Experimental investigation of turbulent characteristics in hydraulic jump with vegetated bottom

Rongfu Ning, Ruidi Bai, Hang Wang, Shanjun Liu

State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University

Chengdu 610065, China

**Abstract:** Hydraulic jump is a characteristic hydraulic phenomenon that is the transformation from a supercritical flow to a subcritical flow. Previous studies indicate that the channel bed roughness has a significant effect on jump length, conjugate depth and air water flow properties. However, there is little literature referring to the turbulent characteristics in hydraulic jump on vegetated bottom. This paper presents an experimental investigation of hydraulic jump for a wide range of Froude numbers (5.73 < Fr1 < 9.67) at the relative Reynolds numbers (0.67 × 105 < Re < 1.12 × 105) on the open channel with one grate mat and two vegetation configurations, respectively. The free surface characteristics were systematically investigated ultrasonic displacement meters from the jump toe to far field region. Observations showed that the conjugate depth ratio of vegetated bed had in good agreement with smooth bed. The jump length decreased with increasing bottom roughness. While the maximum free surface fluctuation value was smaller than most previous literatures. The present study highlights significant effects of vegetated covers on flow performances of hydraulic jumps.

**Keywords:** Hydraulic jump; Vegetated bottom; Free surface fluctuation; Jump length.

# Introduction

Hydraulic jump is a characteristic hydraulic phenomenon that is the transformation from a supercritical flow to a subcritical flow. The transformation is sudden, extremely turbulent, and associated with energy dissipation, air entrainment, large-scale turbulence, spray, splashing, and surface waves [1]. Hydraulic jump which can be observed universally in natural waterways and man-made hydraulic structures is often used to dissipate the huge amounts of energy from high-speed water flow. The hydraulic jump is described in term of inflow Froude number Fr1 = *V*1/(*gd*1)0.5, where *V*1 = inflow mean velocity, *d*1 = inflow mean flow depth, and *g* = gravity acceleration. For Fr1 > 4.5 to 9, the hydraulic jump is characterized by a marked roller with large energy dissipation rate and stable free surface profile of downstream, named stable hydraulic jump.

In the last century, hydraulic jump has been extensively studied with smooth bed and rough bed in rectangular channel about the main jump parameter (e.g., jump length; roller length and sequent depth ratio, etc.). Many investigations [2] , [3] , [4] , [5], based on physical model experiment, have been conducted on the characteristics of hydraulic jump on horizontal rectangular channel with smooth bed, including free surface fluctuation, jump toe fluctuation and bubbly flow characteristics etc. The effect of bed roughness on hydraulic jump also has been investigated. Ead and Rajaratnam 2002 [6], Abbaspour 2009 [7] and Mohammadzadeh-habili 2018 [8] investigated the hydraulic jump in horizontal rectangular flume with corrugated bed.

However, hydraulic jump with vegetation bed has rarely been studied. Present study aims to investigate the free surface fluctuation characteristics of hydraulic jump forming in different vegetation density with high inflow Froude number from 5.73 to 9.67, including jump toe fluctuation characteristics, sequent depth ratio, jump length and free surface fluctuation characteristics.

# Experimental setup and instrumentation.

The experimental facility consisted of a head tank (2.5 m long, 2.5 m wide, 1.7 m high) and a horizontal rectangular channel (5.0 m long, 0.4 m wide, 0.5 m high). The channel was made of smooth high-density polyethylene (HDPE) bed and glass sidewalls. The water was discharged to the channel through a smooth convergent nozzle. The nozzle was made of HDPE with 0.6 m long and 0.4 m wide horizontal bottom. The outlet of the nozzle (*x* = 0) was fixed to *d*0 = 0.02 m during the present experiments. The horizontal channel consisted of a 0.7 m long smooth bed and the rest 4.3 m long section of the channel was lowered by 0.03 m to assemble the 0.03 m thick industrial grate mat made of orthogonal plastic strips. The top of the grate mat was at the same level of the upstream smooth bed, defined as *y* = 0 The tail water levels were controlled by a sharp-crested weir at the end of the channel. The sketch of the hydraulic jump in present study is shown in Figure 1(a).

