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FREE-SURFACE FLOWS WITH NEAR-CRITICAL FLOW CONDITIONS

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Abstract

Open channel flow situations with near-critical flow conditions are often characterised by the development of free-surface instabilities (i.e. undulations). The paper develops a review of several near-critical flow situations. Experimental results are compared with ideal-fluid flow calculations. The analysis is completed by a series of new experiments. The results indicate that, for Froude numbers slightly above unity, the free-surface characteristics are very similar. However, with increasing Froude numbers, distinctive flow patterns develop.

Keywords : Open channel flow, critical flow conditions, free-surface undulations, flow instability, undular surge, undular broad-crested weir flow, culvert flow.

Résumé

Pour des écoulements à surface libre, les conditions d'écoulement critique sont souvent caractérisées par des instabilités de la surface libre : c.a.d, ondulations. L'auteur présente une revue de plusieurs types d'écoulements quasi-critiques. On compare des résultats expérimentaux avec des calculs de fluides parfaits. L'auteur présente aussi de nouveaux résultats expérimentaux. Les résultats montrent que, pour des nombres de Froude légérement supérieur à un, les caractéristiques des ondulations sont très similaires. Par contre, pour de nombres de Froude plus importants, chaque type d'écoulements développe des caractéristiques distinctives.

Mots-clé : Ecoulement à surface libre, conditions d'écoulement critioque, ondulations de la surface libre, instabilité de l'écoulement, onde de translation, déversoir à seuil large, culvert.

1. Introduction

'Near-critical flows' are characterised by the occurrence of critical or nearly-critical flow conditions over a 'reasonably-long' distance and period time. At critical flow conditions[1], the specific energy/flow depth relationship (e.g. Henderson 1966) is characterised by an infinitely-large change of flow depth for a very-small change of energy. A small change of flow energy can be caused by a bottom or sidewall irregularity, by turbulence generated in the boundary layers or by an upstream disturbance. The 'unstable' nature of near-critical flows is favourable to the development of large free-surface undulations.

In this paper, it is proposed to review several near-critical flows : undular surges, undular flow above broad-crested weir, free-surface undulations downstream of backward-facing step, and undulations in rectangular cross-section

[1]Flow conditions such that the specific energy is minimum are called 'critical flow conditions'.

culvert (fig. 1). The flow characteristics are compared with undular hydraulic jump flows (Chanson 1993,1995, Chanson and Montes 1995). New qualitative experiments were performed to complete the analysis.

It must be emphasised that other types of near-critical flows may occur than those described in the paper. In particular the reader may wish to consult some Soviet investigations, including Gordienko (1968), Kurganov (1974), Tursunov (1969).

2. Undular surge (travelling bore)

2.1 Presentation

A (positive) surge wave results from a sudden increase in flow depth (e.g. caused by a partial gate closure). As seen by an observer travelling at the surge speed C_s, a (positive) surge is a quasi-steady-flow situation. When the ratio of the sequent depths is close to unity, free-surface undulations develop downstream of the surge front called an undular surge flow (tables 1 and 2).

2.2 Wave characteristics

Several theoretical calculations of wave characteristics (e.g. amplitude and length) were developed since the 19-th century. Among these, two studies proposed a simple form of solutions.

Keulegan and Patterson (1940) analysed the irrotational translation of a solitary wave. The solution shows the existence of an infinite number of undulations of identical size and shape called cnoidal waves. By equating the propagation velocity of the centre of gravity of the solitary wave to that of the wave train itself, they obtained :

[1a] $$\Delta d = \frac{1}{2} (d_2 - d_1)$$

[1b] $$\frac{\Delta d}{d_c} = \frac{\sqrt{1 + 8\,Fr_1^2} - 3}{4\,Fr_1^{2/3}}$$

where d_1 and d_2 are the upstream and downstream depths, d_c is the critical depth, and Δd is the height of the initial undulation. For the experiments of Bazin (1865), Keulegan and Patterson (1940) correlated the wave amplitude data as $\Delta d = (0.61 \pm 0.18)\,(d_2 - d_1)$ which is close to [1a].

Andersen (1978) developed the Boussinesq energy equation (Boussines 1871,1877) as :

[2] $$E_1 = d + \frac{V^2}{2\,g}\left(1 + \frac{2}{3} d \frac{\partial^2 d}{\partial x^2}\right)$$

where E_1 is the upstream specific energy, V is the velocity and d is the flow depth. Using the continuity equation, neglecting the energy losses, and integrating [2], the wave amplitude is the solution of :

[3] $$3\,\frac{E_1}{d_c}\left(\left(\frac{d_2 + \Delta d}{d_c}\right)^2 - \left(\frac{d_1}{d_c}\right)^2\right) - 2\left(\left(\frac{d_2 + \Delta d}{d_c}\right)^3 - \left(\frac{d_1}{d_c}\right)^3\right) - 3\,\mathrm{Ln}\left(\frac{d_2 + \Delta d}{d_1}\right) = 0$$

To a first approximation, [1] and Δd satisfying [3] can be correlated respectively by :

[4] $$\frac{\Delta d}{d_c} = 0.515\,(Fr_1 - 1)^{0.932}$$ correlation of Keulegan and Patterson's theory

[5] $$\frac{\Delta d}{d_c} = 0.741 \ (Fr_1 - 1)^{1.028}$$ correlation of Andersen's theory

The theories of Andersen (1978) and Keulegan and Patterson (1940) give similar results for Froude numbers close to unity. They differ however for Froude numbers[2] larger than 1.3 (fig. 2). Both theories underestimate slightly the wave amplitude compared to experimental data (fig. 2). Note that the data of Benet and Cunge (1971) and Treske (1994) are the *sidewall* amplitudes. In trapezoidal channels (model and field data) and in natural streams (Tricker 1965), the wave amplitude at the banks is larger than on the centreline.

It is worth noting that the wave amplitude decreases sharply immediately before the wave breaking as shown by the data of Treske (1994) (fig. 2) in a similar manner as for undular hydraulic jumps (Chanson and Montes 1995).

For waves amplitudes small compared to the downstream flow depth, the linearization of the Boussinesq energy equation yields (Andersen 1978) :

[6] $$\frac{L_w}{d_c} = \frac{\pi \left(\sqrt{1 + 8 \, Fr_1^2} - 1\right)}{\sqrt{3 \ Fr_1^3 \left(\frac{1}{8 \, Fr_1^2} \left(\sqrt{1 + 8 \, Fr_1^2} - 1\right)^3 - 1\right)}}$$

Equation [6] can be simplified as :

[7] $$\frac{L_w}{d_c} = \frac{3.15}{(Fr_1 - 1)^{0.45}}$$

Andersen's theory is compared with some experimental data on figure 3. For trapezoidal channels and for rough boundaries, the data follow the general trend with some scatter.

2.3 Discussion : new undular surge experiments

The author performed several undular surge experiments in the flume used by Chanson and Montes (1995). The same procedure was used each time for various discharges and channel slopes. Near-critical (super- and sub-critical) uniform flows were established in the flume. Then the downstream gate was closed partially. The travelling surge moved upstream against the uniform flow (i.e. fully-developed boundary layer flow) and was allowed to travel over the 20-m flume length.

In each case, the surge wave front was two-dimensional, except in rare cases discussed below. For an observer moving with the surge, the free-surface profile appeared stationary. Such observations confirm clearly the differences of flow pattern between undular surges and undular jumps observed in the same experimental facility.

In rare cases a weak undular surge would stop before the channel upstream end. And it would become an undular jump after a long period of typically 5-10 minutes. Visual observations indicate that, when the surge celerity falls below a critical value of around few cm/s, the surge flow would then start becoming three-dimensional. And it would take up to 20 minutes before the surge front is stable and stationary, to develop the distinctive three-dimensional flow patterns of undular jumps (Chanson and Montes 1995).

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[2]The Froude number is defined such as Fr = 1 when the specific energy is minimum.

3. Undular flow above a broad-crested weir

3.1 Introduction

A broad-crested weir is a flat-crested structure (fig. 1B). When the crest is long enough to maintain nearly hydrostatic pressure distribution within the flow across the weir, critical flow conditions occur on the crest. The hydraulic characteristics of broad-crested weirs were studied during the 19-th and 20-th centuries. Hager and Schwalt (1994) presented recently a remarkable authoritative study.

