Characteristics of Undular Hydraulic Jump Downstream of A Sluice Gate

Karakteristik Loncatan Hidrolik Undular Di Hilir Pintu Air

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ABSTRACT

Undular hydraulic jump is a hydraulic jump with a low Froude number which is marked by the emergence of a fixed roller. Information about the characteristics of undular hydraulic jump is still very poor. In order for the interests of the development of science, it is necessary to in-depth study of the hydraulic characteristics and phenomenon that appear on the undular hydraulic jump. This research is applying the 2D physical model that used a tilting flume. Sluice gate is used as a tool to generate the undular hydraulic jump. Measurement of distance and depth using a point gauge while the flow velocity was measured using a Nixon Streamflo 422 Currentmeter. Circulation flow is driven by using water pumps with discharge 15 l/s and 30 l/s. The results of this study indicate that the maximum flow velocity of dimensionless velocity distribution are at 0.5 - 0.9. Lowest value of Froude number obtained in running model Q9A1 is Fr_1 = 1.197 and its highest value obtained in running model Q3A1 is $Fr_{1\ limit}$ = 2.258. The wave steepness is mild with a slope range are 0.1 to 0.3 or 10% to 30%. The length and height of the wave form are reduce at the first, second, third and so on until the condition of conjugate depth (y_3). The Energy loss occurs with the value ΔE = 0.03 to 1.039 cm or 0,3% - 10,3%. For more information, the phenomenon of recirculation and flow separation are formed under of the first crest and near of the channel bed. The significant difference value of point velocity gradient near the channel bed between the wave crest to wave trough raises the potential for scouring beneath the wave trough for the mobile bed channel.
Keywords: Undular hydraulic jump, Froude number, Velocity profile

ABSTRAKSI

Loncatan hidrolik undular adalah lompata hidrolik dengan angka Froude yang rendah akibat adanya pintu roller tetap. Informasi tentang karakteristik lompatan hidrolik undular masih sangat kurang. Untuk kepentingan pengembangan ilmu pengetahuan, sangat diperluka penelitian yang mendalam tentang karakteristik dan fenomena yang muncul pada lompatan hidrolik undular. Penelitian dilakukan dengan mengaplikasikan pemodelan fisik 2D yang menggunakan saluran air curam. Pintu air digunakan sebagai alat untuk memba ngkitkan lompatan hidrolik undular. Alat pengukur jarak dan kedalaman menggunakan point gauge, sedangkan alat pengukur kecepatan aliran menggunakan Nixon Streamflow 422 Currentmeter. Air dialirkan menggunakan pompa air dengan kapasitas 15 l/s dan 30 l/s. Hasil penelitian menunjukkan bahwa kecepatan aliran maksimum dari distribusi tidak berdimensi adalah 0,5 – 0,9. Angka Froude terendah dicapai pada model Q9A1 adalah Fr_1 = 1,197 dan nilai tertinggi pada model Q3A1 is $Fr_{1\ limit}$ = 2,258. Kecuraman gelombang sedang dengan kemiringan antara 0,1 dan 0,3 atau 10% sampai 30%. Panjang dan lebar bentuk gelombang berkurang di awal, ke dua dan ke tiga dan seterusnya sampai kondisi kedalaman yang diperkirakan (y_3). Energi hilang terjadi pada ΔE = 0,03 sampai 1,039 cm atau 0,3% - 10,3%. Selanjutnya, fenomena sirkulasi balik dan aliran terpisah terbentuk di bawah puncak pertama dan di dekat saluran dasar. Perbedaan yang signifikan pada gradient kecepatan di dekat saluran dasar antara puncak gelombang dengan lembah gelombang menyebabkan potensi gerusan di bawah lembah gelombang untuk saluran dasar yang begerak.
Kata-kata Kunci : loncatan hidrolik undular, angka Froude, profil kecepatan

INTRODUCTION

Hydraulic jump is a phenomenon that occurs due to suddenly flow changes from supercritical to subcritical flow. The first type of hydraulic jump is undular hydraulic jump. The undular hydraulic jump formed by supercritical flow at the upstream that has a low Froude number value which is the value of Fr is 1 to 1.7 (Chow, 1985). The form of undular hydraulic jump can be found in irrigation channel or flow under the vertical sluice gate and it also usually found at the weir, where the roll of the waves can cause erosion on the channel banks (Chanson, H., 1995).

