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# High Velocity Flow in Channels Having Steep-Sided Channel Walls

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North shore streams which plunge down over the steep escarpment into Lake Superior may, only where the gradients are steepest, attain during flood periods a type of flow characteristic of mountain torrents. Commonly the streams have little velocity, except in regions of cascades and waterfalls, and their flow patterns are not unusual for streams cutting into hard rock. During flood stages in favorable areas the turbulent flow of the streams changes from the streaming to the shooting type. Then the surface of the water is marked by high undulations. Standing waves form where the channel walls are very steepsided, that is, where they are almost perpendicular.

Because of the insufflation of air into the flow of these north shore streams where their velocity is very rapid, the surface of the water is rough and irregular. The action between the air and the water brings about wave formation, and causes the streams to fairly "smoke" with foam and mist. This phenomenon may be seen not only where there are cascades and waterfalls, but sometimes in sections of the streams where the gradient is less steep. At such times the air boundary is important, for resistance to the flow is no longer confined to the stream bed and channel walls, that is, to the solid boundaries of the stream. The gradual entrainment of air brings about a change in the density of the water and in the mean hydraulic radius of the section. There is a marked difference in velocity between the top and bottom of the flow, especially where the water is shallow. The flow is transformed from the liquid phase into an extremely turbulent foamy phase.

When north shore streams have such a high velocity their flow may be variously defined as shooting, high velocity, rapid, or supercritical. The flows are faster than the critical Froude number F. There is a physical difference between streaming or subcritical and supercritical flow. In subcritical flow the velocity head is $V^2(2g)$, and is usually a small percentage of the specific head, $H$. The Froude number is smaller than unity. ($V$ equals the mean velocity. $2g$ is gravitational acceleration.) In supercritical flow $V$ is greater than $\sqrt{gh}$. The Froude number, $F$, is always larger than unity. In flow near the critical velocity, $V$ equals $\sqrt{gh}$, and the Froude number, $F$, is one. When the Froude number, $F$, is in the vicinity of one, it corresponds directly with the "sonic barrier". Flow energies for the subcritical and the supercritical regimes in this region differ so little that the flow is inherently unstable and may swing from one region to the other with the slightest disturbances. For this reason waves may form and then die out quickly and not form again for some time. A small change in stream bed configuration or the alignment of the channel walls changes the Froude number, $F$, and determines whether or not standing waves shall form, and also the relative height of the waves along the channel walls.

## STANDING WAVES

Standing waves were not always formed in those sections of the north shore streams that had supercritical flow. Wall alignments seemed to play a very important part in their formation. Two different cases have been picked to discuss, the straight vertical walled section of Chester Creek in Duluth, Minnesota, and a slightly curved-wall section of Tischer Creek, another stream within the city limits. In every case where standing waves were observed the channel walls were vertical or nearly so. There were, however, surface disturbances of lesser magnitude where the channel walls were less steep.

Two different flow patterns have been seen in Tischer Creek. They were both found in the same place, but not during the same flood flows. The stream is cutting down into lava, and has made a deep trench which is now too wide for it. In one place at the foot of a long steep cascade the stream is squeezed in between vertical walls. At the foot of the last waterfall in the cascade, the bed flattens out abruptly so that it has a very gentle slope. In low stages Tischer Creek plunges down over the series of little falls. Just before it enters the plunge pool, the water is turned aside almost at right angles. It turns again, but in the opposite direction in the plunge pool. The water completes its crooked path within a few feet of its entrance into the plunge pool. Then the flow follows a straight course for a short distance before it plunges down another cascade.

In flood time the stream has such volume that it not only is much deeper, but it is considerably wider. As the flood waters race downstream, they are thrown high against the curving channel walls, change direction, and enter the plunge pool and strike against one of the channel walls. During the last two years the water has torn out a portion of the channel wall above the plunge pool. Perhaps in another year it will have made a short cut so that the cascade will be lengthened and the plunge pool bypassed. As soon as flood waters began to tear down this portion of the channel wall the flow pattern in the plunge pool changed.

The curved outer wall of the plunge pool may be considered as a boundary along which there are a small, but finite number of changes taking place successively. Every angular change thus becomes the origin of a line of small finite disturbances which constitute a wave front. The inner wall of the plunge pool also curves, but only at the plunge pool entrance. It curves in the same direction as does the outer wall, and therefore curves away from the flow, not into it as does the outer wall. Small disturbances originate along the inner wall also.

Standing waves originated at opposite sides of the plunge pool at its upstream end. In this pool the first wave formed came into being along the outer curved wall. It was a positive wave or surge front. It deflected the flow toward the line of disturbance and caused a rise in the water surface. The negative wave or depression front was on the other side of the channel where the boundary wall moved away from the flow. The flow was deflected away from the wave front and there was a lowering of the water surface.