3.2 Undular weir flow

For low discharges (i.e. $d_o/\Delta z$ small), several researchers observed free-surface undulations above the crest of broad-crested weir (table 3). In their recent investigations, Hager and Schwalt (1994) indicated that the undular weir flow occurred for :

[8] $Fr_1 < 1.5$ undular weir flow

where the subscript 1 refers to the minimum flow depth on the crest (fig. 1B).

The author investigated qualitatively the flow pattern of undular weir flow in a glass flume at the University of Queensland. The flume width is 0.25 m, the sill height 0.0646 m, the horizontal crest length 0.42-m and the crest has a rounded upstream edge (28-mm radius) and a tapered downslope (concave upwards). Visual observations indicate that the undular weir flow is two-dimensional. The smallest flow depth (on the crest) is observed always upstream of the first wave crest (fig. 1B), and the undulations propagate over the entire crest.

Further the writer re-analysed the characteristics of free-surface undulations downstream of the first wave crest for undular weir flows (table 4). The data are plotted on figure 4 where Δd and L_w are respectively the wave amplitude and the wave length of the first wave length (see fig. 1B). The results are compared with undular jump data and with the solution of the Boussinesq equation for the undular surge (Andersen 1978).

Figure 4 indicates that the undular weir flows have similar free-surface undulation characteristics as undular hydraulic jumps and undular surges in prismatic channels. Further the relationship between wave amplitude and approach flow Froude number Fr_1 exhibits the same shape as undular hydraulic jumps (fig. 4(A)) :

1- for Froude numbers close to unity, the data follow closely the theoretical solution of the Boussinesq equation, and the wave amplitude is about : $\Delta d/d_c = 0.73\ (Fr_1 - 1)$;

2- with increasing Froude numbers, the wave amplitude data starts diverging from the Boussinesq equation solution and reaches a maximum value;

3- for large Froude numbers, the wave amplitude decreases with increasing Froude numbers as shown by Hager and Schwalt (1994) on their figure 8a.

On figure 4(B), the data of Hager and Schwalt (1994) could be misread. With their data, the wave length appears to increase with increasing Froude numbers. But an increase of Froude number brings also an increase of the aspect ratio d_c/W. Figure 4(B) suggests therefore an increase of wave length with increasing aspect ratio : i.e., as for undular hydraulic jump flows (Chanson and Montes 1995).

3.3 Discussion

On figure 4, some data are plotted for subcritical Froude numbers. In these cases, supercritical flow conditions were not observed at all. The data are reported for completeness.

A particular feature of undular weir flow is the developing boundary layer along the flat crest. The boundary layer development is a function of the upstream edge shape. Isaacs (1981) discussed specifically the effects of the boundary layer for a broad-crested weir.

Undular weir flows occur always for low flow depth and the effects of the boundary layer cannot be ignored. Further the rapid pressure and velocity redistributions at the upstream end of the sill modify substantially the upstream flow properties. For these reasons, the analogy between undular weir flow and undular jump or undular surge should be limited.

4. Free-surface undulations downstream of a backward-facing step and related cases

4 1 Undular flow downstream of drop

Undular flows are observed sometimes downstream of backward-facing steps, i.e. drops (fig. 1C). Hager and Kawagoshi (1990) showed excellent photographs of undular flow downstream of rounded-edge drops. Several researchers (table 5) proposed criterion for the establishment of free-surface undulations.

The author re-analysed the characteristics of undular flow downstream of backward facing steps. The experimental flow conditions are summarised in table 6. Figure 5 present a comparison between wave amplitude data and ideal fluid flow calculations. A similar trend is observed but the data of wave amplitude are smaller than undular surge results.

4.2 Related cases

Other flow situations can be related to the flow downstream of a drop (fig. 1D,E). These are the flow downstream of an impinging jet, the flow downstream of a submerged body and the flow downstream of a submerged sharp-crested weir. In each case, the flows impinge a downstream subcritical flow as a slightly-inclined planar jet and the downstream free-surface undulations form above a developing shear layer/wake region (fig. 1F). The flow conditions for the existence of undular flow are summarised in table 5. It is interesting to note the reasonably-close agreement between the various criteria despite the different geometries.

Wave amplitude and wave length data are reported on figures 5, 6, 7 and 8. Details of the experimental flow conditions are given in table 6. Figures 5 and 6 show the wave parameters as functions of the impinging jet Froude number. The characteristics of undular flow downstream of a submerged body are presented in figures 7 and 8, where the Froude number is defined as that satisfying the Bélanger equation for the measured ratio d_1/d_2 where d_1 is the minimum flow depth upstream of the first wave crest (fig. 1D,E) and d_2 is the downstream flow depth.

The wave amplitude data compare well with ideal fluid flow calculations. Some discrepancy is noted between wave length data and Andersen's (1978) calculations.

5 Undular flow in culverts

5.1 Presentation

A culvert is a covered channel of relatively short length to pass waters through an embankment (e.g. highway). Most culverts consist of three parts : the intake (or 'fan'), the barrel and the diffuser. The design varies from a simple geometry (i.e. box culvert) to a hydraulically-smooth shape (i.e. MEL culvert[3]) (fig. 9).

A culvert is designed normally to operate as an open channel. The basic principle of the culvert is to induce 'critical flow conditions' in the barrel in order to maximise the discharge per unit width and to reduce the barrel cross-section.

The flow upstream and downstream of the culvert is subcritical typically. As the flow approaches the culvert, the constriction (i.e. intake section) induces an increase in Froude number. For the design discharge, the flow becomes near-critical in the barrel. In practice, perfect-critical flow conditions in the barrel are difficult to establish : they are characterised by 'choking' effects and free-surface instabilities. Usually, the Froude number in the barrel is about 0.7 to 0.9.

5.2 Hydraulic design of culvert

A culvert is designed for a specific flow rate. Its hydraulic performances are the maximum discharge Q_w^{max} (i.e. design discharge) and the maximum head loss ΔH. Substantial head losses might induce upstream backwater effects and must be minimised.

The hydraulic calculations are based upon the assumptions of smooth intake and diffuser, no (or minimum) energy loss, and critical flow conditions in the barrel. For a rectangular cross-section, the maximum discharge per unit width is achieved for critical flow conditions :

$$[9] \qquad q_w^{max} = \sqrt{g} \left(\frac{2}{3} (E_o + \Delta z - \Delta H)\right)^{3/2}$$

The minimum barrel width for critical flow conditions is then :

$$[10] \qquad W_{min} = \frac{Q_w^{max}}{\sqrt{g}} \left(\frac{2}{3} (E_o + \Delta z - \Delta H)\right)^{-3/2}$$

were E_o is the upstream specific energy, Δz the bed elevation difference between the upstream channel and the barrel bottom (fig. 9) and ΔH the head loss.

Equation [10] gives the minimum barrel width to obtain near-critical flow without 'choking' effects. It shows that the barrel width can be reduced by lowering the barrel bottom elevation. Designers must however choose an adequate barrel width to avoid the risks of culvert obstruction by debris (e.g. rocks, trees).

5.3 Undular flow in the barrel

In the barrel, the near-critical flow at design discharge is characterised by the establishment of stationary free-surface undulations (e.g. fig. 10). For the designers, the characteristics of the free-surface undulations are important for the sizing of the culvert height. Henderson (1966) recommended that the ratio upstream head over barrel height should be

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[3]The design of a Minimum Energy Loss culvert is associated with the concept of constant total head. The inlet and outlet must be streamlined in such a way that significant form losses are avoided. For a complete review of Minimum Energy Loss culverts, see Apelt (1983).

less that 1.2 for the establishment of free-surface flow in the barrel. Such a ratio gives a minimum clearance above the free-surface level in the barrel of about 20%.

Two culvert experiments are performed in the Hydraulics/Fluid Mechanics Laboratory of the University of Queensland : a box culvert model and a MEL culvert model (table 7). For the design discharge (i.e. 0.01 m^3/s), undular flows are clearly observed in the barrel of both models. In each case, the free-surface undulations are two-dimensional.