Undular hydraulic jump type are rare. The form of undular hydraulic jump can be observed in three different types. The first type is standing undular jump with flat bed. This condition is usually found in the flow under the sluice gate. The second type is a moving undular hydraulic jump or generally called undular bore. This form can be observed due to the tides in estuaries. The third type is the undular hydraulic jump caused by the submerge weir at the bottom of the channel, such as the groin in a river.

The purpose and the objective of this present research was to make observations and analysis of the characteristics of undular hydraulic jump at the downstream of the sluice gate, which is to look for the lower limit value (Fr_1) and the upper limit of Froude number (Fr_{1limit}) that cause an undular hydraulic jump and also the velocity distribution and flow characteristics at the bottom of the channel that occurs in undular hydraulic jump.

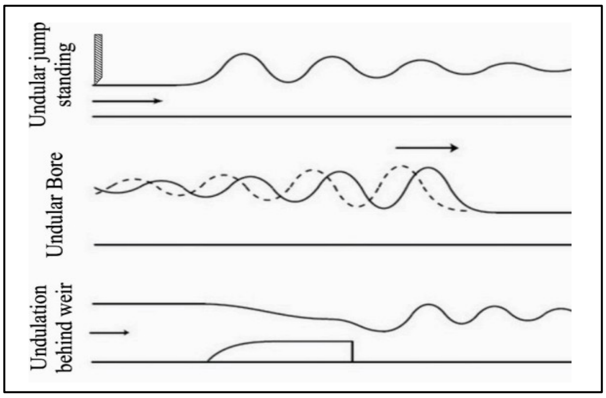

Figure 1. Sketch of undular hydraulic jump

LITERATURE REVIEW

Undular hydraulic jump is a series of steady free surface waves that causes jump in downstream areas. Undular hydraulic jump have Froude numbers 1 to 1.7 (Chow, VT, 1985). Further, the hydraulic conditions to form an undular hydraulic jump in flow under a sluice gate can be predicted by using hydraulic formulations at the vena contracta and the toe of the jump location (Ohtsu et al, 2001). An Undular hydraulic jump can affect a distribution channel and irrigation during the period of tides in estuaries and in the rapid flow that has a low depth. When this undular hydraulic jump come into the channel, waves with large periods will cause a jump in downstream areas. Waves can cause runoff (over-topping) and damage to the banks of the channel (Chanson and Montes, 1995).

Froude number (*Fr*) is a dimensionless number that states the characteristics of flow in a transverse (cross-sectional flow characteristic) which shows the ratio of inertial forces with the force of gravity. Froude number can be obtained by the following formula:

$$Fr = \frac{U}{\sqrt{gy}} \quad (1)$$

Conjugate Depth

Conjugate depth formulations of undular hydraulic jump can be written as:

$$\frac{y_3}{y_1} = \frac{1}{2}\left(\sqrt{1+8Fr_1^2}-1\right) \quad (2)$$

Energy loss of undular hydraulic jump

Loss of energy (energy dissipation) is the energy difference between the specific energy before and after the jump. The amount of energy loss that occurs in a hydraulic jump can be written as:

$$\Delta E = E_1 - E_3 \quad (3)$$

By doing a mathematical operation, Equation 3 above becomes

$$\Delta E = E_1 - E_3 = \frac{(y_3 - y_1)^3}{4 y_1 y_3} \quad (4)$$

Velocity distribution and gradient of flow velocity

Velocity distribution is uneven at every point. Distribution of vertical velocity can be known by measuring the vertical direction at various depths. The gradient of flow velocity studied based on the velocity distribution with the formula as follows:

$$m_u = \frac{du_z}{dz} \quad (5)$$

Determination of surface profile of a hydraulic jump will help us in designing of the free board or retaining walls of a stilling basin where stepping occurred. In addition, knowing the surface of a hydraulic jump will also help us to estimate the amount of pressure at the channels bed.

