Measurement of Turbulent Flows and Shear Stress on Open Channels

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Abstract. The phenomenon of turbulent flows becomes a virtual object in any changes in open channel flow hydraulics. Turbulent flow and shear stress have a role in the geometrical changes of bed channel and sediment movement. The dynamics of turbulent flow are consequences of hydraulic channel dynamics. Turbulent flow has excessive kinetic energy resulting in resistance force because the increase of friction effect and infraction in turbulent flow creates a complex phenomenon. Shear stress is in the eternal pressure of flow against the deformation of the primary basic form of channel. The research aims to analyze turbulent flow, shear stress, and bed scours’ phenomena and potential. Measurement of turbulent flows is by measuring the flow velocity in four segments at a distance of 100 cm each. The channel's cross-section is divided into nine parts and five measurement points in the flow depth of inner and outer regions. There are three variations of channel discharge and slope, i.e., low discharge (Q1), medium discharge (Q2), large discharge (Q3), and downward slope (S1), medium slope (S2), and high pitch (S3). The parameter of turbulent flow analysis, shear stress includes flow velocity average (U), flow depth (h), channel slope (S), viscosity (ν), the mass density of the liquid (ρ), the characteristic length or hydraulic radius (L/R) by using an empirical equation approach. Turbulent flow analysis used dimensionless Reynolds’ number equation approach. The effect of hydrodynamic on turbulent flow causes the distribution of shear and scour stress, transport, and sediment deposition. The increase in the slope of the channel affects the increase in the values of shear stress.

1. Introduction

Turbulent flow is a flow characteristic that occurs both in open and closed channels, and it creates a separate phenomenon in channel hydraulics. Turbulent flow causes problems at the bed and channel slope that triggers changes in the channel to each shift in turbulent flow and shear stress. It is interesting to observe the parameters that contribute to turbulent flow and shear stress by making direct measurements on the open channel to obtain the phenomena.

Research on Reynolds’ shear stress has been conducted with various types of channel or river bed materials to date, including the effect of adding large rock base materials on turbulent flow characteristics [1], the spread of large rock have a small impact on the magnitude of the base flow velocity (stream wise), but tends to reduce the gradient of velocity in near-bed, thereby affecting the bed shear stress [2], the effect of rock spacing and the ratio of sub-merge of the rock on the bed shear stress...
on the gravel-bottom flume [3], direct measurement of the bed shear stress [4][5], the massive rock or boulders affect the average and turbulent flow characteristics [6][7], the bed channel with the spatial variability of the boulders at the bed shear stress [8][9], the bed roughness, the shear stress variability [10], the bed channel slope affects the increase in the values of shear stress [4][11], the distribution of Reynolds’ shear stress, the area near the bed and the inner side of the bend has a more excellent value [12].

Research on turbulent flow as a trigger for scouring due to shear stress, among others, the phenomenon of turbulent flow [13][14], turbulent flow affects the bottom's transport. Elevated sediments [2] Bend in 650 in the upstream channel affects the distribution of velocity and shear stress in the channel bend [12], flow characteristics contribute significantly to sediment erosion and deposition [8], turbulence intensity and average velocity occur due to the habitat selection parameters of the channel conditions [1]. Turbulent flow eddies are evenly distributed to the two boundary sections [15]. Denser boulders contribute to a more uniform contribution of turbulent flow events (Reynolds) and shear stress [16], building models contribute significantly to increasing the total flow of turbulent kinetic energy [11]. The groin on the channel bends causes new turbulence flow phenomena, shear stresses, and local scouring [17]. However, it is still necessary to vary the turbulent flow contribution pattern and shear stress for some raw materials for channels or rivers.

Curing time has a significant effect on the increase of the compressive strength test of the clay soil. [18], the wave reflection coefficient decreases with the rise of wave steepness [19], Effect of Froude Number, the smaller the scour depth that occurs [20]. The pattern of sediment movement happening in the BiliBili Reservoir [21]. The more significant the Froude number causes, the greater the scour depth [22].

The research was conducted to improve understanding of the role of turbulent flow and shear stress. The study's objective is to analyze the turbulent flow, shear stress, and the phenomena and potential of bed scour. The problem of turbulent flow becomes a particular problem in river hydraulics and bed shear stress.

2. Method and Material

2.1. Preparation of tools and materials

The testing was carried out in the hydraulics laboratory of Hasanuddin University, Faculty of Engineering. It is conducted between May and July 2020 by using a channel flume, (b) 35 cm in width, (h) 45 cm in height, (L) 900 cm in length, and equipped with a pump, inlet, and outlet reservoir as shown in Figures 1 and 2.