For the MEL culvert experiment, the maximum free-surface height in the barrel is about 20% above the mean free-surface level. Further the free-surface undulation characteristics are very close to undular weir flow (fig. 4). Both the broad-crested weir and the culvert are designed specifically for near-critical flow above the crest and in the barrel, respectively. It is therefore justified to compare their wave properties as shown on figure 4. Note that undular weir flows are usually thin nappes affected by the developing bottom boundary layer, while the barrel of a culvert is usually narrow inducing thick flows which are affected by developing bottom and sidewall boundary layers.

6 Summary and conclusion

The present study develops a re-analysis of near-critical flows and a comparison with recent undular jump flow experiments. For Froude numbers slightly above unity, the characteristics of the free-surface undulations are comparable in most near-critical flow situations. And ideal fluid flow theories (e.g. Keulegan and Patterson 1940, Andersen 1978) can predict reasonably well the wave properties. However, with increasing Froude numbers, each type of near-critical flows exhibits a different behaviour, e.g., the flow properties of undular hydraulic jumps (Chanson 1993,1995) cannot be predicted with ideal-fluid theories for larger Froude numbers.

The similarity between the various types of near-critical flows might provide some order of magnitude for free-surface undulations at near-critical flows. The generalisation of the results should currently not be extended to precise calculations. The basic flow patterns are strongly affected by the upstream flow conditions, the wall friction and the related developing boundary layers, and by possible flow separation and wake region (e.g. downstream of a backward-facing step).

The study has highlighted the lack of experimental data and some limitations of ideal-fluid flow theories. It is hoped that new investigations will follow to provide additional information for hydraulic engineers.

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9. List of symbols

A	cross-section area (m^2) : for a rectangular channel : $A = W\ d$;
C_s	surge celerity (m/s) as seen by an observer standing on the channel bank;
d	flow depth (m) measured perpendicular to the channel bottom;
d_c	critical flow depth (m) : for a rectangular channel : $d_c = \sqrt[3]{q_w^2/g}$;
d_o	flow depth (m) upstream of a hydraulic obstacle (e.g. weir, submerged body);
E	specific energy (m);
E_o	mean specific energy (m) upstream of a hydraulic obstacle (e.g. weir, submerged body);

Fr	1- Froude number; for steady open channel flow : $Fr = V/\sqrt{g\ A/W}$;
	2- surge Froude number : $Fr = (V - C_s)/\sqrt{g\ A/W}$;
Fr_o	Froude number upstream of a hydraulic obstacle (e.g. culvert);
g	gravity constant : $g = 9.80$ m/s^2 in Brisbane, Australia;
L_w	wave length (m);
Q_w	water discharge (m^3/s);
Q_w^{max}	maximum water discharge (m^3/s) for a given specific energy : i.e., water discharge at critical flow conditions;
q_w	water discharge per unit width (m^2/s);
q_w^{max}	maximum water discharge per unit width (m^2/s) for a given specific energy : i.e., water discharge at critical flow conditions;
V	velocity (m/s);
W	channel width (m); for a channel of irregular cross-section, W is the free-surface width;
W_{min}	minimum design width (m) of a culvert barrel;
x	longitudinal distance (m) measured along the channel bottom;
α	channel slope;
Δd	wave amplitude (m);
ΔH	head loss (m);
Δz	drop height (m);

Subscript

1	1- flow conditions upstream of the hydraulic jump;
	2- initial flow conditions before the passage of a positive surge;
2	1- flow conditions downstream of the hydraulic jump;
	2- new flow conditions after the passage of a positive surge.

Table 1 - Conditions of existence of undular surges (travelling bores)

Reference (1)	Condition for undular surge flow (2)	Remarks (3)
Favre (1935)	$\frac{d_2}{d_1} < 1.28$	Laboratory experiments. Rectangular cross-section (W = 0.42 m). Zero initial velocity ($V_1 = 0$).
Rouse (1938)	$\frac{d_2}{d_1} < 2$	
Henderson (1966)	$\frac{d_2}{d_1} < 1.35$ to 1.95	1.35 for smooth channel; 1.95 for rough channel.
Benet and Cunge (1971)	$d_2/d_1 < 1.29$ for $V_1 = 0$ $d_2/d_1 < 1.35$ for $0 < V_1/\sqrt{g\ d_1} < 0.1$ $d_2/d_1 < 1.37$ for $0.1 < V_1/\sqrt{g\ d_1}$	Laboratory experiments in trapezoidal channel (see table 2).
Treske (1994)	$Fr_1 < 1.38$ ($d_1 = 0.16$ m) $Fr_1 < 1.34$ ($d_1 = 0.08$ m)	Laboratory experiments in rectangular channel (see table 2).
	$Fr_1 < 1.33$	Laboratory experiments in trapezoidal channel (see table 2)

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Table 2 - Experimental investigations of undular surges (travelling bores)

Reference	Initial flow V_1 m/s	d_1 m	Surge type	Channel geometry	Remarks
(1)	(2)	(3)	(4)	(5)	(6)
Favre (1935) ([1])	0	0.106 to 0.206	+ U/S	Rectangular (W = 0.42 m) $\alpha = 0$ deg.	Laboratory experiments. Flume length : 73.8 m.
	<> 0	0.109 to 0.265	+ U/S	Rectangular (W = 0.42 m) $\alpha = 0.017$ deg.	
Zienkiewicz and Sandover (1957)		0.05 to 0.11	+	Rectangular (W = 0.127 m) $\alpha = 0$ deg. Smooth flume : glass Rough flume : wire mesh	Laboratory experiments. Flume length : 12.2 m.
Benet and Cunge (1971)	0 to 0.198	0.057 to 0.138	+ D/S	Trapezoidal (base width : 0.172 m, sideslope : 2H:1V) $\alpha = 0.021$ deg.	Laboratory experiments. Flume length : 32.5 m.
	0.59 to 1.08	6.61 to 9.16	+ U/S	Trapezoidal (base width : 9 m, sideslope : 2H:1V) $\alpha = 0.006$ to 0.0086 deg.	Oraison power plant intake channel.
	1.51 to 2.31	5.62 to 7.53	+ U/S	Trapezoidal (base width : 8.6 m, sideslope : 2H:1V)	Jouques-Saint Estève intake channel.
Treske (1994)		0.08 to 0.16	+ U/S	Rectangular (W = 1 m) $\alpha = 0.001$ deg.	Laboratory experiments. Flume length : 100 m. Concrete channel.
		0.04 to 0.16	+ U/S, + D/S, -	Trapezoidal (base width : 1.24 m, sideslope : 3H:1V) $\alpha = 0$ deg.	Laboratory experiments. Flume length : 124 m. Concrete channel.
Present study	0.4 to 1.2	0.02 to 0.15	+ U/S	Rectangular (W = 0.25 m) $\alpha = 0.19$ to 0.54 deg.	Laboratory experiments. Flume length : 20 m.

Notes :

([1]) see also Benet and Cunge (1971).

Surge type : + = positive surge; - = negative surge; U/S = moving upstream; D/S = moving downstream.

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Table 3 - Undular flow conditions above broad-crested weirs

Reference (1)	d_c/W (2)	Flow conditions (3)	Remarks (4)
Undular jump at broad-crested weir			
Govinda Rao and Muralidhar (1963)		Fr_1 such as ratio head on crest over weir length < 0.1	
BOS (1976)		Fr_1 such as ratio head on crest over weir length < 0.08	
Hager and Schwalt (1994)	0.033 to 0.073	$Fr_1 < 1.5$ ([a])	Laboratory experiments (see table 4).

Note : ([a]) corresponding to a ratio Head-on-crest over weir length less than 0.102.

Table 4 - Summary of experimental flow conditions - Undular weir flows

Reference (1)	Q_w L/s (2)	Fr_1 (3)	d_c/W (4)	Comments (5)
Woodburn (1932)	4.8 to 7.6	0.86 to 1.09	0.096 to 0.131	W = 0.305 m.
Tison (1950)	39.6 to 45.9	0.91 to 1.30	0.172 to 0.190	W = 0.5 m. Data re-analysed by Serre (1953).
Hager and Schwalt (1994)	3.15 to 8.25	1.19 to 1.45	0.032 to 0.061	W = 0.499 m. Δz = 0.401 m. Crest length : 0.5 m
Present study	up to 4			W = 0.25 m. Δz = 0.0646 m. Crest length : 0.42 m. Substantial effect of the developing boundary layer (see ISAACS 1981).

