# Drainage Services Department Practice Note No. 3/2003

## Design Considerations for Open Channels Accommodating Supercritical Flows

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## 1. SCOPE

1.1 This Practice Note sets out the critical issues to be considered in the design of open channels accommodating supercritical flows, in particular when the occurrence of hydraulic jump is anticipated. It also stipulates the requirements for linings and bedding against uplift forces and aggravated erosion under the effects of supercritical flows and higher velocities in localized areas of the channels.

## 2. GENERAL

2.1 Designing channels for water flows at or near critical depth should be avoided if possible as this kind of hydraulic condition is unstable and small changes in roughness or bed slope can produce relatively large changes in depth, which may in any instance launch the hydraulic regime into either supercritical or subcritical flow conditions.

2.2 It is generally recognized that subcritical flow in channels presents less of a problem but the situation is different for supercritical flow.

2.3 Supercritical flow in channels is characterized by shallow water flowing in high velocities. The water depths are smaller than those computed under critical or subcritical flow conditions but the energy is channeled into the velocity head resulting in significantly greater flow velocities.

2.4 Supercritical flow situation can occur at the upstream part of the drainage catchment where the channel bed gradient is relatively steep, or at the downstream end of inline structures such as spillways, sluice gates, weirs and gauging flumes, or when water flows over a hump or encounters a sudden expansion/contraction (blockage), where there is a pronounced and abrupt change in potential energy.

2.5 Under supercritical flow conditions, standing waves would often be created by small changes in sidewall alignments, and the influence of these waves will continue some distances downstream, though any such influence will not travel upstream.

2.6 In dimensionless terms, supercritical flow is represented by the Froude Number "F" as having exceeded unity, i.e. $F > 1$.

2.7 This type of flow can exert large forces on the channel surfaces, causing erosion, cavitation, up-lifting and spin-off at curved banks. Another phenomenon is that if triggered by some means, the flow can change to subcritical (i.e. $F < 1$), resulting in a substantial increase in water depth at the transition, commonly known as a hydraulic jump (Figure 1), which can cause severe erosion at the channel bed.

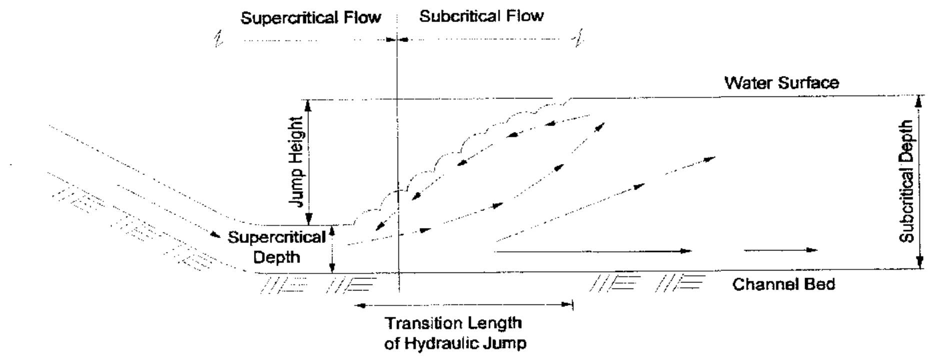


Figure 1 Hydraulic Jump at Transition from Supercritical to Subcritical Flow

2.8 A hydraulic jump is a means by nature to dissipate energy and reduce flow velocity in the water over a transition length from supercritical to subcritical flow. Since energy is lost, the energy conservation principles can no longer apply, calculation of hydraulic performance or physical conditions should be based on force-momentum balance.

2.9 On the other hand, the change from subcritical to supercritical flow involves little loss of energy and the transition is comparatively smooth. However, the resulting reduction in water depth, which is sometimes known as a hydraulic drop, will be accompanied by an increase in flow velocity.

