A STUDY ON THE HYDRAULIC JUMP CHARACTERISTICS ON THE ISLAND SURFACE

KAJIAN KARAKTERISTIK LONCAT AIR PADA PULAU DI SUNGAI

Agus Maryono
Lecturer, Faculty of Engineering, Gadjah Mada University, Jl. Grafika 2 Yogyakarta, Indonesia.
e-mail: agusmaryono@yahoo.com

Franz Nestmann
Karlsruhe Institute for Technology Germany

ABSTRACT

River restoration projects are being implemented in several developed countries and artificial islands are normally constructed as eco-hydraulic components of river ecosystem. Those artificial islands with non cemented material (natural construction) can be damaged and eroded by hydraulic jump. The hydraulic jump with high velocity and high Froude number (Fr>1) can initiate intensive erosion on the island surface. This research is conducted in Theodor Rechbock Laboratory, University of Karlsruhe, Germany and to understand the characteristic of hydraulic jump over an island. The research focuses on the influence of Froude number (Fr) and relative water depth (y/h_{island}) on the location and type of the hydraulic jumps. The hydraulic jump can arise in the front, behind, above and both sites of island. The research result concludes; that the hydraulic jump occur doe to the direct changing from supercritical to sub critical flow condition over island and the Froude number and relative water depth (Fr and y/h_{pulau}) have significant influence on the type and location of those hydraulic jumps. A diagram expresses the relationship between Fr, (y/h_{pulau}), type and location of hydraulic jump is resulted and can be used to predict the hydraulic jump characteristic over an island in a river by different flow condition and water depth.
Keywords : hydraulic jump, island and river restoration

ABSTRAK

Proyek-proyek restorasi sungai sudah banyak dilakukan di negara-negara maju, dan pulau buatan biasanya dibangun pada proyek tersebut dan dipakai sebagai komponen ekohidraulik dalam ekosistem sungai. Pulau-pulau buatan dengan konstruksi tidak bersemen (konstruksi mendekati alamiah) dapat mengalami kerusakan dan tererosi kerena terjadinya loncat hidraulik (loncat hidraulik). Peristiwa loncat hidraulik dengan kecepat tinggi dan angka Froude tinggi (Fr>1) dapat menginisisasi terjadinya erosi pada permukaan konstruksi pulau buatan tersebut. Penelitian ini dilakukan untuk mengetahui karakteristik loncat hidraulik melewati suatu pulau. Fokus penelitian ini adalah pada pengaruh angka Froude (Fr) and kedalaman relatif aliran (y/h_{pulau}) terhadap tipe dan lokasi loncat hidraulik. Loncat hidraulik dapat terjadi di depan, di belakang, di atas dan di kedua sisi sebuah pualu. Hasil penelitian ini menyimpulkan bahwa: terjadinya loncat hidraulik pada pulau dikarenakan adanya perubahan langsung dari aliran super kritis menuju aliran sub kritis saat aliran melewati pulau; angka Fraoud (Fr) dan kedalaman aliran relatif (y/h_{pulau}) mempunyai pengaruh signifikan terhadap tipe dan lokasi loncat hidraulik. Penelitian ini juga menghasilkan sebuah diagram yang menggambarkan hubungan antara Fr, (y/h_{pulau}), tipe dan lokasi loncat hidraulik yang dapat digunakan untuk memprediksi karakteristik loncat hidraulik melewati pulau dengan variasi kondisi dan kedalaman aliran.
Kata kunci : loncat hidraulik, pulau, restorasi sungai

INTRODUCTION

River restoration projects are being implemented in several developed countries and artificial islands are normally constructed as eco-hydraulic components of river ecosystem, such as river restoration in Enz River, Stuttgart, Germany (Dittrich, 1998). Those artificial islands with non cemented material can be damaged and eroded by hydraulic jump over islands. Energy loss in form turbulent in the hydraulic jump can initiate intensive erosion (Figure 1).