RESEARCH METHOD

Equipment

Research carried out by using the facilities of prismatic standard tilting flume with acrylic base material on the walls and aluminum on the bottom. This channel has a width (B) 30 cm, length (L) 1000 cm, and height 50 cm with a channel wall thickness is 10 mm. Bottom slope of this channel can be set manually with a range of channel bed slope +1% and -1%.

Sluice gate that was used is an Armfield brand vertical sluice gate that has material specification of steel with dimensions of width 30 cm, height 45 cm, the maximum aperture (a) 15 cm and a minimum aperture (a) 0 cm. Velocity measurements using a current meter Nixon Streamflo type 422 with a brand of Armfield. Point gauge used to measure the depth of flow and is also used to measure and control the high flow to ensure that the flow is uniform. This present study is using water pump as a regulator of the circulation flow. Discharge used around 7 l/s to 30 l/2 with 10 experimental models.

Examination Tools

1. Initial examination flume circuit
2. This examination is conducted in the form of checks readiness and condition of the circuit including the pump and flume slope of the channel to match the desired conditions of the study.
3. Examination of velocity measuring devices
4. In this examination, the reading speed is using measuring devices called current meter which is compared with theoretical discharge of direct velocity measurement results.
5. Checking flow rates
6. This examination aims to find out exactly how much discharge is flowing in the channel in the experiment this time.

Implementation of Measurement

In this research, the implementation of the measurement is done by starting to prepare the materials and equipment which necessary. The steps of procedures for the implementation of this research are:

1. After the power switch is turned on and the engine pump is turned on, then we open the water tap to drain water into the channel. Do not forget to check the slope of the channels we happened to order in accordance with the desired in this research.

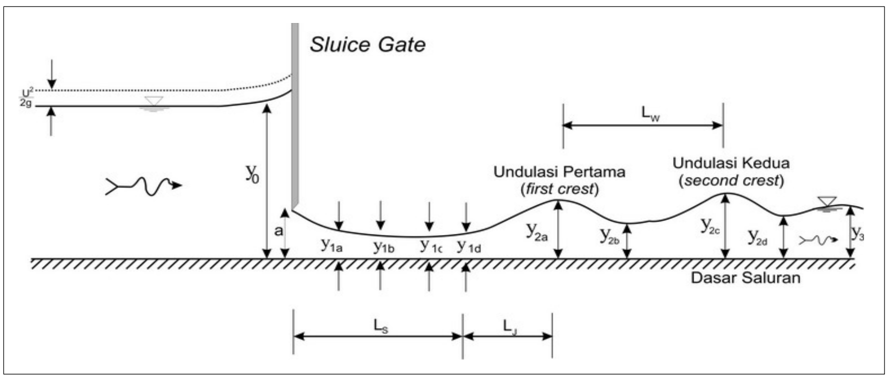

Figure 2. The scheme of depth and distance measurement of an undular hydraulic jump

2. Having monitored the flow is stable, thus we install the sluice gate on the channel. By doing a variation of discharge (Q) and the variation of aperture (a), each experiment was given a name or label for each experiment.
3. For each model, running was done until the model is formed an undular hydraulic jump.
4. Water surface elevation in both the upstream and downstream of the sluice gate were investigated by using point gauge and mica ruler attached to the channel wall.
5. Vertical velocities were measured for each respective model running. This measurement is done in 10 point depth of flow at various points namely at the beginning of vena contracta, at the beginning of stepping, and at three waves of undular hydraulic jump.

RESULTS AND DISCUSSION

Velocity Profiles

Measurements were taken at the center lain of the channel on the supercritical flow and subcritical flow regions. Velocity measurement results are given in Figure 3 and 4 below. Generally it can be seen that the velocity profile occurring along the undular hydraulic jump formed shows that there is a relationship between Froude number before the jump with the form of the wave that occur.

It shows that the velocity profile at the toe of the jump to give the maximum value is at y/y_{1d} = 0.5 - 0.6. As for the first wave, the wave crest giving a maximum velocity value is at y/y_{2a} = 0.5 - 0.7 and the maximum value for the wave trough is at y/y_{2b} = 0.7 to 0.8. For the data on second wave, the data obtained for the maximum velocity of the first wave is at y/y_{2c} = 0.7 to 0.8, while in the wave tough is at y/y_{2d} = 0.8 to 0.9.

