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EFFECTS OF TEST STARTUP CONDITIONS ON SCOUR IN COHESIONLESS SOILS BY PLANE TURBULENT WALL JETS

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Abstract: This paper presents some interesting observations deduced from tests carried out to assess the effect of test startup conditions on scour of cohesionless soil by plane turbulent wall jets. An evaluation of several earlier studies indicates that the startup conditions are quite varied among the tests. In an effort to clarify some of the differences noticed in the earlier results and the three-dimensional features noted in the scour characteristics, three different test startup conditions were adopted. Velocity measurements conducted using a laser Doppler anemometer indicates that the flow gradually evolves to a state that is independent of the startup conditions. However, the scour profiles appear to be dependant on the startup conditions for a longer duration.

1 Introduction

The prediction of scour in the vicinity of hydraulic structures is complex due to the various flow patterns encountered. Scour is usually caused by turbulent jets, which possess high velocities that can dislodge sediments from the bed, lift and hold them in suspension, and then transport the particles downstream. Studies on scour in cohesionless soils by plane turbulent wall jets have broadly been classified into deeply submerged and shallow submergence cases. Most previous studies focused on the erosion or scour of cohesionless soils by deeply submerged plane turbulent wall jets (Laursen, 1952; Tarapore, 1956; Rajaratnam, 1981; Aderibigbe and Rajaratnam, 1998), although there also have been some which have considered submergence effects (Rajaratnam and Macdougall, 1983; Ali and Lim, 1986; Johnston, 1990; Mohamed and McCorquodale, 1992; Chatterjee et al, 1994; Balachandar et al., 2000 and Kells et al., 2001).

A cursory evaluation of the test startup conditions in the studies noted above indicates that they are quite varied. Here, ‘startup’ is defined as the commencement of flow through the nozzle on to the sand bed. For example, Kells et al (2001) had the nozzle outlet plugged whereas, Mohamed and McCorquodale (1992) had the sluice gate closed until proper head and tailwater conditions were established. Following this, the nozzle was unplugged or the sluice gate opened to a predetermined extent to generate the jet flow. This requires a certain amount of time before a steady jet discharge can be established. Other researchers (e.g. Aderibigbe and Rajaratnam, 1998; Chatterjee et al, 1994; Rajaratnam, 1981) have first established the required tailwater conditions by filling the downstream side of the flume prior to generating the jet by a constant head arrangement or by applying a suitable head difference across the sluice gate opening. Johnston (1990) and Ali and Lim (1986) used a suitably sized aluminium sheet to cover the leveled bed in order to prevent it from being disrupted on commencement of the flow. The inflow was started; the flow and tailwater depths were then set to desired values following which the sheet was slowly removed. During the preliminary phase of this study, an effort was made to duplicate the test conditions adopted in previous studies such as the tailwater depth and jet exit velocity. However, the resulting scour pattern did not conform to earlier studies. Furthermore, there are several empirical scour prediction formulae that are available in literature for asymptotic conditions. These formulae provide for different predictions for identical flow conditions (Ahsan, 2003; Ali and Lim, 1986; Rajaratnam, 1981).

It is clear that even for a simple flow emanating from nozzles (or sluice gates), the flow pattern can become complex due to various influences. A proper analysis of the velocity field and the resulting scour is required. Some earlier studies and also some preliminary experiments carried out as part of this study showed that the scour pattern can be three-dimensional even though the flow field is nominally two-dimensional. This paper therefore investigates the effect of test startup conditions on plane turbulent wall jet behavior and the resulting scour profiles.

2 Experimental set up and procedure

The experiments were carried out in a rectangular flume of 0.4 m width, 0.9 m depth, and 15 m in length. A sand bed, 0.4 m wide, 0.3 m deep and 2.4 m long, was set within the test section. A rectangular nozzle of 0.4 m width and having an opening (b_o) of 25.4 mm was placed upstream of the sand bed so that the jet was initially parallel to the bed. The sand bed made of cohesionless sand particles was approximately uniform in size with a median diameter D_{50} of 2.15 mm. The average jet velocity (U_o) at the nozzle exit was maintained constant at 1.16 m/s. Additional details can be found in Deshpande (2004). Scour profiles were obtained using a digital point gauge with a resolution of 0.01 mm. All profiles were measured at three sections, i.e., along the jet centreline (denoted as CL), at a distance of 50 mm from the front Plexiglas wall (NW), and at 50 mm from the far wall (FW). The velocity measurements were carried out with a single-component fiber-optic LDA (Dantec Inc). Sufficient number of particles was present in the water and hence no artificial seeding was required. No measurements were possible at locations less than about $3b_o$ from the nozzle exit due to the restrictions imposed by the geometry of the transmitting optics and the flume support structures.