In Figure 1 the positive wave's point of origin is at $A$, and the negative wave's at $A'$. The two waves left the channel walls and traversed the flow at some typical angle $\beta$, which is fixed by the Froude number, $F$, of the flow. The waves met in the middle of the channel at point $M$. As the negative wave passed the point $M$, the positive wave crossed over it and filled in the depression made by the negative wave. The positive wave struck the inner wall at point $B$, whereas the negative wave hit the outer wall at point $B'$. Both waves were reflected from wall to wall at successive downstream points, $C$, $C'$ and $D$, $D'$, The waves crossed in the middle of the channel at point $M'$ and still farther downstream at point $M''$. Beyond

$DM''D$ the surface of the water was very broken and uneven. By the time the standing waves reached $C$ and $C'$ they were getting small, and they died out after reaching $D$ and $D'$.

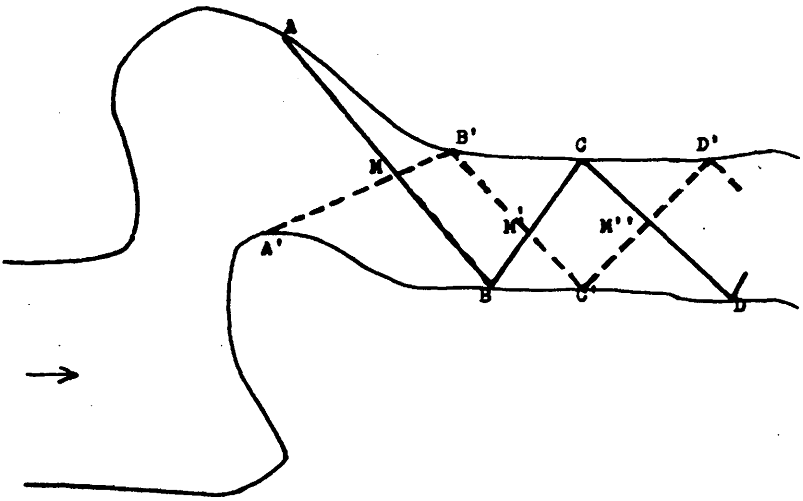

*FIGURE 1. Diagram of the Paths of Positive Waves, A, and Negative Wave, A', in a Steep-walled Stream, Duluth, Minnesota.*

While the standing waves were being reflected from wall to wall, the water level on the outer channel wall was seen to rise in rounded peaks above the other part of the flow. On the opposite side of the channel the water level was depressed below its normal height, except at those points where the positive wave hit the wall. The peaks of these waves were rounded also, instead of being cusplike.

The standing waves varied in height. Sometimes they attained a height of perhaps a foot from trough to crest. Often they were only half that when they first formed, and they died quicker than did the larger ones.

At point $A$ where the positive wave formed, a number of small wavelets came into being one after the other in very rapid succession. The surface of the flow in an area about a square foot in extent was chopped with these small waves as they alternately formed and broke. Sometimes the minor disturbances become synchronized in the time of their formation so that a larger wave formed which had the energy to cross the channel. Negative disturbances that formed at point $A'$ acted in the same manner.

It was evident during the flood flow of last spring that the pattern of wave forms in this plunge pool was changing. Sometimes the negative wave alone came into being. However, it consisted merely of a series of very minor disturbances or wavelets that chopped the water about their point of origin. The change in pattern reflects a change in channel wall alignment. Slight changes in boundary alignment influence the hydrostatic pressure distribution. The changes cause slight variations in $H$. The results are large disturbances in the flow if it is near the critical velocity. In this plunge pool it may be that the negative waves will form before the positive ones do. It is possible that standing waves would cease to form.

There is one section of Chester Creek where the stream is confined between straight vertical walls for a distance of about 25 feet. The stream bed in this place has only a gentle slope, although it is only a short distance either upstream or downstream to water falls. During very high stages the stream rushes through this trough with supercritical flow. Its surface water is then marked by numerous undulations that attain in this small stream a height of perhaps six inches. A multitude of disturbances originate at successive points along the sides of the channel walls, and meet in the middle of the flow to form a series of *V*-shaped undulations with downstream pointing apices. It is at the point of the "*V*" that each undulation is highest. Only at the entrance to this section of the channel do standing waves form. They break soon after they form, and in breaking they cause a loss of energy to the flow.

This channel section, because it does not have even the slight curvature found on that in Tischer Creek, is not as favorable for the generation of standing waves. The shallowness of the stream may be responsible for the flow pattern consisting of undulations instead of waves. Rock debris is heaped up in the upper part of this section of the stream. The sudden change of depth of water would cause a change in the Froude number. Although cavitation will cause a loss of kinetic energy to the flow, it is doubtful that it is a contributing factor in this stream.