Froude Number

Froude number calculations performed on all models of running are done. Froude number value at the upstream of undular hydraulic jump will determine the type of undular hydraulic jump that occur. This present research has obtained variety value of Froude number. Table 1 shows the lowest Froude number value is on the model Q9A1 Fr_1 = 1.197 and the highest one is on Q3A1 model as Fr_{1limit} = 2.258. These results have a same results of other research obtained by Iwao Ohtsu and Hubert Chanson is the latest research to obtain the highest Froude number value is Fr_{1limit} = 2.3 and = 2.4.

Characteristics of Free Water Surface of Undular Hydraulic Jump

Measurement of the undular hydraulic jump free water surface profile at the centre line of the channel is using measuring instruments called points gauge, and for the canal walls water surface profiles were observed using a mica ruler.

Figure 7 above had been seen that the results of research data showed that the ratio of depth to the depth of critical flow rate is 0.7 to 1.5. This value resembles the results obtained by Chanson in his research.

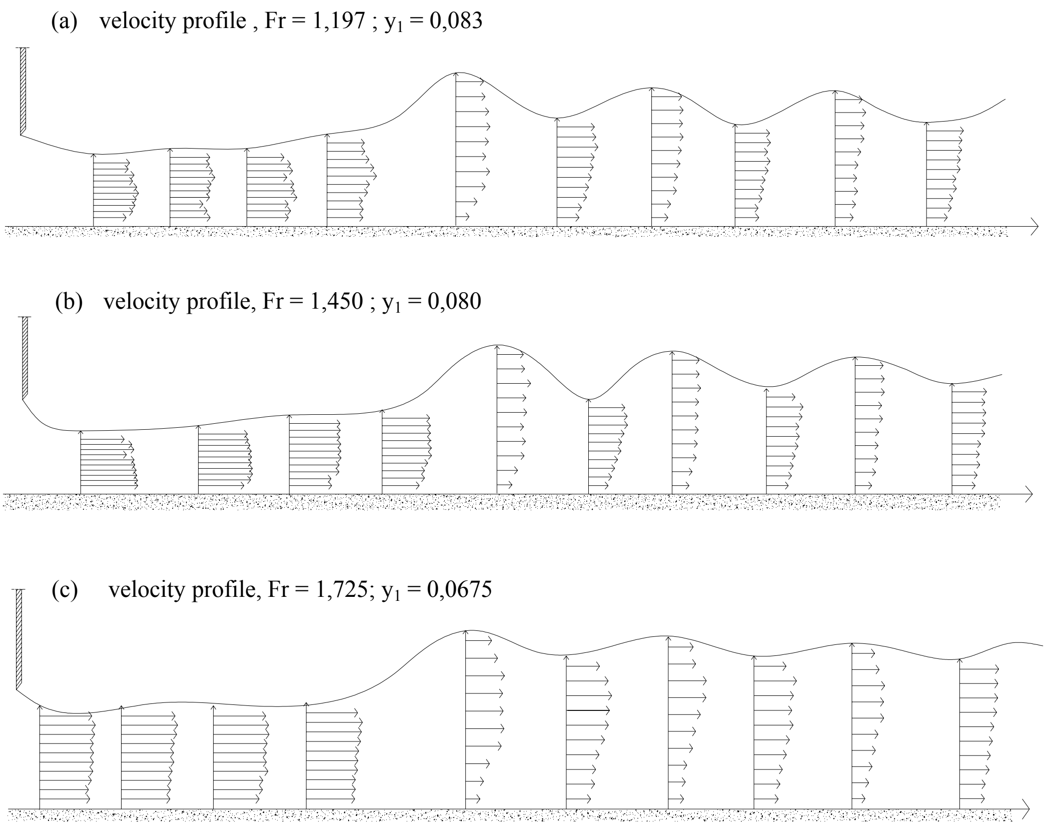

Figure 3. velocity profile of undular hydraulic jump

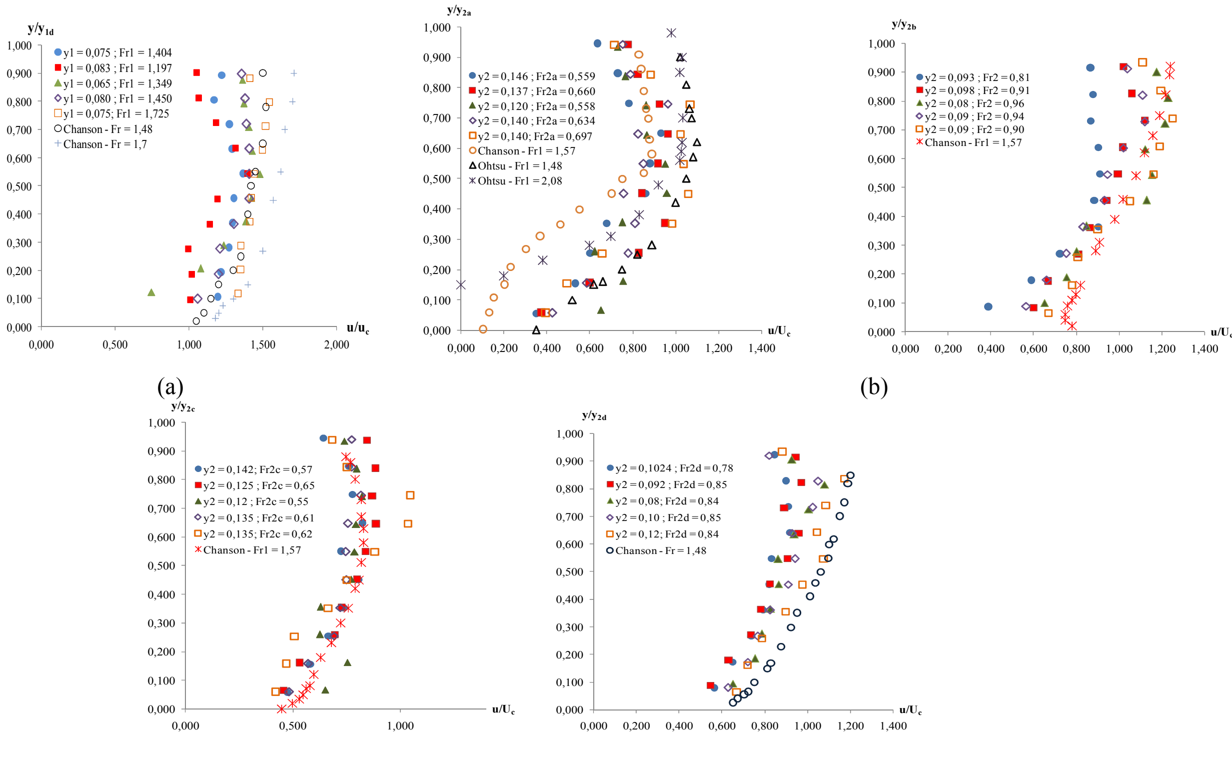

Figure 4. (a) Velocity distribution at the toe of the jump, (b) Velocity distribution at the 1st wave, and (c) Velocity distribution at the 2st wave

Table 1. Calculation of Froude number at the toe of the jump

No	Model	g	y_1	U_1	Fr_1	No	Model	g	y_1	U_1	Fr_1
		(m/d^2)	(m)	(m/d)				(m/d^2)	(m)	(m/d)	
1	Q1A1	9.81	0.0255	1.088	2.175	8	Q8A1	9.81	0.0720	1.220	1.452
2	Q2A1	9.81	0.0340	0.919	1.592	9	Q9A1	9.81	0.0830	1.080	1.197
3	Q3A1	9.81	0.0325	1.275	2.258	10	Q9A2	9.81	0.0750	1.204	1.404
4	Q3A2	9.81	0.0410	0.919	1.449	11	Q10A1	9.81	0.0675	1.404	1.725
5	Q4A1	9.81	0.0525	1.101	1.534	12	Q10A2	9.81	0.0750	1.299	1.514
6	Q5A1	9.81	0.0500	1.197	1.709	13	Q10A3	9.81	0.0800	1.285	1.450
7	Q6A1	9.81	0.0650	1.077	1.349	14	Q10A4	9.81	0.0840	1.178	1.298