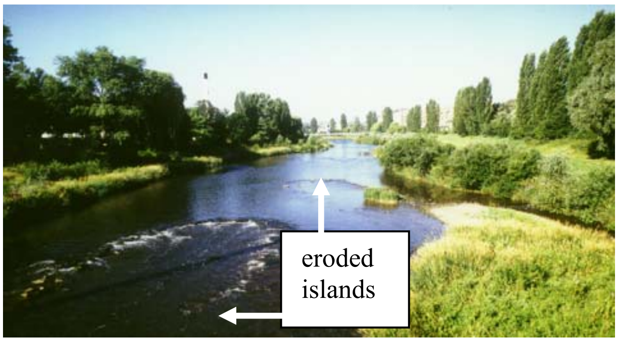

Figure 1. Eroded island (artificial islands) caused by hydraulic jump in 1994 flood even, Enz River, Stuttgart, Germany.

Hydraulic jump researches on rectangular channel, in spillway, abrupt channel with obstruction, etc. are numerous, while researches about hydraulic jump on islands or sandbars are few. Thus the knowledge about that hydraulic jump is necessary to be intensively developed.

This research focuses on how to predict hydraulic jump on an island if the conditions of flow, the inertia force of the flow (Froude number, Fr) and the water depth relative to island high (y/h_{island}) over the island are known. The value variation of Fr and y/h_{island} gives the condition; the type and the location of hydraulic jump. The location can be in the front, behind, above and both sites of an island. In addition, there is a condition where in certain value of Fr and (y/h_{island}) the hydraulic jump does not occur.

The result of this research is then presented in a diagram. It is about the relation of the flow characteristics (Fr) and island relative height (y/h_{island}) with the type and location of hydraulic jump. This diagram can be used as basic reference in predicting the hydraulic jump on an (natural/artificial) island. Additionally, the result of this research is expected to help the comprehension understanding about river and island.

THEORETICAL BACKGROUND

Hydraulic jump is the flow change from supercritical flow into sub critical. The geometry of hydraulic jump in an open rectangular channel is characterized by the upstream water depth (y_1), downstream water depth (y_2), and flow velocity (V_1) or in the form of Froude number (Fr) (Rajaratnam, 1965 and Rouse, 1971). The correlation of y_1 and y_2 (conjunctive depth) can be governed from impulse equation with some requirement. They are equal velocity distribution in the channel and the hydrostatic pressure as well as the friction is not considered. The following is the equation of the correlation between y_1 and y_2;

$$\frac{y_2}{y_1} = 0.5(\sqrt{1+8Fr^2} - 1)\,;\; Fr_1 = \frac{V_1}{\sqrt{gy_1}} \qquad (1)$$

While, energy loss (ΔH) caused by hydraulic jump (it creates turbulence and is dangerous for an island and other constructions), can be governed from the energy equation as follow:

$$\Delta H = y_1 . \left[\frac{(\frac{y_2}{y_1} - 1)^3}{4\frac{y_2}{y_1}} \right] \qquad (2)$$

Naudasher, 1999 reviews the results researches about the relation between Froude number ($Fr = V_1/\sqrt{(gy_1)}$), upstream and downstream (y_2/y_1) water depth, the relative length of the hydraulic jump (L/y_2) and the energy loss $\Delta H/y_1$ as presented in the following diagram.

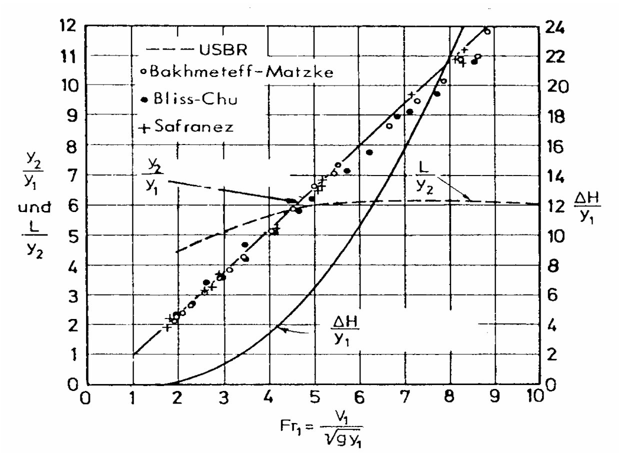

Figure 2. Factors which influence hydraulic jump in rectangular spillway (Naudascher, 1987)

A structure such as ground sill, bar (sand bed) and island in a river can be higher than the water level, it can causes arise on the water level in front of and decrease the water level on above or behind the structure. The water depth in the downstream of the structure tends gradually to normal. The supercritical flow through an island in river can be turned into a sub critical flow. When the flow upstream of the structure is super critical, then the hydraulic jump will occur (figure 4). This hydraulic jump causes turbulence and height energy loss (ΔH), thus cause erosion on the island (Figure 1 and 4).