The effects of three different startup conditions were studied. This includes a gradual startup condition, a stepwise startup condition and an instantaneous startup condition. A gradual startup condition is defined when the flow is commenced with the valves set for the minimum velocity at the nozzle exit, which are then gradually opened to reach the desired test velocity. The velocity is simultaneously monitored using the LDA. A stepwise startup condition is defined when the flow is commenced with the valves set for the minimum velocity at the nozzle exit. This velocity is maintained for a time period of 300 s, following which the valves are opened to increase the flow to a second condition. This flow condition is once again maintained for 300 s following which there is another stepwise increase. This process is repeated till the desired test velocity is reached. An instantaneous startup condition is defined as a condition where the valves were set so that the desired test velocity is reached almost instantaneously once the flow is initiated. After a set of preliminary studies it was noticed that for $y_t/b_o = 20$ (where, y_t is the tailwater depth above the original bed level), the visual flow pattern of the scour mechanism and its associated flow field along with the scour profiles are very similar to those seen by various researchers for deep submergences. For $y_t/b_o = 4$, the flow field and the scour mechanism was very similar to that at low submergences (Balachandar et al., 2000). Consequently, it was decided to study the effect of startup conditions at $y_t/b_o = 4$ and $y_t/b_o = 20$ so that both the flow fields are accounted for.

3 Results

Visual observations with respect to test startup conditions showed that the initial rate of scouring was lower for gradual and stepwise startup conditions as compared with the instantaneous condition. This is to be expected as the test is directly commenced at a higher jet exit velocity for the instantaneous condition. Figure 1 (where, V denotes the instantaneous velocity in m/s and t denotes the time in seconds) shows the velocity-time history for the three startup conditions at $y_t/b_o = 20$. The measurements were conducted at $x/b_o = 3$ along the nozzle centreline. Figure 1a shows that for the instantaneous startup condition the velocity is highly turbulent ($u_{rms}/U_o \approx 22\%$) showing large scale changes about the mean. The white solid line represents the mean velocity. The desired flow velocity is attained in a very short time span and the mean does not change significantly after that. Figure 1b shows the velocity-time history for the stepwise startup condition. The increase in velocity by the stepwise adjustment of the valve is clearly seen in the figure. At the first setting of the valve there was no significant scour. At the second step, as scour commences, there is a slight increase in the mean velocity accompanied by an increase in the velocity fluctuations. With further opening of the valve, the mean velocity is gradually increased and at the final step, velocity distribution is similar to that noticed in the instantaneous condition. Figure 1c shows the time history for gradual change in startup condition. To enhance visualization of the velocity data for the first 600 s, a line based on adjacent averaging is drawn through the data (Figure 1c). The data clearly indicates that up to about 150 s when there is no large scale scour, there is a gradual increase in velocity with increased opening of the valve. However, beyond 150 s one notes a significant dip in the mean velocity accompanied by large scale increase in turbulence. Following this, any increase in opening of the valve causes a further increase in the velocity. The increasing discharge provides for velocities to be greater than the critical velocity needed for large scale scour and correspondingly the fluctuations about the mean increase significantly. For $t > 400$ s, one can note the presence of low frequency fluctuations (imposed on the high frequency turbulence), the origins of which are discussed in the following paragraph. It should be noted that the desired velocity was attained after $t = 2000$ s in the case of stepwise startup condition (Figure 1b) and after $t = 600$ s for gradual startup condition (Figure 1c).

In order to better understand the influence of the startup condition soon after the desired velocity is attained, the velocity-time history is analyzed at time $t = 40$ minutes at the nozzle centreline and at a distance of $3b_o$ from the nozzle exit. At this time, the flow has attained the desired velocity and no more changes are being made to the operating conditions. To distinguish turbulent features of the jet from the movement of the reattachment point, a low pass Fast Fourier Transform filtering of the data was carried out and the filtered information is presented as a solid white line in Figure 2 for $y_t/b_o = 20$. In these graphs, the occurrence of higher velocities indicates the tendency of the jet to be parallel to the initial bed at the point of measurement. The occurrence of larger turbulence indicates that the jet is bent towards the bed and the measurement point is possibly in the entraining zone of the jet. Comparing Figures 2a and 2b with Figure 2c, one can note the occurrence of a larger number of peaks (in the filtered data) in the same time interval for gradual startup condition. This indicates that though the mean flow is similar there are still features in the flow field that have not subsided to the conditions noted in the instantaneous flow. A similar analysis was carried out at other time intervals for the instantaneous condition (Figure 3) for $y_t/b_o = 20$, and one can note that the flow features gradually change with no significant difference in the filtered data beyond time $t = 6$ hours. Further, a similar behavior was noticed for the other two startup conditions and is not shown here for brevity. The velocity features (time history) near the nozzle exit for all startup conditions at the lowest submergence ($y_t/b_o = 4$) were very similar to that noticed at the highest submergence ($y_t/b_o = 20$) as seen in Figure 1. The features noticed in the gradual startup condition in Figure 1c also occur at lower submergence and is not shown here for brevity.