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Table 5 - Conditions for free-surface undulations downstream of backward facing steps and weirs

Reference (1)	d_c/W (2)	Flow conditions (3)	Remarks (4)
Undular flow d/s of rounded drop			
Sharp (1974)		$Fr_1 < 2.2$ for $\Delta z/d_1 = 2$ $Fr_1 < 4$ for $\Delta z/d_1 = 3.5$	Laboratory experiments. ([a])
Hager and Kawagoshi (1990)	0.03 to 0.135	$Fr_1 < 2.44 + 0.28 \frac{\Delta z}{d_1}$	Laboratory experiments. ([a])
Undular flow d/s of abrupt drop			
Chow (1959)		$\frac{1}{2} \frac{d_2}{d_1 - d_2} \left(1 - \left(\frac{d_2}{d_1} - \frac{\Delta z}{d_1}\right)\right)^2 < Fr_1^2 < \frac{1}{2} \frac{d_2}{d_1 - d_2} \left(\left(1 + \frac{\Delta z}{d_1}\right)^2 - \left(\frac{d_2}{d_1}\right)^2\right)$	([a])
Undular flow d/s of sharp-crested weir			
Bazin (1888-1898)		$\frac{d_1 - d_2}{\Delta z} < \frac{1}{6}$ to $\frac{1}{5}$ ([b])	Large-scale experiments.
Undular flow d/s of weir with circular crest			
Rehbock (1929)		$0.18 < \frac{d_1 - d_2}{\Delta z} < 0.233$ ([b])	Laboratory experiments ($q_w = 0.027$ m^2/s, $\Delta z = 0.15$ m).
Undular flow d/s plane plunging jet			
Sene (1984)	0.0073 & 0.0358	10 < Jet angle < 30 degrees	Laboratory experiments.
Undular flow d/s of submerged body			
Duncan (1983)		$\frac{\Delta z}{d_o} < 0.132$ for V = 0.8 m/s	Laboratory experiments. ([c])
Voutsis and McKinnon (1994)	0.299 & 0.311	$\frac{\Delta z}{d_o} < 0.47$	Laboratory experiments. ([c])

Notes :

([a]) : see fig. 1 for the definition of symbols.

([b]) : d_1 and d_2 are the flow upstream and downstream depths measured above the weir crest.

([c]) : see fig. 1 and table 6 for the definition of symbols and additional information.

Table 6 - Experiments with backward facing steps and related cases

Reference	q_w m^2/s	d_1 m	Fr_1	d_c/W	U/S Flow	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Undular jump d/s of rounded drop						
Sharp (1974)	--	--	--	--	P/D	W = 0.203 m. ([b])
Hager and Kawagoshi (1990)	--	--	--	0.03 to 0.135	P/D	W = 0.5 m. ([b])
Undular flow d/s of plane plunging jet						
Sene (1984)	0.0073 & 0.0359	0.006 to 0.016	3.2 to 7.7 ([a])	0.1099 & 0.3177		Bidimensional jet (jet angle between 10 and 30 deg.) ([b]). W = 0.16 m.
Undular flow d/s of submerged body						
Duncan (1983)	Foil speed : 0.6 to 1 m/s	0.3 to 0.45			At rest	NACA 0012-shape hydrofoil moving in a 24-m long flume (W = 0.61 m). Foil at 0.175 m above the tank bottom.
Voutsis and McKinnon (1994)	0.064			0.299	P/D	T-piece model ([b]). W = 0.25 m.
	0.064 & 0.068			0.299 & 0.311	P/D	4-girder (AASHTO IV) concrete bridge model ([b]). W = 0.25 m.

Notes :

U/S Flow : upstream flow conditions : F/D = fully developed - P/D = partially developed boundary layer.

([a]) : jet Froude number defined in term of the jet thickness.

([b]) : see fig. 1 for the definition of symbols.

Table 7 - Culvert experiments

Experiment	Design discharge Q_w^{max} m^3/s	Barrel dimension Width W_{min} m	Height m	Length m	Remarks
(1)	(2)	(3)	(4)	(5)	(6)
Present study					
Box culvert	0.01	0.15	0.11	0.5	Upstream channel width : 1 m. Intake and exit : 45-degree diffuser. $\Delta z = 0$. $E_o/d_c = 1.915$, $Fr_o = 0.431$.
MEL culvert	0.01	0.10	0.17	0.6	Upstream channel width : 1 m. $\Delta z = 0.14$ m. $E_o/d_c = 1.915$, $Fr_o = 0.431$.

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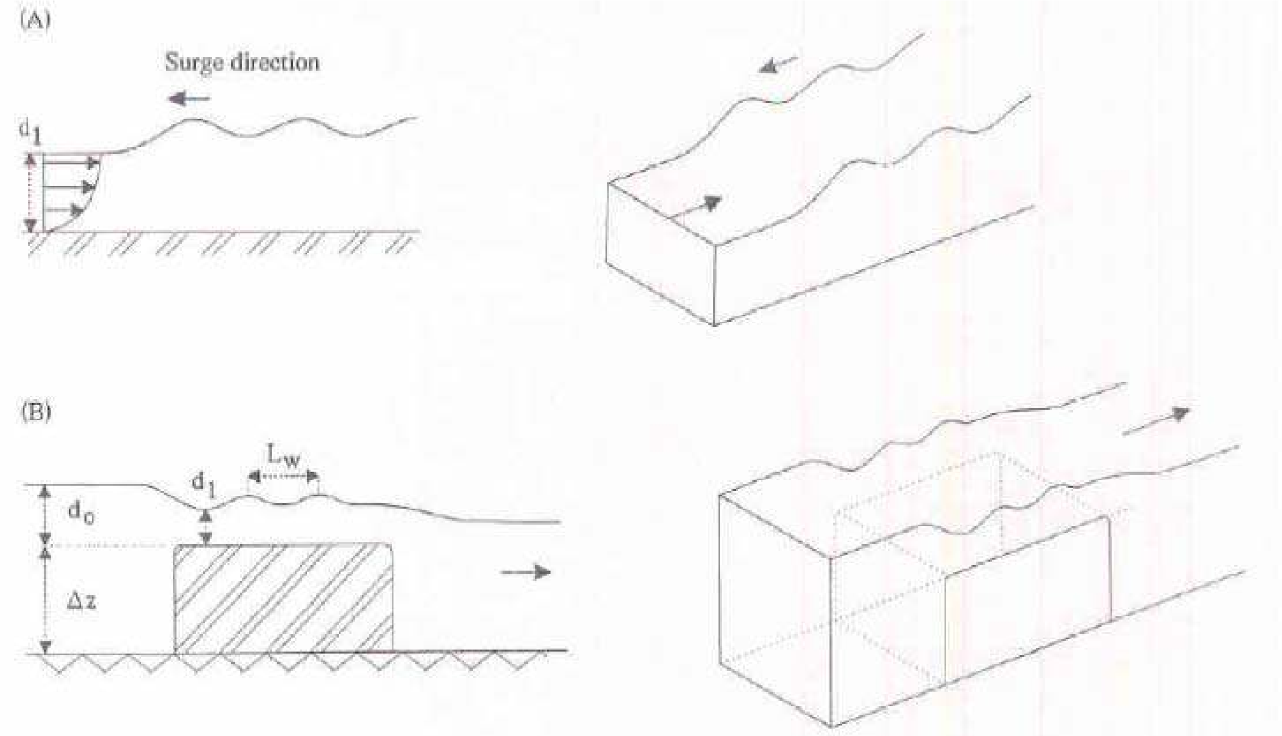
Fig. 1 - Sketch of near-critical undular flows

