Hydraulic jump simulation with Mike 11

River system modelling

Shaoxu Zheng (1064735), Water Science & Engineering (HI), IHE-Delft, Institute for Water Education, Delft, the Netherlands.

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Model design

Hydraulic jump concept

A hydraulic jump mainly works as an energy dissipating method to decrease the extra energy of downstream flow of hydraulic building, for example sluice gate and dam. The hydraulic jump occurs when the flow transits from supercritical to subcritical. The upstream flow goes up to connect with its alternative depth.

In order to form such a hydraulic phenomenon, the boundary shape of a local channel must changes sharply to cause a flow pattern change. In the channel model, there are mainly three methods, namely plane bending, section change and friction change. This corresponds to the changes in slope, width and Manning Coefficient in the mathematical expressions. Here we do not discuss the change in Manning Coefficient, since it is hard to achieve in the real channels.

Target image

Initially, the water surface line was between norm depth and critical depth, and then it happens a submerged jump. Viewed the image, the flow profile changes occur before the channel changing point, connecting with S1 curve on the slope.

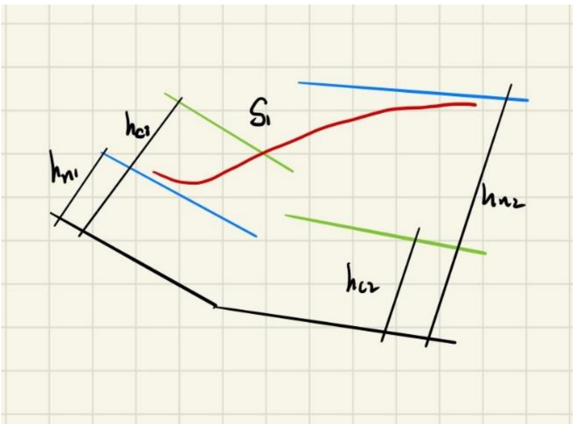

Figure 1. The sketch

According to speculation, the following relationship exists:

$$h_{n1} < h_{c1} < h_{c2} < h_{n2} \quad (1)$$

I apply the upstream Froude number as the distribution method, which is divided into three schemes: $1 < Fr < 1.7$, $4.5 < Fr < 9.0$, $Fr > 9.0$.

Case 1--1 < Fr < 1.7, Undular jump

Dataset

Table 1. Cross section data

Chainage	Width (m)	Height (m)	Datum (m)
0	200	8	5.25
2500	200	8	0.25
2501	20	12	0.25
5000	20	12	0

Table 2. Boundaries and parameters

Key	Value
Upstream condition	Inflow: 500m^3/s
Downstream condition	Rating curve
Initial condition	Depth: 0.705m; Discharge:500m^3/s
Bed resist	Manning coefficient : 0.01

Before plotting, we calculate the depth of the two channel parts.

The critical depth of two parts:

$$\mathrm{h}_{c1} = (\frac{Q^2}{gB^2})^{\frac{1}{3}} = (\frac{500^2}{9.8 \times 200^2})^{\frac{1}{3}} = 0.85m \tag{2}$$

$$\mathrm{h}_{c2} = (\frac{Q^2}{gB^2})^{\frac{1}{3}} = (\frac{500^2}{9.8 \times 20^2})^{\frac{1}{3}} = 4.00m \tag{3}$$

The normal depth of two parts:

$$\mathrm{h}_{n1} = (\frac{nQ}{B\sqrt{S_0}})^{\frac{3}{5}} = (\frac{0.01 \times 500}{200 \times \sqrt{0.002}})^{\frac{3}{5}} = 0.71\mathrm{m} \tag{4}$$

When the width and height are close, we cannot apply the above formula. Replaced by the rating curve, h_{n2}= 9 m

To sum up, this case meets inequality requirements, $\mathrm{h}_{n1} < \mathrm{h}_{c1} < \mathrm{h}_{c2} < \mathrm{h}_{n2}$.