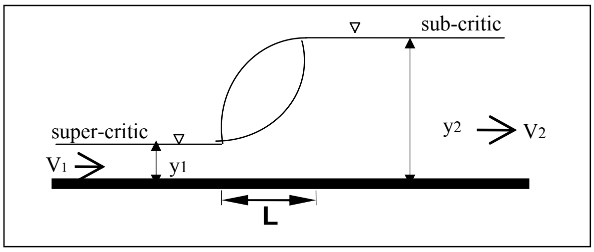

Figure 3. Profile of the hydraulic jump in square open channel (Rajaratnam, 1965)

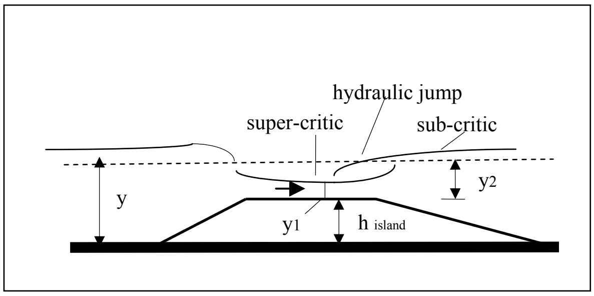

Figure 4: Profile of the hydraulic jump above an island

From Figure 4 (hydraulic jump in an island) shows two important parameters cause the hydraulic jump. There are Fr and relative water depth (y/h_{island}). Furthermore the length and the geometry of the island have effect to the occurrence of the hydraulic jump. The island length will affect the water depth above the island (y_1), whereas the island profile affects the rise of water surface in front of the island.

In this hydraulic jump research, it is investigated the type and location of the hydraulic jump on island starting from the sub-critical flow condition to super-critical flow ($0,15<Fr<1,6$) and the relative surface water depth starting from less than the island height up to exceeding the island ($0,45<y/h_{island}<2,7$). The final result of the research is a diagram shows the relationship between the Fr, y/h_{island}, the location and type of the hydraulic jump over an island with certain size and geometry.

RESEARCH METHOD

The research of hydraulic jump over an island was done in the Theodore Rechbock Hydraulic Laboratory, University of Karlsruhe, Germany using open channel flume with 50 m length, 100 cm wide, and 40 cm depth (Figure 5).

The effect of side wall to the flow can be neglected because the island model width is not more than one third of the channel width. The island model is put on the channel with various declivities. Discharge, depth, and velocity of water flow can be variously made so that various Froude number can be obtained. Water flow with variety of depth and velocity flows through the island model which is set in the middle of the channel. When the water flow is coming pass the island, the rise of water level in front of island will occur as the effect of impounding. The flow is than accelerated above the island. The flow with high speed can turn into a critical flow. It will meet the sub-critical flow at downstream (behind the island). The join between super-critical and sub-critical flow will result a hydraulic jump as shown in Figure 4.