Figure 4a shows the effect of the startup conditions on scour at the lowest submergence at three hours from the commencement of the flow. Due to the prevailing short time scale feature of the digging phase and the occurrence of refilling over a longer period of time, the scour profiles corresponding to the refilling phase are used as a basis of discussion. One can notice the occurrence of an intermediate mound very close to the nozzle exit, which is gradually flattened out due to the refilling action. There are no large scale differences in the profiles measured that can be attributed to startup conditions. However the stepwise and gradual startup conditions indicate that the mound was slightly higher and longer. It was noticed during the test that the digging phase continued for a longer time for these two startup conditions while for the instantaneous condition the first refilling phase commenced quite quickly. Consequently, there has been more digging action and this is reflected in the profiles. This is an important aspect to note while comparing scour profiles from different studies carried out with different startup conditions. Figure 4b shows the profiles along the nozzle centreline for the three startup conditions at 24 hours from the commencement of the test for lowest submergence. No significant differences can be found in the profiles and any minor differences that were noticed earlier have vanished. Figure 4c shows the scour profiles at the three startup conditions at 36 hours for the deepest submergence. Clearly, the effects of test startup conditions are not manifest at t = 36 h. One can conclude that the effects of test startup conditions do not influence the long term scouring process.

Further, the velocity profiles obtained along the nozzle axis at the mouth of the nozzle ($x = 3b_o$) after the desired test velocity has been attained, the start of the mound ($x/b_o \cong 20$) and at the top of the mound for all the three startup conditions were consistent indicating that the flow evolves to a similar state independent of the startup conditions and conforms to the conclusion drawn from the scour profiles.

4 Conclusions

The present study indicates that the effect of startup conditions linger on for about 40 minutes as noticed from the velocity measurements. However, the scour profiles are influenced for a longer period of time and once can notice differences up to a period of three hours. Beyond 24 hours one cannot distinguish any significant differences in both velocity and scour profiles. With increasing time the low pass filtered data indicates no significant changes in the flow field characteristics after about 6 hours.

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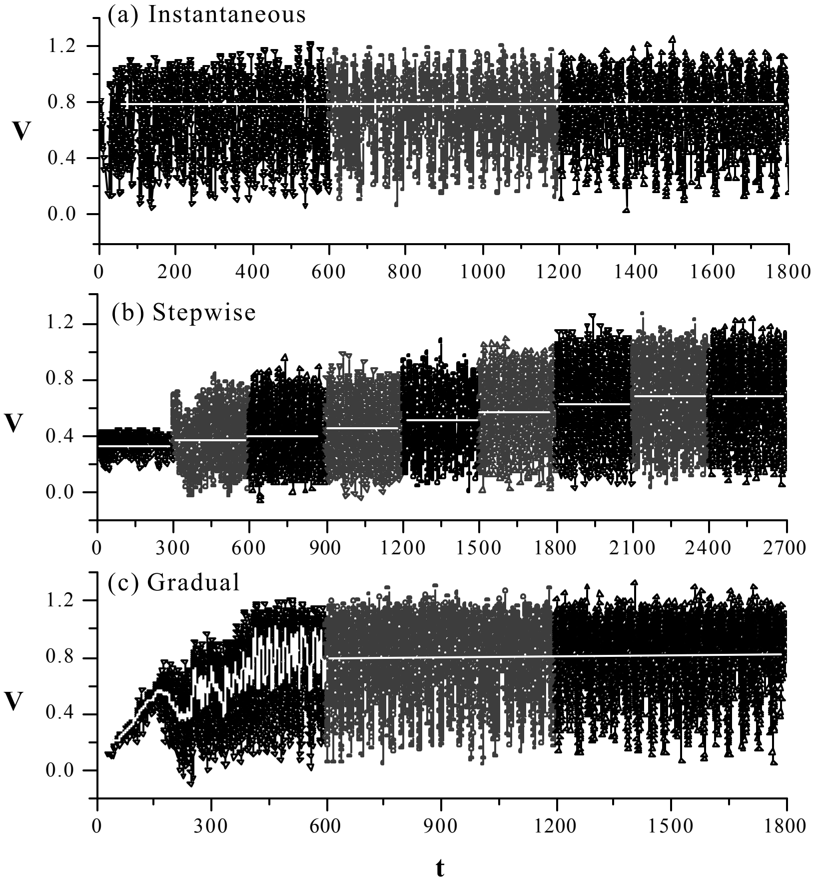


Figure 1. Effect of test startup conditions for $y_t/b_o = 20$.