## 3. DESIGN CONSIDERATIONS FOR SUPERCRITICAL FLOW OPEN CHANNELS

3.1 Design of channels should be based on maximum permissible velocities, which may help to ensure that the flow in the particular channel sections can remain stable up to those velocities and flow behaviour can be predicted under the design flow regime.

3.2 In addition to checking the water level to guard against overflow and the velocity along the whole channel, the Froude Number should be computed and checked to establish the design flow regime.

*Design to Accommodate Hydraulic Jump*

3.3 Particular attention should be made at locations where the Froude Number changes from greater than 1 to below 1 as hydraulic jump may be triggered.

3.4 The designer should check whether there are any abrupt changes in bed gradient of channel, flow direction (due to confluences or joining of open channels and pipes), sudden contraction of cross-sections, the presence of hydraulic control structures such as weirs and sluice gates, the existence of backwater effects and the hydraulic effect of bridge pier in the channel. Most of these are conducive to the formation of hydraulic jumps in open channels.

3.5 Change in flow condition and hence the triggering of a hydraulic jump may also occur when the channel bedding or lining changes from smooth concrete to rougher lining.

3.6 When a hydraulic jump occurs, greater turbulence and a stronger flow pattern would exist in the start of the jump than in normal open channel flow conditions. Hydraulic jump should be contained to where the jump is designed to occur, and in no circumstances be allowed to happen at an erodable channel section.

3.7 Hydraulic jump should be confined to an energy dissipation or drop structure. It may be desirable to stabilize the position of the hydraulic jump by means of physical controls, e.g. a step in the channel bed, and to provide a stilling basin over most of the length of the jump in order to help dissipating the kinetic energy. The transition length over the hydraulic jump should be determined taking into consideration the design of the channel section and linings. As a rule of thumb, the designer should allow for a minimum transition length of seven times the height of the jump if it occurs in a rectangular channel.

*Erosion of Channel Linings and Bedding*

3.8 Considerations should be given to reducing potential erosion to the channel surface carrying supercritical flows to an acceptable level. Channel linings and bedding should be designed to resist erosion under the anticipated velocities.

3.9 Siltation on channel bed during times of low flow will increase the roughness. However, concrete channel bed assumed to be fully silted in the design (and accordingly with higher roughness values assigned) would invariably under-estimate the actual velocity, the Froude Number and consequently the degree of erosion. The designer should consider the contrasting scenarios of low conveyance due to high roughness and fast flow velocity from lower roughness. The former scenario is for channel sizing and the latter for lining design.

3.10 Detailing of the edge of the soft lining is important as erosion often starts there, i.e. the interface between hard and soft linings. The lining interface should be designed in such a way that the hard lining extends below the scour depth to avoid undermining.

3.11 Consideration should be given to protect the toe of the bank from undermining by scour, which can be caused by stream flow, wave action or seepage.

3.12 Up-lifting of hard/rigid lining due to high velocity over its surface should be checked. In particular, joints in channel lining should be properly design to guard against damage by uplift forces.

*Flow Velocities and Section Design*

3.13 Asymmetric channel section design may lead to higher velocity locally, e.g. concrete surface on only one side may induce localised higher velocity than the cross-sectional average velocity, leading to the possibility of uneven erosion.

3.14 Due to the effect of superelevation, the velocity on the outer bank of a bend will be higher than that at the inner bank, exacerbating erosion on the outer bank. Furthermore, spinning-off of flood flow at curved alignment should also be checked and confined.

3.15 Consideration should be given to protect the crest of the bank to withstand overtopping in extreme flood events. Adequate freeboard, with the side slopes' hard linings extended to at least the top of the minimum required freeboard, should be provided.

3.16 Air entrainment is possible in rapid flow channels and will become appreciable when the Froude Number is higher than about 1.6. This phenomenon will result in bulking of the flow, i.e. a greater water volume than normally computed. It may therefore necessitate an increase in channel wall height to confine the water splash.

