A preliminary study on scour at submerged weirs in live bed conditions

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ABSTRACT: Submerged weirs are low head hydraulic structures that span the full width of the channel for limiting excessive bed degradation and for bed stabilization. However, in alluvial rivers their presence in the flow also results in local scour which may undermine the structures themselves. A preliminary study on the scouring process at submerged weirs under live bed scour conditions is presented. It is observed that the average maximum scour depths upstream of the weir are found to be strongly dependent on the steepness of the approaching bedforms, and inversely dependent on weir height. The flow transitions from a surface flow regime to an impinging jet flow regime as the water level difference across the weir increases to a certain threshold; two different scour mechanisms downstream of the weir are observed corresponding to these two different flow regimes. The normalized downstream average maximum scour depth increases with increasing weir height.

1 INTRODUCTION

Local scour typically occurs around hydraulic structures in streams and rivers with erodible beds as a result of flow disturbance. Weirs or sills are low head hydraulic structures that span the full width of the channel for limiting excessive bed degradation and for bed stabilization, raising upstream water level and reducing flow velocity. However, in alluvial rivers their presence in the flow also results in a local scour phenomenon, which may undermine the structures themselves. The subject of scour downstream of bed sills has been extensively studied, and many scour prediction equations have been published (Bormann & Julien, 1991, Gaudio et al., 2000, Lenzi et al., 2003, Marion et al., 2006, D'Agostino & Ferro, 2004). However, almost all these equations were developed for unsubmerged weirs or partially submerged sills, downstream of which scouring is a result of free over fall plunging (or partially submerged impinging) jets. Study of the effect of upstream sediment supply on scouring

at bed sills is still very limited (Marion et al., 2006) due to difficulties in experimental control and scour development measurement. Depending on the upstream sediment transport conditions, the local scour can be classified as either clear water scour or live bed scour. During live bed scour, the scour process becomes complex due to upstream sediment transport at the structure and scouring occurring both upstream and downstream of the weir.

For a fully submerged weir, Wu & Rajaratnam (1996) classified flow regimes over the weir as (1) impinging jet; (2) breaking wave (or surface jump); (3) surface wave; and (4) surface jet. For the impinging jet regime, the flow over the weir plunges into the tailwater, diffuses as a plane submerged jet, and eventually hits the bed of the downstream channel. For the other three regimes, which might be collectively named the surface flow regime, the flow remains as a jet at the surface in the downstream channel, with its thickness increasing downstream because of turbulent mixing (Wu & Rajaratnam,
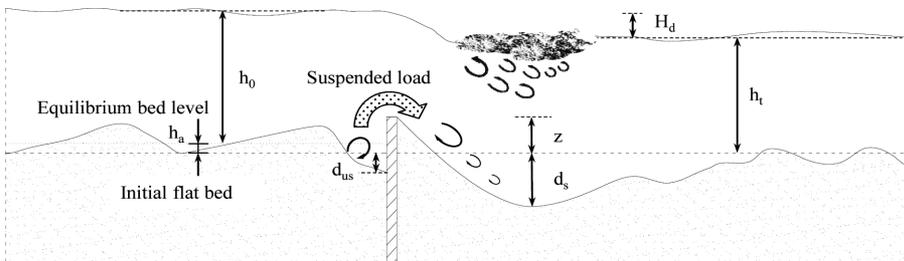

Figure 1. Sketch of live bed scour at a submerged weir.

1998). To date, flow regime effects on the scouring process at submerged weirs have not been studied. In addition, no local scouring observations have been made for submerged weirs in conditions of the propagation of upstream bedforms, which is likely to occur in alluvial rivers during flood events (see Fig. 1). This work aims to investigate the scour process at submerged weirs under live bed conditions.