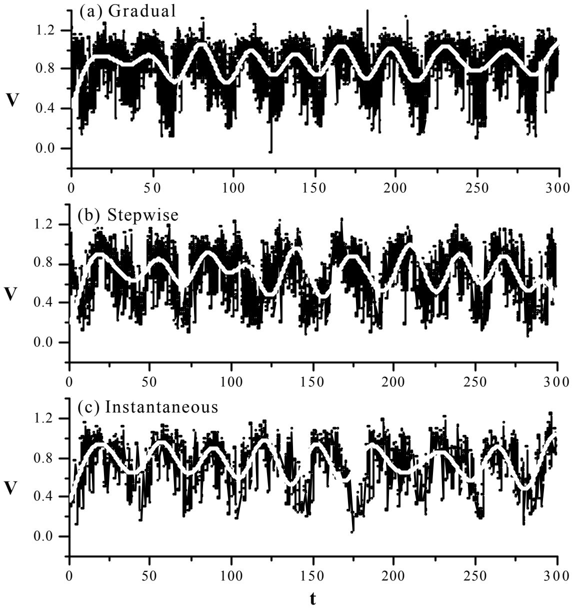


Figure 2. Comparison of different startup conditions for $y_t/b_o = 20$ at t = 40 min.

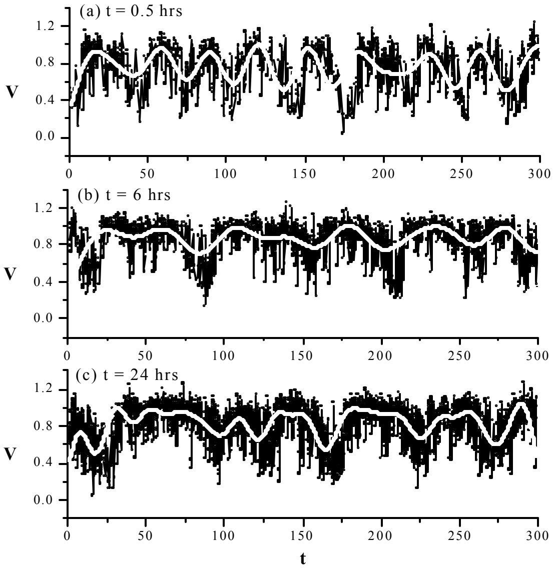
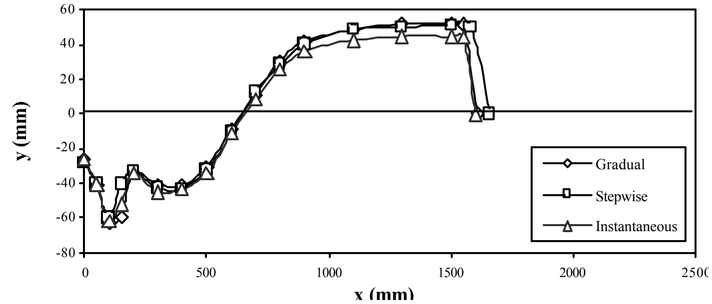
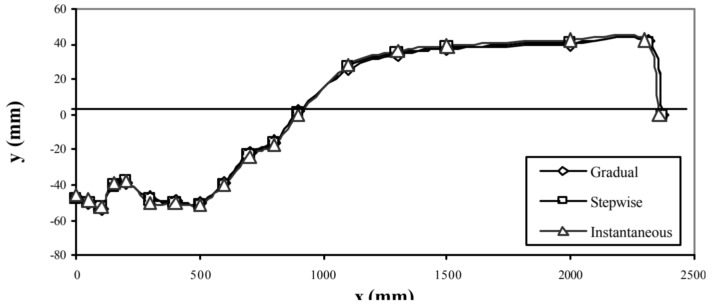


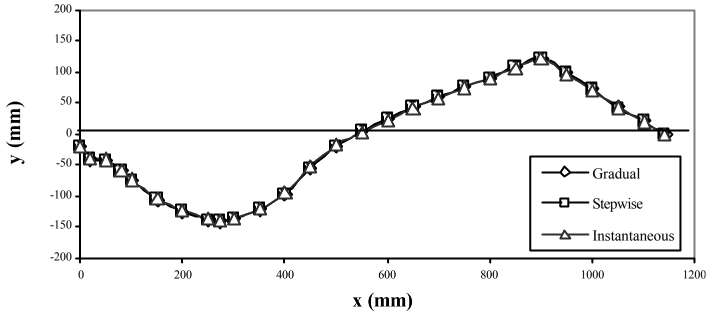
Figure 3. Velocity time history for instantaneous startup condition at $y_t/b_o = 20$.



(a) Nozzle centreline, y_t/b_o = 4, t = 3 h



(b) Nozzle centreline, y_t/b_o = 4, t = 24 h



(c) Nozzle centreline, y_t/b_o = 20, t = 36

Figure 4. Effects of test startup conditions on the scour profiles.