Figures 1. The layout of the channel model
It was carried out by laboratory experiments on observations under artificial conditions to investigate the relationship between variables gives specification treatments to several experimental groups with a control comparison.

2.2. Measurement of flow velocity and data validation
Flow velocity is an essential factor in the turbulent flow that can increase the velocity and shear stress. The data of flow velocity and height become the primary data of this research. Measurement of velocity distribution in the inner region or near-bed and outer region or far-bed channel [23]. Measurement of turbulent flow is done by measuring flow velocity in four segments with a distance of 100 cm each, i.e., the upstream, middle, and downstream channels. The channel's cross-section is divided into nine sections, 1/30 b, 1/16 b, 1/8 b, ¼ b, ½ b, and five measurement points at flow depth, channel 0.3 cm, 0.1 h, 0.2 h, 0.6 h, 0.8 h (cm). There are three variations of discharge and channel slope, i.e., low, medium, and high discharge, and downward slope, (S1) medium slope (S2), high slope (S3). The tool used in measuring flow velocity is a portable automatic Pitot by the following equation:

\[ u = \sqrt{4.24 \Delta h} \text{ (m/dt)} \]  
\[ U = \frac{1}{n} \cdot R^{2/3} \cdot S^{1/2} \text{ (m/dt)} \]  
\[ U = C \sqrt{R \cdot S} \text{ (m/dt)} \]

2.3. Data Analysis Parameter
The parameters used in analyzing turbulent flow, stress, and shear velocity were bottom flow velocity (u), near-surface flow velocity (U), flow velocity inner region or near-bed (u) flow depth (h), and channel slope (S), viscosity (\( \phi \)), the mass density of the liquid (\( \rho \)), the characteristic length or hydraulic radius (L/R) by using an empirical equation approach. The dimensionless variables used for the classification of Reynolds’ number (Re) as follows:

\[ Re = \frac{\rho u R}{\mu} \]  

The turbulent flow shear stress (\( \tau_t \)) [4] can be calculated by using the following equation:

\[ \tau_t = \rho w \cdot g \cdot R \cdot S \text{ or } \tau_t = = \rho_w \cdot u^2 \text{ and} \]  
\[ u_* = \sqrt{g \cdot R \cdot S} \]  

The bed shear stress (\( \tau_o \)) can be calculated by using the following equation:

\[ \tau_o = \rho w \cdot g \cdot h \cdot S \]  

3. Results and Discussions
3.1. Analysis of Flow Characteristics based on Reynolds’ Number and Shear Stress
According to Richard Feynman, the flow characteristics are a separate phenomenon in a flow system and the part of flow dynamics of the channel, who is describing the turbulence of flow until now has not
been resolved in classical physics. Turbulent flow occurs because it is dominated by inertia, while the dominant viscosity force that occurs is laminar flow. The turbulent flow measurement in the outer region or far-bed of the channel in four segments, i.e., upstream, middle 1, middle two, and downstream, and the turbulent flow calculation are described in Tables 1, 2, 3, and 4.

**Table 1. Calculation of flow characteristics based on the Reynolds’ number in the upstream segment**

| Scenario | Discharge (m³/dt) | S (%) | U (m/dt) | Re | τᵢ (kg/m²) | τₒ (kg/m²) | u* (m/dt) |
|----------|-------------------|-------|----------|----|-------------|-------------|------------|
| TKTSQ₁   | 0.00871           | 0.00056| 0.3160   | 3,003.84| 0.000801    | 0.00128     | 0.028466   |
| TKTSQ₂   | 0.00871           | 0.0189 | 0.3189   | 2,816.76| 0.002122 | 0.000341     | 0.046339   |
| TKTSQ₃   | 0.00871           | 0.0267 | 0.3377   | 2,809.54| 0.002769 | 0.000444     | 0.052940   |
| TKTSQ₁   | 0.00982           | 0.0056 | 0.3198   | 3,145.12| 0.000801 | 0.000131     | 0.028474   |
| TKTSQ₂   | 0.00982           | 0.0189 | 0.3297   | 2,901.04| 0.002140 | 0.000353     | 0.046540   |
| TKTSQ₃   | 0.00982           | 0.0267 | 0.3414   | 2,816.60| 0.002747 | 0.000455     | 0.052724   |
| TKTSQ₁   | 0.01011           | 0.0056 | 0.3252   | 3,225.39| 0.000802 | 0.000135     | 0.028483   |
| TKTSQ₂   | 0.01011           | 0.0189 | 0.3353   | 2,969.12| 0.002082 | 0.000353     | 0.045903   |
| TKTSQ₃   | 0.01011           | 0.0267 | 0.3457   | 2,934.06| 0.002725 | 0.000464     | 0.052519   |