2 EXPERIMENTAL METHODOLOGY

The experiments were conducted in a tilting flume, 12 m long, 0.44 m wide and 0.58 m deep, in the Hydraulic Laboratory of the University of Auckland. The flume has two pumps for recirculating both sediment and water. The speed of the main pump was controlled by a variable speed electronic control unit while the sediment pump speed was set to a constant speed that gave adequate capacity. At the upstream end of the flume, water and sediment are fed into a mixing chamber and enter the flume through a honeycomb flow straightener which effectively eliminates any rotational flow component induced in the return pipelines. At the downstream end, bed load sediment is trapped in a separate hopper-like sump and pumped to the inlet by the sediment pump; water and a small amount of suspended sediment are pumped by the main pump.

The sediment used in the experiments was coarse sand, with the median diameter, $d_{50} = 0.85$ mm and relative submerged particle density $\Delta = 1.65$. The sediment size distribution was near uniform with a standard deviation $\sigma_g = 1.3$. The weirs used in experiments were 10 mm-thick rectangular plastic plates, with the same width as the flume.

The scour development around the weir and the bed elevation changes in the approach flow were measured as a function of time throughout the experiment using Seatek's Multiple Transducer Arrays (MTAs). The instrument is an ultrasonic ranging system, comprising 64 transducers, which can detect the distance from the sensors to reflective objects. The measuring accuracy of the system is approximately ± 1 mm. A detailed description of this device was given by Friedrich et al. (2005). The transducers were installed in straight metal tubes with a diameter of 14 mm, which were mounted in the frames on the top rail of the flume. The system was operated with 40 transducers (Fig. 2). Transducers 1~2 are used for recording bed elevation changes in the approach flow, Transducers 3~5 are used for recording scour process upstream of the weir, and transducers 6~40 are used for recording the scour process downstream of the weir. For the clear water scour tests, the scour holes downstream of the weir have a relatively large length, and the scour process is very slow and lasts a long time to reach the equilibrium. Thus the measurement of the maximum scour depth was not continually recorded with stationary transducers. Instead, a moving carriage with 25 transducers mounted was used to profile the clear water scour bed as a function of time. The detailed description for transducers arrangement and maximum scour depths extraction is given in Guan et al. (2014).

During live bed scour tests, the averaged approach velocity, U_0, was determined from the calibrated flow rate and the approach averaged water depth, h_0. The corresponding critical average approach velocity, U_c, is calculated from the logarithmic form of the approach velocity profile $U_0/u_{*c} = 5.75 \log(5.53\ h_0/d_{50})$, where the average approach flow critical shear velocity $u_{*c} = 0.021$ m/s was determined using the Shields diagram for the respective particle size (Melville, 1997). In this study, 6 clear water scour tests and 31 live bed scour tests were carried out, and 3 weir heights, z, (30 mm, 40 mm, 50 mm) were used. For each weir height tested, the flowrate, Q, was systematically varied and the tailwater depth, h_t, was adjusted to normal depth at the beginning of the test by adjusting the flume slope and the level of the overflow pipe in the sump at the end of the flume. The water surface profiles were measured using a point gage with an accuracy of ± 1 mm to determine the water level difference, H_d, across the weir. The average approach flow depth, h_0, is calculated as $h_0 = h_t + H_d - h_a$, in
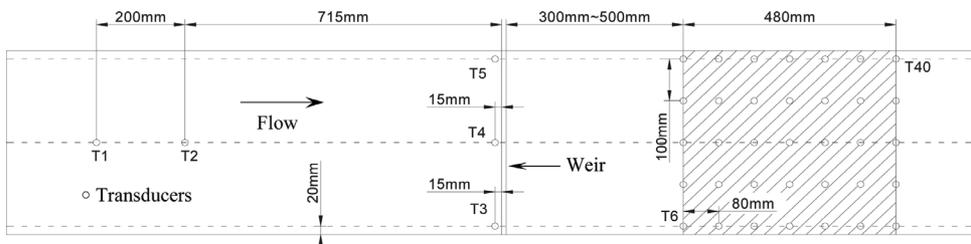

Figure 2.   Transducer arrangement for bed elevation changes in the scour zone.

which h_a is aggregation height in the equilibrium stage. To optimize the amount of data obtained during the available time, a continuous experimental method was used to reduce the required setup time. For each weir height, the higher velocity tests were a continuation of a previous lower velocity test; the flow velocity was increased at the end of the previous test to reach the equilibrium for the next velocity. The same method was used by Sheppard and Miller (2006). For all the tests, only one tailwater depth, $h_t = 150$ mm, was used.