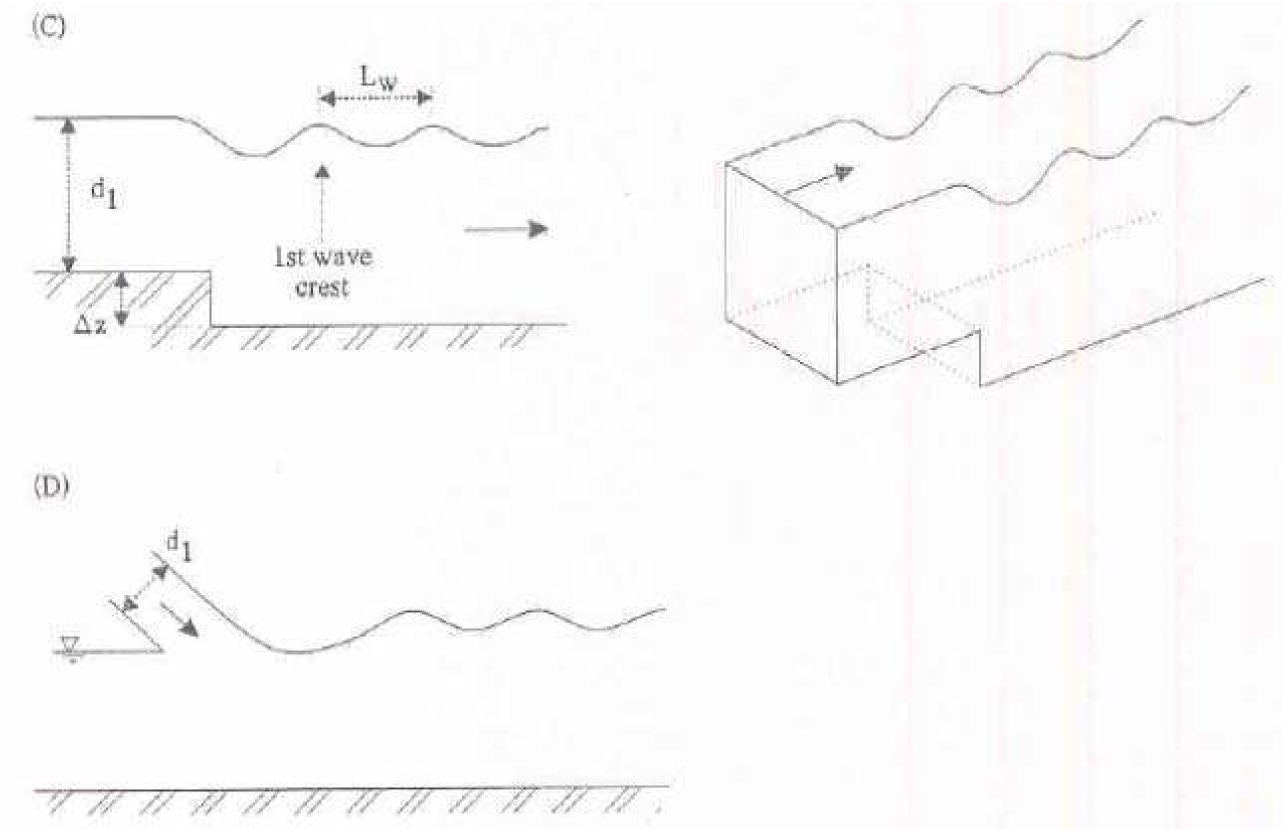
(A) Undular surges

(B) Undular flow at weirs



(C) Undular flow downstream of drop

(D) Undular flows downstream of impinging jet



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(E) Undular flows downstream of submerged bodies

(F) Undular flows developing above wake and shear flow regions

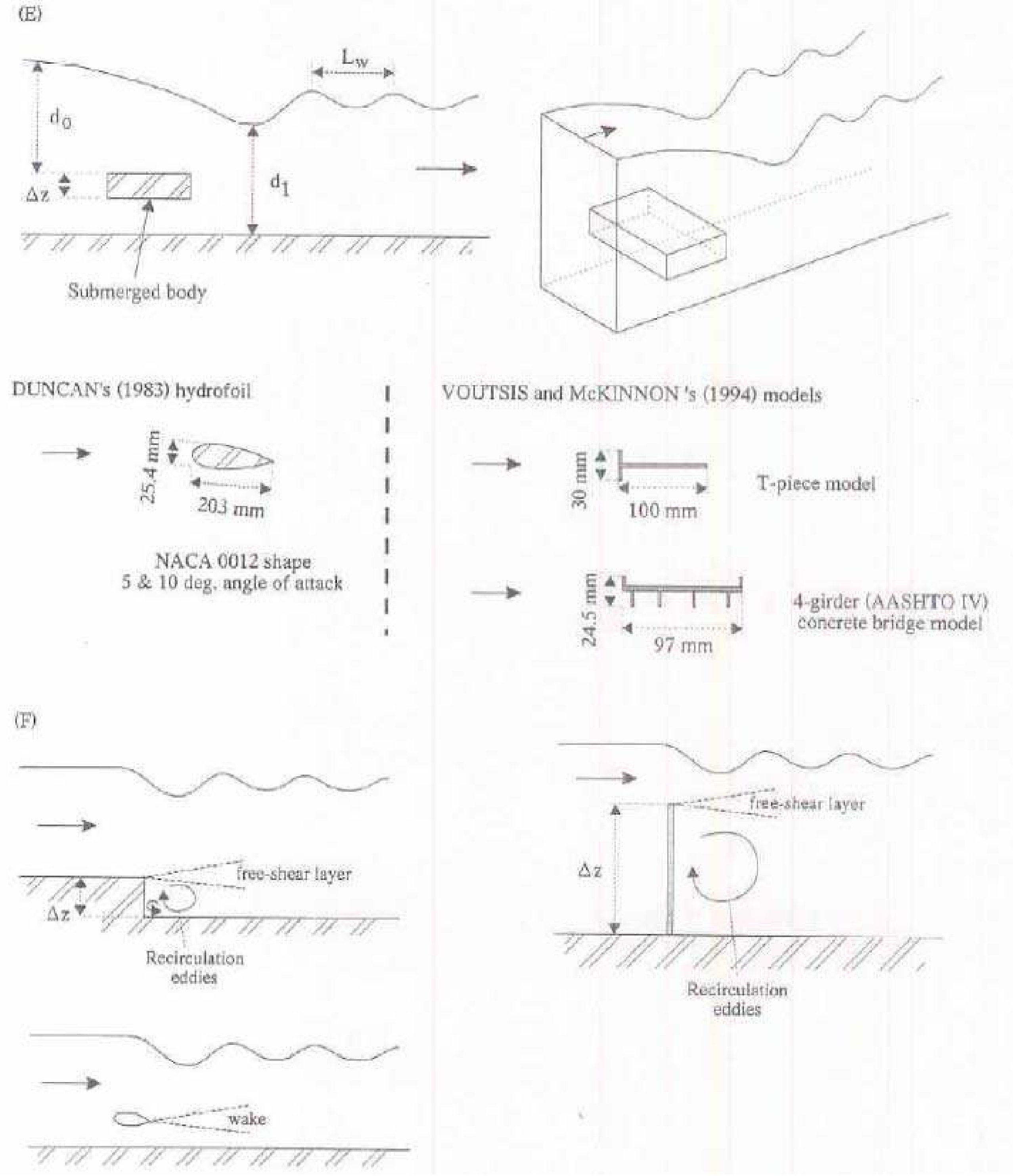

Fig. 2 - Undular surge : wave amplitude $\Delta d/d_c$ as a function of the upstream Froude number Fr_1

Comparison between the theories of Keulegan and Patterson (1940), Andersen (1978) and experimental data (table 2)

