above the flow at the downstream [illegible]

Mounting

There are three possible ways of mounting the tailbox:

1. Support the tailbox in a fixed position, either on the laboratory floor or hanging from ceiling. The downstream end of the test section then changes position relative to the tailbox when the flume tilts, but this is of no importance. Sheet rubber makes a good junction. The only possible disadvantage, a very minor one, would be that with certain headbox intake arrangements the greater vertical displacement of the head-tank causes more variation in entrance conditions where the water enters the head tank.
2. Attach the tailbox rigidly to the test section and truss. Here the tailbox shifts position, relative to the laboratory floor, as the flume tilts. Many closed recirculating flumes, at least those that are not large, use this arrangement.
3. Use a combination of the above two methods, i.e. make the tailbox in two sections which are joined by a rubber sleeve, so that the upper half of the tank shifts with the flume while the lower half remains fixed in position (fig. 1E and 52D). The California Institute of Technology developed this design during the 1960's and has found it to be very good.

With any of the above three arrangements the pump and/or return line can be supported by the flume truss, the laboratory floor or the ceiling. The truss-support method probably is more common with small flumes. With large flumes the pump, piping and water usually amount to a lot of weight, and it's well worthwhile letting the laboratory floor arrangement you usually need a flexible rubber pipe of the same diameter as the return line (see, for example, fig. 25). The rubber pipe section connects to whichever tank (headbox and/or tailbox) shifts position as the flume tilts. Short sections of rubber pipe are very common on flumes.

Tailbox on free-overfall recirculating flumes

On free-overfall recirculating flumes the tailbox rests on (or below) the laboratory floor (figs. 2A and 53), so you don't have to worry about mounting. Concrete or steel are probably the best building materials.

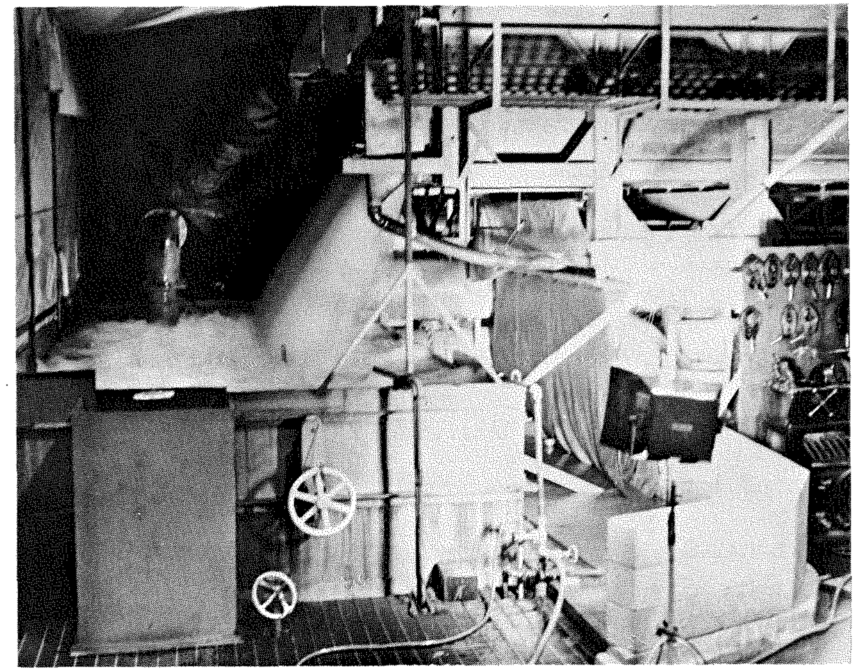
The main goals to keep in mind when planning the tailbox on a free-overfall recirculating flume are:

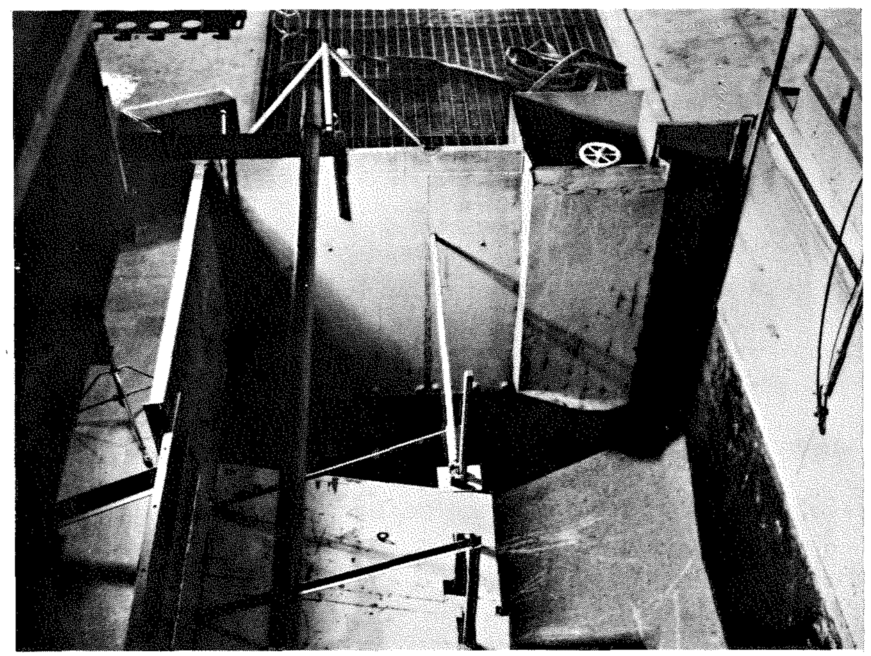
1. Make the tank large enough to store lots of water, as explained below.
2. Make the tank deep enough to eliminate the vortex.
3. Keep air out of the pump and return lines.
4. Channel the sand toward the pump by sloping the floor.
5. Keep the top edge of the tank low enough to allow the maximum desirable flume slope.

Dimensions

One of the functions of the tailbox on a free-overfall recirculating flume is to act as a storage tank so that you can pump more water into the flume for deeper test depths or store water from the flume for shallow flow depths. The tailbox therefore should be larger than that on a closed recirculating flume.

Most pumps suitable for this type of flume will





tailbox and the tailbox should be at least five or six feet deep. A greater depth would be even better because this provides greater tailbox volume for water storage and makes it easier to have sloping floors.

The length and width of the tank must each be about two to four flume widths for research flumes. Except for small flumes you'll have trouble sloping the tank floor and preventing sediment storage if either the length or width exceeds about four flume widths. On the other hand unless the tank length and width are at least two flume widths you'll have a lot of air-entrainment problems.

Unfortunately it will probably be impossible to make the tailbox large enough to hold all the water in the flume system when the flume is not in operation. That is, the volume of water in the flume (length x width x depth) plus that in the piping and headbox will very probably add up to more than the tailbox can hold. So you will need either a sump to hold the excess water or a drain to carry away the overflow from the tailbox when you shut off the pump. A drain therefore should be nearly as large as your maximum expected cross-sectional flow area. The advantage of a sump or drain for excess water will immediately become apparent in the event of a power failure during flume operation.

Air entrainment

A lot of air mixes with the water where the flow plunges into the tailbox. The best way to keep this air from getting to the pump is to make the water travel as far as possible from its entry to its exit, within the tailbox. With this purpose in mind, you'll probably

want to orient the tailbox such that the incoming flow lands in one corner of the tank. Then put the outlet to the pump in the corner or tank wall diagonally opposite. But even more important than the outlet location is the use of partitions in the tank. Arrange one, two or three partial walls inside the tank in such a way that the water must follow a lengthy, circuitous path to get to the tank outlet.

In Colorado State University's 200-foot flume the water travels about 16 feet through the tailbox, and in their 60-foot flume (2 feet wide with tailbox area about 4 ft x 6 ft) it travels about eight feet.

You can help prevent a vortex at the tank outlet (which may be a foot or so above the tank floor if the pump is on the same level as the floor) by installing a pipe in the tank outlet. The pipe from the pump inlet should enter the tank and then turn downward, ending near the tailbox floor. A partition or plate (correctly placed, by trial and error) near the tailbox outlet can also help prevent a vortex at the outlet.

Sediment storage

Ideally there should be no sediment stored in the tailbox. The baffles needed to make the water travel farther also help reduce sediment storage. They do this by constricting the cross-sectional flow area within the tank, thus increasing the velocity.

Another trick in reducing or eliminating sediment storage is to put a slope on the floor as with the tailbox on closed recirculating flumes. Concrete is probably the best material for this. You'll save a lot of trouble by installing this floor slope during the initial construction. Otherwise it will be a matter of trial-and-error and operational delays later.

The downward-turning pipe just inside the tank outlet also helps prevent sediment storage. Because the pipe ends very close to the floor the pump can suck up the sand more effectively.

Sump (nonrecirculating flumes)

A recirculating flume either has no water-storage tank, as with closed-circuit flumes, or has its own water-storage tank - the tail-box on the free-overfall flumes. A nonrecirculating flume, unless it draws water from an outside reservoir, always has a large water-storage reservoir called a sump. This tank accepts or gives up water like the tailbox on free-overfall recirculating flumes but it often serves several pieces of laboratory equipment at one time. For this reason a sump must be a lot bigger than a tailbox and must be kept free of sediment. (Note that by blocking off part of a sump to make it smaller you might be able to operate a nonrecirculating flume as a free-overfall recirculating flume.)

The sump is usually placed below the laboratory floor, and it can take such forms as a large tank in a pit or basement or a spacious channel just under the laboratory floor. (The sump must be lower than the overflow leaving the sediment collection box so that the water leaving this box will flow by gravity to the sump.) You'll probably be able to locate a sump where it will occupy little or no valuable

If the sump is a single large tank try to avoid placing it directly under the sediment collection box. Sometimes the box may not retain all the sediment, and if the sump is some distance away you have another chance to trap this sediment. (See below under "Return Channel.")

Concrete is by far the most common building material for sumps.

The main feature to determine about the sump is its size (volume). In general the sump should be large enough to hold the total amount of water which could fill (1) every piece of laboratory equipment connected to it plus (2) the pipes and tanks associated with the equipment. The sump in fact must hold even more water than this because with all the laboratory facilities full of water the water level in the sump must still be above the pump intake. (The pump therefore should be placed at a height near the floor of the sump, as explained in the next chapter.) Thus you must compute the maximum volume of water which the flume will hold and also the volume of all piping and auxiliary tanks. Then do the same for every other piece of experimental equipment which will use the sump. Minimum acceptable capacity of sump = volume of water in all test equipment + volume in tanks + volume in piping + volume needed to fill sump above pump intake. A water depth of about two feet will probably be enough to fill the sump above the pump intake.

Overdesign the sump capacity by a factor of about 1.5, if space permits. You may want to install more test equipment in the future, for example. A wide area and lesser depth for the sump are much better than a small area and deep depth, in order to minimize the maximum elevation difference which the water surface can have. (The chapter on "Pump and Pipelines" explains why this is important.)

Install several spare outlets of various pipe sizes near the bottom of one sump wall for possible future addition of pumps or drains.

If the bottom of the sump happens to be high enough to permit gravity flow to a sewer outlet, put in a pipe and valve to the sewer. This gives you an easy method of getting rid of dirty water and cleaning the sump.

Put in a safety outlet just below the top of one sump wall, to insure against overflow.

Return channel (nonrecirculating flumes - optional)

In nonrecirculating flumes the water leaving the sediment collection box goes directly back to the sump. If the sump is a large tank directly under the sediment collection box (the simplest arrangement) you lose the chance of stopping the occasional errant sediment grains from entering the sump. (Once in the sump they can be drawn into the pump.) Three ways to avoid this possible problem are (1) guard the sump outlet with fine-mesh screening (not the best solution because the screen may get plugged and the pumping rate could change), (2) make the sump in the form of a long, shallow channel with a sediment trap near the entrance, or (3) don't place the sump underneath the downstream end of the flume. In the latter case you can then connect the downstream end of the flume to the sump by a large

A return channel need not be very long (10 feet is probably long enough) but it must have a large cross-sectional flow area to reduce the water velocity. The width especially should be large - preferably at least twice the flume width. In any event be sure to make this return channel wider and deeper than the flume test section. This helps the sand particles settle out and assures you that the return channel can accommodate Q_{max}.

Roughening the bottom will increase the flow depth and hence lower the velocity still further, thus increasing the chances of retaining any sand.

An arrangement whereby the flow returns to the sump below the water level in the sump, i.e. does not plunge in from above, will reduce the noise in the laboratory to a significant extent.

The sediment trap can consist of one or more simple dams or pits in the return channel. Some screening might be feasible, too.

For in-place weighing where the collection box rests directly on a scale platform the easiest arrangement is to install a metal grating as a permeable floor about a foot or so under the collection box. Then put the return channel just under the grating. In this manner the water leaving the sediment collection box filters through the grating and into the return channel. Be sure the spaces in the grating add up to at least the maximum cross-sectional flow area which the flume will carry.

Constant-head tank (nonrecirculating flumes - optional)

On nonrecirculating flumes the water can be pumped directly from the sump to the stilling tank (headbox) at the head of the flume (USWES), as with free-overfall recirculating flumes. Many people, however, include a constant-head tank between the pump and the flume headbox. This is a tank located at an elevation somewhat higher than the headboxes of the various facilities and from which the water flows by gravity from a constant elevation (head). The water thus flows to the equipment from an "unvarying pressure" and without the occasional pulsations in the flow caused by the pump.

The advantages of including a constant-head tank in the system are:

1. The same pump can supply various pieces of experimental equipment simultaneously.
2. The water flows more steadily through the pipes because the tank absorbs any effects of slight voltage changes on the pump.

The disadvantages of having a constant-head tank are:

1. If the flume will be the only piece of experimental equipment, you'll spend a lot more money by including a constant-head tank. The money will go for the tank itself, the extra piping and the more powerful pump. (And with several pieces of equipment you may need more than one pump to get the water up to the tank.)
2. More laboratory space is taken up.
3. You have the structural problem of mounting a large water-tank at a high elevation in the laboratory.

Although constant-head tanks are common in laboratories, the worth of such tanks for flumes is debatable. Indeed there are good arguments to nullify each of the above-listed advantages of including a constant-head tank. For example, it is pretty rare when a constant-head tank has to supply several pieces of equipment at one time. And frequently you'll need more than one pump, anyway, to pump a lot of water up to a constant-head tank. Thus the large amount of money saved by deleting this tank, piping and extra-capacity pump or pumps could be spent on several cheaper pumps - one for each of the several pieces of equipment. Another possibility is the system which the Asian Institute of Technology in Bangkok and the Georgia Institute of Technology have adopted: use one or more portable pumps and transfer them from flume to flume as required. This portable pump idea applies only to clear water (nonrecirculating flumes); for sediment-water mixtures (recirculating flumes) you'll need an individual pump for each flume.

Pulsations in the pump discharge are rare with modern pumps and voltage controls. But even voltage variations as much as 10 percent (extremely unlikely to occur) cause a change of no more than 1 percent in the discharge pumped. This has been proven in experiments at the Asian Institute of Technology in Bangkok (M. R. Carstens, oral communication, 1970) and can also be determined theoretically. A well-designed headbox and tailbox (large and well-baffled) will dampen if not eliminate pump surges. And if pulsations should become a problem, a by-pass piping system together with the pump will give a more steady flow, as explained in the next chapter.

In conclusion, therefore, you may as well pump the water directly from the sump to the flume headtank, in a nonrecirculating flume. Rousé (1961, p. 6) gives some information on designing a constant-head tank, if you want to include one.

Summary

In order to decrease the turbulence and get a symmetrical velocity distribution at the start of the test section the headbox should have a large cross-sectional flow area and baffles. Also, the point of entry of the water should be on the extended center line of the test channel. To contain the water at fast experimental flow velocities you'll need either high tank walls or a lid on the tank. Effective baffles can be made from vanes, metal screens, weirs, wood grating, boards floating on the water surface and stacks of short thin-walled tubes. The headbox can be mounted on the laboratory floor or on the flume truss.

The tailbox on closed recirculating flumes has to be large enough to keep air from being sucked into the return line and should have sloping walls, at least in the lower portion, to prevent sediment storage. Usually the tailbox is mounted on the flume truss, though there is no outstanding advantage in doing so.

The two goals of tailbox design of free-overfall recirculating flumes are (1) make the water travel the longest possible distance through the tank so that entrained air can escape before it gets to

the tank outlet and (2) prevent sediment storage. Walls across part of the tank interior and a slightly-sloping floor, respectively, are the best means of doing this. A sump can be provided to store the water used in the flume.

Nonrecirculating flumes have a sump to hold the water supply. The sump should be large enough to contain (1) all the water in the facilities and conduits plus (2) another two feet or so of depth in order to keep the water surface above the pump intake. By not locating the sediment collection box directly over the sump you get a chance to trap any grains that may escape from the collection box. For this arrangement you need a channel to carry the water from the region of the collection box to the sump. This return channel must be large enough to accommodate Q_{max} and should have one or more pits or sills to trap sediment.

Recirculating flumes do not have a constant-head tank, and even for nonrecirculating flumes this item is optional. You will probably come out ahead in terms of money, laboratory space, time and construction troubles by omitting a constant-head tank, and the pumped water will nearly always flow just as steadily.

PUMP AND PIPELINES

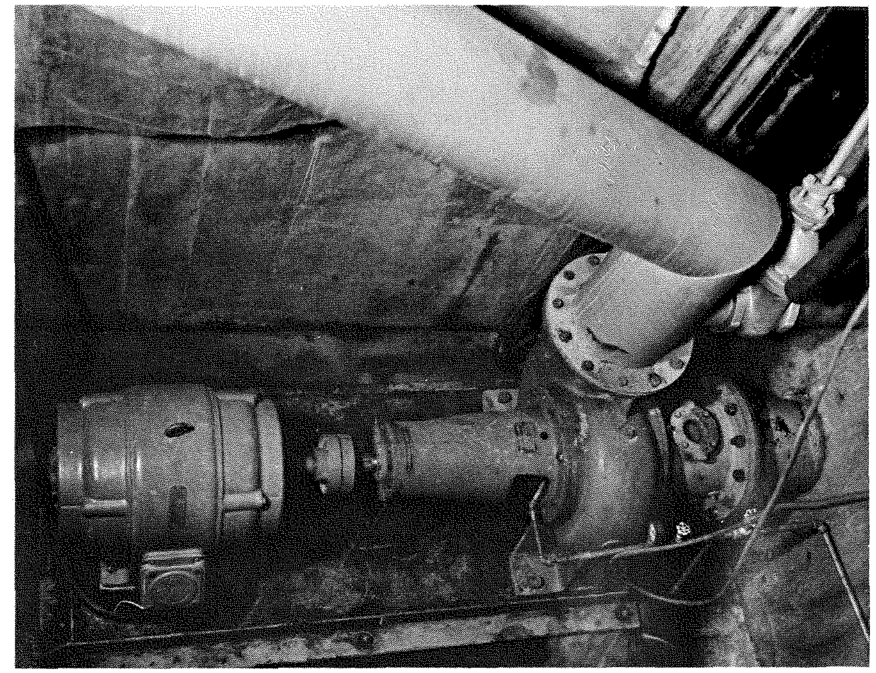
By this time we have covered many of the important features of the flume. Step number nine is selecting the right pump and pipe.