Bed elevation changes at all locations shown in Figure 2 were continually recorded by the 40 transducers during all live bed scour tests. The measurement environments were very challenging due to the fast evolution of underwater mobile topographies. The raw data records are inevitably contaminated with noise from various sources, such as reflections of suspended load, air bubbles or instrumentation contact errors. The contamination levels vary for different flow rates and different measurement locations. Where the slope between a point and its neighbours was larger than a certain threshold, the data were treated as erroneous spikes and given an interpolated value. For this study, due to the short time interval between two adjacent recorded points, a threshold of 2 mm per time step was used. This technique is based on work by Friedrich (2010).

After bed topographical data pre-process, the filtered time-series dataset $X_i(t)$ for transducer i ($i = 1\sim40$) was obtained with zero datum at the initial flat bed level. Upstream bedform characteristics and the upstream aggregation height were extracted from $X_1(t) \sim X_2(t)$.

The location of the maximum scour depth upstream of the weir shifted in the frontal zone of the upstream face of the weir. This is because of the irregular shape of approaching migrating bedforms. In this study, the measurement points were set on the centreline of the flume and near the side walls. Based on observations during preliminary live bed scour tests, the maximum scour depths frequently occur at these three locations. For each live bed scour test, the evolution of maximum scour depth upstream of the weir, $d_{us}(t)$, was extracted from datasets $X_3(t) \sim X_5(t)$.

It was observed that a scour and fill process occurred immediately upstream of the weir during live bed scour tests. The scour hole at the upstream base of the weir develops as a bedform trough approaches the weir, and reaches its maximum depth when the bedform trough arrives at the weir, then gradually fills as the next dune crest approaches. Therefore, the average value, d_{us_a}, of the maximum scour depth during a scour and fill cycle is adopted as the upstream average maximum scour depth in this study.

The scour process downstream of the weir is recorded by datasets $X_6(t) \sim X_{40}(t)$. For each live bed test, the evolution of maximum scour depth downstream of the weir, $d_s(t)$, was extracted from datasets $X_6(t) \sim X_{40}(t)$. The average equilibrium value, d_{s_a}, of data series $d_s(t)$ for each live scour tests was calculated.

3 RESULTS AND DISCUSSIONS

For clear water scour, the equilibrium of the scour process is defined as the condition when the dimensions of the scour hole do not grow with time (Melville & Chiew 1999). Due to flume size limitation and the long duration of the clear water scour process, only 6 clear water scour tests were done in this study. Under clear water scour conditions, a small scour hole was observed at the upstream base of the weir. This scour hole was produced by weak vortices, generated by the interaction of the approach flow and the associated back flow. The temporal development of maximum scour depth downstream of the weir has three stages: 1) initial fast stage; 2) progressing stage; 3) equilibrium stage (Guan et al., 2014).

For live bed scour, the scour occurs both upstream and downstream of the weir, and sediment transport processes are highly influenced by strong turbulence created by the submerged weir. At the upstream face of the weir, strong downflow and secondary flow are generated when a bedform trough is approaching the weir upstream face. The downflow interacts with the main flow to create principal vortices which cause the scour process upstream of the weir. The secondary flows alter the directions of the rotational axis of the principal vortices, resulting in helical motions of sediment in the scour hole. Generally, these helical motions of sediment laterally move from bottom to top in the frontal zone of the weir upstream face. As these motions move to the weir top edge, the sediment is entrained by the main flow as suspended load, and is injected into the downstream scour hole.

As the flow passes over a dune crest, a flow separation zone forms on the leeside of the dune. Associated with the separation zone is a turbulent-free shear layer generating large scale eddies that travel through the flow domain and toward the surface while dissipating (Stoesser et al., 2008). Therefore, it can be inferred that periodic interactions between this flow structure in the dune trough and the helical vortices at the upstream base of the weir result in a scour and fill process occurring immediately upstream of the weir.