**Table 2. Calculation of flow characteristics based on the Reynolds’ number in the middle one segment**

| Scenario | Discharge (m³/dt) | S (%) | U (m/dt) | Re | τᵢ (kg/m²) | τₒ (kg/m²) | u* (m/dt) |
|----------|-------------------|-------|----------|----|-------------|-------------|------------|
| TKTSQ₁   | 0.00871           | 0.00056| 0.3147   | 3,031.54| 0.000801  | 0.001277    | 0.028466   |
| TKTSQ₂   | 0.00871           | 0.0189 | 0.3244   | 2,860.12| 0.002122 | 0.000349     | 0.046339   |
| TKTSQ₃   | 0.00871           | 0.0267 | 0.3364   | 2,794.34| 0.002769 | 0.000410     | 0.052940   |
| TKTSQ₁   | 0.00982           | 0.0056 | 0.3189   | 3,161.76| 0.002140 | 0.000353     | 0.046540   |
| TKTSQ₂   | 0.00982           | 0.0189 | 0.3290   | 2,927.87| 0.002140 | 0.000353     | 0.046540   |
| TKTSQ₃   | 0.00982           | 0.0267 | 0.3436   | 2,905.50| 0.002746 | 0.000454     | 0.052724   |
| TKTSQ₁   | 0.01011           | 0.0056 | 0.3255   | 3,281.49| 0.000790 | 0.000133     | 0.028284   |
| TKTSQ₂   | 0.01011           | 0.0189 | 0.3352   | 2,982.26| 0.002082 | 0.000353     | 0.045903   |
| TKTSQ₃   | 0.01011           | 0.0267 | 0.3479   | 2,739.93| 0.002725 | 0.000459     | 0.052519   |

**Table 3. Calculation of flow characteristics based on the Reynolds’ number in the middle two segments**

| Scenario | Discharge (m³/dt) | S (%) | U (m/dt) | Re | τᵢ (kg/m²) | τₒ (kg/m²) | u* (m/dt) |
|----------|-------------------|-------|----------|----|-------------|-------------|------------|
| TKTSQ₁   | 0.00871           | 0.00056| 0.3161   | 3,005.72| 0.000801  | 0.001241    | 0.028465   |
| TKTSQ₂   | 0.00871           | 0.0189 | 0.3333   | 2,944.47| 0.002125 | 0.000359     | 0.046386   |
| TKTSQ₃   | 0.00871           | 0.0267 | 0.3363   | 2,932.11| 0.002769 | 0.000459     | 0.052940   |
| TKTSQ₁   | 0.00982           | 0.0056 | 0.3183   | 3,153.49| 0.000801 | 0.000134     | 0.028474   |
| TKTSQ₂   | 0.00982           | 0.0189 | 0.3268   | 2,406.34| 0.002140 | 0.000353     | 0.0465401  |
| TKTSQ₃   | 0.00982           | 0.0267 | 0.3442   | 2,993.52| 0.002746 | 0.000459     | 0.052274   |
| TKTSQ₁   | 0.01011           | 0.0056 | 0.3253   | 3,269.30| 0.001855 | 0.000331     | 0.042777   |
| TKTSQ₂   | 0.01011           | 0.0189 | 0.3344   | 2,869.13| 0.002081 | 0.0003845    | 0.0459027  |
| TKTSQ₃   | 0.01011           | 0.0267 | 0.3518   | 2,622.68| 0.001185 | 0.0004373    | 0.0332764  |

Turbulent flow occurs because the flow particles move in an irregular path, both in terms of space and time, to meet the turbulent flow requirements. Turbulent flow is influenced by inertia and viscosity. The bed shear stress calculation is done in the inner region, or near-bed, while in the outer area or far-
bed the channel for the analysis for turbulent shear stress. Shear stress is influenced by several factors such as water density, gravitational, flow height, hydraulic radius as characteristic length.

Table 4. Calculation of flow characteristics based on the Reynolds’ number in the downstream segment