Location of pump

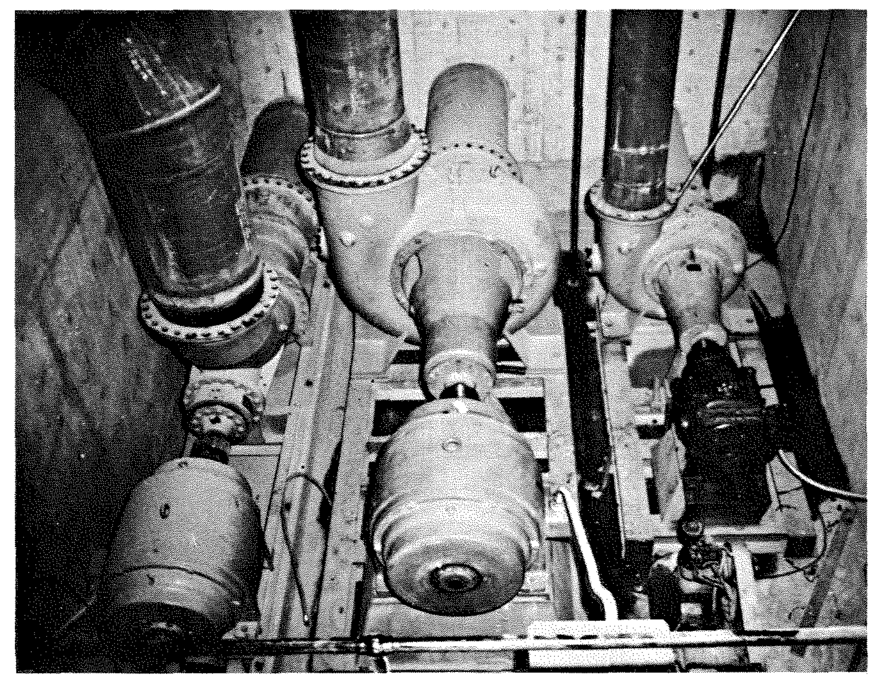
In the early days of flumes people would put the pump anyplace along the return conduit. But they soon found that if the pump was near the head of the flume, the flow disturbances from the pump showed up in the flume test section and could not be eliminated. This fact, combined with the need for a long, straight reach of pipe in order to use many of the popular discharge-measuring devices, means that at least for research flumes the pump will have to be at the start of the return conduit near the downstream end of the flume.

In addition to the general location you have to be careful about the elevation of the pump with research flumes.

In recirculating flumes you'll want to prevent air from being sucked into the pump. The way to do this is to put the pump impeller several feet below the level of the water surface in the tailbox - at least five or six feet lower on large flumes and three feet on small flumes (figs. 54 and 25). Pumps on modern recirculating flumes are

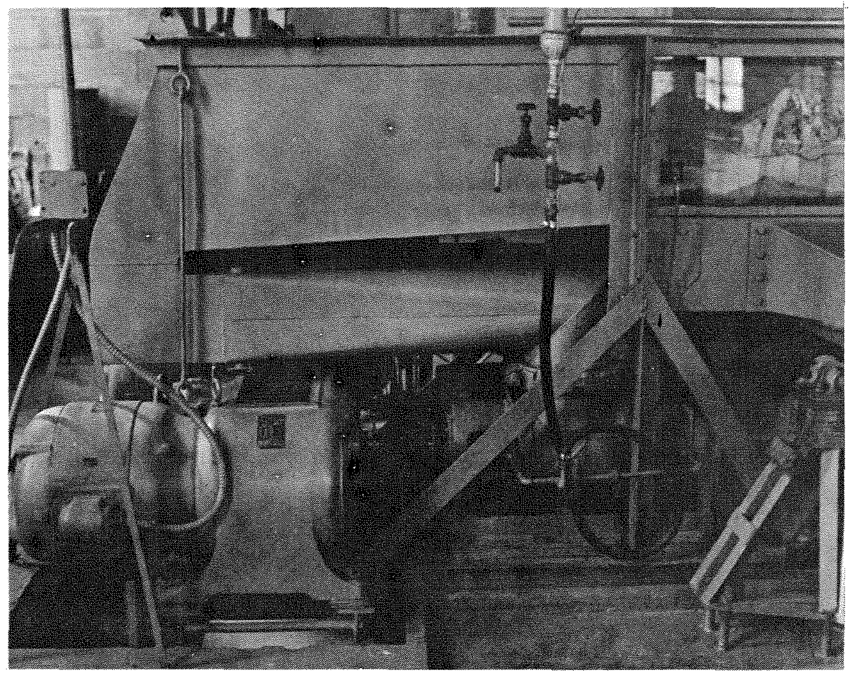


A. 60-foot free-overfall flume, Colorado State Univ.

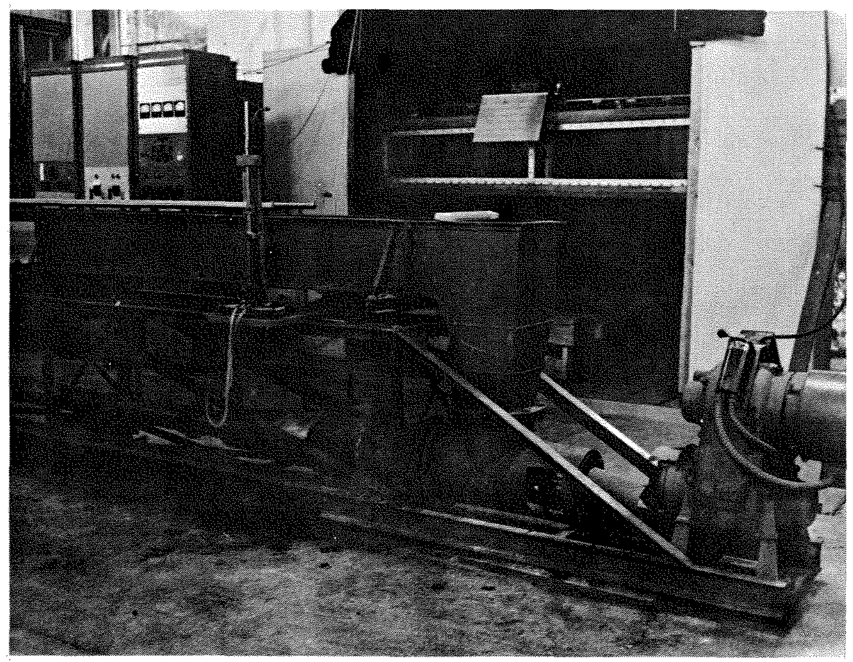


B. 200-foot free-overfall flume, Colorado State Univ.

Figure 54.--Typical pumping plants on recirculating flumes. See also fig. 1C.

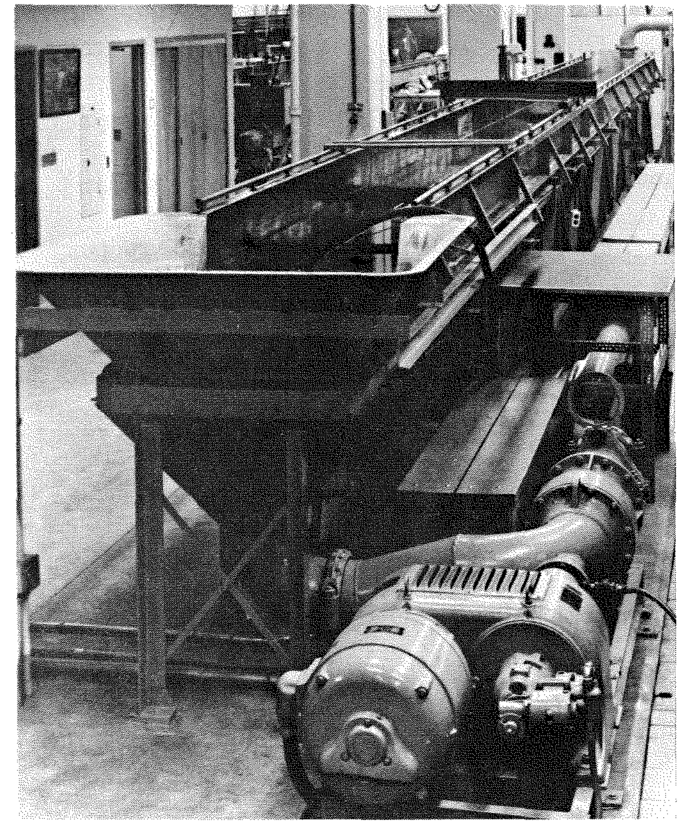


C. Iowa 90-foot sediment flume (two pumping units, side by side).

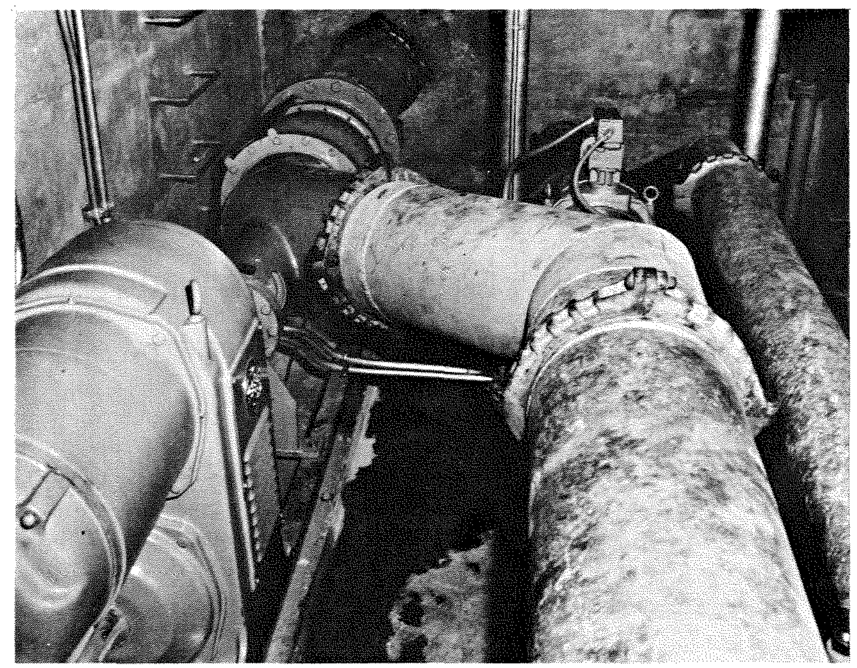


D. 40-foot flume, California Inst. Tech. (Cal Tech photo).

Figure 54, continued.



E. California Inst. Tech. 60-foot flume (Cal Tech photo).



F. California Inst. Tech. 130-foot flume (Cal Tech photo).

Figure 54, continued.

rarely if ever higher than the bottom of the tailbox. (No pump will operate if placed higher than its net operating suction head. The concept of "head" is discussed later in this chapter.)

Pumps must first be primed (filled with water) in order to work properly. For nonrecirculating flumes the best pump location therefore is near the bottom of the sump just outside the sump wall. Water then flows into the pump by gravity, so that you have no suction, priming or air entrainment problems, at least if the water level in the sump in the region next to the pump is deeper than about three feet. The second-best location with nonrecirculating flumes is on the laboratory floor close to the sump (USWES) with a suction line extending from near the bottom of the sump up to the pump intake. For this arrangement you can prime the pump with city water, say a 1-inch or $1\frac{1}{2}$-inch line, tapping in to the top of the suction line. Also, you need a foot valve on the bottom of the suction line. The foot valve opens when the pump is in operation and closes automatically when the pump stops, thus theoretically keeping the suction line full of water at all times. The vertical suction line on such arrangements cannot exceed the net positive suction head of the pump as given by the manufacturer (commonly about 20 feet for pumps used on flumes) and in general should be as short and direct as possible. A more-expensive alternative to priming the pump with city water is to buy a self-priming pump.

A final consideration for nonrecirculating flumes is that the pump inlet should always be as far as possible from the region where the water from the test section or sediment trap plunges into the

sump. As on free-overfall recirculating flumes, the purpose here is to allow any entrained air bubbles to escape to the surface, so that they won't be sucked into the pump.

Types of pump

Only two kinds of pump are usually found with laboratory flumes. Both types belong to the general category known as centrifugal pumps. A centrifugal pump consists basically of a stationary casing which houses a vaned rotating element called an impeller. A shaft driven by a motor supplies the power to the impeller. The shape of the impeller determines the direction the water takes in leaving the impeller and distinguishes the two kinds of centrifugal pumps you will be concerned with: radial-flow and axial-flow.

The brief description that follows merely points out the differences between these pump types. Unless you are very familiar with pumps, you should not try to decide which type to get for your flume. Instead, call in a representative from a pump company for this technical decision. Consult more than one company, in fact, as the service is free. The pump agent will want to know the maximum desired discharge (Q_{max}) and will need certain computed data (total suction head) which we'll get into later in this chapter. Be sure to tell him that you may want to pump solids of a certain size along with the water. (Some impellers and bearings are specially treated to last longer under the impact of sand grains.) Also, explain the flume plans to him to make sure he understands the direction of the water route and the location of the pump.

This is because a pump normally pulls the water toward the pump, but your situation may require that the water be sent away from the pump. It may therefore be necessary to run the motor backwards or to put the impeller in a reverse orientation (USDA at Oxford).

Either type of pump can be used on recirculating or nonrecirculating flumes, though as explained below radial-flow pumps are more popular with nonrecirculating flumes and axial-flow pumps are generally used with recirculating flumes.

One feature to keep in mind when buying a pump for a recirculating flume is that the packing gland should be very accessible. Sand passing through the pump can get into the packing around the pump shaft and also into the bearings. Any sand that gets into the packing must be removed, because just a little sand will soon scour the pump shaft. So the packing has to be replaced or repacked much more often when you pump sand, and it's convenient to have the packing as accessible as possible.

The bearings need frequent surveillance with either type of pump when you are pumping sand. To keep sand out of the bearings force a small, steady flow of water (e.g. 3-5 pounds of pressure through a $\frac{1}{2}$-inch line) from an outside source (city water or constant-head tank) into the bearings. (Greater pressure can damage the bearings.) This small flow backflushes the bearings and keeps sand out.

The amount of water entering the flume in this manner usually is negligible. To keep an exact volume of water in the flume system you can always install an overflow weir in the headbox or tailbox. This

should be designed so that it will take away the excess water without removing any sediment. A good way to do this is to guard the weir with a fine-mesh wire screen. Make the weir 1-2 feet long, to decrease the mean velocity of any overflowing water.

Another possible backflushing arrangement is to use water from the flume system rather than from an outside source. This method keeps the volume of water in the system constant. The Department of Earth and Planetary Sciences at the Massachusetts Institute of Technology has a good example. A small ($\frac{1}{4}$ H. P.) centrifugal pump sends water from the tailbox to a small stilling barrel into which all sediment settles. The water is then routed from the upper part of the barrel to the bearings on the flume pump for flushing.

Figure 55 shows a typical arrangement for backflushing the bearings on a recirculating flume, and figures 54A and 54C show other examples. The pump company can advise you about this procedure. Some pumps are specially designed with water taps to eliminate sand, so that you would not have to rig up a flushing system yourself. (On these pumps water comes from the discharge side of the pump back to the packing box to flush the bearings.)

There is less problem with sand if the pump operates with some suction head (1 to 2 feet) rather than a positive head.

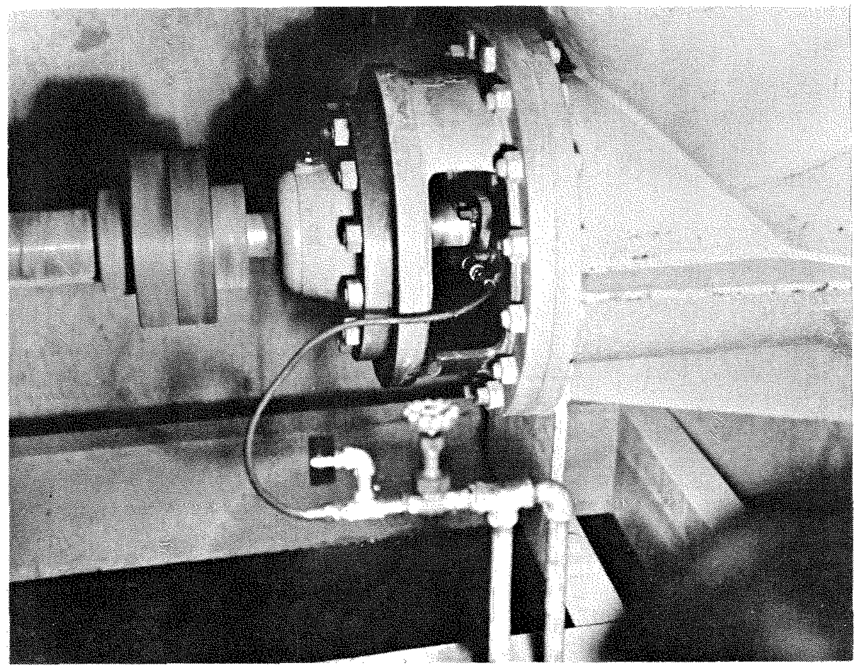


Figure 55.--Backflushing the pump bearings to keep out sand (Colorado State Univ. 200-foot flume).

Radial-flow centrifugal pumps

The impeller on a radial-flow centrifugal pump is shaped so as to force water radially outward in a direction at right angles to the pump shaft. This type of pump is more common with nonrecirculating flumes, probably because it pumps to a higher head (elevation) (e.g. sump to headbox or constant-head tank) more efficiently than does an axial-flow pump. Radial-flow pumps are slightly less popular with recirculating flumes, partly because the solids strike the casing and tend to wear out the casing and impeller sooner.

The discharge from a radial-flow pump is usually regulated by opening or closing a valve in the pipeline on the discharge side of the pump, with the motor always operating at a constant speed. This in fact is an advantage of the radial-flow pump: the discharge can be regulated by opening or closing a valve, without damage to the pump. (The valve is much cheaper than a motor speed control.)

Axial-flow centrifugal pumps

On axial-flow (propeller) pumps the impeller is shaped so as to force the water in an axial direction, i.e. along surfaces of revolution concentric with the pump shaft. Guide vanes next to the impeller help remove the tangential whirl from the water and straighten the flow. The impeller usually consists of only two to four blades and therefore has larger openings than on a radial-flow pump. This means that propeller pumps are usually cheaper than radial-flow pumps and for a given amount of money spent will pass bigger solids. Furthermore, because the flow through the impeller is more axial than radial and because of the larger openings sand grains do not strike the impeller as much as on radial-flow pumps. Hence for sediment studies a given impeller lasts longer on a propeller-type pump. For these reasons propeller pumps are a little more common on recirculating flumes. Also, axial-flow pumps generally are designed to operate under conditions of relatively low head, a situation common with recirculating flumes.

A minor disadvantage to propeller pumps is that ordinarily you can't use a valve in the discharge line to control a wide range of discharges. (Throttling down a propeller pump, i.e. closing the discharge line to any significant extent, increases the load on the motor and may cause it to overheat and destroy itself. The pump must therefore be started with both the suction and discharge sides open.) The most common way of regulating discharges on propeller pumps, especially on closed recirculating flumes, is by means of a speed control on the motor. These "vari-drives" unfortunately are expensive.