Source: data analysis

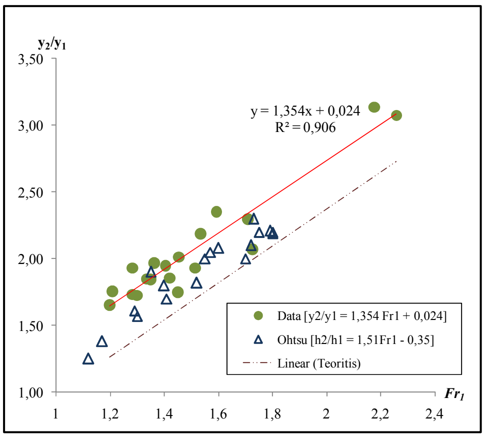

Figure 5. Experimental relationship of Fr_1 with y_2/y_1 for undular hydraulic jump

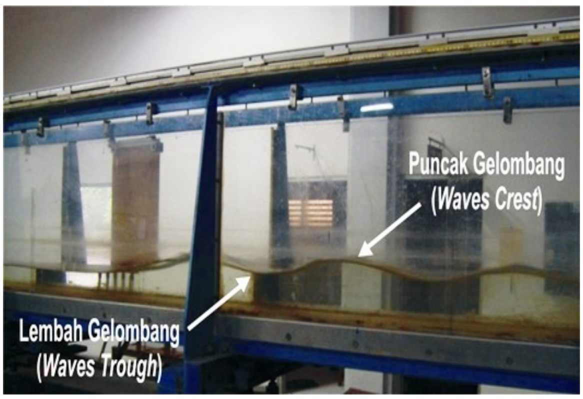

Figure 6. Undular hydraulic jump, $Fr = 1,450$; $y_1 = 0,008$ m

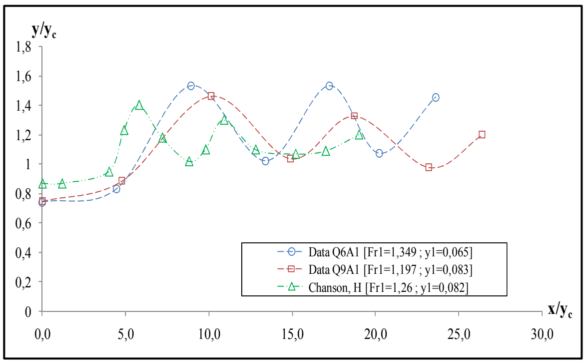

Figure 7. Free water surface profile

Specific Energy and Specific Momentum

In this research, using Equation (3) dan (4) the result of energy loss analysis of the models Q10A3 amounted ΔEs = 0.1953 cm. In general, the values of energy loss that occurs in this research varies for each model, and it ranged ΔE = 0.03 to 1.039 cm or atau 0,297% - 10,276%. In addition, from analysis of all experimental models in this research, the researcher obtained value α = 0.94 -1.11 and the value β = 0.89 to 1.20

In general, the bed gradient of flow velocity under the wave trough has a greater value than the bed gradient of flow velocity under the wave crest. This significant difference, by the author, is indicated to cause the occurrence or provide the potential for scour on the mobile bed channel.

CONCLUSIONS AND SUGGESTIONS

Conclusion

The conclusions that can be obtained from the research of undular hydraulic jump characteristics at the downstream of sluice gate are:

1. In general, the maximum velocity at the wave crest is below the surface while in the wave trough is on the surface flow.
2. For Froude number value, the lowest values obtained on running the model Q9A1 is Fr1= 1.197 and highest value in model Q3A1 is Fr1limit = 2.258.
3. This undular hydraulic jump is also has a loss of energy ΔE = 0.03 to 1.039 cm or 0,297% - 10,276%. The value of energy coefficient is (α) = 0.94 -1.11 and the coefficient value of force / momentum (β) is = 0.89 to 1.20.
4. There is a difference in significant value of bed gradient of flow velocity between the under of the wave crest with the under of wave trough. This difference is potentially caused scour beneath the wave trough in a mobile bed channel.