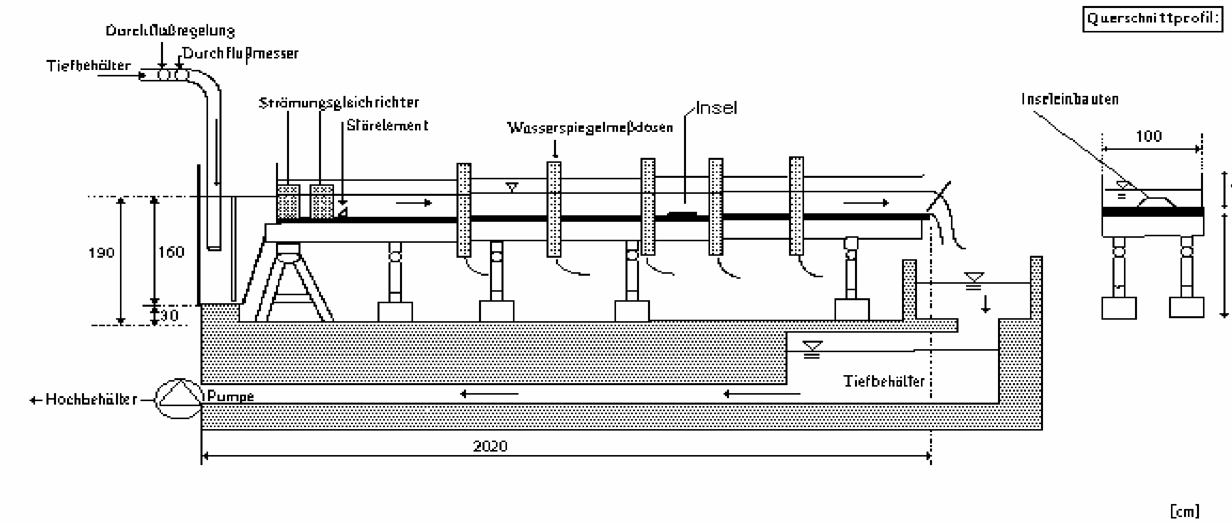

Figure 5. Flume Theodore Rechbock Hydraulic Laboratory, University of Karlsruhe, Germany
(with 50 m length, 100 cm wide, and 40 cm depth)

The Research about the hydraulic jump on an island is begun with the research of flow passes an island. This initial research is important to know the water flow pattern in general around the island. After knowing the water flow pattern, the research of hydraulic jump is done. The investigation of the hydraulic jump on the island is done intensively in the front part, middle part, back part, and as well as in the side part of island. It is done because the hydraulic jump may happen in the front above part, back above part, and in the downstream of the island. The downstream hydraulic jump is the resultant of two supercritical flows from both sides of the island.

The island model being used is an island with stream line geometry (Modi, 1995) from PVC material (Figure 6). The island geometry of stream line is mostly found in natural rivers (Leopold, 1964, Kellerhal at al., 1979). In this research, the change of the island geometry as the result of flow erosion is excluded because the island model is massive and made from PVC.

In the research of the effect of island length toward the hydraulic jump, the same model (Figure 6) is used, by adding the length of the island in the middle part (Figure 7). So that, the relative island length toward island wide can be made variously.

The flow condition being used is steady flow and subcritical to super-critical flow with various number of Fr and y/h_{island}. The research begins with the smallest Fr number, 0.15 up to the biggest 1.6. Each flow condition with certain Fr number is next done with a relative water depth (y/h_{island}) change from 0.6 up to 2.7. The various relative water depth and Froude number are created by changing the water discharge in accordance with analytical calculation and the channel slope adjustment so that the expected water depth and Froude number is obtained.

Some variety conditions between Fr and y/h_{island} were not done, since the result of the data plotting (into the diagram of relationship Fr, y/h_{island}) shows that result is similar to other variations which get close to.. For example, by Fr = 1.6 and y/h_{island} = 0.6 there is no hydraulic jump occurs, so logically the experiment with y/h_{island} > 0.6 is not done because it can be ensured that there is no hydraulic jump. That happens also to Fr = 0.37. The research is not done with y/h_{island} > 1.15 because the result will get close to the condition of Fr = 0.35.

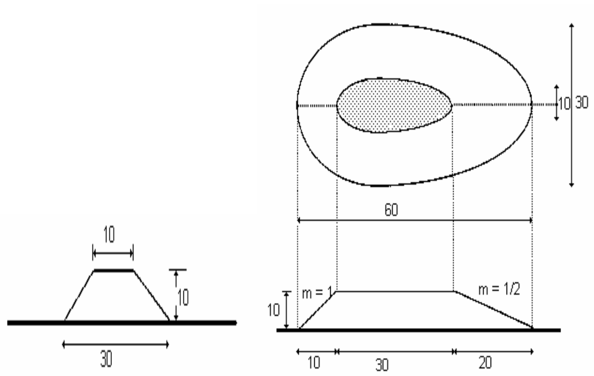

Figure 6. Island model (in cm), Modi, 1985.