You can use a valve to regulate the discharge from a constant-speed propeller pump if you install a special bypass pipe. This saves a lot of money by eliminating the speed control. To adjust the discharge with this arrangement you need a bypass line going from the discharge side of the pump directly back to the intake side (on closed recirculating flumes) or to the sump (fig. 56). The diameter of the bypass should be

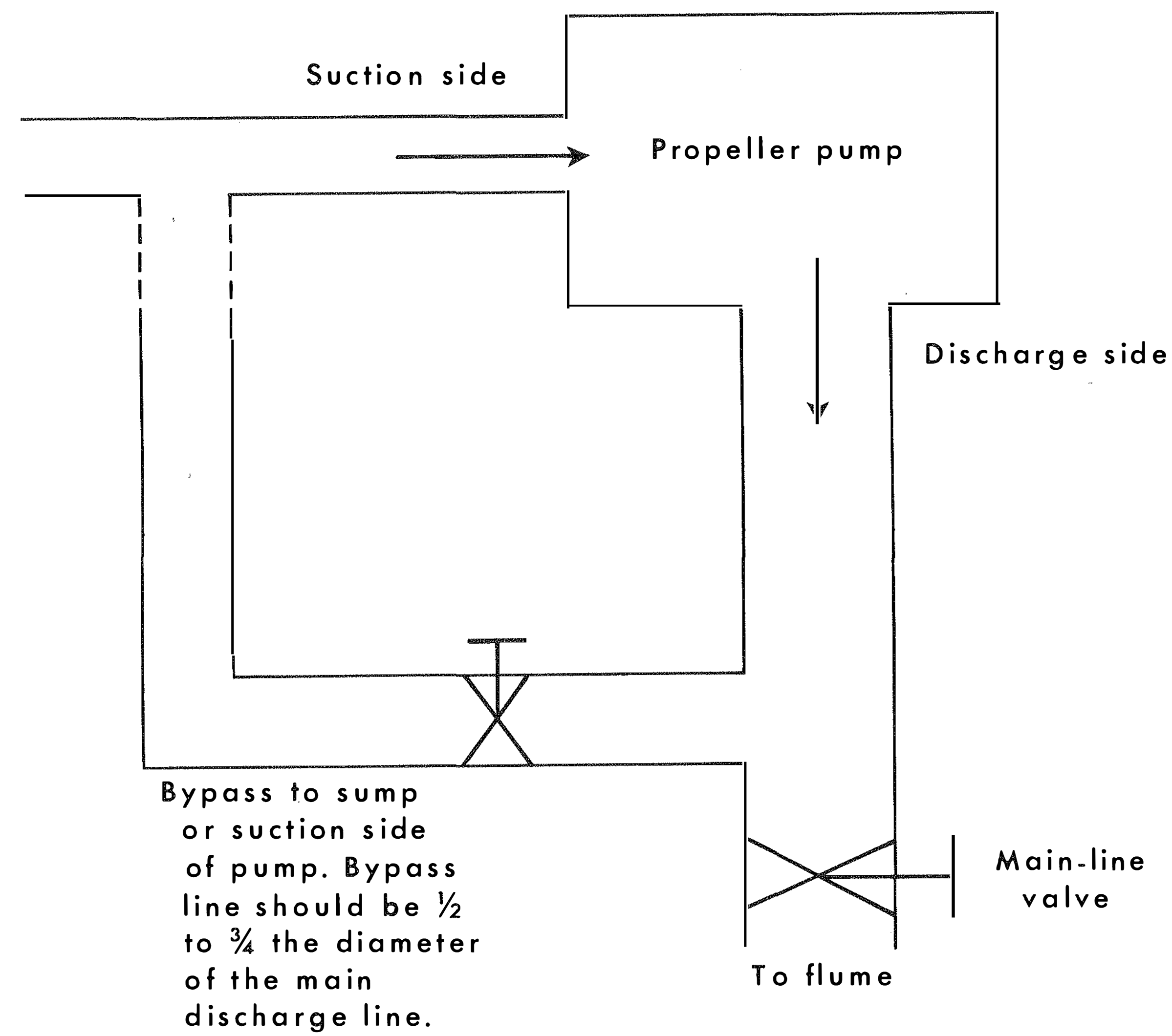


Figure 56.--Bypass system to permit use of control valve with propeller pump.

about 1/2 to 3/4 the diameter of the discharge line. When starting the system the bypass is open and the main line control valve is closed. Next the main line control valve is opened, so that the pump sends water through both lines. Then by gradually closing the bypass you increase the discharge through the main line, to provide the needed flume discharge. Colorado State University uses this system on several of their flumes (fig. 54A). About the only disadvantage is that you can't get a fine control over very low discharges.

The U.S. Department of Agriculture at Oxford uses a bypass of this sort to get a more steady flow, i.e. to do the job of a constant-head tank.

With demonstration flumes cost will be more important than air entrainment. Propeller pumps, being cheaper, are probably your best buy. Or, you may want to improvise. For example, the Amherst demonstration flume simply uses the propeller of an outboard motor, operated by a 1 H. P. variable-speed D. C. motor (Hand, 1966). You may come out ahead financially with this simple arrangement if you can get the motor and propeller on surplus. The disadvantage is that you have no guarantee how efficiently it will move the water in your particular flume.

There is a third class of pumps, known as mixed-flow pumps, with characteristics in between the radial-flow and axial-flow types. Mixed-flow pumps, though not too popular, can be used on flumes. The California Institute of Technology 130-foot flume, for example, has pumps of this type.

Mounting the pump

The pump on demonstration flumes can be mounted in any convenient way - on a table, on the laboratory floor, or attached to the flume itself.

With research flumes that do not recirculate sediment or with free-overfall recirculating flumes the pump always sits on the laboratory or pit floor, so you have no mounting problems whatsoever.

Pumps on large closed-circuit recirculating flumes can also sit on the laboratory or pit floor (figs. 54A, 54B, 54D, 54E, 54F, and 25). A few people, however, have chosen to mount the pump on the flume truss so that it shifts up and down with the flume when the flume tilts. Iowa (fig. 54C), the University of California at Berkeley and the USDA at Oxford have this latter arrangement. Fastening the pump to the flume truss may present vibration problems, both in flume design and in research operations.

Except for demonstration flumes the ease of installation, simplified truss design and lighter truss have persuaded most people to put the pump directly on the laboratory or pit floor, even with closed recirculating flumes. The only advantage to the truss-mounting method is that you might save a little floor or pit space. Even with a strong truss you may need a counterweight system, as at Iowa, to relieve the truss of some of the weight of the pump and motor.

The required power of the pump depends partly on several features of the pipeline, so we're now going to shift temporarily to a discussion of pipes. We'll return to pumps later in this chapter.

Pipe materials

Some of the larger research flumes have standard galvanized-steel pipe. This pipe is thick-walled and therefore heavy and expensive. For flumes you probably won't be dealing with sufficiently high pressures to warrant this kind of piping unless you are pumping to a constant-head tank many feet above the flume. So use instead the light-weight galvanized-steel "culvert" pipe (fig. 45B), either spiral-weld or straight-weld. (Unfortunately this type isn't made in diameters less than six inches as of this writing.) Its advantages are that it is easy to handle, long-lasting and cheap and will therefore save a lot of time, trouble and money. Light-weight galvanized steel pipe is only about one-fourth the price of the heavier standard type.

The couplings (Victaulic or Dresser) used on the light-weight variety need only two or four bolts to clamp two pipe sections together. The heavier pipe can use either these slip-on couplings or threaded flanges. The cost of two flanges and having two pipe ends threaded is about three times the cost of a Victaulic or Dresser coupling. The slip-on couplings are also much quicker and easier to install. Hence they are probably best for flumes.

If the flume will be used daily or frequently you can probably get by with ordinary black pipe rather than galvanized. But for intermittent flume usage rust problems can become serious unless galvanized or other rust-proof material is used. An alternative on smaller flumes is to drain the pipes and dry them by means of a hot-air blower.

Demonstration flumes can use any of a variety of pipe materials. Some flumes which are essentially on one level, such as the flume at the Swiss Federal Institute of Technology at Zurich (Johnson, 1943) and the Amherst flume, have no pipes at all.

The plastic flumes at Colorado State University and Washington, D. C. (USGS) have pipelines wholly or mostly of clear plastic. The advantage of clear plastic is that you can see any sand storage that occurs.

On larger research flumes it would be too risky making the whole return line out of plastic, because plastic certainly cracks more readily than steel. (Hence a plastic pipe needs stronger support than steel.) But it definitely would be worthwhile including a short clear-plastic section (say two or three feet long) to check for sand storage (fig. 57). This again is another example where many people say they wish they had such a check. Plastic pipes are available in all nominal pipe sizes from $\frac{1}{4}$-inch through 16 inches.

If you put the pump of a tilting flume on the laboratory or pit floor you'll need rubber piping at one or maybe two points along the return route. We'll get into the subject of possible pipe layouts in the next section. Rubber piping, as with plastic, is available in any of the pipe diameters you will need.

Route and details of pipelines

Your next job is to plan the route of the piping. In doing this there are a number of things to keep in mind.

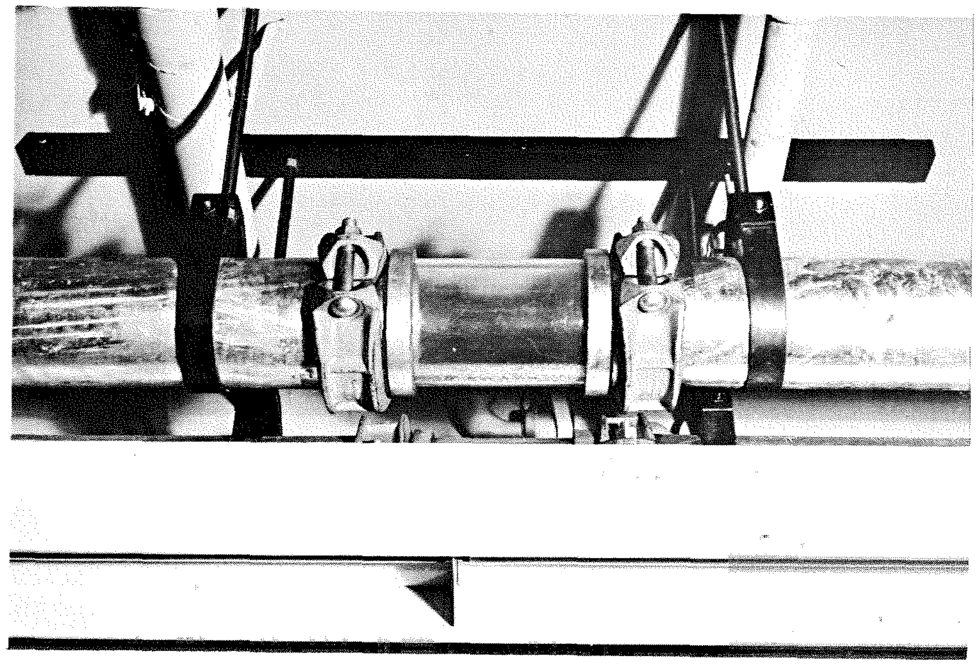


Figure 57.--Short clear-plastic section in return line for revealing any sand storage (MIT photo).

To begin with, water discharges are often measured by devices within the pipeline, as explained later. Right now all you have to remember is that these measuring devices need a long straight section of pipe upstream — usually about 20 pipe diameters in length. (You'll want to read the section on measuring discharge before reaching any final decisions on the pipe.) Since you don't know the pipe diameter yet, plan on including a straight section of pipe with a length at least equal to half the flume length. This will be ample for nearly all flumes.

The second thing to consider is where the water will enter the head tank. The point of entry should be on the extended center line of the test section, as mentioned earlier. Water can come in through the tank floor, the front or rear wall or can spill into the tank from above.

Bringing the pipeline into the headbox wall or floor usually is more direct and takes less piping. So most flumes have floor or wall entries. Several flumes, however, route the pipe downward into the headbox from above. Examples of this top entry are at the Georgia Institute of Technology, USWES (fig. 30A) and the California Institute of Technology's 60-foot flume (fig. 54E). The two advantages to this method are (1) you don't have to install a flexible rubber pipe-connection where the pipe enters the headbox, as you otherwise would when the pipe rests on the laboratory floor while the headbox tilts with the flume, and (2) you don't have to worry about the size of the pipe inlet where the pipe enters the headbox. The latter convenience makes it easier to change pipe sizes and to add or subtract pipes at any time. One possible disadvantage is the need for better baffling in the headbox. The top inlet on the California Institute of Technology 60-foot flume casts a wake which persists for some distance downstream.

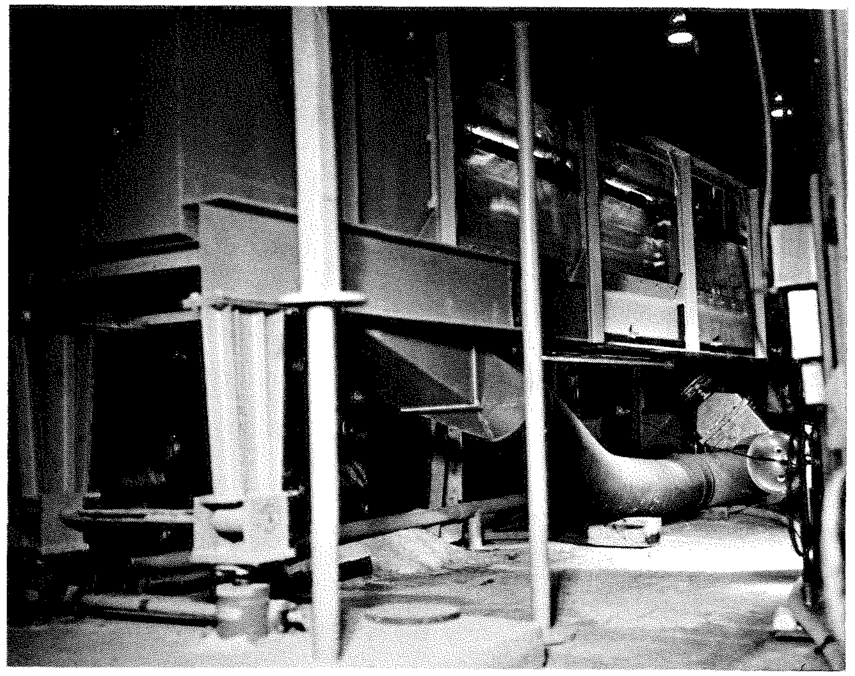
If the pipe comes downward into the top of the head-tank, the best arrangement is to expand the pipe to the full width of the flume and submerge the outlet. In other words, make a transition with guide vanes and extend this transition to at least the level of the flume floor. Submerging the outlet rather than pouring the water in provides better baffling. Also, by submerging the outlet the pump only has to raise the water to the water surface in the headbox rather than to the highest point in the pipeline. This lightens the pump's job. There is only one minor advantage to leaving the pipe outlet exposed. Sometimes a change in flume slope can cause detectable changes in the discharge, even though you haven't touched the valve or motor-speed control which governs the discharge. The reason is that changing the slope has changed (possibly significantly) the net elevation difference between the water levels in the headbox and tailbox (or sump). This net elevation change means the pump has to push water to a greater or lesser net elevation. Thus after a slope change you might have to readjust the valve or pump speed slightly, to keep the same discharge

if the pipe outlet is submerged. This would be important only in certain research projects and even then is not a major handicap.

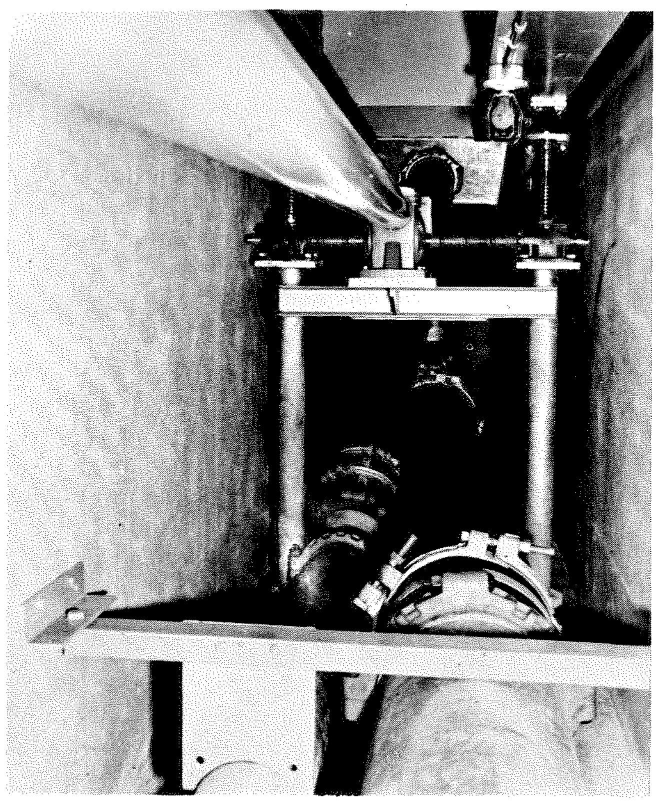
With nonrecirculating and free-overfall recirculating flumes the sump or tailbox, pump and pipelines rest on the laboratory floor. On large flumes this is a big advantage in regard to the required strength of the flume truss. You might consider resting horizontal pipes on 6-inch high cement blocks rather than lying the pipe directly on the laboratory floor. This makes it much easier to tighten the bottom bolts, when bolting adjoining pipe sections together. If floor space is really scarce you may be able to suspend pipes from the ceiling, unless this interferes with overhead devices such as cranes. However, this is not advisable on flumes which have no valve in the pipeline. The reason is that air then gets into the line, and this has several disadvantages, as explained below.

If the headbox is rigidly fixed to the tiltable flume truss and the pipe rests on the laboratory or pit floor, you need a short piece of flexible rubber pipe where the regular pipe approaches the headbox (fig. 58).

Closed-circuit recirculating flumes often have the return pipe attached to the flume truss. This presents no problem on smaller flumes and eliminates the need for a flexible connection between the return pipe and the headbox (fig. 22). Larger flumes can and do have this arrangement, too (fig. 16C), but the heavy weight of the pipe



A. Colorado State Univ. 60-foot flume.



B. California Inst. Tech. 130-foot flume (Cal Tech photo).

Figure 58.--Rubber pipe connections at or near the entrance to the headtank.

plus water means you'll have a more complicated and expensive flume truss. With the return pipe fixed to the truss you may or may not need rubber connections at the pump. None are needed if the pump and pipe both sit on the flume truss (Iowa 90-foot flume), but two are needed (one on each side of the pump) when the pump sits on the laboratory floor (fig. 1D).

If you put the return piping on the laboratory floor you have a choice of putting it directly underneath the flume or out to one side. Underneath the flume is probably the more popular location, as this looks neater and takes up less floor space. Some larger flumes (e.g. USWES; Colorado State University; USGS) have the floor-supported return pipe out to one side. This permits easier access to the pipe, pipe fittings and flow meter. Also, the pipe is then out of the way for changes in flume slope, so that you may get greater slopes.

The pipe diameter on some flumes stays constant right up to the headbox (fig. 16B). Research flumes however, often have a transition section about 10 feet long where the supply line expands as it approaches the headbox. The Oxford 100-foot flume is one example of an expanding transition. The advantage of an expanding transition (see fig. 18G and also fig. 58A) is that the flow enters the headbox more quietly. You therefore have fewer baffling problems and possibly better flow conditions at the entrance of the test channel. This type of transition is particularly suited to rigid boundary studies where you aren't worrying about pushing solid particles up into the headbox. A constricting transition may be needed for some sediment-transport studies. This is because the constricting flow area increases the water velocity and thereby gives a helpful boost to the sediment grains.

With radial-flow centrifugal pumps you need a valve in the line to control the discharge. Put this valve in such a location as to keep the pipeline full of water after you close the valve and stop the pump. Keeping the pipe full of water prevents air from getting into the manometer which you probably will have for discharge measurement. Otherwise you'll have to flush the manometer lines and reset the manometer prior to each starting of the pump. Another reason for keeping the pipe full is that empty black steel pipes start to rust, and this will then contaminate the whole water supply when you resume operating.

If the best valve location happens to be in a pit or inconveniently high, attach a rod-like extension to the wheel of the valve.

On larger pipes, say 12 inches or more in diameter, a regular gate valve can be a little difficult to open and close. You can easily gear down these gate valves, so that the gear reduction enables you to operate the valve very easily by turning a small handle (USWES).

Most flumes have only one pipe supplying the water to the headbox. Some recirculating flumes, however, have two supply lines - one large and one small. This is because the mean flow velocity through the pipe has to be fast enough to keep the sediment moving through the whole return route, and a single large pipe may not produce sufficiently fast

flow velocities at low discharges. More about this later. Two pipelines also give you a more accurate control and measurement of small and large discharges.

On nonrecirculating flumes or on recirculating-type flumes which won't be used for sediment studies you can get a good control of large and small discharges by means of bypasses which circumvent the main valve (important only on research flumes). To arrange this, choose one pipeline large enough to provide Q_{max}, as explained below. Then, in the region of the valve which regulates the flow through the line, install one or more bypass lines with separate valves (fig. 59). Make these bypass lines considerably smaller than the major pipe. The main valve can then be closed and an auxiliary valve in a bypass opened, to get a good control over lower discharges. (Remember not to close the discharge line very much, if you have a propeller pump.) The diameter of the bypass lines can be as small as you want. If you want to measure discharge by a device placed in the pipeline (see the chapter on measuring discharge), the bypass line will have to be at least 25 pipe-diameters long. Otherwise it need be only long enough to get around the valve in the main line (fig. 59).