Suggestion

It is recommended to perform measurements with the ADV instrument side-looking and doing research with a mobile bed channel.

REFERENCES

Chanson, H., and Montes, J.S. (1995). "Characteristics of Undular Hydraulic Jumps. Experimental Apparatus and Flow Patterns." *Journal of Hyd. Eng., ASCE*, Vol. 121, No. 2, pp. 129-144

Chow, V.T. (1985). *Open Channel Hydraulics (translation)*, Erlangga, Jakarta.

Montes, J.S., and Chanson, H. (1998). "Characteristics of Undular Hydraulic Jumps. Results and Calculations." *Journal of Hyd. Eng.*, ASCE, Vol. 124, No. 2, pp. 192-205.

Ohtsu, I., Yasuda, Y., and Gotoh, H. (2001). "Hydraulic Condition for Undular-Jump Formations." *Journal of Hyd. Res., IAHR*, Vol. 39, No. 2, pp. 203-209.

Raju, K.G.R., (1986). *Flow Through Open Channels (translation)*, Erlangga, Jakarta.

Wols, B.A. (2005). "Undular Hydraulic Jump." M.Sc. Thesis, Delft University of Technology, Delft.

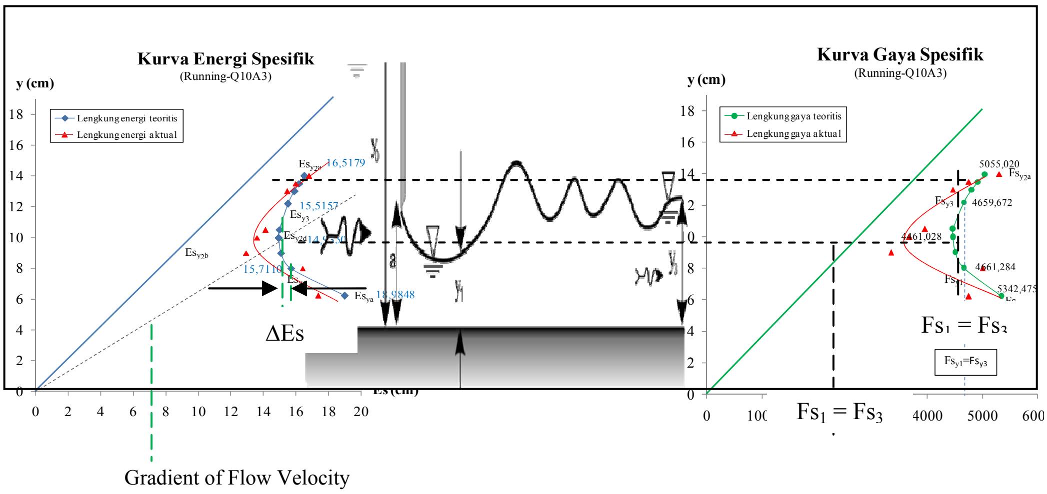

Figure 8. Curve of specific energy and specific momentum at the undular hydraulic jump for model Q10A3

