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The influence of energy-reducing structure placement on friction velocity distribution in open channel

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Abstract. Energy Reducing Structure (ERS) is aimed at controlling the flow velocity that causes scouring on the main abutment structure of the bridge from its structural failure. It is needed information on the measurement of flow velocity and other parameters of flow, particularly in analyzing the friction velocity and shear stress on the channel bed to identify the effects of ERS placement on the scouring around the abutment area. The experiment was performed in a flume/channel with a length of 8.00 m, a width of 0.40 m, and a height of 0.40 m. The slope of the channel was 0.05% and 0.15%. The type of flow was uniform turbulent flow, using 3 (three) variation of inlet discharge (Q), with and without Energy Reducing Structure (ERS) in the form of a triangular plate with its height determined based on the average maximum rate of 0.6D from the average water surface of 0.06 m from the channel bed. In measuring the distribution of flow velocity with structure, the measurement was conducted in the upstream and downstream areas of the structure, where the structure was placed at x distance of = 4.00 m. Each measurement was performed at the distance of x = 3.50 m ; x = 4.25 m ; x = 4.50 m ; x = 5.00 and x = 5.50 m. The analysis of friction velocity follows the logarithmic law (log-law) applicable to the open channel. The results of the experiment showed that the smallest friction velocity value (u^*) was on average happened at x distance = 4.25 m – x = 4.50 m ranging from 0.70 cm/sec – 1.37 cm/sec, as the friction velocity was decreasing. On the other hand, however, the constant of integration (Br) showed great values ranging from 19.27 – 48.79, which implied that the flow rate after passing ERS had the flow velocity beyond the normal range and it would be back to normal after moving away from ERS.

1. Introduction

Scouring is a term used to describe the lowering of channel bed until it goes under the initial surface [1]. It is a natural phenomenon caused by sediment velocity in the area exceeding the sediment velocity at the upstream. It happens when the channel flowrate exceeds the velocity which causes the material at the bed to move. Scouring does not only happen to the structure, yet it is not a critical problem. Scouring will lead to problems when the lowering of the riverbed causes structure instability or failure near the river area. The structure that is commonly found near a river is a bridge. The statistical survey on the reason for bridge failure investigation implies that most of the bridge has failed due to over-scouring on the elements of infrastructure during flooding [2].



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Many research has been conducted to reduce the local scouring in pillars and abutment by conducting local scouring engineering around the elements of bridge structure with several purposes such as providing shape to the pillars and abutment, regulating the slope of the channel bed, making roughness of materials on pillars and abutment, and reducing flow velocity with various models of an obstacle. The most common method is constructing rip-rap by placing rocks into the most potential scouring holes. Rip-rap is the most effective protection to control scouring holes by piling rocks into the scouring with a size of the width of 2-3b and thickness of 3dr [3].

Essentially, water structure planning such as flood control structures, bridge abutment planning in an open channel, or closed channel, as well as other structures around the river often require information on flow velocity. The measurement of flow velocity in the middle of the flow is a significant consideration from many perspectives to obtain the flow parameter, especially in analyzing the friction velocity and shear stress on the channel. By identifying the friction velocity in a channel, it will support the continuity of analyses including the initial movement of sediment grain, erosion process, sedimentation, and many more related to the phenomena happens in the riverbed.

Similar to Energy Reducing Structure (ERS) that aims at protecting the main structure such as bridge abutment from structural failure, the needs for information on the flow velocity that can be minimized by the reducing structure significantly affects the success of the planning, particularly the position of Energy Reducing Structure (ERS) to the bridge abutment.

Flow is significantly affected by natural or artificial structured. The presence of structure in the channel bed may represent the flow velocity at the surroundings. The flow velocity at the structure is the effect of turbulent flow affected by friction drag due to its fluid viscosity. Friction drag depends on the Reynold figure of the flow based on the flow velocity (V) and the length of approaching flow (L) [4]. The supporting data that can be used to determine the value of flow viscosity are discharge, water level, water quality, and temperature, where the forecast data shows that indications of flash floods are likely to occur if extreme spikes occur from several parameters of the current river conditions [5].