While we're on the subject of pipes, a one-inch garden hose from an outside source such as city water supply is big enough to fill most closed recirculating flumes in only a few minutes. The other flume-types have a sump or large tailbox, and a two- or three-inch diameter line is enough in these cases.

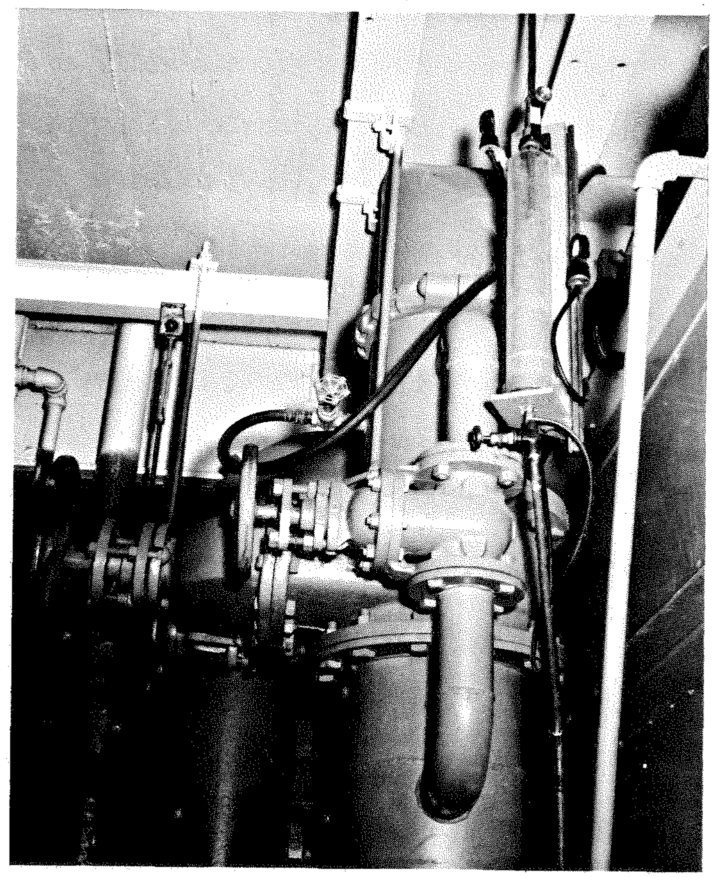


Figure 59.--Bypass lines with separate valves for a fine control of a wide range of discharges (Iowa 85-foot flume). Flow is downward. The valve in the main pipeline is flanked by two auxiliary valves, one mostly hidden, in an intermediate and small bypass, respectively. The faucet on the garden hose in the photograph is a fourth such valve, for extremely low flows. The picture also shows the stilling well and point gage used to measure the water-surface elevation upstream from a weir in the headtank. Note small lights to illuminate water surface and vernier.

Be sure to make some provision for getting rid of the water, because it quickly becomes dirty, at least with sediment in the flume. There are several ways to do this, depending partly on the type of flume and whether you want to remove or keep the sediment.

1. The easiest way is a gravity flow from the base of a tailbox or sump to a sewer. This gets rid of all of the water in nonrecirculating and free-overfall recirculating flumes and of most of the water in closed recirculating flumes.
2. Use a small portable pump.
3. If a gravity flow from the sump is not possible on nonrecirculating flumes put a tee and an extra valve in the pipeline just upstream from the valve that governs the discharge to the flume. Connect firehose or some other inexpensive hose (say two or three inches in diameter) to this auxiliary valve. You can then keep the main valve closed, open the auxiliary valve and use the flume pump to pump the dirty water out through the hose.
4. On closed recirculating flumes you'll need an outlet on the bottom of the return pipe at the downstream end of the flume. This is the lowest point in the circulation system and serves for getting rid of all of the water. Unless retained by a tailgate in the test section (USDA at Oxford) sand will also escape here. However, a hopper in the test section, as described earlier in this manual, is much faster than a pipe drain for removing the sediment. To remove nearly all of the water and keep the sand in the flume put a drain in the vertical section of the return conduit, a short distance up from the bottom, at the downstream end of the flume.

Pump capacity and pipe diameter

The only two features of pumps and pipes which you have left to determine are the capacity of the pump and the pipe diameter. These closely-related features have to be determined simultaneously, and this is the reason we're discussing pumps and pipelines in the same chapter. (In many cases, for example with large research flumes, the pump representative will want to go over all of these computations with you.)

Computing total head on the pump

Pumps can be described in terms of the water discharge they can pump up to a given height (head). When the pump is not operating water will pass through the pump and adjoining pipeline and will rise until it reaches a level equal to that of the water in the tailbox or sump. Thus the height to which the pump must elevate the water is reckoned from the elevation of the water surface in the sump or tailbox. (The calculations will therefore be more dependable if the water level in the sump changes as little as possible. This is why a sump should have a large free-surface area. The variation in its water-surface elevation then will be minimized regardless of how much water is borrowed.)

The pump must have enough capacity to deliver Q_{max} to the flume head tank. To do this the pump must firstly raise the water the vertical distance from the water surface in the tailbox or sump to the water surface in the headbox, a distance normally called "static head" and which we will designate as Δz. In addition, the pump must overcome certain resistances which the water will encounter in flowing through

the pipe. These resistances reduce the height (head) to which the pump could send the water in their absence and are therefore called head losses. The two types of head losses are:

1. The frictional losses due to the surface friction between the pipe wall and the moving fluid. These losses take place along the entire length (L) of the pipeline and are influenced by the inside diameter (d) of the pipe, the wall roughness or pipe material and the mean flow velocity.

$$\text{Frictional head loss} = \frac{fL}{d}\,\frac{V^2}{2g} \qquad (3)$$

   where f is the Darcy-Weisbach friction factor.

2. The local losses due to disturbances in the normal flow of the stream. Such disturbances are the separation of the flow from the pipe wall and the eddying which occur at bends, valves, changes in section, entrance, exit, and other places.

$$\text{Local head loss} = K\,\frac{V^2}{2g} \qquad (4)$$

   where K is a coefficient having values that are known from empirical studies for 90° bends, entrances, exits, valves and other pipe fittings. Assume that frictional losses are negligible in these local head losses.

These last two equations describe frictional and local head losses in terms of vertical feet of head.

The pump, then, must be able to raise the desired Q_{max} a vertical distance equal to (Δz + frictional head losses + local head losses).

This total distance is called the total head or simply head (ΔH). Total head on pump = Δz + frictional head losses + sum of local head losses, or

$$\text{Total head } \Delta H = \Delta z + \frac{fL}{d}\frac{V^2}{2g} + \Sigma\left(K\frac{V^2}{2g}\right). \qquad (5)$$

The required pump horsepower (HP) is

$$HP = \frac{62.4\, Q_{max}\, \Delta H}{e\ 550} \qquad (6)$$

where e is the efficiency of the pump, normally between 0.85 and 0.95.

The water-surface elevation in the tailbox or sump subtracted from that in the head-tank gives the elevation difference Δz. (Figure on the greatest probable Δz.) Your main task, therefore, is to find the various head losses.

To determine the head losses you need the details of the pipeline from the pump to the headbox. The factors involved in the head loss computation are the pipe material (reflecting the wall roughness), pipe length, pipe diameter, number of elbows and other fittings in the line and the maximum flow velocity.

The only items we haven't examined from this group are the pipe diameter and the flow velocity. Now, of course, you don't want to waste money on a pipe that is larger than necessary. But as the pipe gets smaller the mean velocity must increase in order to produce the same discharge. The frictional head loss increases with the square of the velocity and with smaller pipe diameters (equation 3), so the faster mean velocity and smaller pipe mean the pump has to be larger and more powerful (more costly) as you go to smaller pipes. Your object, therefore, is simply to find the most practical compromise between pipe diameter, desired flow velocities within the pipe and available pumps.

The first step in determining these factors is to estimate the maximum (and minimum) flow velocity you need in the pipeline, as explained later. You then use equation (5) to find what the total head will be for various pipe diameters and equation (6) for the horsepower of the pump. The pump and pipe-size to buy will be the cheapest combination which will deliver Q_{max} to the flume while providing your chosen flow velocities within the pipe.

Pumps and pipelines will be a major expense. Therefore, any economies you can achieve in obtaining pumps and pipelines can mean a substantial lowering in the cost of the flume. The cost of a pump is approximately proportional to total head, so it's to your advantage to minimize the total head as much as possible.

For several reasons, you may need more than one pipeline, at least on larger flumes, in spite of the added expense. Firstly, it may not be practical to have pipelines larger than about 2 feet in diameter in a laboratory, so to get deep depths and fast velocities (high discharges) in the flume you may well need at least two pipelines. The Colorado State University 200-foot flume, for example, has three pipelines - 30, 24, and 18 inches in diameter. Secondly, on recirculating flumes the mean velocity in the pipe must always be fast enough to push the largest grains up the vertical return section. If you're studying low discharges, a single large pipe may not have a sufficiently high mean velocity. So you'd need one large and one small pipe to circulate sediment particles over a wide range of discharges. And as mentioned before you get a much better control and measurement of discharges with one small and one larger pipe, compared to a single large line.

Nonrecirculating flumes

The job of finding the right pump and pipe-size is a little easier with nonrecirculating flumes. With no solids to be returned to the headbox you don't care what the minimum flow velocity is. The maximum flow velocity should not be greater than about 9 or 10 ft/sec, because at mean velocities faster than this the head loss becomes very large.

You can now figure the local head losses. These are equal to $K\frac{V^2}{2g}$ (equation 4). Compute the head loss due to each elbow, valve, etc. using values of K as given in table 1. The sum of all such terms is the local head loss. We'll see an example of this computation in a minute. (Note from the table that you can save on head loss by using two 45° bends rather than two 90° bends, avoiding tees, etc.).

Unless you are quite proficient at these computations have the pump agent compute the head loss for an orifice or Venturi meter (discussed in the next chapter), as this local head loss varies with the relative diameters of the pipe and constricted section, in addition to the flow velocities.

The static head Δz and the local head losses won't change with different pipe diameters, for constant V. So now the total head on the pump depends only on the frictional head losses. These will vary inversely with the pipe diameter, since you have already chosen the maximum velocity through the pipe and the pipe details.

You may have to make more than one calculation of the frictional head loss ($f\frac{L}{d}\frac{V^2}{2g}$), to determine the head loss for different pipe diameters. (Pipe diameters come in standard sizes: every half-inch up through 4 inches, then 5, 6, 8, 10, 12, 14, 16, 18, 20, 24, 30-inches and larger.) Table 2, based on Giles (1962), lists values of f for a known type of pipe, pipe diameter and flow velocity. To begin, compute an approximate value of d by using the continuity relation $Q_{max} = AV = \frac{\pi d^2}{4}(10)$, or $d = \sqrt{Q_{max}/8}$. Round this value to the nearest

TABLE 1.--Typical head-loss items (from Giles, 1962).
Subscript 1 = upstream and subscript 2 = downstream.

ITEM	AVERAGE LOST HEAD
1. From Tank to Pipe - flush connection (entrance loss)	$0.50 \frac{V_2^2}{2g}$
- projecting connection	$1.00 \frac{V_2^2}{2g}$
- rounded connection	$0.05 \frac{V_2^2}{2g}$
2. From Pipe to Tank (exit loss)	$1.00 \frac{V_1^2}{2g}$
3. Sudden Enlargement	$\frac{(V_1 - V_2)^2}{2g}$
4. Elbows, Fittings, Valves Some typical values of K are: 45° Bend .... 0.35 to 0.45 90° Bend .... 0.50 to 0.75 Tees .... 1.50 to 2.00 Gate Valves (open) .... about 0.25 Check Valves (open) .... about 3.0	$K \frac{V^2}{2g}$

TABLE 2.--Friction factors f for water (based on Giles, 1962).

(f = tabular value x 10^{-4})

DIAMETER (inches) and TYPE OF PIPE		VELOCITY (ft/sec)							
		1	2	3	4	5	6	8	10
4"	New, galvanized steel	300	265	250	240	230	225	220	210
	Very smooth (plastic)	240	205	190	180	170	165	155	150
6"	New, galvanized steel	275	250	240	225	220	210	205	200
	Very smooth (plastic)	220	190	175	165	160	150	145	140
8"	New, galvanized steel	265	240	225	220	210	205	200	190
	Very smooth (plastic	205	180	165	155	150	140	135	130
10"	New, galvanized steel	260	230	220	210	205	200	190	185
	Very smooth (plastic)	200	170	160	150	145	135	130	125
12"	New, galvanized steel	250	225	210	205	200	195	190	180
	Very smooth (plastic)	190	165	150	140	140	135	125	120
16"	New, galvanized steel	240	220	205	200	195	190	180	175
	Very smooth (plastic)	180	155	140	135	130	125	120	115
20"	New, galvanized steel	230	210	200	195	190	180	175	170
	Very smooth (plastic)	170	150	135	130	125	120	115	110
24"	New, galvanized steel	225	200	195	190	185	180	175	170
	Very smooth (plastic)	165	140	135	125	120	120	115	110
30"	New, galvanized steel	220	195	190	185	180	175	170	165
	Very smooth (plastic)	160	135	130	120	115	115	110	110

commercial pipe size. Next, go to table 2 and get the associated value of f for the type of pipe and for V = 10 ft/sec. Finally, calculate the frictional head losses. These will be the frictional head losses which the pump would have to overcome for this type and diameter of pipe, at V = 10 ft/sec.

Rubber sections are often short enough (relative to the total length of the return route) to be ignored in computing frictional head losses. Otherwise use f values of about 0.024 to 0.032. (These are approximate values for corrugated steel culvert pipe and are close enough for your purposes.)

Adding the static head, local head losses and frictional head losses gives the total head. The pump representative will recommend a pump that will produce the desired Q_{max} with this total head. If the computed total head is too much for a reasonably-priced pump you'll have to refigure the frictional head losses, using a larger pipe diameter.

Now let's go through all of this with a sample calculation. Suppose you want a maximum discharge of 3.0 cfs to be delivered from the sump to the headbox. The outlet of the supply line is submerged in the headbox. The water surface in the stilling tank at this highest discharge is 10 feet higher than the water surface in the sump. What is the total head on the pump and what pump horsepower will be required?

From the design completed thus far you know the routing of the pipeline and therefore the length of straight pipe, number of 90^o bends, etc. Suppose that for your case the details are:

total length of straight pipe	=	50 ft.
number of 90^o bends	=	3
number of gate valves	=	1
number of tees in line	=	1
pipe condition	=	new, galvanized steel pipe.

The procedure is:

1. Calculate the local head losses $(K \frac{V^2}{2g})$, taking K-values from table 1, with V = 10 ft/sec.
2. Compute an approximate pipe diameter using the relation $Q_{max} = \frac{\pi d^2}{4} (V)$, with V = 10 ft/sec, and rounding the answer to the nearest commercial pipe diameter.
3. Go to table 2 for the associated value of f, using V = 10 ft/sec in new pipe.
4. Compute the frictional head loss $f \frac{L}{d} \frac{V^2}{2g}$.
5. Add Δz, local head losses and frictional head losses to get the total head.
6. Calculate the pump horsepower: $HP = \frac{62.4\, Q_{max}\, \Delta H}{550\, e}$, with e = 0.8.

Now let's carry out each step:

1. For local head losses (equation 4), taking K values from table 1:
   a. Entrance loss, sump to pipeline $= K \frac{V^2}{2g} = 0.5 \left(\frac{100}{64.4}\right) = 0.8$ ft
   b. 90^o bend $= 0.75 \left(\frac{100}{64.4}\right) = 1.2$ ft

      Hence 3 elbows = 3.6 ft
   c. Gate valve (open) $= 0.25 \left(\frac{100}{64.4}\right) = 0.4$ ft
   d. Tee $= 2.00 \left(\frac{100}{64.4}\right) = 3.1$ ft
   e. Exit loss, pipe to stilling tank

      $= 1.00 \left(\frac{V^2}{2g}\right) = 1.6$ ft

Thus the local head losses = 0.8 + 3.6 + 0.4 + 3.1 + 1.6 ft = 9.5 feet.

2. Pipe diameter $d = \sqrt{4Q_{max}/\pi V} = \sqrt{Q_{max}/7.85} = 0.618$ feet ≈ 7.4 inches. Round to 8 inches.

3. From table 2 we find that f = 0.0190 (new steel pipe, d = 8 inches, V = 10 ft/sec).

4. For the frictional head losses (equation 3):

$$\frac{fLV^2}{d\ 2g} = \frac{(.0190)\ (50)\ (100)}{(0.67)\ \ (64.4)} = 2.2 \text{ ft}$$

5. Total head to be overcome by pump = Δz + head losses = 10 ft + 9.5 ft + 2.2 ft = 21.7 ft. Increase this estimate by about 15 percent (overdesign!) to allow for possible additional head losses. The discharge-measuring device, for example, may cause a head loss of two or three feet. And the friction factor for the pipe material may increase slightly over the years. Also, you may in the future want to change the discharge-measuring device or increase Δz. So for the present example take the total head as 25 feet.

6. Pump horsepower $HP = \frac{62.4\ Q_{max}\ \Delta H}{550\ e} = \frac{(62.4)\ (3)\ (25)}{(550)\ (0.8)}$

$= 10.6$ horsepower.

The next step is to consult two or three pump companies. The pump agent will probably want to see your design and compute the total head himself. From experience he will probably be able to quickly determine the size of pipe you need, in view of the required conditions and available pumps. Don't order any pipe or pump until you have discussed the design with the representative of the pump manufacturer.

Recirculating flumes

If you are certain that you won't be using sediment in a recirculating flume, figure the pump capacity and pipe diameter in the manner just described for nonrecirculating flumes.

For sediment-transport studies in recirculating flumes you have the additional problem of preventing a significant amount of sediment storage in the return conduit. (As mentioned earlier the storage of sand means you need more stock sediment and experiments take longer to reach equilibrium. Also, sand deposits near a discharge-measuring device in the return pipe can cause erroneous discharge readings.) To prevent this storage you have to maintain a certain minimum mean velocity, depending on the grain size, in the return pipe. For a given experimental discharge the only two factors you can manipulate to keep the desired velocity in the return conduit are the diameter (cross-sectional flow area) of the conduit and the energy which the pump contributes.

The first step in determining the pipe diameter and pump in this case is to estimate the largest grain size you will want to investigate. This tells you the minimum acceptable size of the passageways through the pump impeller and enables you to estimate the settling velocity of the largest grain (fig. 5). We'll come back to the importance of this settling velocity in a minute.

Next you have to decide (approximately) on the lowest discharge you will ever want to use with these large grains. (The lowest discharge and largest grains, you see, will be the worst situation in regard to moving the particles from the tailbox to the flume head-tank.) Unfortunately there is no accurate way to determine this discharge.

The best available method is only a crude one. Figure 60, taken from Sundborg (1956), gives an approximate mean velocity needed to move grains of a given size. The product of this velocity, your shallowest probable flow depth (say 0.05 foot) and the flume width will be the approximate lowest discharge that you'll be using for these grains.

The job now is to choose a pipe diameter which, at this low discharge, will produce a mean velocity fast enough to move the large grains through the complete return route. The critical section of the return route is usually the region near the head of the flume (also just beyond the pump on free-overfall recirculating flumes), as here the conduit often is vertical or nearly so. The mean flow velocity in a vertical section must be faster than the settling velocity of the largest grains, or the water won't be able to push these grains up the conduit. (For this reason the common expanding transition from return pipe to headbox on closed recirculating flumes may present a problem with large particles.) To include a safety factor a good rule-of-thumb in regard to the vertical section of the return line is that the minimum acceptable mean velocity should be about twice the settling velocity of the largest grains. So to estimate the required pipe diameter simply take the lowest discharge and divide by a mean pipe velocity equal to twice the fall velocity of the largest particles. This gives the cross-sectional pipe area and hence the pipe diameter. Round the diameter estimate to the next-lowest standard pipe size.