The flow rate *Qw* was measured with a V-notch weir with a ±2% measurement accuracy at the downstream of the channel. In present study, the time average position of the jump toe was located at *x*1 = 0.7 m. And the clear water depth *d*1 was measured with point gauge with an accuracy of 0.1 mm, *d*1 = 0.024 m for all tests. In present study, free surface fluctuating elevations above the hydraulic jump in the centerline of the channel was measured with two identical ultrasonic displacement meters (ADMs, MicrosonicTM Mic + 25/IU/TC) parted 0.12 m each other. The measurement section was covered from *x* = 0.7 m to *x* = 3.2 m. Each ADM sensor signal was sampled at 100 Hz for 180 s at each location. The jump toe fluctuation was observed using a high speed video camera recording at 250 frames per second for 180 s. The images of hydraulic jumps over great mat bed and vegetated bed are presented in Figure 1(b) and 1(c).

|  |
| --- |
|  |
| (a) |
|  |
| (b) |
|  |
| (c) |

Figure. 1. Sketch of hydraulic jump in present study (a); Images of hydraulic jumps over great mat bottom (b) and vegetated bottom (c)

# Experimental flow conditions and bed configurations

The constant clear water was pumped to the head tank and discharged to the channel through the fixed opening height nozzle. In present study, experiments were conducted for a range of inflow Froude number 5.73 < Fr1 < 9.67 at the relative Reynolds number 0.67 × 105 < Re < 1.12 × 105 for a range of water flow rate 0.0267 < *Qw* <0.045 m3/s. The experiment flow conditions were summarized in Table 1.

Table 1. Experimental flow conditions.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Type | Test | *ks*  (mm) | *Qw*  (m3/s) | *d*1  (m) | *V*1  (m/s) | *d*2  (m) | Fr1 | Re  (×105) | *L*j  (m) |
| Rough bed | T1-1 | 18.2 | 0.0267 | 0.024 | 2.78 | 0.182 | 5.73 | 0.67 | 0.83 |
| T1-2 | 0.0334 | 0.024 | 3.48 | 0.224 | 7.17 | 0.83 | 1.07 |
| T1-3 | 0.0450 | 0.024 | 4.69 | 0.281 | 9.67 | 1.12 | 1.37 |
| Vegetated bed I | T2-1 | 65 | 0.0267 | 0.024 | 2.78 | 0.185 | 5.73 | 0.67 | 0.59 |
| T2-2 | 0.0334 | 0.024 | 3.48 | 0.219 | 7.17 | 0.83 | 0.74 |
| T2-3 | 0.0450 | 0.024 | 4.69 | 0.276 | 9.67 | 1.12 | 1.07 |
| Vegetated bed II | T3-1 | 96 | 0.0267 | 0.024 | 2.78 | 0.181 | 5.73 | 0.67 | 0.58 |
| T3-2 | 0.0334 | 0.024 | 3.48 | 0.219 | 7.17 | 0.83 | 0.71 |
| T3-3 | 0.0450 | 0.024 | 4.69 | 0.282 | 9.67 | 1.12 | 0.83 |

In order to investigate the vegetation effects on hydraulic jump, there were two different densities flexible artificial saplings fixed on the great mat. Three different bed types, including one great mat bottom (named rough bed) and two different sapling densities vegetated bottom (low-density vegetated bed was named vegetated bed I and high-densities vegetated bed was named vegetated bed II), were tested. For rough bed, the test series were named T1, and the test series T2 and T3 for vegetated I and II respectively. The coverage range of vegetation was started at *x* = 1.0 m.