Various analysis methods on friction velocity have been introduced to describe the flow velocity distribution on a section, one of them is Caluser's Method. Clauser Method is based on the profile of tangential velocity and it is still considered following the logarithmic equation. This method is widely used by taking into account its ease of use and high accuracy [6]. Related to this matter, this research describes how significant the effects of triangular plate energy reducing structure have on the friction velocity in the longitudinal direction, including the effects of the slope of channel bed on the friction velocity distribution

2. Research method

The experiment was performed in a flume channel with a length of 8.00 m, a width of 0.40 m, and a height of 0.40 m. During the experiment, the slope of the channel was 0.05% and 0.25%. The flow condition used 3 (three) variation of discharge (Q), with and without Energy Reducing Structure (ERS) in the form of a triangular plate with its height determined based on the average maximum velocity of 0.6D from the average water surface of 0.06 m from the channel bed.

The measurement data of velocity distribution included the velocity distribution on uniform flow without structure (6 velocity distributions), and with structure (24 velocity distributions). In measuring the velocity distribution with structure, the measurement was conducted in the upstream and downstream areas of the structure, where the structure was placed x distance = 4.00 m. Each measurement was performed at x distance = 3.50 m ; x = 4.25 ; x = 4.50 ; x = 5.00 and x = 5.50.

The measurement of flow velocity distribution used the measuring instrument Pitot Tube Portable Automatic which is a tool for measuring flow pressure (P) at a certain depth and then the difference of pressure values was converted into the velocity [7]. The equation using shown in equation 1.

$$u = \sqrt{\frac{2gh(1000-784)}{1000}}$$

$$u = \sqrt{4.24 \Delta h} \quad (1)$$

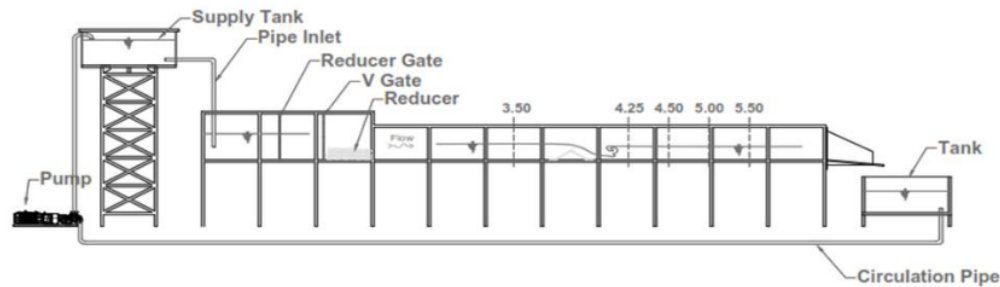


Figure 1. Experiment scheme on an open channel

At each running flow, each data has nomenclature consisting of letters and numbers as shown in table 1. For the first letter code, L and M describe that the flow measurement is obtained at a condition without structure (Loss) and with structure (Model). The second digit code shows the discharge (Q), with a variation of discharge presented in numbers. The fourth digit code is a variation of slope of the bed (slope) stated in code S and added by numbers as the variation code.

Table 1. Main parameter of flow without structure

Run	Q (l/s)	So (-)	D (Cm)	b (Cm)	A Cm2	b/D (-)	R (Cm)	$\vartheta \times 10^{-3}$ (Cm ² /sec)	U (Cm/sec)	Re x 10 ⁻⁵ (-)	Fr (-)
LQ1S1	7.54	0.0005	8.20	40.00	328,00	4.88	5.82	8.28	22.99	0.65	0.26
LQ1S2	7.54	0.0025	7.20	40.00	288,00	5.56	5.29	8.28	26.56	0.68	0.32
LQ2S1	9.24	0.0005	9.20	40.00	368,00	4.35	6.30	8.28	28.17	0.86	0.30
LQ2S2	9.24	0.0025	8.10	40.00	324,00	4.94	5.77	8.28	30.00	0.84	0.34
LQ3S1	9.97	0.0005	9.50	40.00	380,00	4.21	6.44	8.28	30.40	0.95	0.31
LQ3S2	9.97	0.0025	8.70	40.00	348,00	4.60	6.06	8.28	34.10	1.00	0.37

Q = measured flow discharge; So = slope of channel bed; D = depth of flow; b/D = aspect ratio; b = width of flume/channel (=40 cm); ϑ = kinematic viscosity; R = hydraulic radius (A/(2D+B)); Re = 4RU/ ϑ – Reynolds number; Fr = U/(gD)^{0,5}; U = average velocity of (vertical) flow.