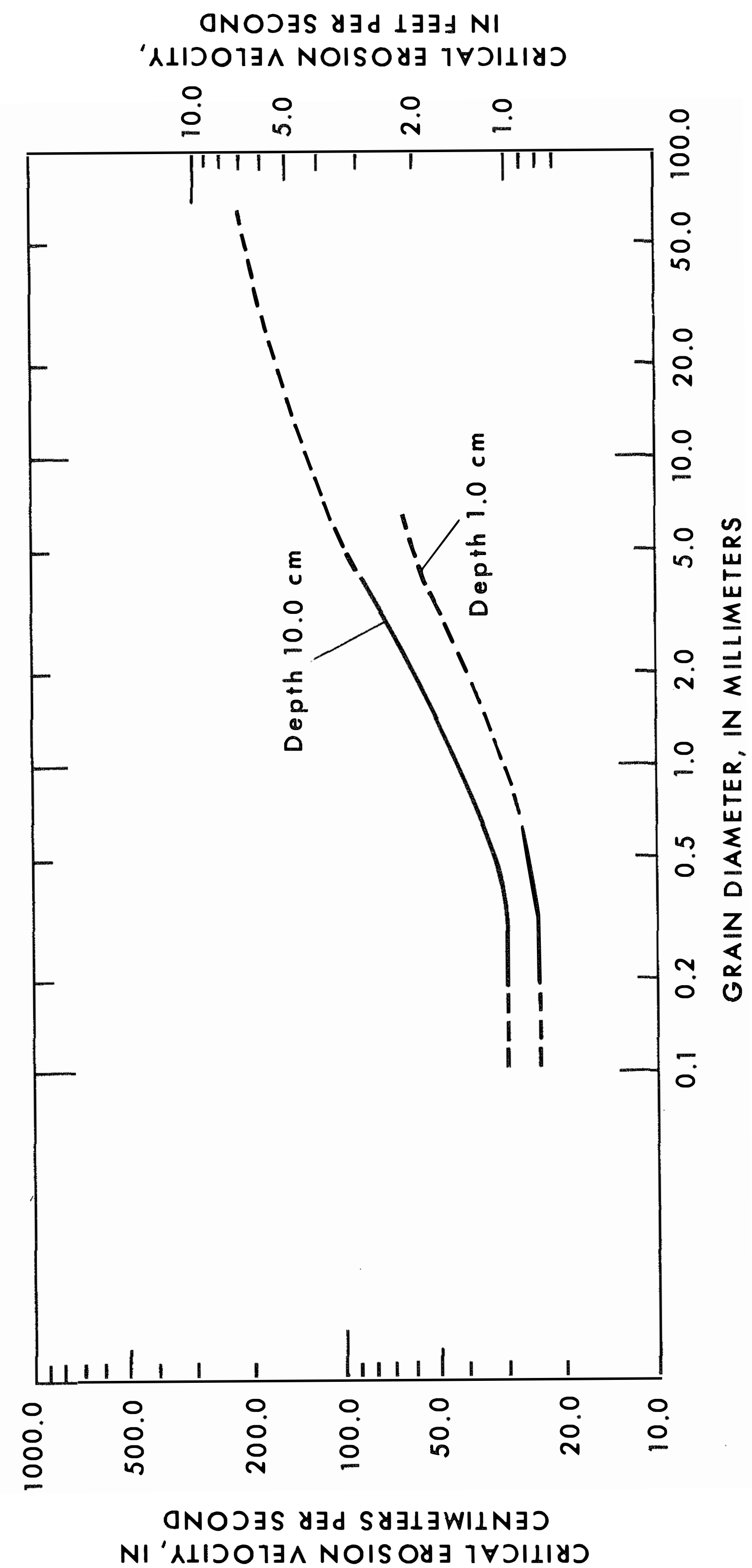


Figure 60.--Approximate critical erosion velocities for quartz grains (from Sundborg, 1956, p. 177).

Now that you have estimated a pipe diameter that will transport large grains at low discharges, the remaining question is what is the maximum discharge that a reasonably-priced pump can send through the pipe you have just selected. In other words, will a reasonably-priced pump be able to deliver Q_{max} through this pipe? There is a good chance that the answer will be no, probably because the head losses may be too great. If the available pumps will not send Q_{max} through the estimated pipe size, you have at least three choices: (1) install two pipelines, one small and one large, to cover the complete range of flume discharges; (2) use one pipeline, pick a smaller maximum grain size and strive for a "happy medium" between pipe diameter, grain sizes and obtainable discharges from the available pumps; or (3) use one pipeline for most flow conditions and change pipe sizes for the more unusual study conditions. The best policy is to discuss all of these possibilities with the pump agent.

Some of the pipe lengths you need to buy and the local head losses will depend on whether or not you want to insert a discharge-measuring device in the pipeline. The next chapter deals with ways to measure discharge.

Summary

The two kinds of pumps generally used for flumes are radial-flow centrifugal pumps (more popular with nonrecirculating flumes) and axial-flow centrifugal pumps. A valve in the pipeline regulates the

discharge with radial-flow pumps. On axial-flow pumps you need a special bypass pipeline in order to use a valve; the discharge on most axial-flow pumps is regulated by the more expensive method of a speed control on the motor. Put the pump at the beginning of the return conduit, either just outside the base of the sump wall (nonrecirculating flumes) or close to the tailbox at a height several feet below the tailbox water surface (recirculating flumes). With large flumes, mount the pump on the laboratory or pit floor rather than on the flume truss. The pump bearings on recirculating flumes must be backflushed with a small, steady flow of water to keep sand out of the bearings.

Galvanized steel, clear plastic and flexible rubber are the most common pipe materials, and a single flume might use all three of these. Light-weight steel is probably best for most of the return route; however, a plastic section, though expensive, is worthwhile on recirculating flumes to check for sand storage. You'll probably need one or more rubber pipe-sections on tilting flumes. The pipe can be mounted on the laboratory floor or on the flume truss, although on large flumes the floor-mounting is best because of the heavy weight of the pipe and water. Don't forget to make some provision for removing dirty water from the flume.

Pumps are described in terms of the water discharge they can pump for a given head. The total head on the pump is the sum of the static head and the head losses (equation 5). The pipe material, length, diameter, number and type of fittings and the water velocity are the factors which affect the head losses. Hence these factors determine the required pump horsepower (equation 6) and must be evaluated in conjunction with the selection of the pump.

Pick the pump location and design the routing of the pipeline yourself, and make some preliminary calculations to estimate the head losses for a given pipe diameter. Then call various pump manufacturers and rely on their engineering recommendation for the best pump and pipe diameter. Choosing these items is a little harder with recirculating flumes because of the desirability of minimizing sand storage in the return route. The mean flow velocity everywhere in the return route of recirculating flumes must exceed the settling velocity of the largest sediment particle, preferably by a factor of two.

DISCHARGE MEASUREMENT

The tenth step is to decide how to measure the water discharge. Albertson, et al. (1960), Moore (1960), and Addison (1941) give good discussions of the many popular methods. For laboratory flumes the most common methods are by the use of Venturi meters, orifice plates, bend meters, weirs and (especially for very low discharges) by direct volumetric or weight measurement. Recirculating flumes usually use either a Venturi meter or an orifice plate.

Except for the volumetric or weight method a coefficient must be known. This coefficient preferably should be determined by calibration of the measuring device in place. You can calibrate meters in-place by direct volumetric or weight measurements, by installing a weir in the flume, by Pitot-tube measurements in the test channel (to get mean velocity for the cross-sectional flow area), by tracer-velocity measurements or by tracer-dilution methods (Filmer and Yevdjevich, 1966). Where in-place laboratory calibration is not possible, calibrate the meter in a pipe arrangement as similar as possible to your flume pipe arrangement. For commerical meters the company which supplies the meter can usually do this at the company laboratory.

The most important rule to remember is that you must be able to measure the very highest as well as the lowest discharge that conceivably will ever be used. You may need more than one measuring device to do this.

If a device is to be placed within a pipeline (Venturi meter, orifice plate, or bend meter), you will need a straight reach of pipe immediately upstream from the meter to ensure better flow conditions through the meter. Allow a length of at least 20 to 25 pipe diameters for this. Under certain conditions a lesser distance may suffice, as specified by the company that produces the meter. In any case do not place a flow-meter close to a pump.

Meters that fit into a pipeline require a manometer. Hence we're going to briefly discuss manometers first, as this will simplify the explanation of meters.

Manometers

A manometer actually measures liquid pressures, which in turn reflect flow rates. The instrument consists of a transparent tube bent into a U-shape and an indicator fluid which occupies the bottom of the U. For measuring water discharge a differential manometer is used. This device measures the difference in pressure between two points, in our case these points being two locations along a pipe. Each of the two points connects to a leg of the U-tube, and the vertical distance between the levels of the indicating fluid gives the pressure difference. This pressure difference is calibrated with the flow rate (discharge) through the pipe.

At low discharges (up to about 2 cfs) the differential pressure usually amounts to no more than a few feet of water. For these discharges, therefore, you can easily observe both levels in the manometer

with water as the indicating fluid. For this purpose tap an extra line into the bent part of the U, orient the U-tube upside down and force air into the upper portion of the manometer.

Higher discharges create a pressure difference of many feet of water. It would therefore be too awkward for a person to read both levels of a water-air interface. Consequently a heavier indicating fluid (often mercury) commonly is used. With mercury and water the U-tube remains right-side-up and the mercury occupies the bottom portion of the tube. Thus the type of manometer you need will be determined by the maximum discharge which the pipe will carry.

A popular variation of the U-type manometer is the well-type or pot-type manometer. This type has the advantage that you need only read the fluid level in one leg.

All of these manometers are available commercially. If you buy both the flow meter and manometer from the same company get a scale which reads directly in the desired flow units, such as cubic feet per second, rather than length units. Otherwise it will be better if the manometer scale is in length units. Also, if the calibration changes you don't have to change the scale if it is in length units.

Lines leading from the openings in the pipe wall to the manometer can be of any length. For convenience in adjusting discharge, station the manometer (but not the flow meter) next to the valve which regulates the flow.

For additional remarks on manometers see Rouse (1961, pp. 27-30).

Now, about measuring discharge.

Volumetric measurement

The most accurate way to measure discharge (volume or weight rate of flow) is to measure the actual volume or weight of water which accumulates over a given time. Very small discharges are quite easy to measure volumetrically. Indeed, this may be the only feasible method for measuring discharges below the range of accuracy of any other measuring devices installed in the system. For higher discharges this method unfortunately is often impractical for flumes, as it would require the installation of a rather large special tank and a by-pass conduit.

If you have room in the laboratory for a volumetric tank, put one in. Such a tank is useful not only for measuring flow rates during experiments but also for in-place calibration of other discharge-measuring devices. The U.S. Bureau of Reclamation reference (1953, pp. 6-9) gives a good illustration of a volumetric tank. The Georgia Institute of Technology, St. Anthony Falls Hydraulics Lab, Iowa Institute, University of Calfiornia at Berkeley, and Colorado State University, to cite just a few, have good examples, too. Be sure to make the tank large enough to measure the maximum pump discharge. Also, volume (water-surface elevation) or weight measurements will be more accurate if you can avoid taking readings while water is pouring into the tank. For large tanks a stilling well and point gage are very useful for getting the water-surface elevation.

Addison (1941, pp. 64-71 and 90-94) discusses other possible arrangements for measuring discharge by weight or volume.

There are two methods for in-place volumetric calibration of a discharge-measuring device if you don't have a special volumetric or weighing tank. Firstly, by blocking off the downstream end of the flume test channel you may be able to use the flume itself as a large volumetric tank (fig. 61). (The volume of the flume headtank would have to be taken into account.) Secondly, you can use a large sediment-collection box to calibrate a flow-measuring device. For such a purpose you might consider attaching a swinging spout to the end of the flume, to direct the flow (see Rouse, 1961, p. 8).

Weirs

A weir is a partial barrier in a watercourse which causes a rise in the water surface immediately upstream. As such it can be used to control and measure the flow of water in an open channel. Usually there is an opening along the top edge of the weir plate rather than having a straight dam across the channel. The shape of the opening can be any of several standard forms, such as triangular or rectangular. The water surface falls as the water flows over the weir, but upstream from the weir the water surface elevation remains at its dammed-up height. The height (H) of this upstream water surface above the weir crest reflects the rate of flow. For example, the discharge over a triangular weir is given by $Q = mH^{2.5}$ where m is a coefficient. The coefficient often must be determined by calibration of the wier in-place in the laboratory. The weir can be located in such places as the return channel or stilling tank. You may need some baffling to insure

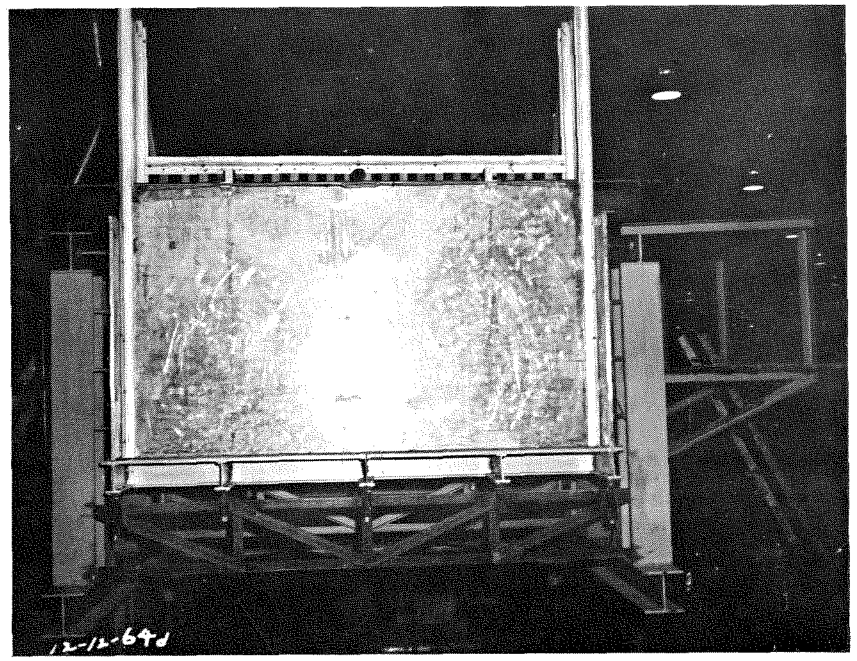


Figure 61.--Bulkhead at downstream tip of Colorado State Univ. 200-foot flume (CSU photo).

that surges and turbulence are dampened in the crucial region immediately upstream from the weir.

The water-surface elevation upstream from the weir can be measured much more accurately in a stilling well rather than in the actual tank or channel. This stilling well is a simple piezometer and is explained in the next chapter.

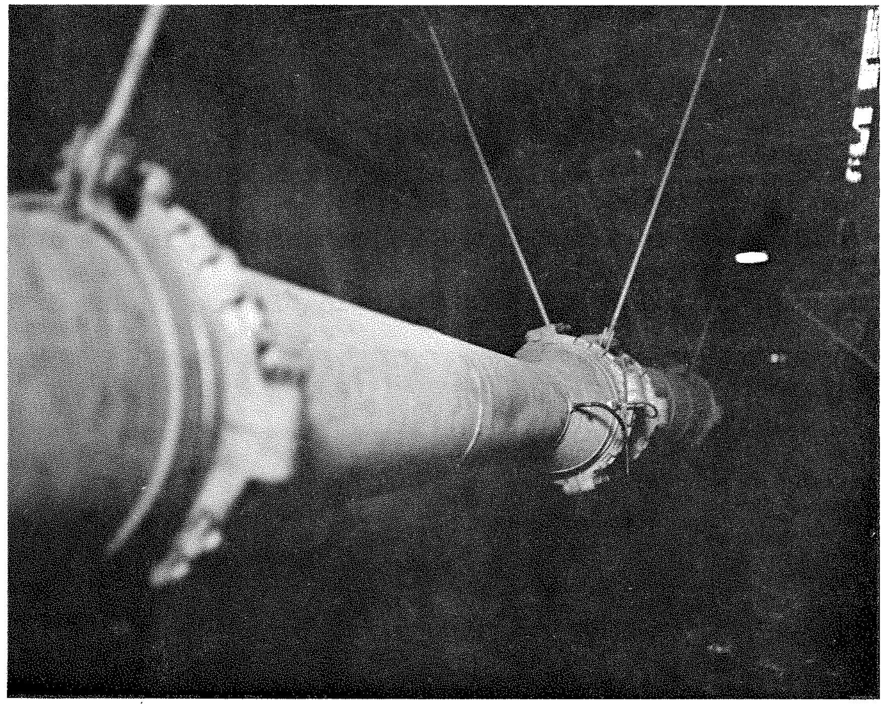
Venturi meters

A Venturi meter consists of (1) a special constricted pipe section and (2) a manometer or other type of pressure gage to measure differential pressure. The special pipe section converges from the inside diameter of the regular pipe to a contracted portion and then diverges again back to the regular pipe diameter (fig. 62). In the contracted portion the velocity increases because the product of cross-sectional flow area times mean velocity must remain equal to the existing discharge. The increase in velocity reduces the static pressure. The pressure difference between inlet (normal pipe diameter) and throat (contracted zone) reflects the rate of flow.

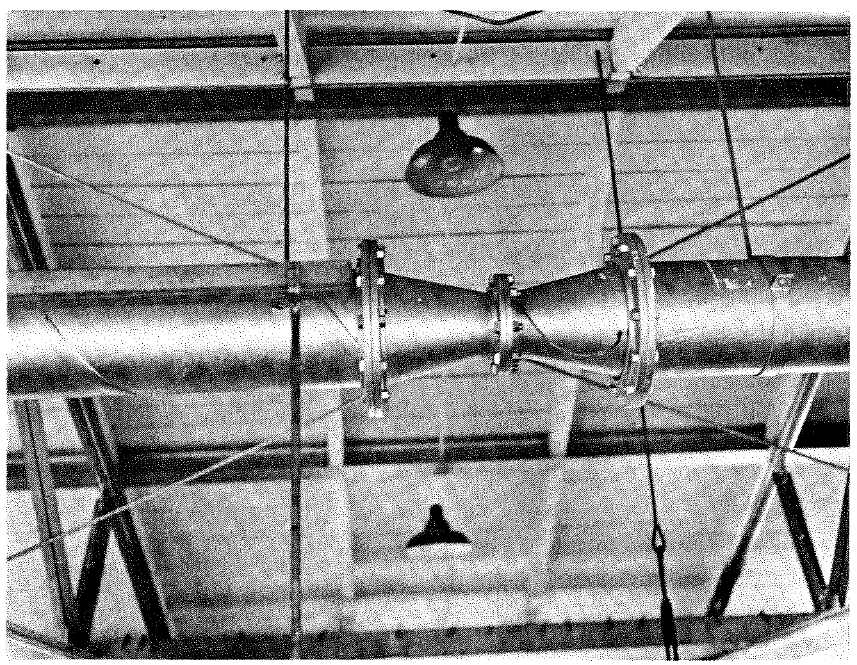
The discharge equation is

$$Q = C_d A_2 \sqrt{2g\Delta h} \qquad (7)$$

Here C_d is a discharge coefficient, A_2 is the cross-sectional area in the contraction and Δh is the difference in head across the meter, as shown on a differential manometer. The coefficient C_d preferably should be determined by calibrating the meter in-place, although factory calibrations are usually reliable if the Venturi is installed as prescribed by the manufacturer.