The equivalent roughness height *ks* of the rough and vegetated beds were obtained with three experiments conducted in a different rectangular flume under a subcritical clear water condition. The flume was 12 m long, 0.5 m wide and inclined to a 0.0055 slope (Figure 2). For three bed configurations, two vertical cross-sections in the developing flow region were measured using Prandtl-Pitot tube to obtain the flow velocity profiles. The equivalent sand roughness height *ks* was calculated basing upon the velocity profiles in the developing boundary layer. The dimensionless boundary shear stress could be estimated from the momentum integral equation [9] :

 (1)

where *f*M= friction factor, *V*0 = free-surface velocity, *δ*1 and *δ*2 = displacement and momentum thicknesses, respectively.

 (2)

 (3)

where *δ* = boundary layer thickness from the bottom to the outer edge of the boundary layer where *V* = 0.99*V*0. The equivalent roughness height *ks* was then calculated from the Colebrook-White formula for fully-rough turbulent flows [10]:

 (4)

where *D*H is the hydraulic diameter. Herein the results of momentum integral equation were adopted and marked in Table 1.

|  |
| --- |
|  |

Figure 2. Laboratory characterization of bottom vegetation roughness heights: flume bed covered with flexible plastic plants.

# Free-surface characteristics

## Jump toe fluctuation

In the present study for Fr1 > 5, hydraulic jumps were clearly observed with a stable fluctuated jump toe at the time average position *x*1 = 0.7 m and a marked roller on the rough bed and vegetated beds. The jump toe movements in the longitudinal direction were recorded with a high speed camera for 180 s. Figure 3 presents the dimensionless jump toe fluctuations *x*toe′/*d*1 and characteristic Strouhal numbers *F*toe*d*1/*V*1 as a function of inflow Froude number Fr1. Experiment data showed that the jump toe fluctuation *x*toe′/*d*1 presented an upward trend with increasing inflow Froude number Fr1, however, that was consistent larger than previous data measured on smooth beds [11], [12], [5] (Figure 3a). The effect of roughness caused by vegetation on jump toe magnitude *x*toe′ was slight. Further, the dimensionless frequency *F*toe*d*1/*V*1 of present data showed a decreased trend with increasing Fr1, which was slight larger than the empirical correlation of Zhang et al. (2013) [13], as showed in Figure 3b.

|  |  |
| --- | --- |
|  |  |
| (a) | (b) |

Figure 3. Jump toe characteristics for different bed types: (a) Jump toe longitudinal fluctuations *x*′toe/*d*1 and compared with Wang and Chanson (2015) [5]; (b) Dimensionless jump toe oscillation *F*toe*d*1/*V*1 and compared with Zhang et al. (2013) [13].

## Conjugate depth and jump length

Downstream of jump toe, a marked increase in free surface was observed with strong fluctuation in hydraulic jump length region. The dimensionless of mean free surface level *η*/*d*1 and fluctuation *η*′/*d*1 are presented in Figure 4(a) and 4(b) respectively as a function of (*x* - *x*1)/*d*1, where *η* = flow depth, and *η*′ = turbulent fluctuation. For rough bed, the mean free surface profile increased monotonously to the maximum flow depth *η*max, then reached a quasi-constant value to the downstream. However, for vegetated bed, there was an obvious peak flow depth value. It first increased monotonously to the *η*max, then decreased to a lower flow depth (valley point) forming the second jump to a higher quasi-constant flow depth. It is obvious in high-densities vegetated bed for high inflow Froude number, especially.

|  |  |
| --- | --- |
|  |  |
| a-1 | b-1 |
|  |  |
| a-2 | b-2 |
|  |  |
| a-3 | b-3 |

Figure. 4. (a) Longitudnal developments of mean free surface elevation for different Froude numbers; (b) Longitudinal developments of fluctuation magnitude for different Froude numbers.