3. Discussion

The flow velocity in an open channel is usually varied from one point to another. It has three directional components based on cartesian coordinates. However, the vertical and lateral directional component is usually small and can be ignored. So, only the flow velocity in the same direction is calculated.

3.1. Validation of measurement data

The measurement was conducted in a permanent uniform flow condition without structure at a distance of x = 4.50 m from the inlet and with an Energy Reducing Structure (ERS) along with variations in discharge and slope. The distribution of flow velocity in the vertical and longitudinal direction can be seen in figure 2.

Figure 2 shows the flow in a dimensionless vertical and longitudinal direction at 0.05% and 0.15% slope with low and large discharge occurring in the flowrate conditions without a structure (solid line, figure a) and with ERS before passing through the structure with a distance x = 3.50 (Solid Line, figure b) and after passing through the ERS at x = 4.50 and x = 5.00 m (dotted line), where the flow velocity is decreasing and the stress at the bed is getting smaller. The next analysis is to analyze the reduction in velocity that occurs at the bed, which is referred to as the friction velocity (u*).

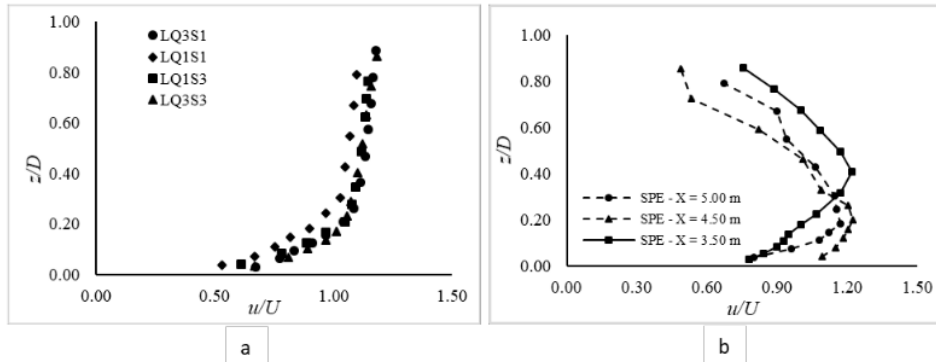


Figure 2. Profile of longitudinal flow velocity a). Vertical flow direction without ERS; b). Longitudinal flow direction with ERS

To determine the basic friction velocity without structure, a measurement of velocity distribution near the bed area is used (inner region), at $z/D \leq 0,2$, along with the equation of logarithmic velocity distribution (equation 1). The equation of logarithmic velocity distribution provides a correlation (linear equation), if the obtained u describes the function (y/ks) , and gives the line slope $m = u^*/\kappa$, and constant value Br . By taking the value $\kappa = 0,4$, it is obtained u^* .

The logarithmic velocity distribution (the law of the wall) in the inner region limited by $z/D < 0,2$ can be formulated as equation 2.

$$\frac{u}{u^*} = \frac{1}{\kappa} \ln\left(\frac{z}{ks}\right) + Br \tag{2}$$

As the first step to find whether or not the Clauser's Method can still be used, the measurement results of velocity distribution are plotted at the data of velocity (u) versus depth (z/D) by taking the measurement data up to the depth of $z/D \leq 0,2$ see figure 3.

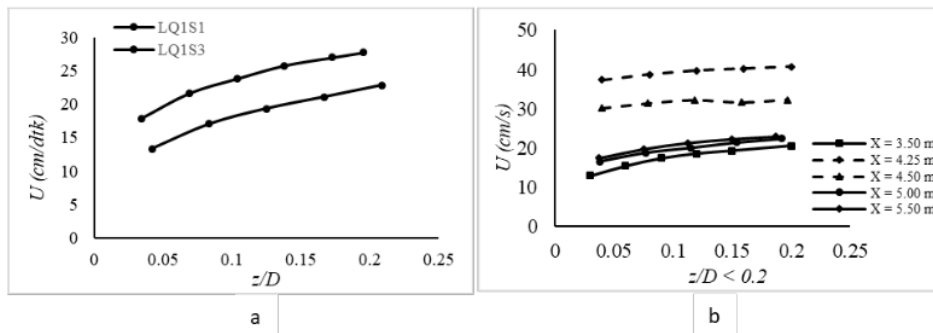


Figure 3. Distribution of Flow Velocity on channel bed a). Data without ERS; b). Data with ERS

Figure 3a shows that flow velocity distribution without ERS follows the logarithmic law (log-law) both on channels with and without slope. On the contrary, if the flow passes through the ERS see figure 3b at x distance = 4.25, there is a change in the flow velocity up to the distance $\pm x = 4.50$ and the function of logarithmic law will revert to valid at x distance = 5.00 m – $x = 5.50$ m.