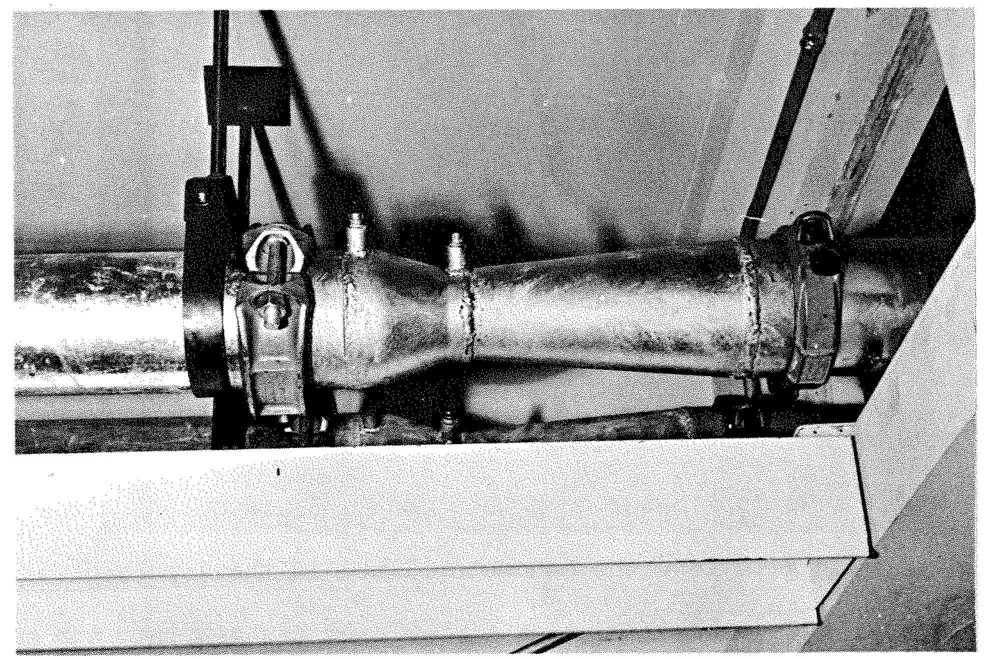


A. USDA commercial Venturi meter on the 100-foot flume.



B. Georgia Tech home-made meter, using two standard pipe reducers. Taps are plugged as in photo when meter is not in use.

Figure 62.--Venturi meters.



C. Home-made meter at Dept. of Earth and Planetary Sciences, Massachusetts Inst. Tech. (MIT photo).

Figure 62, continued.

Venturi meters, orifice meters and bend meters preferably should be located at the end of a straight reach of pipe so that the flow will be stabilized and uninterrupted. The straight length of pipe should be at least 20 to 25 pipe diameters long. Don't insert any tees, valves or other fittings in this section. You should also have at least 5 pipe diameters of straight pipe downstream from the meter before any elbows, tees, etc.

Venturi meters cause less head loss than orifice plates (but more than bend meters, because the bend or elbow is part of the pipe route anyway) and are quite popular. They are produced commercially, but you can easily make one yourself by constricting a short portion of the pipeline, as at the University of California at Berkeley. Either build the pipe section specially (fig. 62C) or fill in an ordinary pipe with cement, or use a pair of standard pipe reducers, back to back (fig. 62B). Any "home-made" meter definitely has to be calibrated in-place.

Orient a Venturi meter such that the taps are on the sides of the pipeline. Air gets into the manometer lines if the taps are on the top of the pipe, and on recirculating flumes sand can get into the manometer line if the taps are on the bottom.

Orifice meters

An orifice meter has two main components: a gage (manometer) for measuring a pressure differential and a thin plate with a hole in it. The plate is fixed normal to the flow inside a pipeline (fig. 63), usually between two flanges. The hole is concentric with, and smaller than, the inner pipe diameter. The flow speeds up as it becomes restricted in

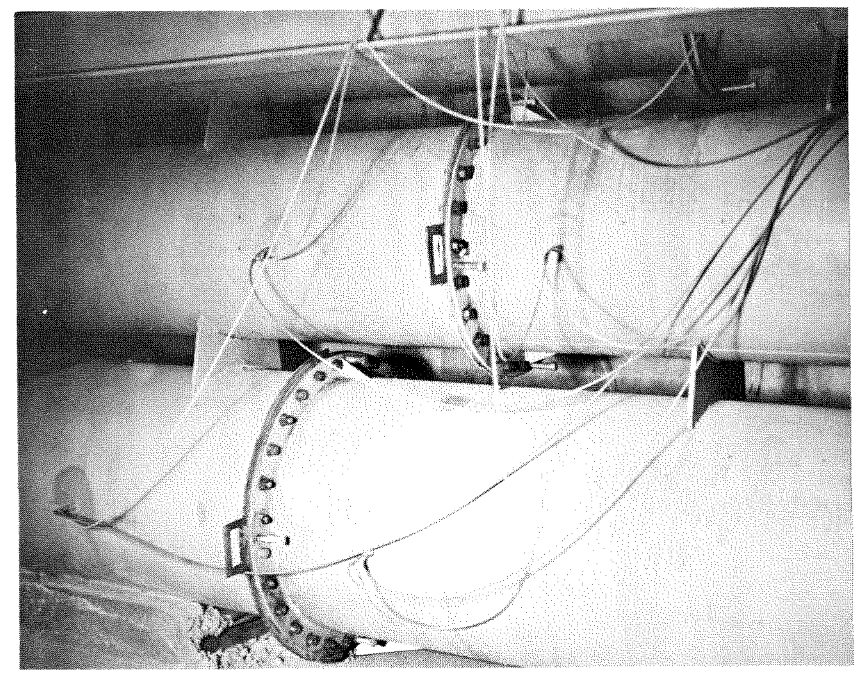


Figure 63.--Orifice meters in return pipes of the Colorado State Univ. 200-foot flume.

area to pass through the hole in the plate, and this velocity increase causes a pressure drop. Pressure connections or taps are inserted through the pipe wall on both sides of the plate to measure this pressure drop. As with the Venturi meter, the difference in pressure is related to the discharge by the equation $Q = C_d A_2 \sqrt{2g\Delta h}$.

Different types of gages, different hole sizes, and different locations for the piezometer holes can be used. The three most-common locations for the two holes are:

1. One pipe diameter upstream and at the point of greatest flow contraction ("Vena contracta taps"); or
2. One inch upstream and one inch downstream from the plate ("flange taps"); or
3. $2\frac{1}{2}$ pipe diameters upstream and 8 pipe diameters downstream from the plates ("pipe taps").

The orifice plate customarily is clamped in place between two pipe flanges. If the pressure holes are one inch upstream and one inch downstream from the plate, they are drilled through the pipe flanges. The Meriam Instrument Company of Cleveland, Ohio supplies predrilled flanges together with the orifice plate and manometer, for various pipe diameters.

For standard arrangements of at least 20-25 pipe diameters upstream from the meter you can have the plate and its associated manometer scale calibrated at the factory.

In general an orifice plate is cheaper and easier to install than a Venturi meter but causes more head loss. It is also subject to more wear than a Venturi, at least with sediment circulating through the pipeline.

Bend meters

Water flowing around a bend in a pipeline exerts a greater pressure on the outside of the bend than on the inside. The magnitude of this pressure difference reflects the rate of flow. An ordinary 90^o pipe elbow in this manner can be used as a flow meter. Drill a $\frac{1}{4}$-inch-diameter hole through the inside and a similar hole through the outer side of the elbow, at the center of curvature (Iansford, 1936). Then connect the two holes to a differential manometer.

The general discharge relationship again is $Q = C_d A\sqrt{2g\Delta h}$, A being the cross-sectional pipe area. As usual, C_d is determined by calibration in-place in the laboratory or at least under standard conditions of 20-30 pipe diameters of straight pipe existing upstream from the bend.

Bend meters have two decided advantages: you get a flow meter at no extra cost, and the meter offers no additional resistance to the flow. One disadvantage is that whereas Venturi meters and orifice plates can be pre-calibrated by the factory you'll always have to calibrate an elbow meter yourself.

Summary

The most common devices for measuring flow rates in laboratory flumes are weirs, volumetric tanks, Venturi meters, orifice plates, and bend meters. Volumetric tanks are useful not only for measuring discharges during flume experiments but also for calibrating other flow meters. Venturi meters, orifice plates and bend meters require (1) a straight section of undisturbed pipe at least 20 pipe diameters long upstream from the meter, (2) a manometer and (3) a coefficient, preferably determined by in-place calibration.

MEASURING ELEVATIONS AND SLOPES

Except for demonstration flumes you'll have to measure elevations along the flume test section to determine the water depth, water-surface slope, sand-bed slope, flume slope (sometimes) and bed-form heights in sediment studies. Step number 11 is to install the equipment needed for these measurements.

Some methods of measuring elevations and depths on flumes are by means of wall scales, dual channel stream monitors, point gages and piezometers. Point gages and piezometers are by far the most popular.

We'll discuss these methods and then finish the chapter with a look at some good ways to measure the flume slope.

Wall scales

The bed and water surface elevations can be approximately determined from vertical scales on the transparent flume wall. Even with opaque flume walls such scales can be very helpful in getting a general idea of the water-surface slope, for example just after turning on the water discharge. The scales should be perpendicular to the flume floor, at equal intervals along the test section.

Measurements made in this way are not too accurate, especially for depths less than a foot or so. At depths greater than about a foot the minor variations in surface elevations in the channel center as compared to the wall have less effect on the actual depth value. Slight errors in reading the heights also become less important at the deeper depths. The retarding effect of the sidewalls often dampens the surface irregularities to some extent, so some bed-form heights may not be accurate if measured from wall scales.

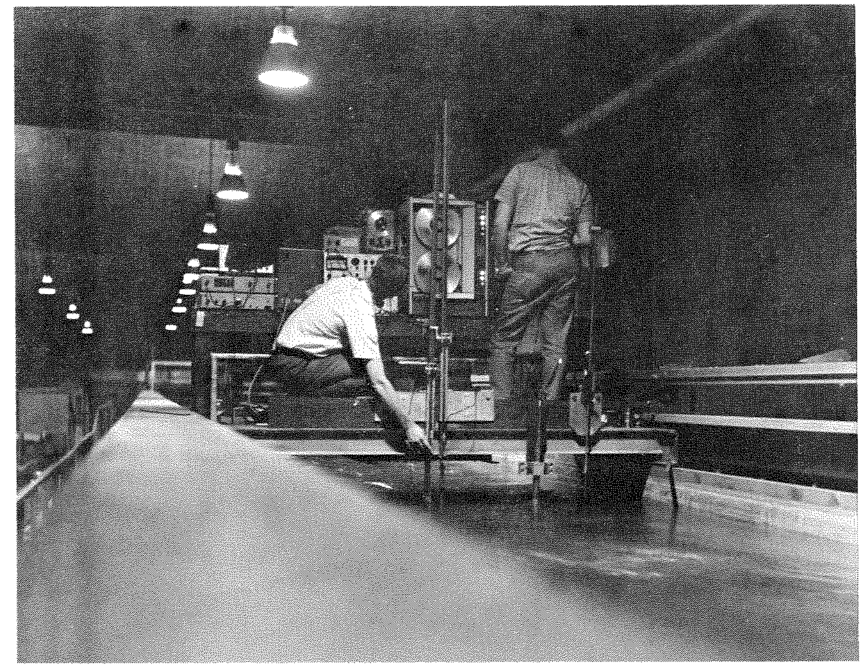
Dual channel stream monitor

A few people, e.g. at the U.S. Department of Agriculture at Oxford and the U.S. Geological Survey at Fort Collins, use a dual channel stream monitor (Karaki, et al., 1961) to measure water depths. This instrument travels on the flume rails and uses the echo-reflecting principle to simultaneously record the water surface and stream bed profiles.

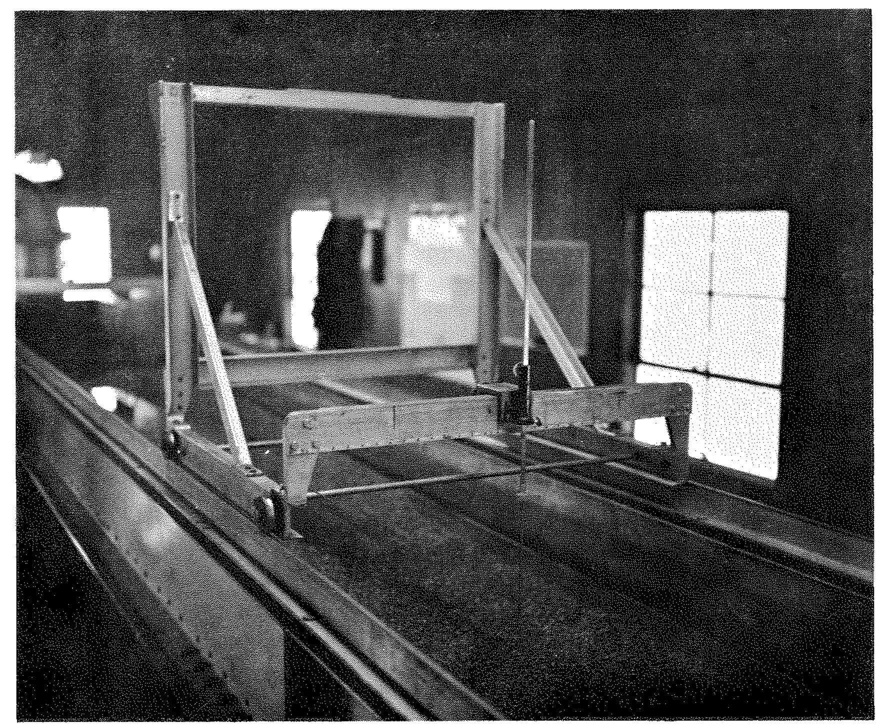
The dual channel stream monitor is much faster and more thorough than a point gage (described below) and works quite well. Two ranges where it is not too reliable are (1) depths less than about 0.3 foot (the two surfaces are too close to one another) and (2) fast transport rates in sediment studies (the bed becomes fluidized and no longer presents a solid surface).

Point gage

Elevations of a water surface or sand bed most commonly are measured from an instrument mounted on a carriage which rides on the flume rails. The instrument normally used is called a point gage. Its main components are two adjacent vertical scales. One scale has vernier gradations and stays fixed as a reference. The other scale is mobile and has a pointed rod attached as a lower extension (fig. 64). This

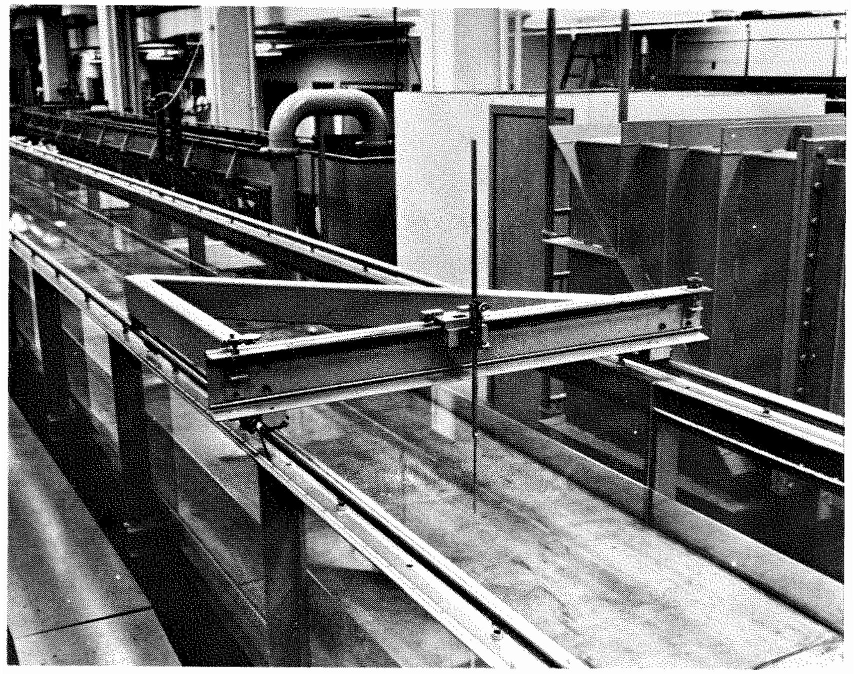


A. Colorado State Univ. 200-foot flume.

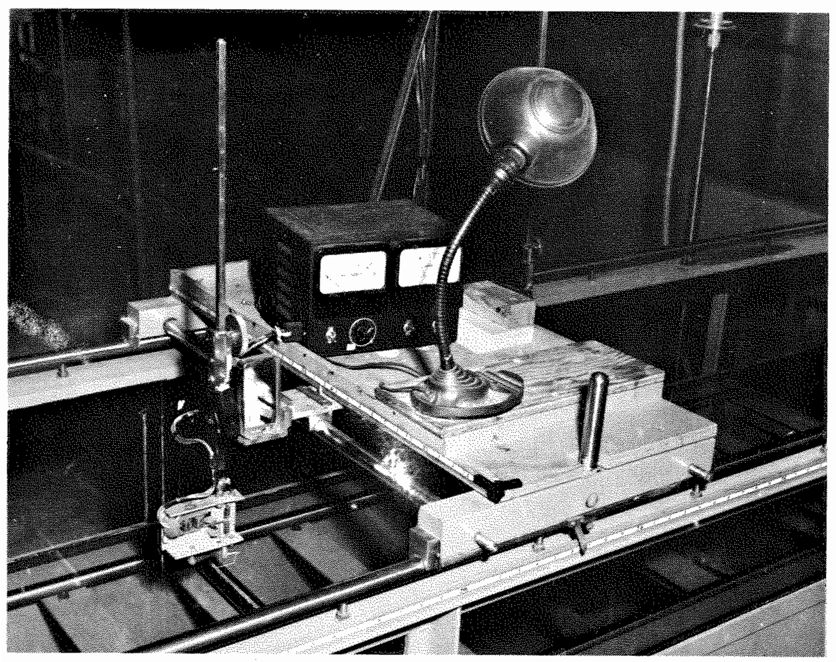


B. USWES 75-foot flume.

Figure 64.–Point gages and carriages.

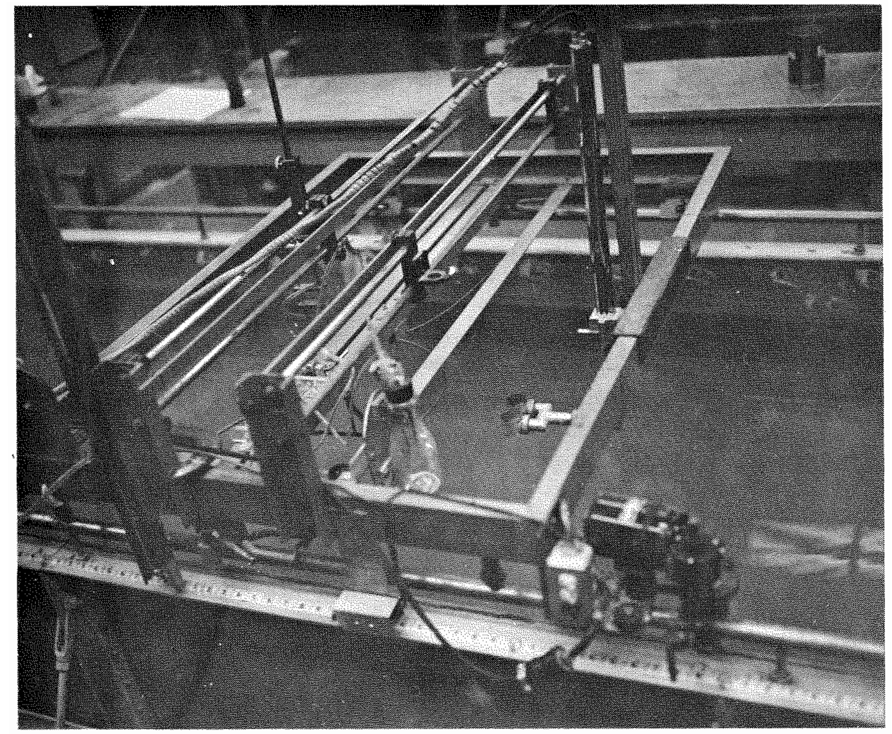


C. California Inst. Tech. 130-foot flume (Cal Tech Photo).

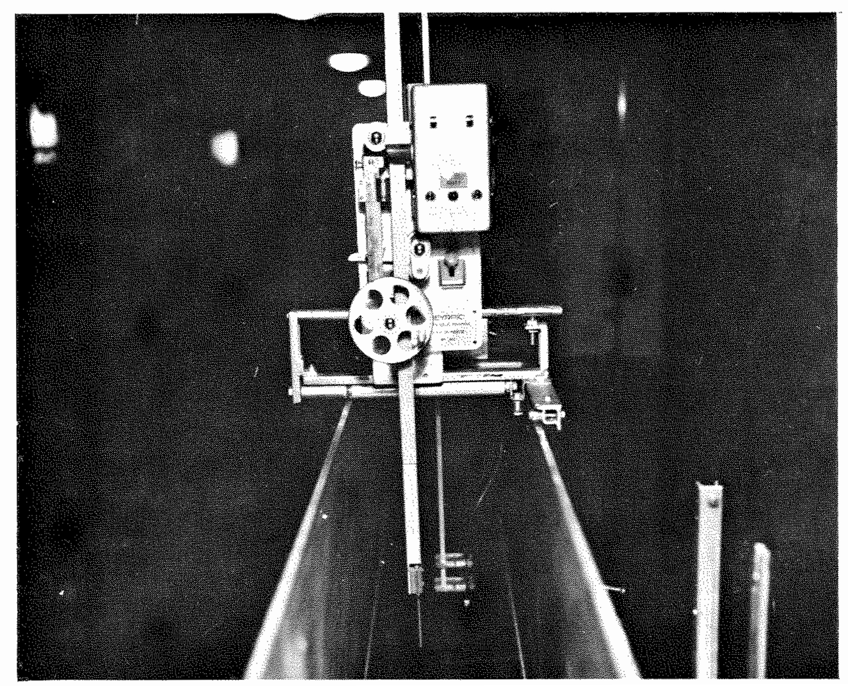


D. Iowa 85-foot flume.

Figure 64, continued.