Result and analysis

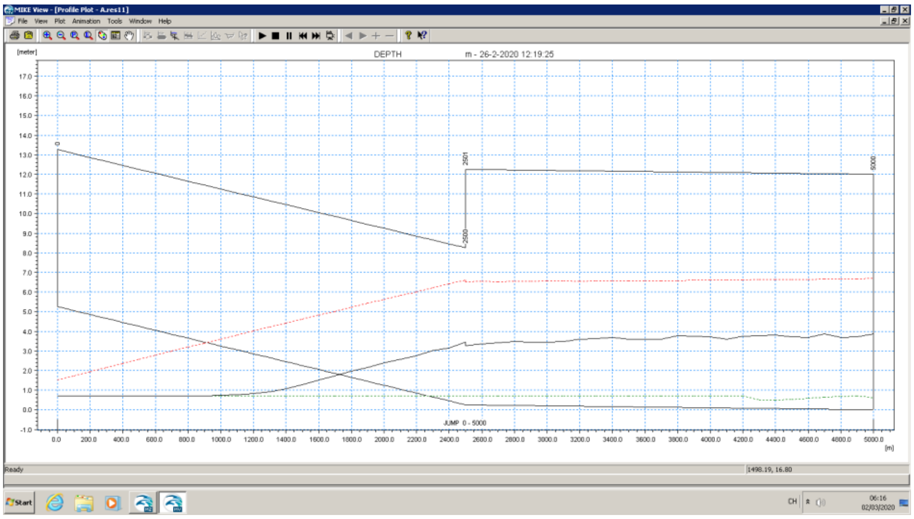

Figure 2. The intermediate profile

This is a diagram of the intermediate process of hydraulic jump. It can be seen that the water level change occurs before 2500m, the channel changing point. This can be called submerged jump. What's more, this phenomenon spreads upstream until it disappears. Model depth will eventually stabilize near the red line. Below we will calculate the Froude number at the jump beginning point and the value of the final state point upstream. For the jump beginning point:

$$\mathrm{F}_{r1} = \frac{V}{\sqrt{gD}} = \frac{Q}{(B \times D) \times \sqrt{gD}} = \frac{500}{(200 \times 0.705) \times \sqrt{9.8 \times 0.705}} = 1.34 \tag{5}$$

This belongs to undular jump. For the final state point upstream:

$$\mathrm{F}_{r} = \frac{Q}{(B \times D) \times \sqrt{gD}} = \frac{500}{(200 \times 3.7) \times \sqrt{9.8 \times 3.7}} = 0.11 \tag{6}$$

This means that all points upstream are higher than critical depth and at subcritical state. The following will draw profile figures of depth and discharge. Each time the left and right borders and midpoints are selected as the research object.

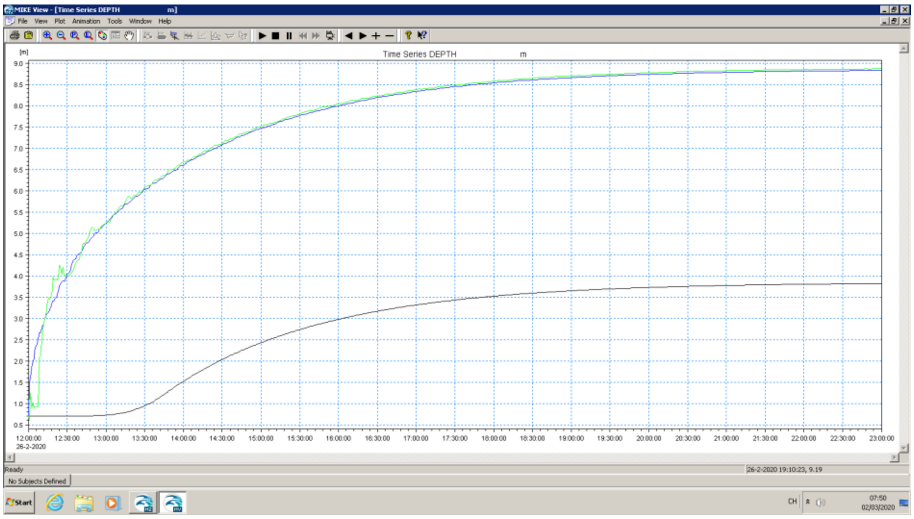

Figure 3. The figure of depth

Among them, the green line is the critical point, and it fluctuates at the initial moment. This is the phenomenon of hydraulic jump. It is not difficult to observe that the profile of the dots behind the critical point has remained almost the same. For the left border point, it keeps normal depth firs, and then goes up until a certain level. The depth is above the critical depth line is called S1 profile.