For measurement data without structure, it has been proven [4], that the equation (2) is still applicable in the middle of the flow until the depth of, $z/D \leq 0,2$. Meanwhile, for the velocity distribution data with Energy Reducing structure, it is not certain to what extent the logarithmic law can still be used. So, in this case, it is necessary to check to what depth and distance the logarithmic law still applies (valid).

According to Cardoso, et al, Clauser’s Method can still be used properly, even though the data in the inner region area is only up to $z/D \approx 0.1$.

3.2. Friction velocity (u^*), constant of integration (Br)

The distribution of the unidirectional velocity consists of the flow profile in the inner region which is near the bed where logarithmic velocity applies, and the outer region is far from the bed where the velocity distribution clearly and systematically deviates the logarithmic law.

Constant of integration (Br), has the same order of magnitude, with a thick laminar layer δ and it is a function that depends on fine to coarse boundary conditions.

Assuming that u is the average velocity of the points at z distance from the reference point; D is the depth of the flow; u^* = friction velocity; constant of Von-Korman, $\kappa = 0,4$; Br is constant of integration, and ks is the roughness of channel bed equivalent Manning. For uniform flow, the value of Br in the middle of the channel (2D flow) is, $Br \approx 8.5 \pm 15\%$.

The next validation analyzes the friction velocity in the middle of the channel following the logarithmic function by plotting the relationship of velocity u versus $\ln(z/ks)$.

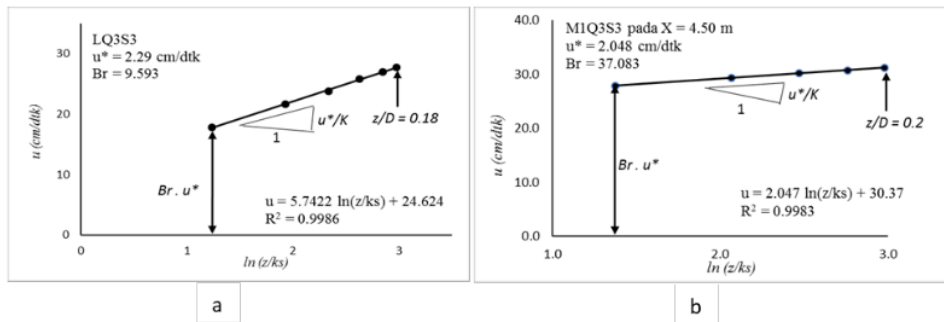


Figure 4. Determination of friction velocity (u^*) and constant of integration (Br) a). Measurement data without ERS; b). Measurement data with ERS at $x = 4.50$ m

Figure 4a shows that the velocity distribution without structure can still follow the function of logarithmic law. Yet in figure 4b, it can be seen that an example of velocity distribution in the x -direction = 4.50 has a range of constant of integration value $Br \gg 8.5$. It shows the friction velocity value is getting smaller and the constant of integration (Br) from the regression equation shows a significant increase even beyond the required range threshold value (see Br value figure 4b with constant value is equal to $Br \cdot u^*$).

3.3. Shear stress (τ)

From the calculation of friction velocity using Clauser’s Method, the magnitude of shear stress can be analyzed. Shear stress τ is the internal stress of the fluid which resists deformation. Shear stress only happens to move fluid. This stress is tangential stress, in contrast to pressure which is normal stress. [8]. Analysis of shear stress in uniform flow conditions can be seen in figure 3.