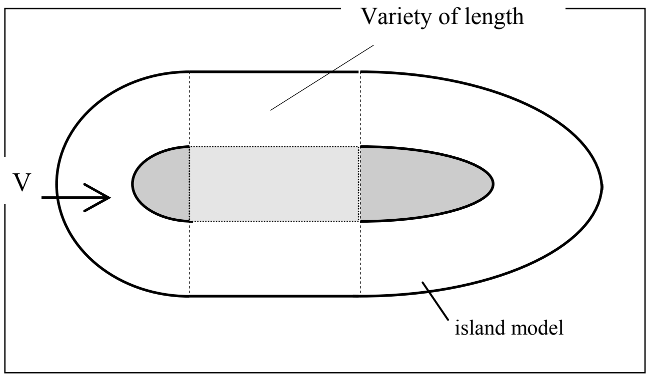

Figure 7. Method to create the variety of island length

Table 1. Research variety (Fr and $y/_{island}$) (42 varieties of Research)

Fr	**y/h_{island}**	**y/h_{island}**	**y/h_{island}**	**y/h_{island}**	**y/h_{island}**	**y/h_{island}**	**y/h_{island}**
0.15	0.68	1.2	1.6	1.8	2	2.5	2.7
0.28	0.45	0.68	0.78				
0.3	0.80	0.9	1.2	1.6	2	2.5	2.7
0.35	1,00	1.08	1.1				
0.37	1.15						
0.45	0.80	1.8	2	2.2	2.4		
0.55	0.90						
0.6	0.60	0.8	1	2.4			
0.7	0.90						
0.75	0.80	2.4	2.5				
0.9	0.70	2.4					
1	0.60						
1.2	0.60						
1.4	0.60						
1.5	-						
1.6	0.60						

The result of the investigation is analyzed and the location and the type of the hydraulic jump (normal hydraulic jump, unshaped hydraulic jump because the inertia force leads to downstream "sweeping out condition" and also the condition that the hydraulic jump is not occur) with various Fr and y/h_{island} are registered. The occurrences are next plotted into a diagram with Fr as an axis, y/h_{island} as an ordinate and inside the diagram there is an explanation of type and location of the hydraulic jump (Figure 8).

The research about the effect of island length upon hydraulic jump is done by extending the body of the island (Figure 6). The island relative length (l), toward the width (d) being examined is l/d = 3, 4, 5, and 6 with y/h_{island} = 0.9 and 1.6. The effect toward the hydraulic jump is examined qualitatively so that only a common rule of hydraulic jump in on island is achieved with variety of island length.

Hypothesis of this research is: the location and type of the hydraulic jump on an island can be predicted with a diagram relationship between Fr and y/h_{island} (see Figure 8).

RESULT AND DISCUSSION

The qualitative research of the flow pattern, the water level changing and the hydraulic jump through an island is conducted first. This initial research is important to know the change of flow pattern in general that happens around the island models. After knowing the water flow pattern, then the qualitative investigation of hydraulic jump is done.

There are several hydraulic jump conditions as follow; hydraulic jump above an island; (h.j,a.i), hydraulic jump behind an island (h.j.b.i) and hydraulic jump caused by the both sides of flow over island (h.j.s.f). Besides, there is *sweeping out* (s.o) condition, where the hydraulic jump initially appears over an island then pushed behind so the intensity weakened and change into water surface waves. The condition where there is no hydraulic jump (n.h.j) generally when the water surface is quite lower than the island height and the water surface is quite higher than the island. The Figure below shows the location and the types of the hydraulic jump happened on the island model.

Froude number (Fr) and relative water level (y/h_{island}) determine the type and the location of the hydraulic jump. Diagram in Figure 9 shows the location and the type of the hydraulic jump with various Froude number and relative water level condition. With this diagram it is possible to predict where and which type of the hydraulic jump will happen if the Fr flow y/h_{island} are known. As example in the condition of Fr = 0,45 and y/h_{island} = 1,2 to 1,7 there will be an hydraulic jump above an island (h.j.a.i). By raising the water level (y/h_{island}> 1,7), so there is no hydraulic jump happens. However, by raising the Fr to 0,75 and 1,2 < y/h_{island}< 1,7 there is hydraulic jump behind he island (h.j.b.i.). On the condition y/h_{island}>1,7 and Fr > 0,75 hydraulic jump did not happen, but there is often *sweeping out* (s.o.). Although with a high Fr (Fr > 0,75) and the water level is raised to y/h_{island}= 0,8, so there will be an hydraulic jump as the result of the two sides flow (h.j.s.f) (Figure 9).