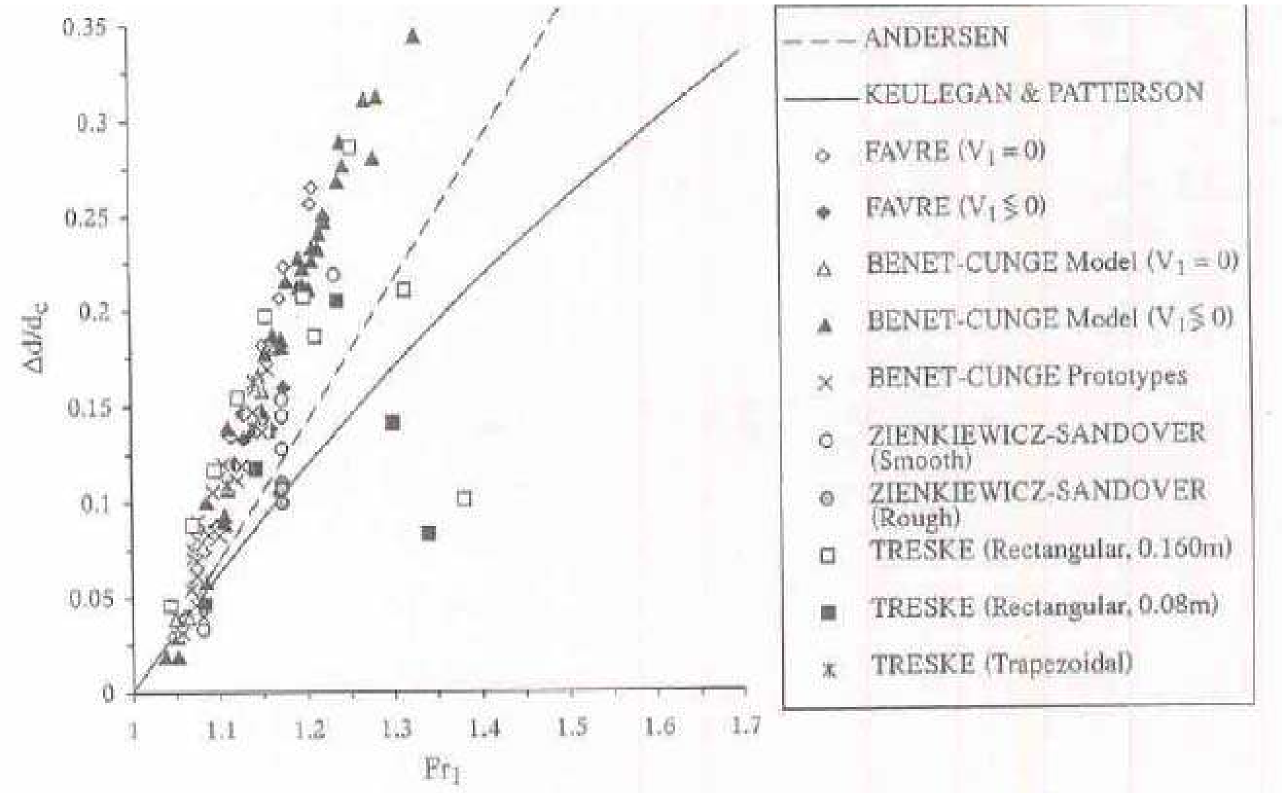

Fig. 3 - Undular surge : dimensionless wave length as a function of the upstream Froude number

Comparison Andersen's (1978) theory and experimental data (table 2)

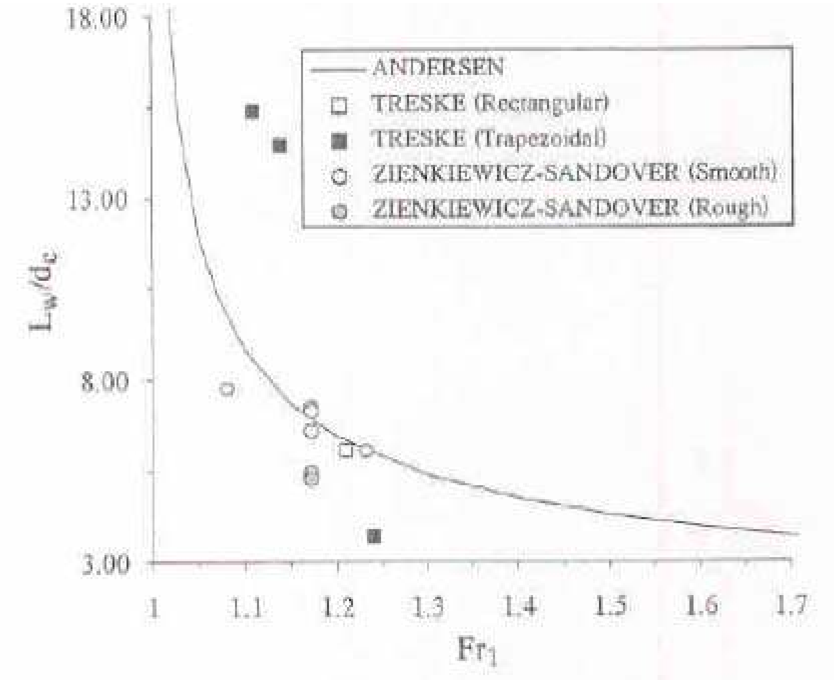

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Fig. 4 - Free-surface undulations characteristics : comparison between undular weir flows (table 4), undular flow in the barrel of a MEL culvert (present study, table 7), undular jump flow (Chanson 1993) and undular surge theory (Andersen 1978)

(A) Dimensionless wave amplitude $\Delta d/d_c$

(B) Dimensionless wave length L_w/d_c

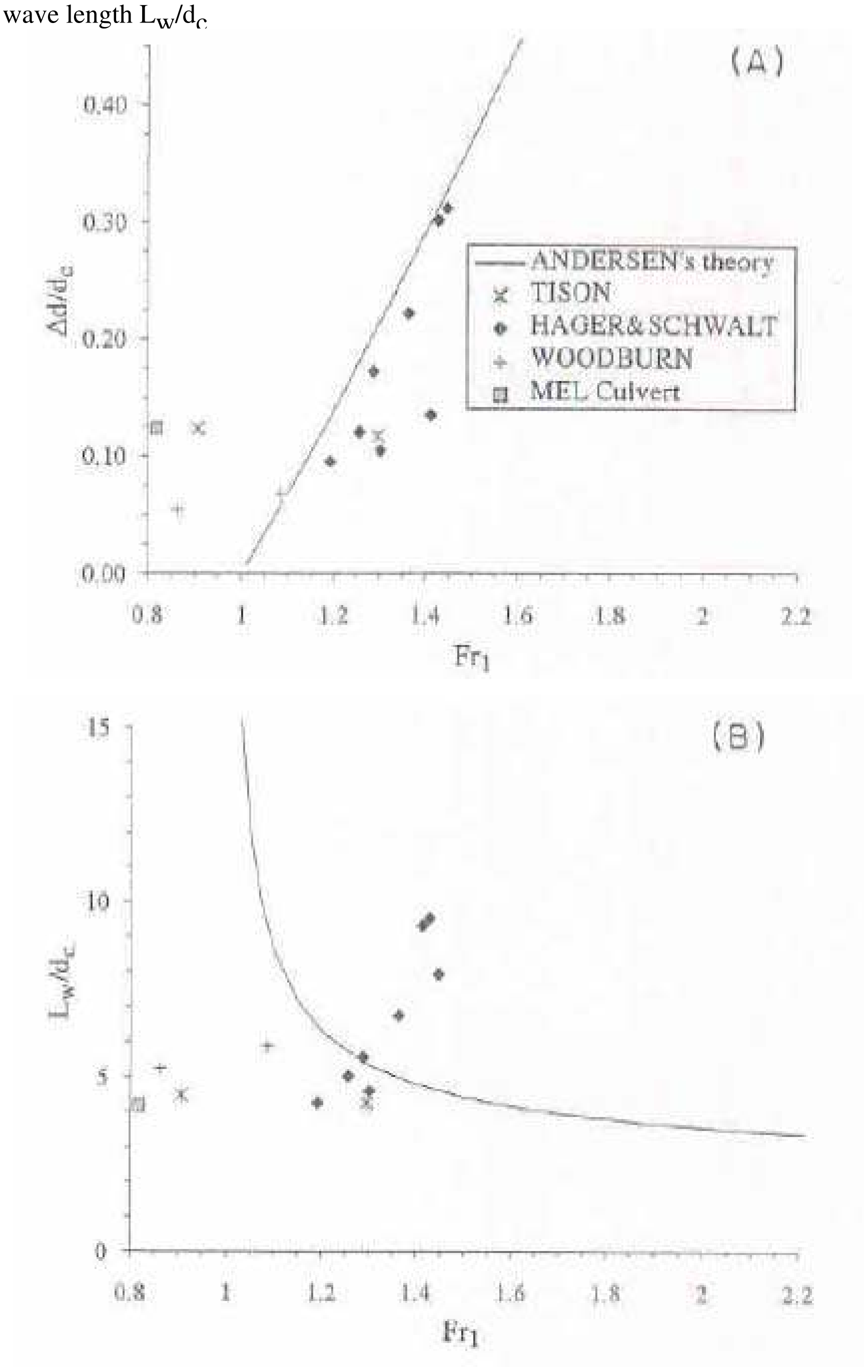

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Fig. 5 - Dimensionless wave amplitude of undular flow downstream of drop and inclined jet