In turbulent flow, the equation of shear stress is shown in equation 3 and equation 4 [7].

$$\tau_t = \rho g R \sin(\theta) = \rho g R S_o \tag{3}$$

With

$$\tau_t = \rho u_*^2 \tag{4}$$

where:

- τ_t is turbulent shear stress
- g is the acceleration of gravity
- ρ is water mass

u_* is friction velocity

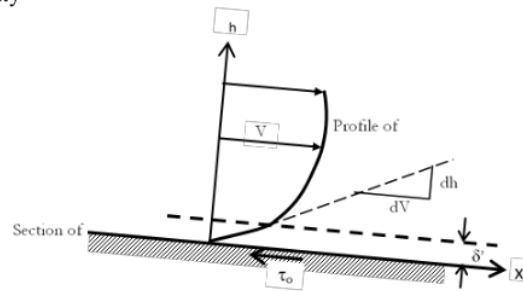


Figure 5. Profile of force on the smooth inclined section

1. The slope angle of channel bed (θ) is relatively small, then $\sin(\theta) \approx \tan(\theta) = S_0$, with S_0 is the slope of the channel bed.
2. Channel with quadrilateral section
3. Depth of flow (h) is the distance
4. Profile of average velocity based on logarithmic law (*log law*).

Recapitulation of calculation of u_* , Br, and τ_{O-z} inflow without structure and flow with the structure shown in table 2 and table 3.

Table 2. Recapitulation of calculation of u_* , Br, and τ_{O-z} (flow without structure)

Run	u_* (cm/sec)	Br	τ_{O-z} (Kg/cm ²)
LQ1S1	1.83	9.29	0.0007
LQ1S2	2.01	8.87	0.0034
LQ2S1	2.30	8.81	0.0009
LQ2S2	2.48	7.68	0.0034
LQ3S1	2.77	8.79	0.0009
LQ3S2	2.90	7.60	0.0045

Table 3. Recapitulation of calculation of u_* , Br, and τ_{O-z} (flow with structure)

Run	u_* (cm/sec)					Br					τ_{O-z} (Kg/cm ²)				
	3.5	4.2	4.5	5.0	5.5	3.50	4.25	4.50	5.00	5.50	3.50	4.25	4.50	5.00	5.50
M1Q1	1.6	0.8	0.7	1.6	1.3	11.0	48.5	46.2	14.5	15.7	0.002	0.000	0.000	0.002	0.001
S1	1	2	0	6	7	4	6	6	4	0	6	7	5	8	9
M1Q1	1.5	0.9	0.5	1.2	1.2	14.4	48.7	44.7	12.9	12.9	0.002	0.000	0.000	0.001	0.001
S2	7	5	5	0	0	4	9	1	0	0	5	9	3	4	4
M1Q2	1.8	0.8	1.0	1.8	1.6	10.4	47.7	29.7	12.4	13.7	0.003	0.000	0.001	0.003	0.002
S1	7	9	0	1	3	0	5	0	3	7	5	8	0	3	7
M1Q2	2.4	1.0	0.8	2.2	2.0		46.8	42.9	13.2	13.2	0.006	0.001	0.000	0.005	0.004
S2	6	5	6	3	3	8.40	6	7	8	3	0	1	7	0	1
M1Q3	1.9	0.9	1.3	1.9	2.2	10.3	47.2	19.2	11.7		0.003	0.000	0.001	0.003	0.005
S1	3	5	7	6	6	4	7	7	5	9.76	7	9	9	9	1
M1Q3	2.5	1.3	0.8	1.5	1.7		41.8	37.0	13.1	10.7	0.006	0.001	0.000	0.002	0.003
S2	2	0	2	7	4	8.78	5	8	8	7	4	7	7	5	0

Table 3 shows that the value of the smallest friction velocity (u_*) on average is at x distance = 4.25 m – x = 4.50 m ranging from 0.70 – 1.30, as well as the shear stress that is decreasing along with the

friction velocity. On the other hand, the constant of integration (Br) shows very great values ranging from 19.27 – 48.79, which implies that the flow velocity after passing the ERS has a flow velocity value beyond the normal range of flow. At a distance of $x = 5.00 - x = 5.50$, the flow begins to follow the log law again.

4. Conclusion

The flow profile of the Energy Reducing Structure (ERS) was investigated experimentally in a rectangular channel and the following results were obtained:

- a) It was found that the Energy Reducing Structure (ERS) causes the turbulent intensity profile distribution to change. At the downstream of the structure, the turbulent intensity profile has appeared non-uniform distribution and has a high flow distribution compared to the upstream area of the structure so that the friction velocity (u^*) that occurs at the bottom is small and is directly proportional to the shear stress (τ_o).
- b) It was quantitatively confirmed that when there is a structure placed at the bottom of the channel, the turbulent intensity will increase after the flow passes through the structure, it can be seen from the significant change in the integration constant (Br) value that exceeds the required value and the flow will return to normal if it leaves the structure.

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