At present study, the jump length was defined as the distance from the position of jump toe *x*1 to the position of maximum flow depth *x*(*η*max), same as Bai et al. 2021a [14] and Murzyn and chanson.2009 [3]. The jump length data was listed in Table 1. For a given value of Fr1, the dimensionless jump length *L*j/*d*1 decreased with increasing rough bed, as presented in Figure 5(a). The conjugate depth *d*2 defined as the quasi-constant flow depth in the tail water. For a hydraulic jump occurred in smooth horizontal rectangular channel, the conjugate depth ratio could be calculated by the Belanger Equation:

 (5)

The conjugate depth ratio *d*2/*d*1 was also presented in Figure 5(a). Compared with the Belanger Equation, the present experiment data had in good agreement with the theoretical formula. The results suggested that the conjugate depth of hydraulic jump was independent of the horizontal bed configurations, which were consistent with the study of Felder and Chanson (2018) [1]. The finding indicated that the presence of vegetation could shorten the length of channel to dissipation same energy. For another words, it could enhance the energy dissipation rate at the same distance.

In the region of jump length, Wang and Chanson (2015) [5] suggested that the monotonically increased dimensionless free surface depth was followed with a self-similar function.

 (6)

where *a* and *b* were coefficients. Experiment data of dimensionless free surface depth along the jump length is presented in Figure 5(b). For smooth bed, Wang and Chanson (2015) [5] indicated that the flow depth at the end of *L*j equal to *d*2, and *a* = 1.0 and *b* = 0.54. The present observations showed that the flow depth at the hydraulic jump end *d*max/*d*2 = 1.01, 1.03 and 1.05 for tests T1, T2 and T3, respectively. In the jump length region, the results showed that the profile shape of the steepened roller were less curved with increasing bed equivalent roughness.

|  |  |
| --- | --- |
|  |  |
| (a) | (b) |

Figure. 5. Free-surface profile characteristics: (a) Jump length and conjugate depth ratio; (b) Self-similar free-surface profile shape over the jump length.

## Free surface fluctuation

During the experiments, strong water surface fluctuations and splashing of water droplets were observed in the hydraulic jump length region. The hydraulic jump free surface fluctuate characteristics were measured with the acoustic displacement meters. And the dimensionless maximum fluctuation *η*′/*d*1 is presented in Figure 4(b) as a function of (*x* – *x*1)/*d*1. At the hydraulic jump length region 0 < (*x* - *x*1)/*L*j < 1, a marked increase of *η*′/*d*1 was observed, and reaching a maximum fluctuation value *η*max′/*d*1 at locations of *x*(*η*max′)/*d*1, which increasing with increasing Fr1. At the downstream of the jump length region (*x* – *x*1)/*L*j > 1, the dimensionless free surface fluctuation *η*′/*d*1 gradually decreased to a merely constant value. Figure 6a and 6b present the data of *η*max′/*d*1 and the relative location *x*(*η*max′)/*d*1 as a function of Fr1, with comparison to the previous observations for smooth bed. The data shown in Figure 6a illustrated that some slight increase in *η*max′ with the increasing equivalent sand roughness height at the same Fr1, especially at larger Fr1. However, the most previous literatures on smooth bed showed the larger maximum fluctuation value than present study. The significant difference may be due to the different calculated methods to deal with the ADM data. At present study, the free surface fluctuation value was calculated from the standard deviation of the Gaussian expression distribution for the ADM data. Figure 6b plotted the longitudinal position of the maximum fluctuation value. The data showed that there was no obvious difference between previous smooth bed and present rough and vegetated bed for lower inflow number, scattered from 2*d*1 to 20*d*1. However, the position of *η*max′ moved to the downstream for 20*d*1 to 30*d*1 for the largest inflow Froude number.

|  |  |
| --- | --- |
|  |  |
| (a) | (b) |

Figure 6. Characteristic parameters of maximum free-surface fluctuations *η*max′/*d*1 (a) and the corresponding locations *x*(*η*max′)/*d*1 as functions of the Froude number and comparison with previous data (b), compared with Murzyn et al. (2007) [2], Kucukali and Chanson (2008) [15], Murzyn and Chanson (2009) [3], Chacherean and Chanson (2011) [4] and Wang (2014) [12].