E. USDA 100-foot flume.



F. Georgia Tech 18-foot flume.

Figure 64, continued.

scale is raised or lowered until the point touches the surface being measured. The elevation, relative to the arbitrary datum, is then read at the reference mark with the vernier.

Point gages are sold commercially (e.g. Leopold and Stevens, of Portland, Oregon) in various lengths and widths.

If the flume sidewalls are not transparent, you can't tell when the point-gage tip reaches the surface of a sand bed. In this case attach a small "foot," say 2-5 inches in diameter, to the point of the gage (University of California at Berkeley). Then read the bed elevation when the foot comes to rest on the bed. Another possibility, developed by Brooks (1954) for use in still water (closed recirculating flumes), is to fasten a flashlight to the end of the carriage. Focus the intense beam of light obliquely onto the bed under the point gage and then lower the gage until the point just touches its own shadow. (Note how much better off you'll be with transparent sidewalls.)

Mount the instrument on the carriage such that the point gage can slide across the full channel width. You can easily make a suitable carriage yourself. Figure 64 shows some typical carriages.

One end of the USWES instrument carriage (fig. 64B) has a bridgework about three feet high, with a horizontal plate on top for mounting a camera.

Piezometers

A piezometer is simply a tube which penetrates the wall of a fluid-containing vessel (flume, pipeline, etc.), with the other end of the tube open to the atmosphere. The open-ended part of the tube is trans-

parent and oriented vertically. Water from the vessel rises in the piezometer tube according to the pressure exerted by the water at the wall tap. The height of the water in the tube is called the pressure head.

Because the tapped vessel (e.g. flume) is open to the atmosphere the water rises in the piezometer tube to the same level as the water in the flume. You then read the water-surface elevation from a scale or grid background placed just behind the tube. By mounting the tubes from various flume stations on a single board (piezometer board) you can easily compare water-surface elevations of these different flume stations.

Piezometers are simple and useful and are very popular in flume work.

To insure a more representative average pressure over the full width of the conduit several piezometer taps are often drilled at the same downstream station. These taps connect to a single tube which in turn goes to a stilling well or piezometer board. Examples are taps into opposite walls of a channel or tank for measuring the water level upstream from a weir or for measuring the water pressure in or near Venturi meters, orifice plates and bend meters. The California Institute of Technology used this principle to get the average water-surface elevation over a sand bed. Their method (Kennedy, 1961) involves fastening a 3/16-inch copper tube laterally onto the flume floor, spanning nearly the full flume width. At 2-inch intervals they drilled three holes, 1/64-inch in diameter, into this copper tubing. Three or four layers of cotton cloth, wrapped around the tube, kept sand out of these tiny piezometer taps. One end of the tube was sealed, while the other end was attached to a fitting which led through the bottom of the flume to plastic tubing running to a piezometer board.

Over a movable sand bed piezometers provide only the water-surface elevation, rather than the water depth, because the elevation of the sand surface continually changes.

Figure 65 shows a good system for a wall piezometer when the flume is used for sediment-transport studies. This arrangement is very similar to the one installed on the University of California at Berkeley 40-foot flume.

For further discussion see Rouse (1961, p. 23) and Addison (1941, pp. 49-52).

Construction details of piezometer taps

Piezometer taps have to be very carefully constructed or they may not register the true ambient pressure (Albertson, et al., 1960, p. 451).

A piezometer hole can be drilled through the channel floor or through either sidewall. Put any sidewall holes close to the floor so that they will be below the water surface for shallow depths.

Make the piezometer hole small. If tapped into a flume or small pipe the hole diameter should not exceed 1/8 inch. The holes in fact can be small enough to permit only a hypodermic needle to fit. For

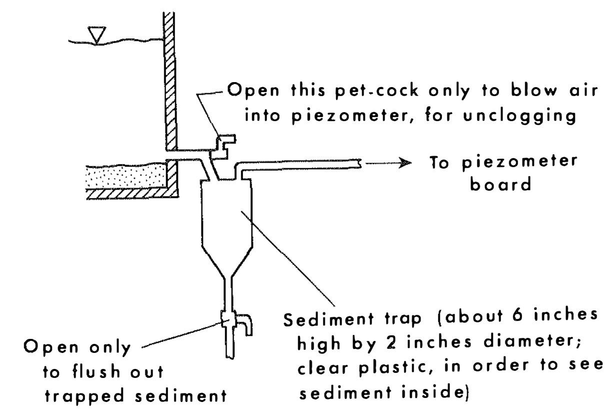


Figure 65.--Trap arrangement for keeping sediment out of piezometer lines (based on a system used at the Univ. of California at Berkeley). Not drawn to scale.

large pipes (12 inches in diameter) the maximum hole diameter should be about 1/4 inch. In general the error in the indicated height of the flowing fluid increases as the diameter of the piezometer opening increases (Emmett and Wallace, 1964).

The fluid in the vessel often is flowing rather than stationary. Be careful in such cases to install the piezometer hole normal to the flow direction (wall), as this normal pressure is what is required. An easy way to make the hole is to insert or thread a hollow plug through the wall. Then connect the outer end of the plug to a flexible tube. Always be sure to make the plug just flush with the inner face of the wall. The edge of the hole should be very slightly rounded and the degree of roundness should be constant. Take care to remove all burrs and other irregularities from the vessel wall in the vicinity of the hole.

Rouse (1961, p. 22) states that "bed piezometers can be drilled either directly in the flume bottom or - to avoid corrosion of the edges - in stainless-steel plugs inserted (press fit rather than threaded) at the proper points."

Piezometer openings which are below a sediment surface yield essentially the same pressure as holes tapped in above the sediment if the grains are of sand size or smaller. For pea gravel and coarser material, however, the true water surface elevation may not be indicated if the piezometer opening lies below the sediment surface (H. A. Einstein, pers. comm., 1967). For determining the water surface slope this would

be of no significance as long as all holes are consistently above or below the bed. On the other hand, if you want the true water surface elevation some error may be introduced. You can avoid this by installing two or more piezometer taps at each downstream location - at least one hole above and another below the level of the sediment in the flume. Connect the various lines with a tee a few inches outside the flume wall, so that only a single tube exists from this point on. The piezometer openings not being used can then be clamped shut between the flume wall and the tee.

With sediment in the flume cover the piezometer holes with rust-proof fine-mesh screening to keep particles out of the lines.

Tube details

To reduce capillary error, make the tube itself in the section next to the scale at least $\frac{1}{2}$ inch in diameter, at least if you want the absolute elevation. Addison (1941, p. 15) states that water in a tube of $\frac{1}{4}$ inch bore will stand 0.18 inch higher in the tube than in the vessel. In many cases, however, smaller tubes are quite adequate - for example, in checking for a change in water level at a selected location with time, or in comparing several water levels. (When comparing water levels at various locations tubes must be of the same bore.)

The shorter the piezometer line the less trouble you will have with air bubbles in the line. Also, air bubbles are less likely to get caught in the line if you can put the lines at a slope, rather than having them horizontal.

Experience has shown that piezometer boards work better if all tubes have a common amount of damping, i.e. if the lines from the piezometer taps to the board are all of the same length.

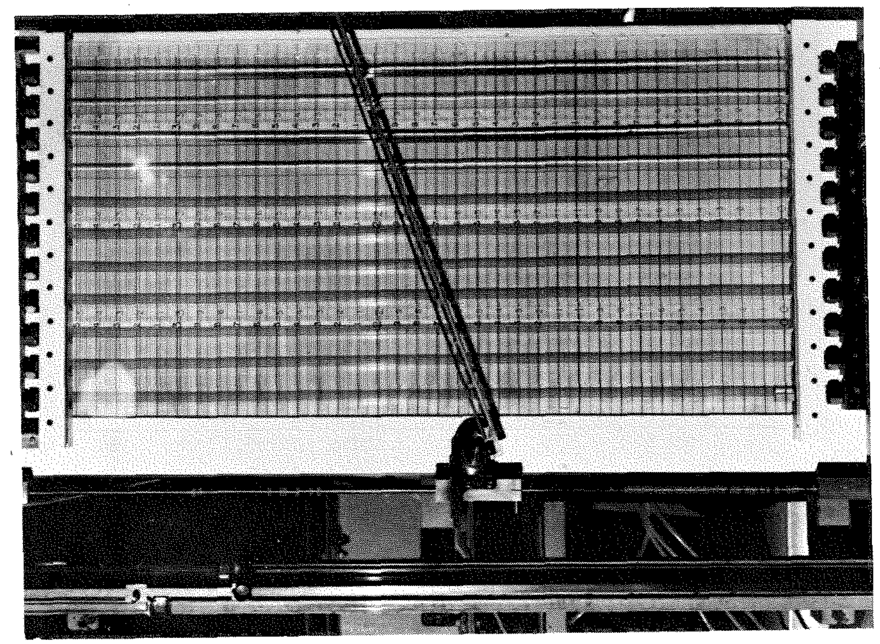
Aids in measuring water levels and water-surface slopes

Piezometers can tell you the water depth directly when the channel bed is plane and fixed. The easiest way to arrange this is to fasten each tube onto the outside of the flume adjacent to the associated hole. Then adjust a scale next to each tube so that zero on the scale is on the same level as the channel floor.

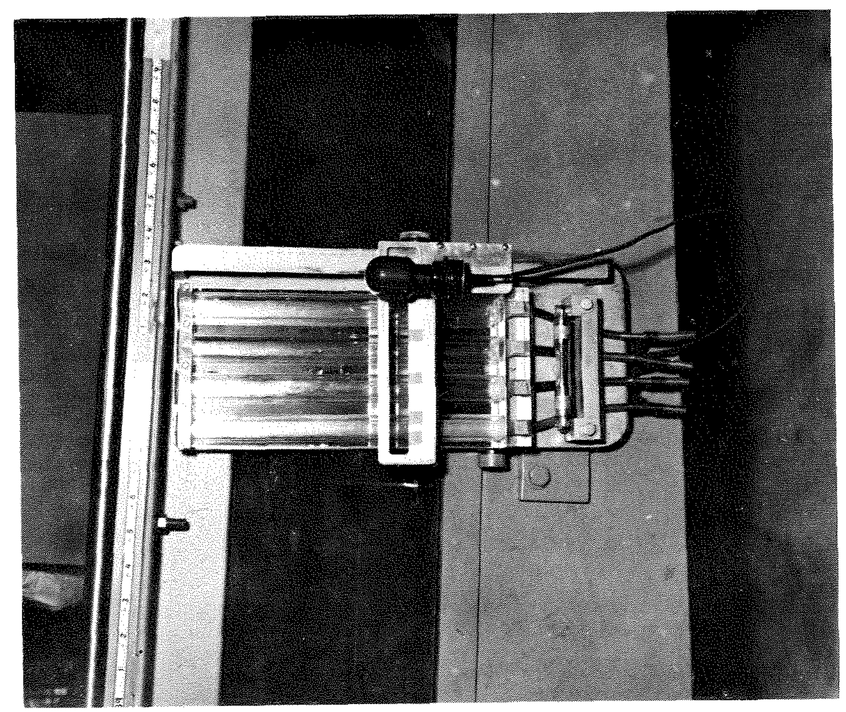
In addition to reading by eye, the water level in a piezometer tube can be measured to 0.001 ft. by means of a point gage or by the use of a vernier on a scale with a cross-wire.

Various peizometer tubes can be fastened next to one another on a single board for an easy determination of pressure differences (fig. 66). The cross-wire indicator mentioned above can be long enough in such cases to span the complete series of tubes. If you use a point gage, mount the gage on a carrier which rides on a horizontal bar or rod, to permit access to each of the tubes.

Water surface elevations alone (and hence the water surface slope) are commonly determined by piezometers. Although two piezometers theoretically are enough to give the water surface slope, you get a much more reliable value of water-surface slope by using a series of piezometers equally-spaced along the flume. Extend each piezometer to a common board by means of plastic tubing, and mount the tubes in a group



B. California Inst. Tech. (Cal Tech photo).



A. Iowa.

Figure 66.--Piezometers mounted in a group for determining water-surface slope. In (A) the board is attached to the flume but can rotate to keep a vertical orientation as the flume tilts.

(fig. 66). In this manner you can more easily detect any single pressure which may be in error (see Bureau of Reclamation, 1953).

Kennedy (1961) described an excellent piezometer board of this sort (fig. 66B). A straightedge covering the full width of the board could be moved vertically and its angle could be readily adjusted. It therefore could be aligned with the water levels in the tubes. The center lines of the vertical tubes on the board were 2 inches apart, whereas the piezometer taps in the flume were five feet apart. The water-surface slope shown by the straightedge on the piezometer board was thus 30 times greater than the water-surface slopes in the flume. This steeper angle provided much greater accuracy in reading the slopes - a very welcome advantage for flat slopes.

Other aids in the use of piezometers include (1) adding a wetting agent, such as liquid soap or aerosol, to reduce surface tension, (2) coloring the water adjacent to the scale with a dye, to provide better definition of the meniscus, and (3) drawing a thin dark line on a board immediately behind the tube (the water magnifies the thickness of the line and a sharper definition appears at the water-air interface).

Photography can provide a permanent record of the piezometer levels. Color the water in the tubes, for this purpose.

Flume slope

If you choose to measure elevations and slopes by means of a point gage that travels on rails fixed to the flume walls, all of your point gage readings are relative to the flume rails. To get the actual slope

of the water surface and sand bed you also have to measure the slope of the flume rails. This measurement will often be a lot easier if you adjust the rails to be parallel to the flume floor, so that the rails' slope equals the flume slope.

Here are six good ways to measure the flume slope:

1. On closed-circuit recirculating flumes use the still-water level in the flume as the horizontal datum and take point-gage readings along the length of the flume. This gives the change in the rails' elevation, relative to the horizontal.
2. Set up a hose and scale arrangement (California Institute of Technology). With this method you need a common garden hose, open at each end, stretching along the laboratory floor over the full length of the flume. The hose turns upward to assume a vertical orientation at each end of the flume and is here mounted independently of, but very close to, the flume. These vertical end sections must be transparent. A scale, reading in fine length units, is attached to each of the transparent vertical end-sections of the hose. Filling the hose with water to a height slightly higher than the flume floor or rails provides a common horizontal datum (the water level) at each end of the flume. You then read the vertical distance from the horizontal datum to the flume rails (or floor), at each end of the flume. The difference between these two elevations gives the net vertical drop of the flume over the known horizontal distance.

3. Use two adjustable-height stilling wells, one attached to each end of the flume, which can give the vertical drop over a known horizontal distance (Colorado State University). Connect the wells by flexible tubing to two tubes on a piezometer board. To get the elevation difference between the two ends of the flume you simply adjust the heights of the stilling wells to make the top edge of each well level with the flume floor or rails. Then fill each well to the brim with water and read the elevation difference at the piezometer board.

   Clear plastic tubes, about 6 inches long and $\frac{1}{2}$ inch in inner diameter, make good wells. For the connecting tubes use $\frac{1}{4}$ inch I.D. vinyl tubing.

4. Use a vertical scale and datum, such as a point gage, at one end of the flume (as far as possible from the pivot). Either the housing and vernier portion or the vertical scale of the point gage must be fixed to the flume, while the other part must be mounted in a permanent position independently from the flume (fig. 67). In this manner each scale reading corresponds to a certain flume slope and you can make a graph relating scale reading to flume slope. Iowa and the USDA at Oxford use this method.

5. Set up a surveyor's transit or a level independently from the flume. Then move the point gage to each end of the flume to measure the drop in elevation over the known horizontal distance (USGS; Colorado State University).

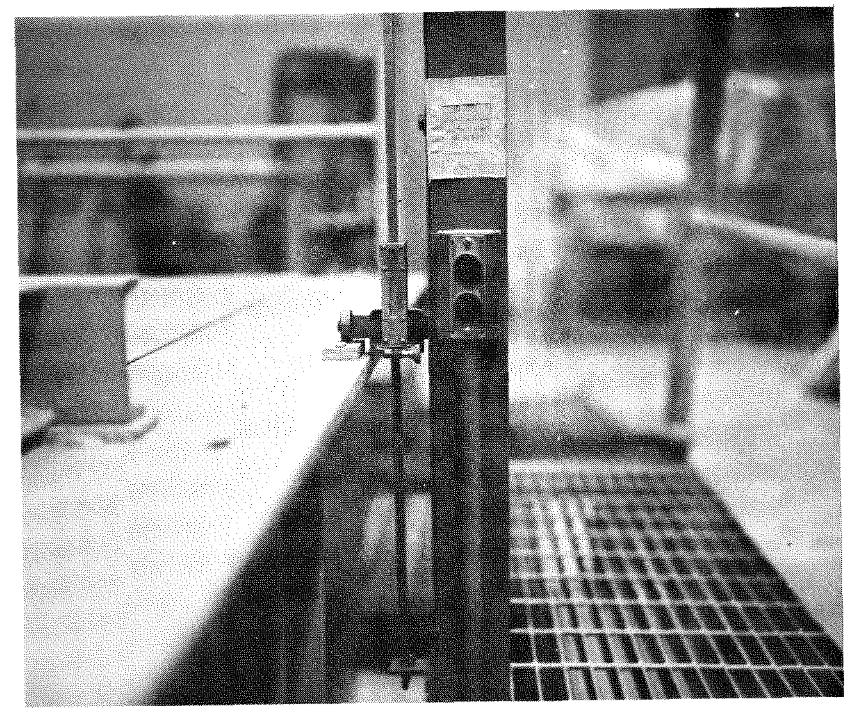


Figure 67.--Point-gage arrangement for measuring the flume slope (USDA 100-foot flume).

6. For flumes which are tilted by one or more screw jacks consider using a mechanical counting device (Georgia Institute of Technology). Attach the counting device to a screw jack or to a shaft connected to a motor which turns the jack. The number of revolutions of the turning shaft can be correlated with the slope of the flume. You would need an initial calibration with this method, but reading the slope value from the counter is quick, easy, and safe.