| Scenario | Discharge (m³/dt) | S (%) | U (m/dt) | Re | τt (kg/m²) | τo (kg/m²) | u* (m/dt) |
|----------|-------------------|-------|----------|----|------------|------------|-----------|
| TKTSQ:S1 | 0.00871           | 0.00056 | 0.3155   | 3,008.61 | 0.0008006 | 0.0001214 | 0.0284656 |
| TKTSQ:S2 | 0.00871           | 0.00189 | 0.3254   | 2,880.33 | 0.0021215 | 0.0003596 | 0.0463386 |
| TKTSQ:S3 | 0.00871           | 0.00267 | 0.3392   | 2,858.03 | 0.0027690 | 0.0004110 | 0.0529400 |
| TKTSQ:S1 | 0.00982           | 0.00056 | 0.3193   | 3,169.63 | 0.0008011 | 0.0001314 | 0.0284744 |
| TKTSQ:S2 | 0.00982           | 0.00189 | 0.3269   | 2,879.95 | 0.0022140 | 0.0003720 | 0.0465401 |
| TKTSQ:S3 | 0.00982           | 0.00267 | 0.3451   | 2,789.65 | 0.0027465 | 0.0004549 | 0.0527244 |
| TKTSQ:S1 | 0.01011           | 0.00056 | 0.3252   | 3,425.96 | 0.0007570 | 0.0001277 | 0.0276804 |
| TKTSQ:S2 | 0.01011           | 0.00189 | 0.3279   | 3,239.34 | 0.0020818 | 0.0003845 | 0.0459027 |
| TKTSQ:S3 | 0.01011           | 0.00267 | 0.3538   | 3,131.87 | 0.0027252 | 0.0004285 | 0.0525198 |

3.2. Effect of Discharge, Slope on Turbulent Flow and Shear Stress

Flow dynamics, as occurred in open channels, cause complex geometrical changes and be part of channel dynamics. Changes in flow parameters, such as flow velocity, slope, and hydraulic radius, lead to channel dynamics. This dynamic affects other flow parameters, i.e., acceleration, turbulent flow, bed shear stress, and turbulent shear stress. The flow velocity distribution in the open channel is influenced by the channel's slope and the necessary roughness factor, and the channel walls.

![Figure 3](image)

Figure 3. Relationship between discharge with velocity flow

Figure 3 shows the change in flow velocity as the flow height increases. Direct measurement of flow velocity in open channels is validated by empirical equations, namely Manning and Chezy, showing a trend or similarity inflow velocity changes. These results show three variations of discharge, namely low discharge (Q1), medium discharge (Q2), high discharge (Q3), and three types of channel slope variations, namely, downward channel slope (S1), medium channel slope (S2), high channel slope. (S3) results in a change in flow height. Changes in increasing flow velocity along with changes in flow height with decreasing flow height (h) cause the flow velocity to be more significant.
Figure 4 shows the channel's bottom slope's variation with direct measurements on the open channel having a trend or similarity in the change in flow velocity with the empirical equation, namely, Manning and Chezy. Figure 5 shows that the difference in channel bottom's slope affects the flow velocity and shear speed due to the greater slope of the channel bottom. Increasing the channel bed slope and slope increase in turbulent kinetic energy [11].

Figure 6 shows the increase in the value of the bed shear stress ($\tau_0$) influenced by the channel slope, flow depth, and gravity. Meanwhile, the turbulent shear stress ($\tau_t$) is controlled by the slope of the channel, the hydraulic radius as a characteristic length [6][7], and gravity, which is dominated by the inertia force. Whereas in Figure 7 shows the increase influences the change in bed shear stress ($\tau_0$) and turbulent shear stress ($\tau_t$) inflow velocity and shear velocity, and the base slope of the channel affects the increase in the value of shear stress [11][4].
Figure 8 shows that the increase in flow velocity and shear velocity is directly proportional to the Reynolds number. The greater the Reynolds number value due to the increase in flow velocity and the greater the shear velocity. Meanwhile, Figure 9 shows the increase in flow turbulence affects changes in shear stress and flow rate. The increase in the Reynolds number affects the turbulent kinetic energy flow so that the potential for scouring and transport of elevated and bottom sediments [2] [13] [14].

4. Conclusion
The results of the analyzed discussion of the main variables of turbulent flow and shear stress can be concluded as follows:

1. The increasing value of turbulent flow is directly proportional to the flow velocity, Viscocity, and hydraulic radius as the characteristic length.
2. Turbulent flow is dominated by inertia force with kinetic energy, which causes the bed channel's stability to be disturbed due to the scouring of the bed and elevated sediments.
3. The bed shear stress is influenced by the slope, gravitational, and flow depth, causing the disturbance of bed stability.
4. Turbulent shear stress is influenced by the channel slope, hydraulic radius, and gravity, causing bed stability disturbance.

5. Suggestions
The results of observation and analysis for several problems become important topics for further researches, including:

1. It is necessary to observe more research variables to determine the phenomena that occur due to turbulent flow.
2. Further research is needed to vary the bed channel material to obtain the value of shear stress for each of these materials.
3. It is necessary to observe the building model variables, which can inhibit turbulent flow and shear stress to reduce the bed channel's excessive scour.
4. Turbulent flow and shear stress become complex study materials so that it is required a variable variation of various parameters that can affect it.
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