Based on the laboratory observation, the relative island length factor influences the type and the location of the hydraulic jump. To know the influence on the hydraulic jump the research is conducted with the island model which is lengthened in the middle part. The comparison of the length and the width of those islands is l/d = 3, 4, 5 and 6. The flow is on the sub critical condition with Fr = 0,45 (low Froude number) and Fr = 0,9 (high Froude number). The relative water depth y/h_{Island}= 1,6 where the water depth exceed the island depth. The water depth condition less than the island depth is not investigated because there is no hydraulic jump over that island.

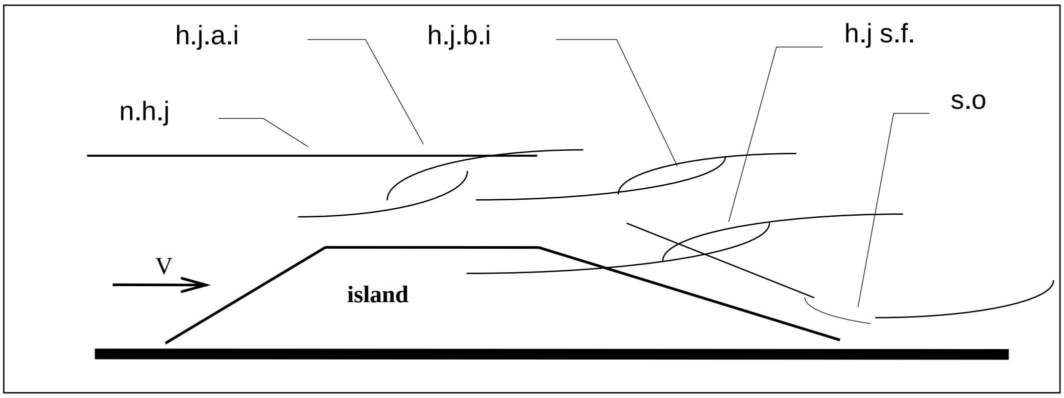

Figure 8. The hydraulic jump location over an island (h.j,a.i = hydraulic jump above an island, h.j.b.i = hydraulic jump behind an island, h.j.s.f = hydraulic jump as the result of beside flow, n.h.j. = no hydraulic jump, s.o. = sweeping out condition)