Figure 3 shows the normalized upstream average maximum scour depth, d_{us_a}/h_t, as a function of flow intensity U_0/U_c. For the live bed scour
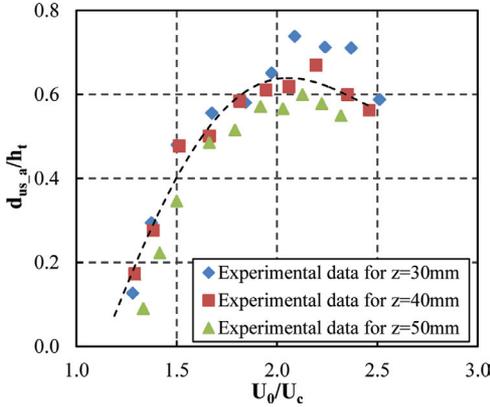
Figure 3. Normalized upstream average scour depth versus flow intensity.

Figure 4. Approaching bedform steepness versus flow intensity.

Figure 5. Flow regimes over the submerged weir.

conditions, the scour and fill process upstream of the weir is induced by the approaching periodic bedforms. As shown in Figure 3, for each weir height, the normalized scour depth has a significant increasing trend for U_0/U_c between 1.2 and 2.2, and then decreases as U_0/U_c increases. A parallel plot of bedform steepness, η/λ (η, λ are bedform height and length, respectively), against U_0/U_c is shown in Figure 4. The bedform steepness is found to be independent of weir height. The developing trends in Figures 3 and 4 clearly show that bedform steepness has a strong correlation with inducement of the scour and fill process upstream of the weir. Another trend that can be seen from Figure 3 is that d_{us_d}/h_t increases as the weir height decreases. This is because aggradation occurs in the approach flow and upstream of the weir. For higher weir heights, the aggradation height has larger values under the same flow intensity conditions.

In this study, the tailwater was controlled to be at a constant level, and the head difference across the weir increases with both increase of flow rate and weir height. As indicated in Figure 5, the flow regime over the weir transits from a surface flow regime to an impinging jet flow regime as the approach flow discharge increases to a weir-height dependent threshold. According to previous research (Wu & Rajaratnam, 1996, Wu & Rajaratnam, 1998), the flow regimes are dependent on the head difference across the weir and the approach flow rate. Because the tailwater depth is controlled, the head difference across the weir is only influenced by weir height and flow rate (or intensity) in this work. Experimental results show that the transition stage between the surface flow regime and impinging jet regime occurs at a value of the parameter $\kappa = (U_0/U_c)(z/h_t)^{0.2} \approx 1.45$. For the surface flow regime ($0 \leq \kappa \leq 1.45$), the flow remains
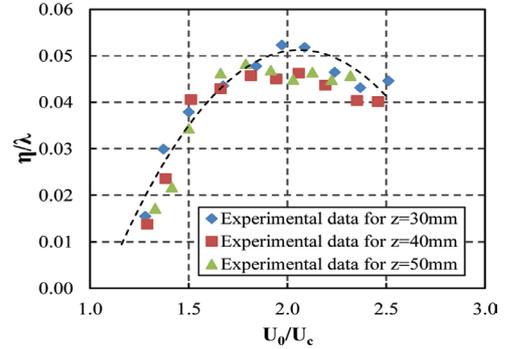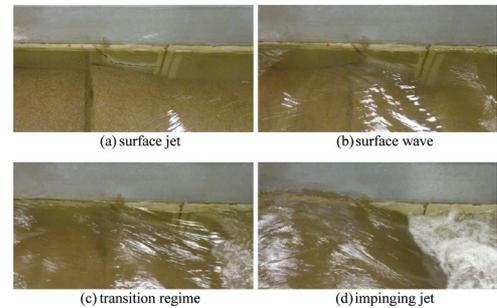
as a surface jet downstream of the submerged weir, and the scour hole downstream of the weir forms due to the increasing jet thickness and turbulence mixing with the tailwater (Fig. 5a, b and c). For the impinging jet regime ($\kappa \geq 1.45$), the flow plunges towards the bed, diffusing as a plane submerged jet, impacting the downstream bed, and inducing scour downstream of the weir (Fig. 5d).