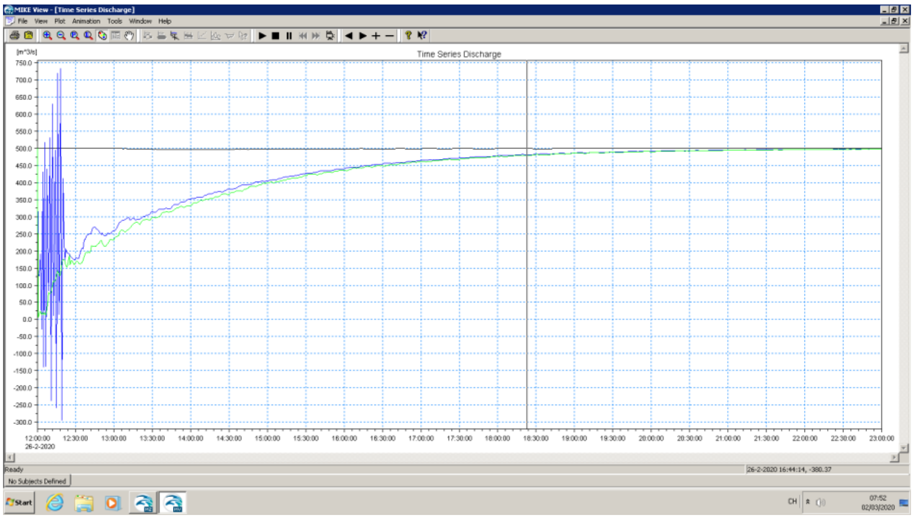

Figure 4. The figure of discharge

The blue curve is the discharge change curve at the critical point. It indicates that the initial jitter is more severe. This is because the water jump occurs on the one hand, and the initial value is disturbed on the other hand when the model checks the process. After a long period of movement, all points in the channel will become Q=500 m^3/s.

For undular jump, the shock is not very obvious, which means low dissipation.

Case 2. 4.5 <Fr <9.0, Stable, well balanced, steady jump

Dataset

Table 3. Cross section data

Chainage	Width (m)	Height (m)	Datum (m)
0	200	8	5.25
2500	200	8	0.25
2501	6	12	0.25
5000	6	12	0

Table 4. Boundaries and parameters

Key	Value
Upstream condition	Inflow: 500m^3/s
Downstream condition	Rating curve
Initial condition	Depth: 0.307m; Discharge:500m^3/s
Bed resist	Manning coefficient : 0.0025

Before plotting, we calculate the depth of the two channel parts.

The critical depth of two parts:

$$\mathrm{h}_{c1} = (\frac{Q^2}{gB^2})^{\frac{1}{3}} = (\frac{500^2}{9.8 \times 200^2})^{\frac{1}{3}} = 0.85m \tag{7}$$

$$\mathrm{h}_{c2} = (\frac{Q^2}{gB^2})^{\frac{1}{3}} = (\frac{500^2}{9.8 \times 6^2})^{\frac{1}{3}} = 8.92m \tag{8}$$

The normal depth of two parts:

$$\mathrm{h}_{n1} = (\frac{nQ}{B\sqrt{S_0}})^{\frac{3}{5}} = (\frac{0.0025 \times 500}{200 \times \sqrt{0.002}})^{\frac{3}{5}} = 0.31\mathrm{m} \tag{9}$$

When the width and height are close, we cannot apply the above formula. Replaced by the rating curve, h_{n2}= 11.70 m

To sum up, this case meets inequality requirements, $\mathrm{h}_{n1} < \mathrm{h}_{c1} < \mathrm{h}_{c2} < \mathrm{h}_{n2}$.