3.17 A rectangular cross-section channel is preferable at the transition from supercritical to subcritical flows to other geometric shapes, for instance trapezoidal section. The flow patterns of non-rectangular channel are very complex, making the determination of the hydraulic jump length uncertain.

## 4. ASSOCIATED FEATURES

4.1 Steps may be incorporated into the channel bed to dissipate the kinetic energy. The steps should be high enough to trigger off effectively turbulence throughout the entire flow depth. Energy dissipating implements such as those commonly erected in dam spillways may also be considered.

4.2 Stilling basins should be provided at suitable locations to trigger off the hydraulic jump in a controllable fashion to provide subcritical condition downstream.

4.3 Protruding features including the mid-berm of channel constructed from soft materials should be assessed for erosion under supercritical flow and hydraulic jump.

4.4 Access ramp should not be sloping down towards the upstream to avoid floodwater over-shooting up the ramp. It is preferable to align the ramp in the same direction of the flow and with a gentle gradient of not more than 10% in excess of the water profile.

*Flow Junction Layout*

4.5 Side-branch joining to the main channel will induce obstruction to the main channel flow due to the momentum of the side-branch flow. Junction with side branches or the confluence of multiple channels should be provided with a smooth merge-in to avoid any uncontrolled loss of energy and violent turbulent conditions. Some design practice even suggested that adjoining junction intersection should preferably be not more than 12° in angle.

4.6 Open channel junction should be designed in such a way as to maintain roughly constant flow depths throughout the junction. The designer should ensure that water surfaces at the main and side channels are at similar elevations before entering the junction.

4.7 A properly designed enlargement of the channel width downstream of the junction will help to arrest the flow turbulence and create a calmer flow condition.

*Bridge Pier within Supercritical Flow Channel*

4.8 Bridge pier should not be placed within channels designed for supercritical flow, if possible. The resulting energy losses will cause disturbances at the immediate upstream and downstream areas.

4.9 Properly designed bridge pier in channel may not necessarily create a hydraulic jump even if the flow is supercritical. The effect of the pier may only split the flow and leave a disturbed wake downstream, with no major effect upstream other than forming some spectacular sprays. The extent of the sprays will depend mainly on the shape of the pier.

4.10 The designer should nevertheless consider the possibility of a rise in water level upstream brought about by the additional head losses at the pier. It is possible that this backwater effect could induce a change in flow regime and consequently the formation of a hydraulic jump further upstream.

4.11 Moreover, the presence of the pier is prone to trapping floating debris or vegetations and induces obstructions, which may help to trigger subcritical flow condition in its vicinity.

4.12 If it is unavoidable to locate pier within a channel, the pier should have streamlined section. It should also be orientated to suit the flow and provided with suitable channel bed at its upstream and downstream areas to protect against scouring. The Froude Number should be small such that only a weak hydraulic jump, if any, will be generated. The hydraulic uplift forces and full dynamic loads imposed on the pier, particularly in the event of major blockage by debris, should also be fully assessed.

## 5. REFERENCE DOCUMENTS

5.1 The designer is recommended to consult the Stormwater Drainage Manual for guidelines on channel design under supercritical flow conditions, particularly Sections 8 and 9. Comprehensive information and design data can be found in the following reference documents:


- Department of the Army, U.S. Army Corps of Engineers, CECW-EH-D Engineer Manual 11102-1601, "Engineering & Design – Hydraulic Design of Flood Control Channels", June 1994.

- State of Arizona, Department of Water Resources, Engineering Division, "State Standard for Supercritical Flow SS 3-94 and State Standard Attachment SSA 3-94 Floodway Modeling Standards for Supercritical Flow", November 1994.

- Clark County Regional Flood Control District, State of Nevada, "Hydrologic Criteria and Drainage Design Manual, Section 700 – Open Channels", August 1999.

- Drainage Services Department, Government of the Hong Kong Special Administrative Region, "Stormwater Drainage Manual – Planning, Design and Management", 3rd Edition, December 2000.


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Deputy Director of Drainage Services