Figure 6 shows the normalized value of the scour depth downstream of the weir, d_{s_d}/h_t, as a function of flow intensity U_0/U_c. It can be seen that the scour depth downstream of the weir has an increasing trend as the weir height increases. For each weir height, the trend of data points shows that the normalized scour depth appears to reach its peak at the transition ($U_0/U_c = 1$) from clear water scour to live bed scour conditions, then experiences a significant drop just beyond the peak, and after reaching its minimum it quickly increases again.

For the live bed scour conditions ($U_0/U_c > 1$), the normalized downstream scour depth d_{s_d}/h_t decreases to its minimum value then increases again with the increase of flow intensity U_0/U_c for each weir height. It is observed that the minimum scour depths occur almost as the flow regime over
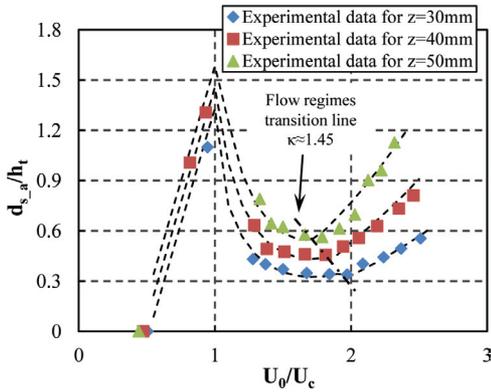
Figure 6. Normalized downstream average (equilibrium) scour depth versus flow intensity.

the weir changes from the surface flow regime to the impinging jet regime (see Fig. 6). As explained above, the impinging jet regime has a direct impact on the downstream bed, which can induce a larger erosive force in the scour hole compared with the scour mechanism under the surface flow regime. The downstream equilibrium scour depth is a balance between the upstream sediment supply rate and scour rate in the scour hole. For the surface flow regime under live bed scour conditions and increasing flow rate, the upstream sediment supply rate is larger than the scour rate, but the rate of increase of sediment supply is less than the rate of increase of scour, resulting in a decreasing trend in the scour depth. As flow conditions change to the impinging jet regime, the scour rate becomes increasingly larger than the upstream sediment supply rate with increasing scour depth downstream of the weir.

For live bed scour at piers or abutments, a similar trend occurs. Scour depth initially reduces with increase in approach flow velocity, reaches a minimum value, and then increases again toward a second maximum. The second maximum occurs at about the transitional flat-bed stage of sediment transport on the channel bed and is termed the live bed peak (Melville, 1992, 1984). Although Figure 6 shows a similar trend as that of scour at piers and abutments, whether the scour depth downstream of the weir reaches a live bed peak at higher flow intensities (bedform plane bed stage and antidune stage) is still unknown due to insufficient experimental data and different scour mechanisms.

4 CONCLUSIONS

Live bed scour and bed load influence at submerged weirs were experimentally studied. Under live bed conditions, a scour and fill process occurs immediately upstream from the weir due to periodic approaching bedforms and flow intensity. The average maximum scour depths upstream of the weir are found to be strongly dependent on the steepness of the approaching bedforms, and inversely dependent on weir height.

For live bed scour downstream of the weir, the scour mechanism changes as the flow regime over the weir transitions from the surface flow regime to the impinging jet regime. The transition stage between the surface flow regime and the impinging jet regime occurs at $\kappa = (U_0/U_c)(z/h_t)^{0.2} \approx 1.45$. Under surface flow regimes, the scour process is due to the downstream increasing jet thickness and turbulence mixing with the tailwater and the scour depth downstream of the weir is increasingly reduced by increasing upstream sediment supply. Under impinging jet regimes, the downstream scour process is caused by jet diffusion and direct impact forces by the impinging jet on the bed; the scour depth starts to increase in response to a rapidly increasing scour rate downstream of the weir. The normalized downstream average maximum scour depth increases with increasing weir height.

Further experiments will be carried out to investigate the quantitative relationship between scour variables and experimentally controlled conditions (such as flow conditions, sediment sizes and structure geometries).

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