Result and analysis

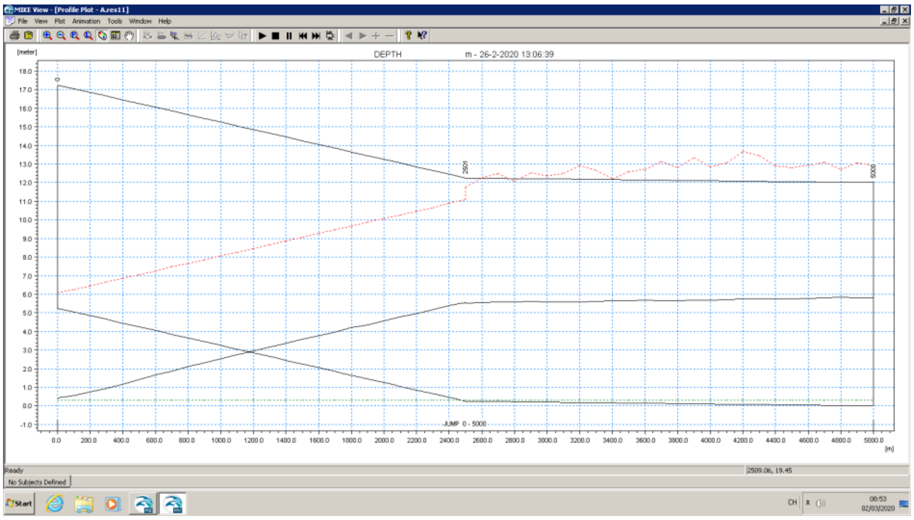

Figure 5. The intermediate profile

This is a diagram of the intermediate process of hydraulic jump. The water level behind of the critical point becomes more jittery with time, while the position of the water jump continues to propagate upstream (submerged jump). Below we will calculate the Froude number at the jump beginning point and the value of the final state point upstream. For the jump beginning point:

$$\mathrm{F}_{r1} = \frac{V}{\sqrt{gD}} = \frac{Q}{(B \times D) \times \sqrt{gD}} = \frac{500}{(200 \times 0.307) \times \sqrt{9.8 \times 0.307}} = 4.69 \tag{10}$$

This belongs to stable, well-balanced, steady jump. For the final state point upstream:

$$\mathrm{F}_{r} = \frac{Q}{(B \times D) \times \sqrt{gD}} = \frac{500}{(200 \times 6.0) \times \sqrt{9.8 \times 6.0}} = 0.05 \tag{11}$$

This means that all points upstream are higher than critical depth and at subcritical state. The following will draw profile figures of depth and discharge. Each time the left and right borders and midpoints are selected as the research object.

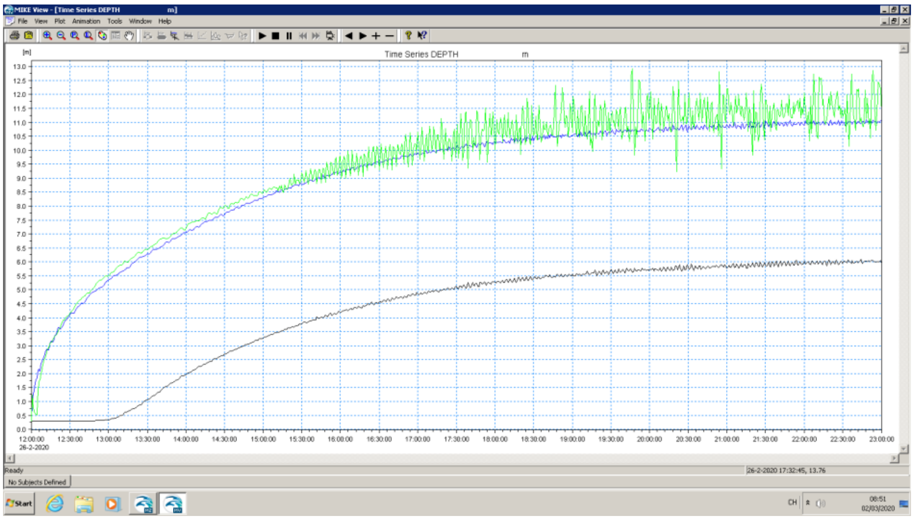

Figure 6. The figure of depth

The curve trend of Case 2 is the same as that of Case 1, but the curve irregularly is more prominent. This is the phenomenon of non-stop swinging water. For a long period of time, the whole profile is basically unchanged, except for jitter near the profile.