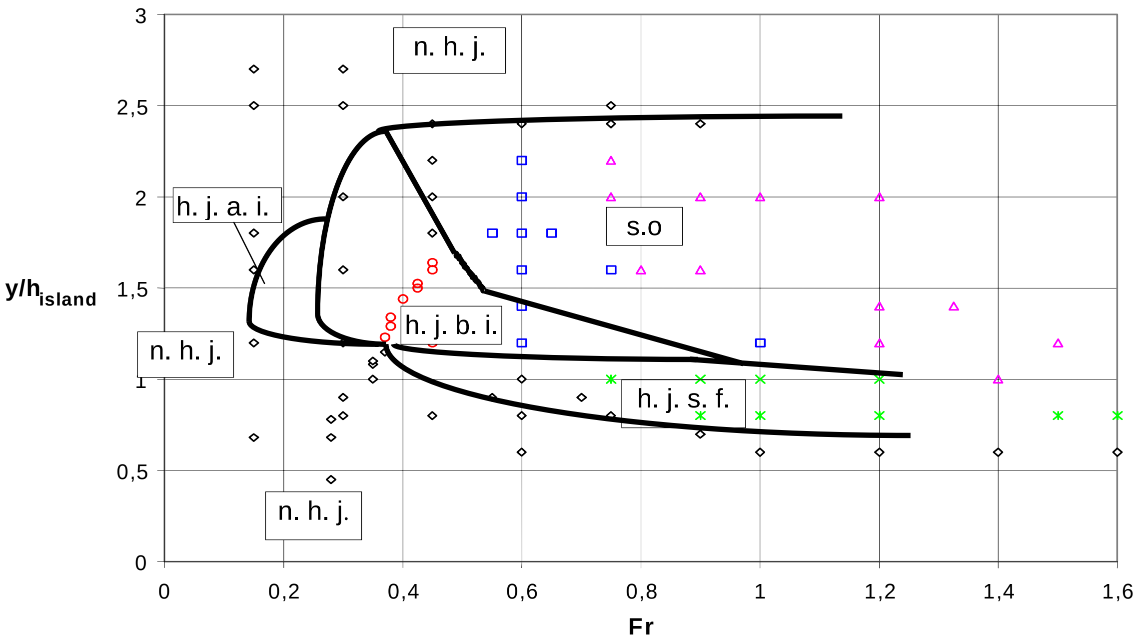

Figure 9. A diagram to determine the type and the location of the hydraulic jump. It will be applicable for initial/natural islands which geometrically are similar to the island model used in this research (Figure5).

The influence of the island length towards the hydraulic jump is significant. As an example with Fr = 0,9 (high Froude number) and $y/_{h\ island}$= 1,6 and l/d = 3 und 4 there is no hydraulic jump, but the hydraulic jump will happen if the island length l/d = 5 and 6. Another example is in the condition Fr = 0,45 (low Froude number) and y/h_{Island}= 1,6 and p/d = 3 und 4 the hydraulic jump happens while in l/d = 5 und 6 it does not happen. From this research, generally there is a classification; if the surface water wave is on the behind the island there will be an hydraulic jump (in this case is the flow over a supercritical island with Fr>1 and behind the flow is sub-critic Fr<1). If the water surface wave in the front part of the island and the wave top is behind the island, there is no hydraulic jump (in this case the top wave and the water level height almost the same, so it does not result hydraulic water). From the analysis of the water surface wave, it can be concluded that the longer the island, the smaller the possibility of the hydraulic jump happens. This can be explained that by the increase of the island length, the speed of the water flow over an island becomes weaken until reach the sub critical flow. The hydraulic jump will happen only if the flow velocity over an island is supercritical (Fr>1) to the condition of the flow behind the island with sub-critical flow (Fr<1).

CONCLUSION AND SUGGESTION

1. Froude number and the relative water surface towards the island height is the significant factor of the hydraulic jump over an island.
2. Diagram in Figure 8 can be used as the base reference to determine the type and the location of the hydraulic jump over an island with *stream line* form..
3. The influence of the island length is significant on the type

and location of the hydraulic jump..

4. It is needed to conduct a further research to complete the diagram of the type and the location of the hydraulic jump over an island (Figure 9), by using other factors such as island geometry and island surface roughness, etc.

REFFERENCES

Dittrich, A., 1998, *Wechselwirkung Morphologie/Strömung naturenaher Fliessgewässer* (Pengaruh Timbal Balik Morp*hologi Sungai dan Aliran Air pada Sungai yang Mendekati Alamiah)*, "Mitteilung" from "Institut für Wasserwirtschaft und Kulturtechnik der Universität Karlsruhe", Heft 198.

Kellerhals R., et al., 1976, Classification and analysis of river processes, *Journal of Hydraulic Division*, ASCE, Vol. 102, No. HY7, pp. 813-829.

Leopold, L. B. et al., 1964, *Fluvial processes in geomorphology*, W.H. Freeman and Company, San Francisco, London

Modi, P. N., 1995, *Irrigation water resources and water power engineering*, 3rd Edition, Standard Book House, Nai Sarak, Delhi, Indien.

Naudascher, E. 1987, *Hidraulik der Gerinne und Gerinnebauwerk*, Springer Verlag, Wina, Austria.

Rajaratnam, N. ,1965, Profile of Hydraulic Jump, *Journal of Hydraulics Division* ASCE, Vol. 94, pp. 663-664.

Rouse, H., 1971, *The role of the Froude number in open chan-nel resistance*, Hydraulic, Mechanics of Fluids, Engineering Education', Dover Publication , Inc. New York.