# Conclusions

Vegetation effects on the free surface characteristics of hydraulic jump were conducted in a wide range inflow Froude number for 5.73 to 9.67, the Reynolds number varied from 0.67×105 to 1.12×105 relatively. The free surface fluctuations are systematically investigated with ultrasonic displacement meters from the jump toe to far field region. It is found that the jump toe fluctuation exhibits a larger value, while the jump toe fluctuation frequencies approximate previous studies with smooth bed. Observations show that the time-average free surface increases from the jump toe to a marked maximum flow depth, and then slightly decreases to the far filed region. The conjugate depth ratio of vegetated bed had in good agreement with smooth bed, while little difference was observed for the maximum free surface fluctuation. For a given inflow Froude number, the jump length decreased with increasing roughness density.

# Acknowledgements

This work was supported by the Natural Science Foundation of Sichuan Province (Grant No. 2022NSFSC0970).

References

1. Felder, S., & Chanson, H. (2018). Air-water flow patterns of hydraulic jumps on uniform beds macroroughness. J. Hydraul. Eng., 144(3), 04017068.
2. Murzyn, F., Mouaze, D., & Chaplin, J.R. (2007). Air-water interface dynamic and free surface features in hydraulic jumps. J. Hydrau. Res., 45(5), 679-685.
3. Murzyn, F., & Chanson, H. (2009). Free-surface fluctuations in hydraulic jumps: experimental observations. Exp. Therm. Fluid Sci., 33(7), 1055-1064.
4. Chachereau, Y., & Chanson, H. (2011) Free-surface fluctuations and turbulence in hydraulic jumps. Exp. Thermal Fluid Sci., 35(6), 896-909.
5. Wang, H., & Chanson, H. (2015a). Experimental study of turbulent fluctuations in hydraulic jumps. J. Hydraul. Eng., 141(7), 04015010.
6. Ead, S., & Rajaratnam, N. (2002). Hydraulic jumps on corrugated beds. J. Hydrau. Eng., 128(7), 656-663.
7. Abbaspour, A., Dalir, A. H., Farsadizadeh, D., & Sadraddini, A. A. . (2009). Effect of sinusoidal corrugated bed on hydraulic jump characteristics. Journal of Hydro-environment Research, 3(2), 109-117.
8. Mohammadzadeh-Habili, J., & Honar, T. . (2018). Theoretical solution for analysis and design of hydraulic jump on corrugated bed. Water S.A, 44(4).
9. Zhang, G., & Chanson, H. (2016). Hydraulics of the developing flow region of stepped spillways. Part II: Pressure and Velocity Fields. J. Hydraul. Eng., 04016016.
10. Idelchik, I.E. (1994). Handbook of hydraulic resistance (3rd ed.), CRC Press, Boca Raton, USA.
11. Long, D., Steffler, P.M., Rajaratnam, N. (1991). Structure of flow in hydraulic jumps. J. Hydrau. Res., 29(2), 207-218.
12. Wang, H., Felder, S., Chanson, H. (2014). An experimental study of turbulent two-phase flow in hydraulic jumps and application of a triple decomposition technique. Experiments in Fluids, 55(7): 1-18.
13. Zhang, G., Wang, H., & Chanson. H. (2013). Turbulence and aeration in hydraulic jumps: Free-surface fluctuation and integral turbulent scale measurements. Environ. Fluid Mech. 13 (2), 189–204.
14. Bai, R., Wang, H., Tang, R., Liu, S., & Xu, W. (2021a). Roller characteristics of pre-aerated high-Froude-number hydraulic jumps. J. Hydraul. Eng., 147(4), 04021008.
15. Kucukali S., Chanson H. (2008). Turbulence measurements in hydraulic jumps with partially-developed inflow conditions, Experimental Thermal and Fluid Science, 33(1): 41–53.