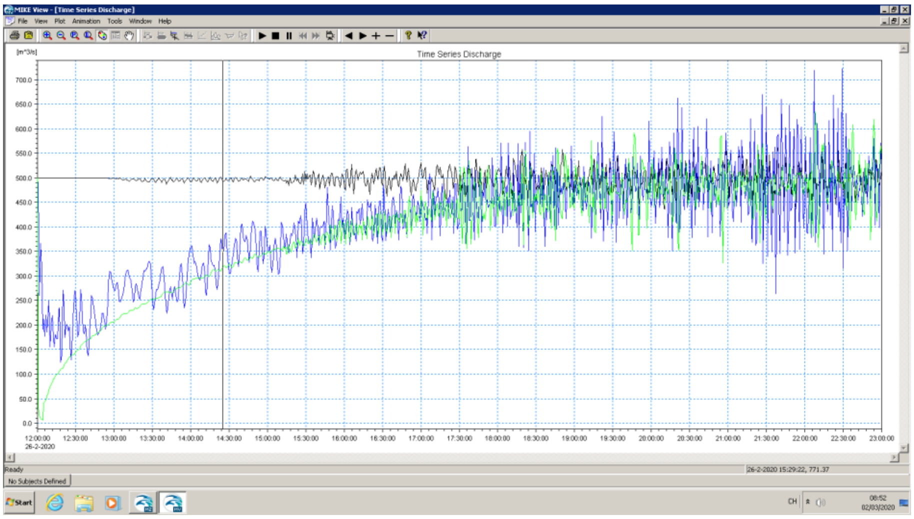

Figure 7. The figure of discharge

The same happens in the discharge figure. For a long period of time, the discharge is all the same value 500 m^3/s with inevitable jitter. Through observation, it was found that shock was more concentrated downstream, and there is no attenuation with increasing time.

For stable, well-balanced, steady jump, the shock is very obvious and insensitive to downstream conditions.

Case 3. Fr > 9.0, Strong jump

Dataset

Table 5. Cross section data

Chainage	Width (m)	Height (m)	Datum (m)
0	200	8	5.25
2500	200	8	0.25
2501	6	12	0.25
5000	6	12	0

Table 6. Boundaries and parameters

Key	Value
Upstream condition	Inflow: 500m^3/s
Downstream condition	Rating curve
Initial condition	Depth: 0.18m; Discharge:500m^3/s
Bed resist	Manning coefficient : 0.001

Before plotting, we calculate the depth of the two channel parts.

The critical depth of two parts:

$$\mathrm{h}_{c1} = (\frac{Q^2}{gB^2})^{\frac{1}{3}} = (\frac{500^2}{9.8 \times 200^2})^{\frac{1}{3}} = 0.85m \quad (12)$$

$$\mathrm{h}_{c2} = (\frac{Q^2}{gB^2})^{\frac{1}{3}} = (\frac{500^2}{9.8 \times 6^2})^{\frac{1}{3}} = 8.92m \quad (13)$$

The normal depth of two parts:

$$\mathrm{h}_{n1} = (\frac{nQ}{B\sqrt{S_0}})^{\frac{3}{5}} = (\frac{0.001 \times 500}{200 \times \sqrt{0.002}})^{\frac{3}{5}} = 0.18\mathrm{m} \quad (14)$$

When the width and height are close, we cannot apply the above formula. Replaced by the rating curve, h_{n2}= 42.00 m

To sum up, this case meets inequality requirements, $\mathrm{h}_{n1} < \mathrm{h}_{c1} < \mathrm{h}_{c2} < \mathrm{h}_{n2}$.

Result and analysis

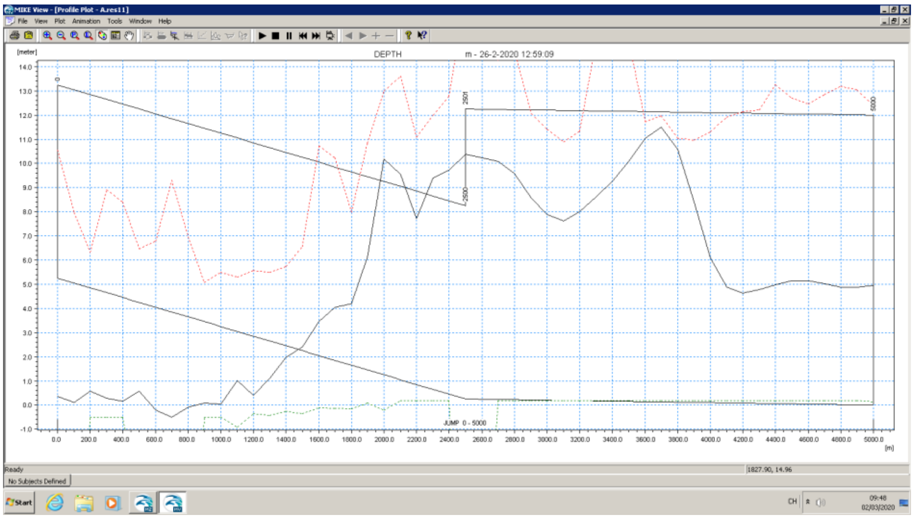

Figure 8. The intermediate profile

This is a diagram of the intermediate process of hydraulic jump. The whole process is very disordered due to the strong jump. Below we will calculate the Froude number at the jump beginning point and the value of the final state point upstream. For the jump beginning point:

$$F_{r1} = \frac{V}{\sqrt{gD}} = \frac{Q}{(B \times D) \times \sqrt{gD}} = \frac{500}{(200 \times 0.18) \times \sqrt{9.8 \times 0.18}} = 10.5 \tag{15}$$

This belongs to strong jump. The following will draw profile figures of depth and discharge. Each time the left and right borders and midpoints are selected as the research object.