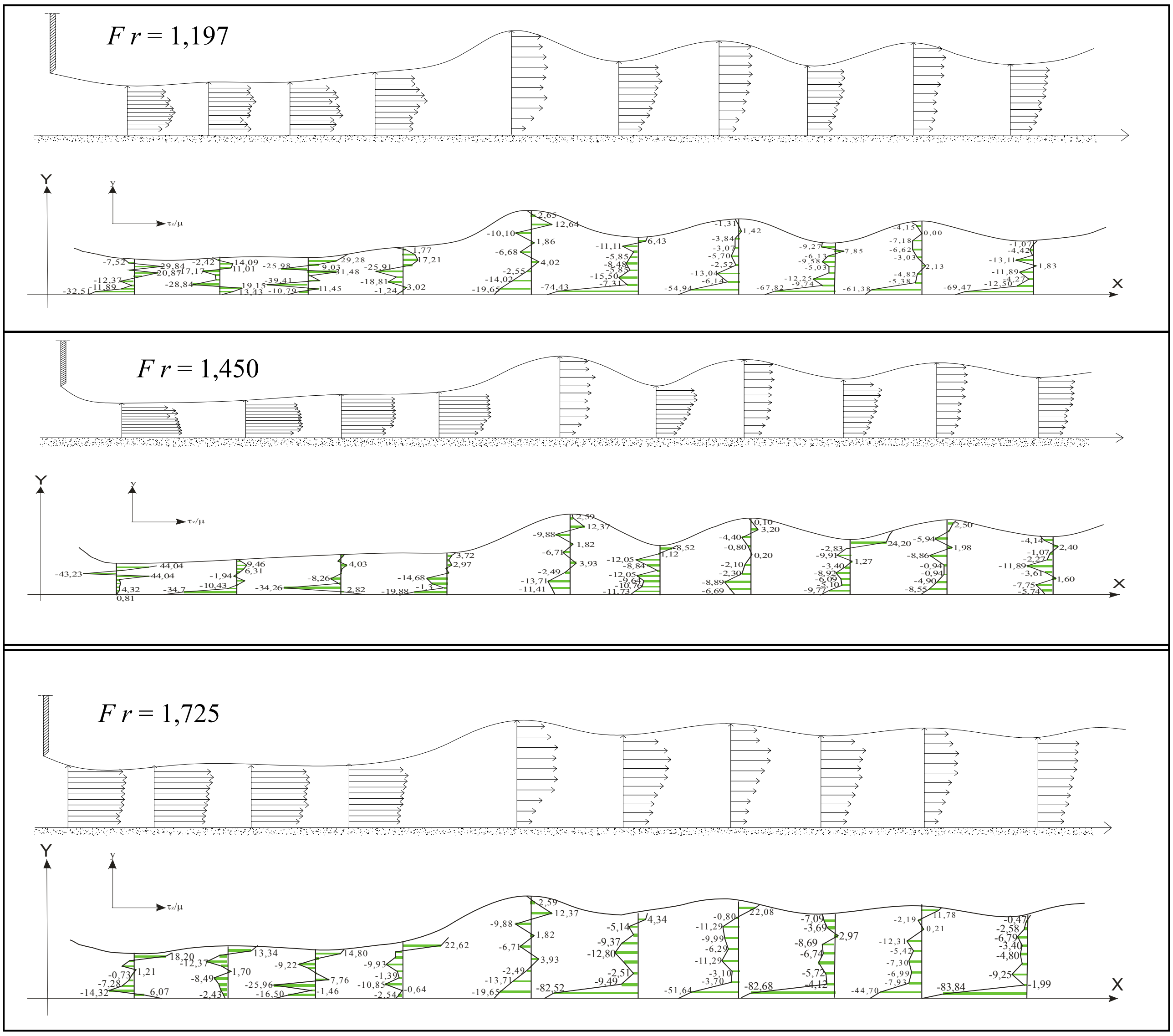

Figure 9. Velocity profile and Gradient of flow velocity profile of undular hydraulic jump

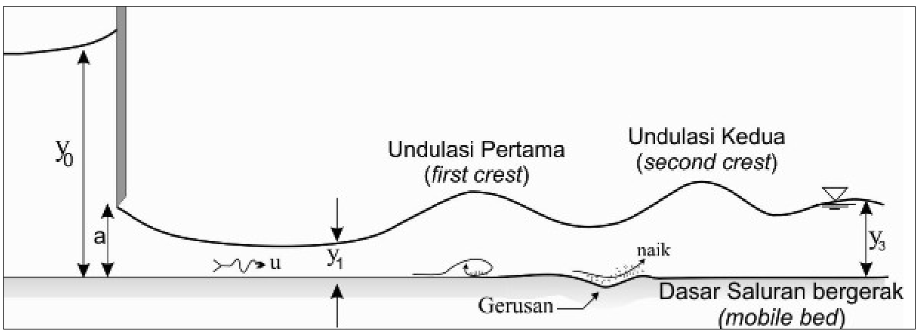

Figure 10. Sketch of scour under the wave trough for a mobile bed channel