Fr_1 is defined on figure 1(D) - Comparison between undular surge theory (Andersen 1978) and experimental data (table 6)

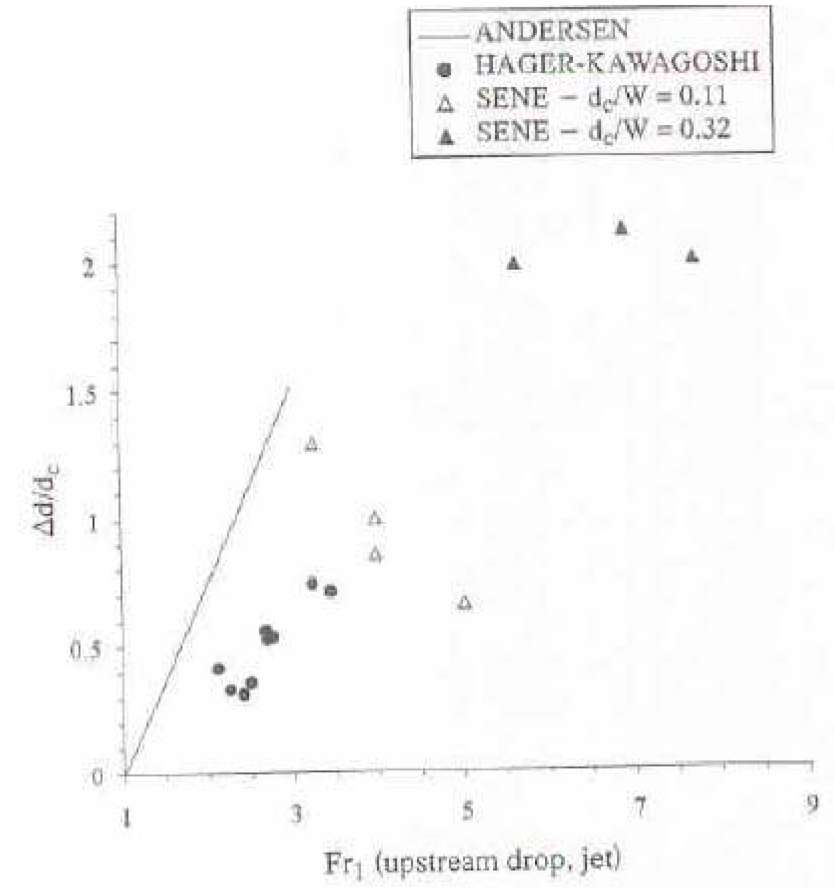

Fig. 6 - Dimensionless wave length of undular flow downstream of an inclined jet

Fr_1 is defined on figure 1(D) - Comparison between undular surge theory (Andersen 1978) and experimental data (table 6)

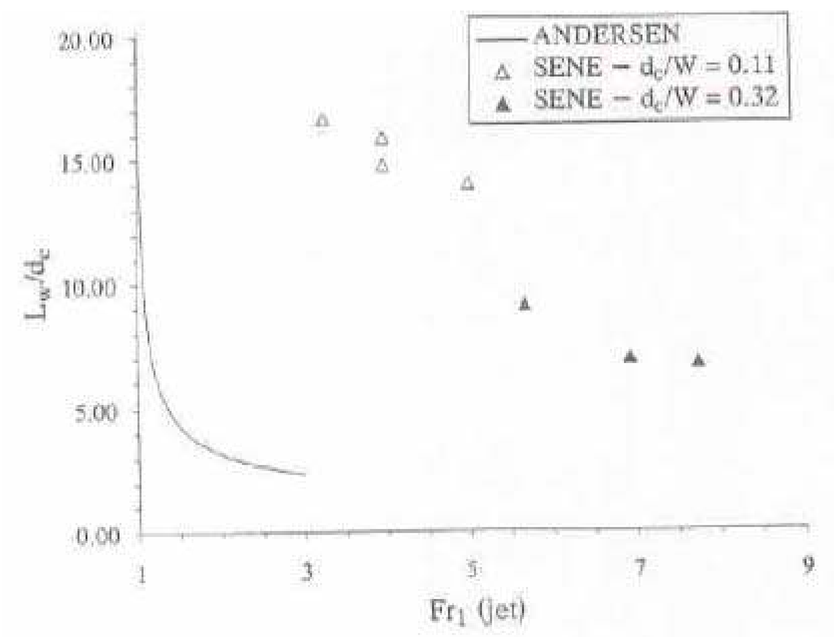

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Fig. 7 - Dimensionless wave amplitude of undular flow downstream of a submerged body

Fr is the Froude number satisfying the Bélanger equation for the measured ratio d_1/d_2 (as defined on fig. 1(E)

Comparison between undular surge theory (Andersen 1978) and experimental data (table 6)

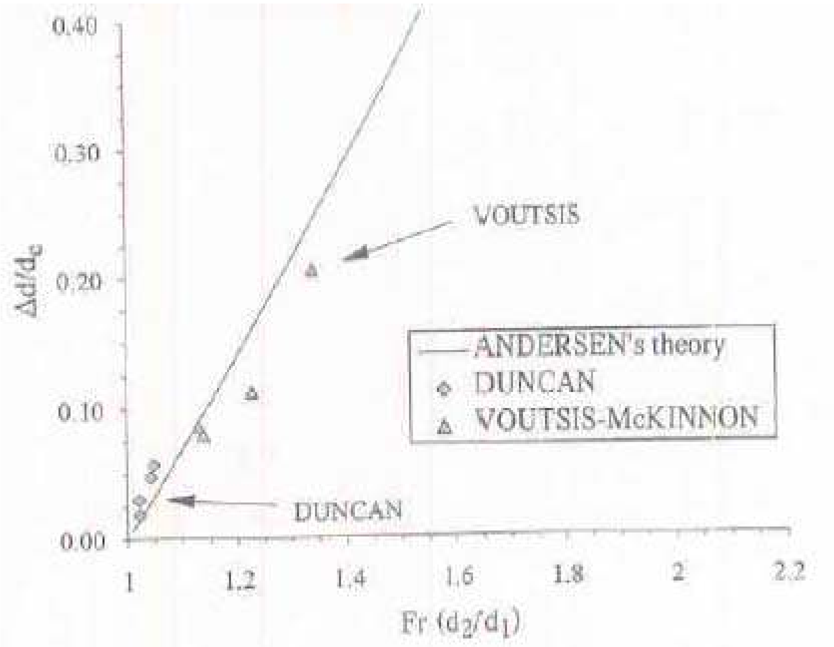

Fig. 8 - Dimensionless wave length of undular flow downstream of a submerged body

Fr is the Froude number satisfying the Bélanger equation for the measured ratio d_1/d_2 (as defined on fig. 1(E))

Comparison between undular surge theory (Andersen 1978) and experimental data (table 6)