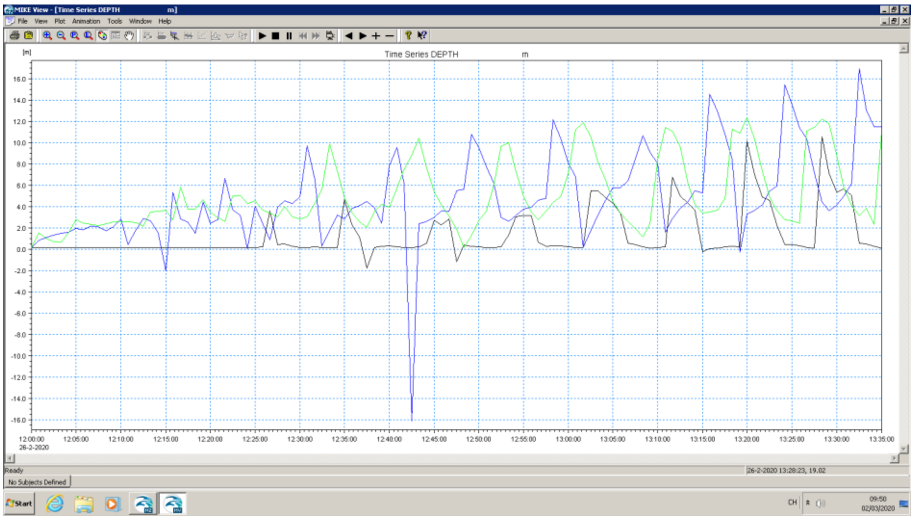

Figure 9. The figure of depth

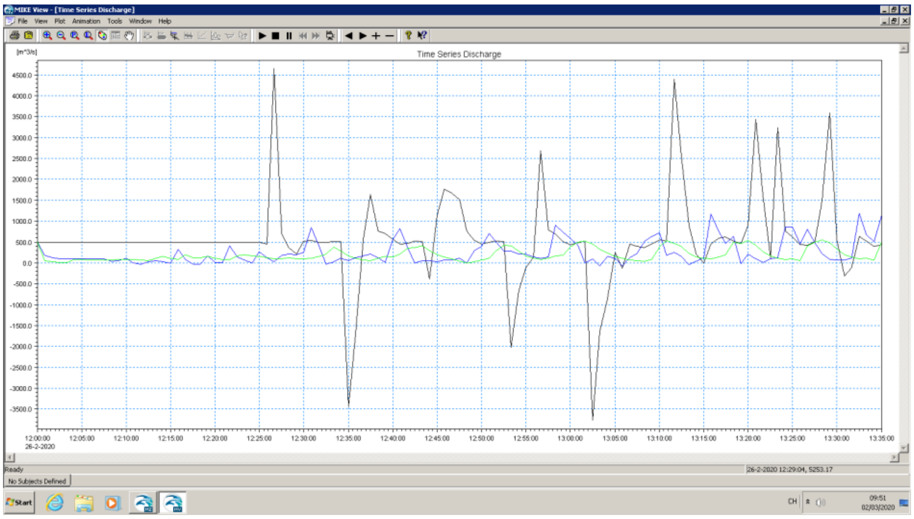

Figure 10. . The figure of discharge

Both figures are very disordered and cannot be effectively simulated. This is because of the eddy current phenomenon of the strong jump, and Mike 11 cannot solve it properly.

Conclusion

- For 1 < Fr < 1.7, this case is known as an undular jump with low dissipation. Hydraulic jump phenomenon is not obvious.
- For 4.5 <Fr <9.0, this case is called stable, well balanced, steady jump, and it is the best design range.
- Fr > 9.0, this case is somewhat intermittent strong jump, but good performance. Mike 11 cannot solve it correctly.