Summary

Elevations along the flume test section must be measured to get the water-surface slope, sand bed slope, water depth, bed-form heights and usually the flume slope. The point gage and piezometers are the two most popular ways to measure these elevations. Piezometer taps should not exceed ½-inch in diameter and are usually smaller than this. Tubes running to a piezometer board should be as steep and as short as possible, to keep air bubbles from lodging in the lines. If you determine elevations with a point gage that rides on the flume sidewalls, you'll have to measure the flume slope in order to get the actual slopes of the water surface and sand bed. Six ways of finding the flume slope are by the still-water level in closed recirculating flumes, a hose and scale arrangement, two adjustable-height stilling wells, a point gage with one component attached to the flume, a transit, and a mechanical counter attached to a screw jack.

AIDS IN OBTAINING UNIFORM FLOW

The final features which you must install in the flume are a sluice-gate at the entrace and a tailgate for controlling the uniformity of flow (step 12).

Many studies or demonstrations are intended to be made under conditions of uniform flow. The flow is uniform when the mean velocity, depth, and width do not change with distance downstream. This means that the average water surface and bed profiles (drawn as straight lines through the measured elevations of each surface) are parallel.

Except for some flow conditions in closed recirculating flumes, uniform flow for a given discharge will not come about by itself. To get uniform flow you have to influence the depth by means of a gate, so that the depth becomes constant along the complete test section (except for the last foot or two). You regulate the depth either at the very downstream end (with a tailgate) or at the upstream end of the flume (with a sluice gate), depending on the Froude number ($V/\sqrt{gD}$).

Tailgates

For Froude numbers less than 1.0 (subcritical flow) the water surface at the downstream end of the flume begins to draw closer and closer to the bed as the water runs off the end of the flume (nonrecirculating and free-overfall recirculating flumes). Since the mean depth is gradually decreasing in this region, uniform flow no longer exists. The affected reach of test channel therefore is lost if you are interested in uniform-flow phenomena. The region affected by this drawdown can amount to a very large part (if not all) of the test section, and becomes less as the Froude number approaches unity.

The standard method of arresting this drawdown problem is to constrict the cross-sectional flow area at the end of the test section in some way. This dams up the water at the downstream end to the extent that the depth (and hence the flow in general) becomes uniform along almost all of the test section. The usual method of constricting the flow is by the use of some sort of gate, called a tailgate. Note that for given flow and transport conditions you cannot obtain a variety of uniform depths by using a tailgate; a tailgate only helps you to find and establish the uniform depth associated with the existing hydraulic conditions.

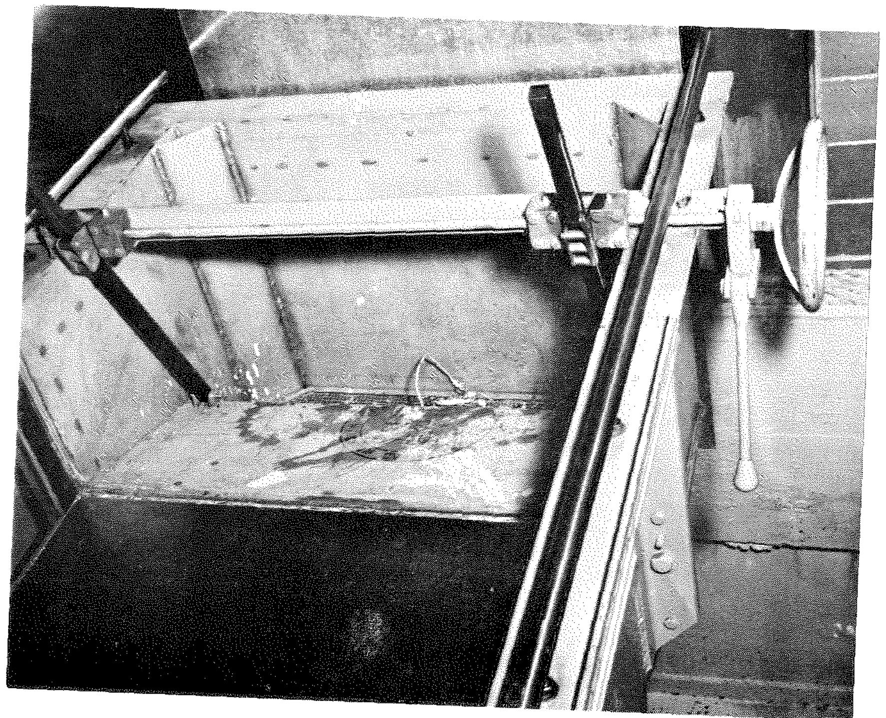
Closed-circuit recirculating flumes do not have a tailgate because with the right amount of water (trial and error) in the flume the water level in the tailbox adjusts itself naturally to provide uniform flow over most of the test section.

Various types of tailgates are used on flumes. Any workable constricting arrangement with a fine control is acceptable. Some common types of tailgates are:

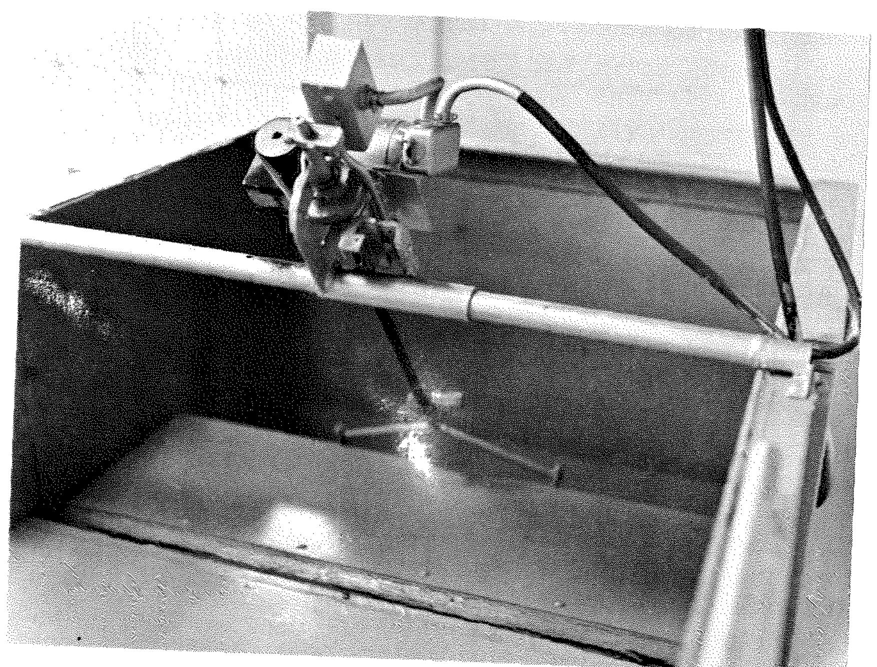
1. A vertically-oriented solid barrier which slides up and down in wall grooves. This type of tailgate can also be used to completely block the downstream end of the flume, in order to use the flume as a towing tank or volumetric tank (fig. 61). For sediment studies in

which the trap is beyond the end of the flume a tailgate of this sort probably will function best by sliding downward from above the channel; otherwise the sediment will have to build a hill to get over the gate. If all sediment is trapped within the flume test section the tailgate can move upward from below the flume floor (USWES) or downward from above the floor.
2. A horizontally-hinged plate which either swings down from above the channel or rotates upward from the channel floor (fig. 68A and 68B). Again the former may be preferable with sediment in the flume.
3. False sidewalls, hinged vertically at their upstream end, which can be drawn together at their downstream end to any extent (Gilbert, 1914; USGS). Make the false walls long enough to permit their downstream ends to touch. A length of two or three feet is usually enough.
4. A barrier of vertical slats across the channel width, built so that every other slat is interconnected to form a movable unit that can be gradually elevated by a rod and gear. Figure 68C shows this type of tailgate, with all slats the same width. Later experience has shown that this tailgate works best if the stationary slats are thinner than the movable members; otherwise, with the mobile slats fully elevated you might still have too much flow obstruction.

Recirculating flumes to be used for sediment studies can use for other purposes a bulkhead similar to type one above, located at the downstream tip of the test section (Colorado State University; USDA at Oxford). This bulkhead is positioned so that its height corresponds

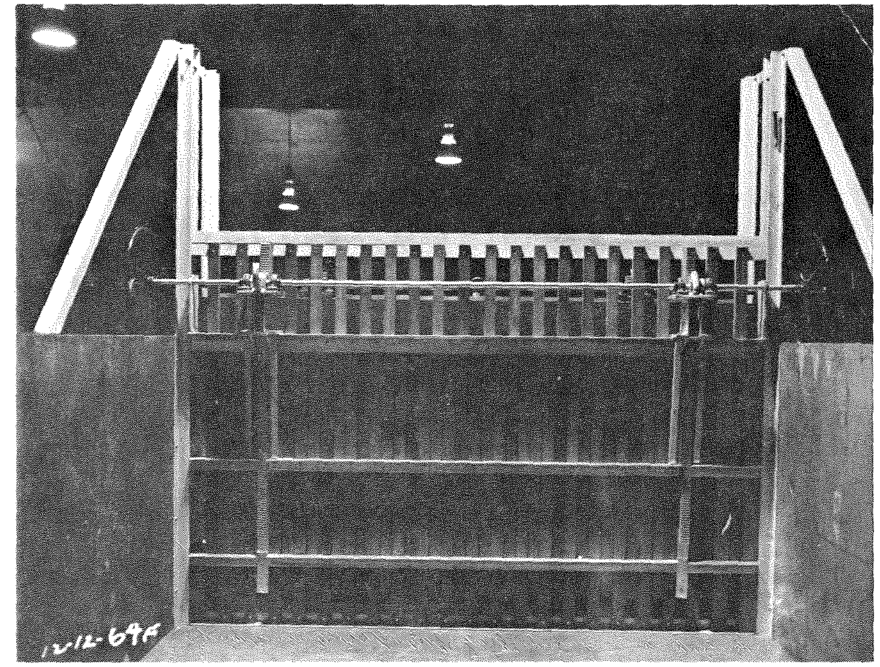


A. Iowa 85-foot flume.



B. Georgia Tech 80-foot flume. The small motor operates the tailgate.

Figure 68.--Typical tailgates.



C. Colorado State Univ. 200-foot flume.

Figure 68, continued.

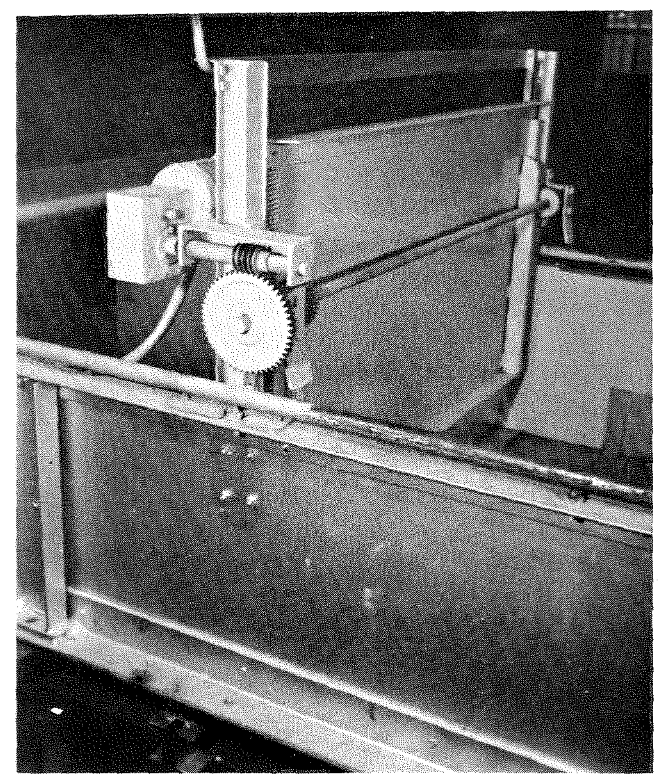


Figure 69.--Sluice gate near head of flume on Georgia Tech 80-foot flume. See also figs. 45C and 51.

to the average depth of the sediment in the test section. The barrier thus preserves the thickness of the sand bed all the way to the end of the flume. Otherwise some scour and slumping of the sand bed occur near the end of the flume and you lose several feet of test section. On free-overfall recirculating flumes you need a separate tailgate in addition to this bulkhead; the bulkhead has to remain at a fixed height and so cannot be used as a tailgate (Colorado State University 200-foot flume). Smaller recirculating flumes can use a fine-mesh wire screen to retain the sand at the end of the test section, rather than a permanently-installed adjustable bulkhead (California Institute of Technology).

For all tailgates you will have to be able to achieve very fine adjustments of the tailgate's position. Figure 68 shows good ways to do this. For false sidewalls use a threaded rod and nut arrangement, with the rod being turned by a handle fixed to its end. Fine adjustments in the water level in the vicinity of the tailgate can also be obtained by inserting a small pipe and faucet into the channel sidewall (Vogel, 1935), with the faucet withdrawing water as needed.

The SUNY at Buffalo nonrecirculating flume operates without a tailgate. Instead, the end of the test section has a small tailbox, such as might be found on closed recirculating flumes. Flow escapes downward through a 4-inch pipe in the tailbox, and a valve in this pipe controls the tailwater level in the downstream part of the flume.

Tailgates which slide in grooves or which rotate around a hinged edge can be made acceptably leakproof along the sides by using sheet rubber as a sealer.

Put in enough time to get a well-functioning tailgate or tailwater control in your flume. You'll use such a device quite often.

Sluice gates

At channel Froude numbers greater than 1.0 (supercritical flow) the drawdown of the water surface does not begin until very near the end of the flume, which means you won't use the tailgate for these fast flows. Under such flow conditions, however, a problem arises at the upstream end of the flume.

The water surface in the head-tank, as mentioned elsewhere, is higher than that in the flume by $K\, V^2/2g$. At fast velocities the greater elevation difference between water surfaces means that the water needs a longer distance to get down to the appropriate depth in the test channel. Without any interference the flow at fast velocities may not reach its eventual depth until very far downstream.

Under such conditions you can get a uniform depth along the full channel test section by using a headgate (sluice gate) (Figs. 69, 45C, and 51). A sluice gate is a solid barrier across the channel which is gradually lowered into the flow from above. It has the effect of raising the water surface immediately upstream and lowering the water surface immediately downstream. In other words, at Froude numbers greater than 1.0 the control for flow uniformity is at the upstream end of the flume. You'll have to lower the sluice gate by small increments and measure the uniformity of depth in the test channel after each change in the gate's height. A unique uniform depth will eventually obtain for the existing flow conditions.

On demonstration flumes you may want to display the flow both upstream and downstream of the gate, which means the gate will have to be located partway along the test section. Some research projects may involve studying flow phenomena on either side of a sluice gate, but other studies will need the longest attainable reach of uniform flow in the test section. So at least on research flumes you may want to change the location of a sluice gate from time to time. The best way to allow for this possibility is to install receded grooves in the flume sidewalls, at two or more downstream stations. One such station should be at the start of the test section, i.e. as far upstream as possible.

In regard to the wall grooves to be used for harboring a sluice gate, Rouse (1961, p. 21) writes that "....Appreciable leakage at the headgate is objectionable and can be prevented by closing the lower ends of the rubber-tube seal, inserting a tire valve in the upper joint, and expanding the seal with a bicycle pump once the gate is in the desired position .... (Grooves) are conveniently arranged between successive glass panels either by machining a steel bar that is then welded in place, or by forming such a section with three thin bars, side by side, one of which is enough narrower to provide the required depth of

groove; stainless steel is recommended in either case. If the flume is short, the provision of such grooves at each panel joint is desirable, and they will be found useful for the insertion of weirs as well as gates."

A sluice gate can occasionally be useful even when the channel Froude number is less than 1.0 as a dampener of undesirable surface waves that originate in the stilling tank. For this purpose lower the gate carefully until it just touches the mean water surface.

For reproducing a given setting of a vertical gate use a vertical scale and a horizontal pointer, one in a fixed position and the other attached to the movable gate.

As with the tailgate, you will have to make very fine adjustments in the sluice gate height. On smaller flumes you may be able to do this simply by raising or lowering the gate by hand and clamping it in position with a C-clamp. Some sort of mechanical arrangement, such as that shown in figs 69, 45C and 51, is much better, though.

The two features discussed in this section--a downstream tailgate and an upstream sluice gate--are necessary items for every flume, except that no tailgate is needed on closed recirculating flumes. When you have decided on the details of these gates you are finished with the major steps in designing your flume.

Summary

The two devices used to help bring about a uniform flow in the flume test channel are the tailgate and the sluice gate. The tailgate, located at the downstream end, is used during relatively slow mean velocities (subcritical or tranquil flow). It dams up the falling water level until the depth is uniform. Closed recirculating flumes don't have tailgates. The sluice gate depresses the high water surface upstream that occurs during fast flow velocities (supercritical or rapid flow). Very slight adjustments in a tailgate or sluice gate can have a pronounced effect on the uniformity of the depth in the test channel.

MISCELLANEOUS

Temperature control

Research flumes, and of course all other kinds, often do not have any means of controlling the water temperature. Several people engaged in research have said they wish their flumes did have such a temperature control.

Of the few flumes that I have seen with water-temperature controls, the USWES has the most thorough system. This is because they can both heat and cool the water. The USWES flume has a water heater and water cooler, of the sort found in homes and office buildings. These are independent of the flume. A sensing element (thermistor) in the flume pipeline, together with an automatic recorder, governs the water temperature and triggers the addition of warmer or colder water to the sump, as needed. The natural circulation in the sump mixes the water.

The USWES flume also has a small pump (1 H. P. motor) to circulate water very slowly through the flume system when the flume is not operating, such as at night. In this manner the temperature control system keeps the water at the desired constant temperature at all times.

The 60-ft closed recirculating flume at the St. Anthony Falls laboratory has thermostatically controlled refrigeration coils in the headbox and tailbox, for cooling the water (Straub, et al., 1958).

One of the California Institute of Technology flumes, the 40-ft one, has a means of heating the water: four 1,000-watt immersion heaters located in the return pipe, near the upstream end of the flume. The switches on the heaters can be operated automatically (by a thermostat) or manually. Three of the heaters are wired for either 110 or 220 volts, so that each of them can produce either 250 or 1,000 watts of heat. The heaters can maintain a temperature that is 19°C warmer than the air in the laboratory.

Counters to reproduce flume slopes and gate settings

Motors that govern such features as the flume slope and sluice gate or tailgate settings can be hooked to a counting device such that a given counter reading corresponds to a definite setting of whatever the motor governs. By using such counters you can quickly reproduce a given tailgate setting or flume slope. As a matter of fact it should be possible to use such counters even when the slope or gate is operated manually.

Testing the flume

After you have got the complete flume system assembled do the following simple tests before putting sediment into the flume:

1. Set the flume slope at approximately horizontal. Turn on a low discharge, then a moderate discharge, and finally turn on Q_{max}. During each of these flow rates check for:

   (a) Leaks or places where the facilities are unable to accommodate the water. (You may not be able to eliminate a few minor leaks.)

   (b) Water behavior in sediment collection box. Look especially for overflowing over the tops of the screened walls at the highest discharge.

   (c) Scale capacity. Make sure capacity is not exceeded. Check weight determination by immersing an object of known weight and specific gravity.

2. Slowly tilt the flume to its maximum slope and repeat the three discharges.

Central reading panels

Recent advances in technology make it possible to connect most or all measurements (discharge, slope, etc.) to a common panel for convenience. Good examples may be found at the Univ. of Auckland, New Zealand and at the USWES at Vicksburg, Miss.

SUMMARY OF STEPS IN DESIGNING FLUMES

Determine the various features of your flume in this order:

1. Purpose of flume.
2. Type of flume.
3. Flume size.
4. Maximum desired discharge.
5. Test channel details.
6. Method of tilting the flume.
7. Sediment-infeed method (only for nonrecirculating flumes).
8. Sediment trapping and weighing.
9. Tank details (head tanks, tailboxes, sumps).
10. Pump and pipelines.
11. Discharge measurement.
12. Methods of measuring elevations and slopes along the test section.
13. Aids in obtaining uniform flow (tailgate, sluice gate).
14. How to control water temperature (research flumes only).

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