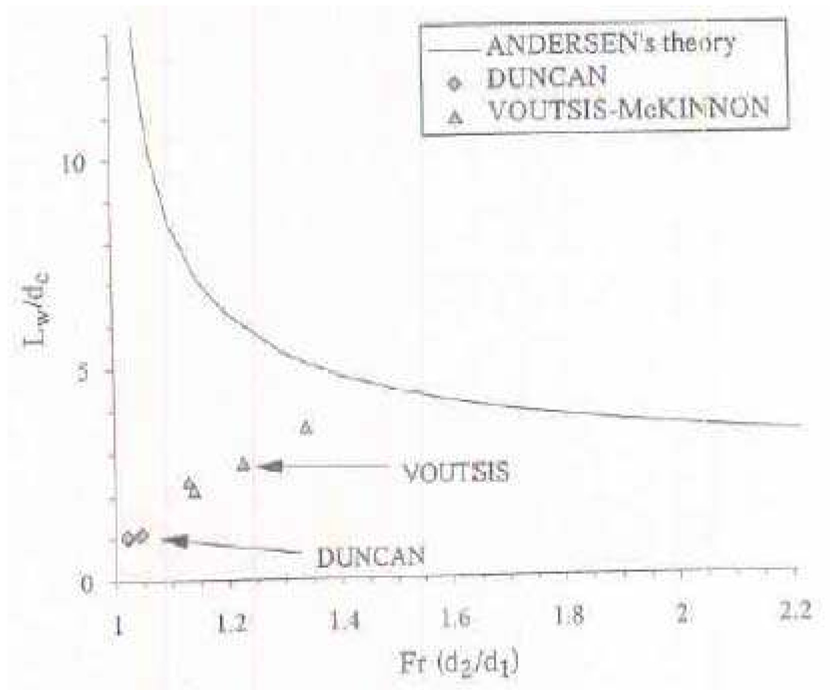

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Fig. 9 - Sketch of culverts

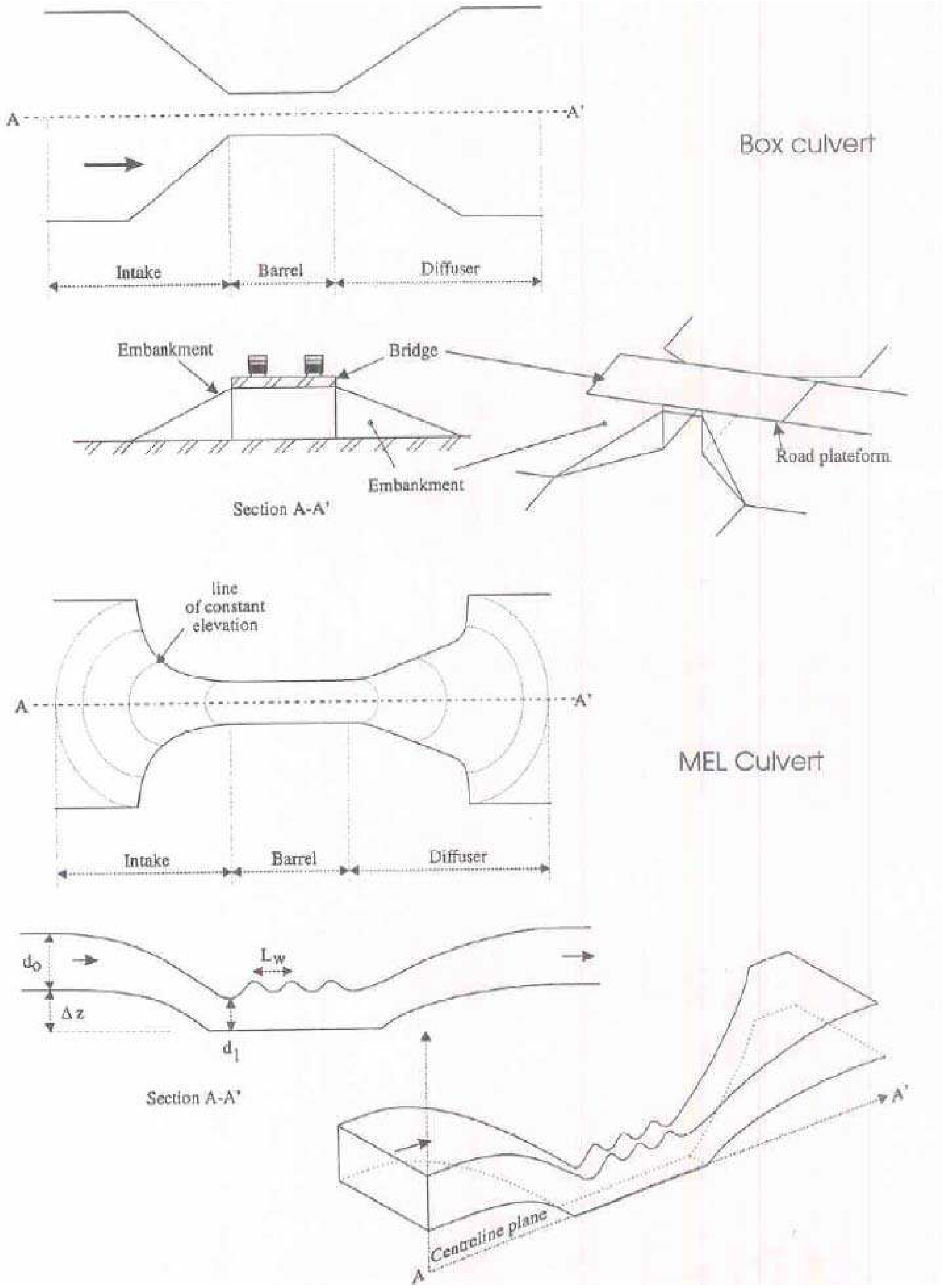

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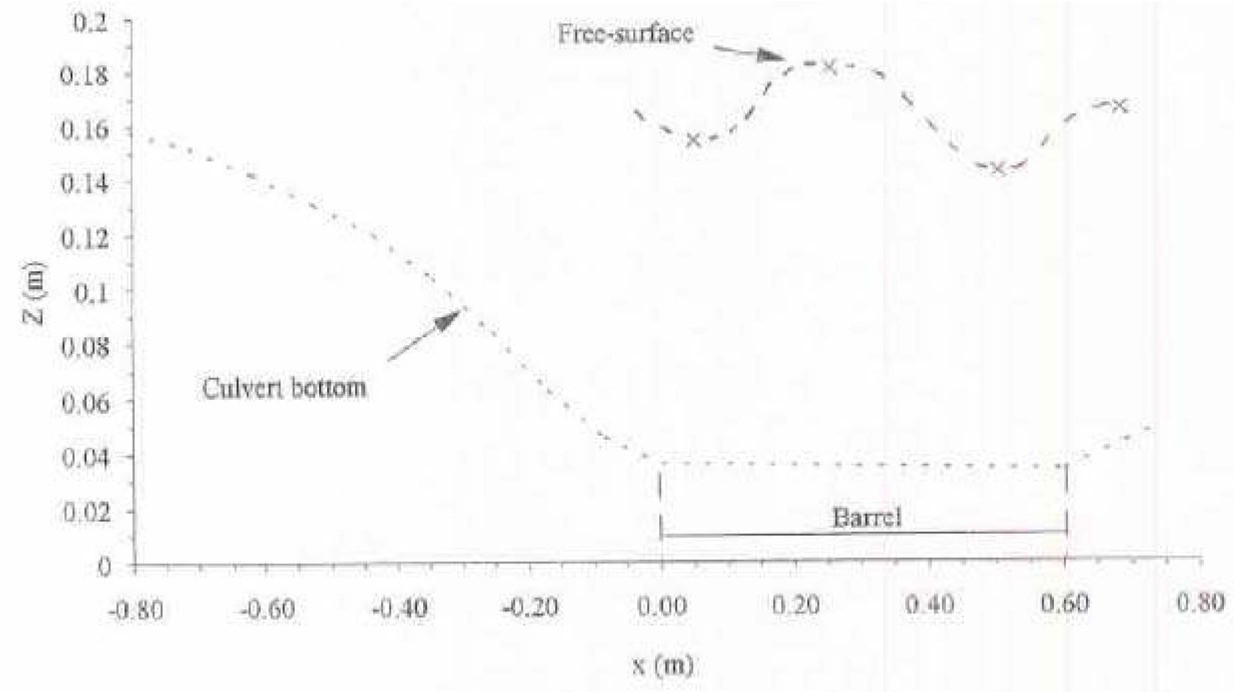
Fig. 10 - Longitudinal free-surface profile in the barrel of the minimum energy loss culvert (MEL culvert)



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