ABSTRACT

Characteristics of flow over uniform gravel-beds at the threshold of motion, within scoured zone of channel contractions and in the developing scour holes at cylindrical piers were measured using an acoustic Doppler velocimeter (ADV). Also, the characteristics of scour within channel contractions and at piers were studied experimentally.

Investigations were carried out to understand the response of the turbulent flow characteristics in zero-pressure gradient flow over uniform gravel-beds at the near-threshold condition. The vertical distributions of time-averaged velocity, turbulence intensities and the Reynolds stress were measured and analyzed. The value of the von Karman constant obtained from the concept of the mixing-length is 0.35. The boundary shear stresses were determined by three independent methods, such as the Clauser method, from the Reynolds stress profiles and bed-slopes. In the inner-layer (depth less than 0.23 times the boundary-layer thickness or flow depth whichever is lower), the universal logarithmic-law of wall for the time-averaged streamwise velocity holds with the von Karman constant 0.35 and a constant of integration 7.8; while in the outer-layer, the law of the wake defines the velocity profiles with an average value of the Coles' wake parameter 0.11. An alternative approach for the prediction of velocity profiles based on the power-law is also put forward. The equation for the friction factor is obtained from the depth averaging of the velocity profile. The turbulence intensities being non-isotropic are defined by an exponential-law. The values of the Shields parameter for the threshold of gravel motion obtained experimentally correspond closely with the curve obtained from the modified model of Dey (1999a) considering the present logarithmic-law of velocity. For all the aforementioned parameters, thorough statistical and error analyses of the experimental data are done.

The laboratory experimental results on scour in long contractions for uniform and nonuniform sediments (gravels and sands) under clear-water scour are used to carry out the flow field and parametric studies. The vertical distributions of time-averaged velocity components, turbulence intensities and Reynolds stresses along the centerline of channel contractions are presented. The bed shear stresses estimated using the measured Reynolds stresses are very close to the threshold values in the scour hole. The equilibrium scour depth increases with an increase in sediment size for gravels, but the curves of scour depth versus sediment size have considerable sag at the transition of sand and gravel. The scour depth gradually reduces with an increase in densimetric Froude number for gravels. However, for

sands, the trend is opposite. Also, the scour depth increases with an increase in approaching flow depth at lower flow depths, but it becomes independent of flow depth at higher flow depths. Further, the scour depth increases with a decrease in channel opening ratio. In case of nonuniform sediments, the scour depth is significantly reduced due to the formation of an armor-layer in the scour hole. Using the experimental data, an empirical equation for the maximum nondimensional equilibrium scour depth (scour depth - approaching flow depth) is developed, which depends on excess approaching flow Froude number, sediment size - approaching flow depth ratio, and channel opening ratio. Based on the energy and continuity equations, an analytical model for the computation of clear-water scour depth in long contractions is developed with and without sidewall correction for the contracted zone. The model is extended for live-bed scour condition by introducing the sediment continuity equation. The potential predictors of the maximum equilibrium scour depth in long contractions are compared with the experimental data. Also, the scour depth within long contractions with thin surface-layers of gravels is studied and the influence of different parameters on the scour depth is determined. The scour depth within a channel contraction with surface-layers is greater than that without surface-layers for the same bed sediments and flow condition. The clear-water scour model is used to compute the maximum equilibrium scour depths within long contractions with gravel-layers. In case of piers embedded within long contractions, a theoretical method is put forward to compute the maximum equilibrium scour depth. It suggests that the scour depth at piers embedded within long contractions is the summation of the scour depths at corresponding pier and within channel contraction. In addition, the effects of various parameters on scour depth at piers embedded within long contractions are explained.

The turbulent flow characteristics of horseshoe vortex within developing (intermediate stages and equilibrium) scour holes at cylindrical piers are analyzed. Experiments were conducted with a sand-bed, as the bed sediment has little influence on the vortical flow field around a pier and also it was convenient to stabilize the scoured bed. Three intermediate scour holes (having scour depths of 25 percent, 50 percent and 75 percent of equilibrium scour depth) at a circular pier and equilibrium scour holes at circular and square piers of sides equaling the diameter of the circular pier were used for the flow field study. The contours of the time-averaged velocities, turbulence intensities and Reynolds stresses at different azimuthal planes (0°, 45° and 90°) are depicted. Vector plots of the flow field at azimuthal planes reveal the evolution of the characteristics of the horseshoe vortex flow associated with a downflow from intermediate stages to equilibrium condition of scour holes. The bed shear

stresses on the scoured bed are determined from the Reynolds stresses distributions. Also, the flow characteristics of the horseshoe vortex are discussed from the point of view of self-preservation with the velocity and turbulence characteristic scales. The observation is that the flow and turbulence intensities in horseshoe vortex flow in a developing scour hole are reasonably self-preserving.

The experimental results on scour at piers in uniform and nonuniform gravels under clear-water scour condition are used for the detailed parametric study. The equilibrium scour depth is related to the pier size, gravel size and gradation and approaching flow depth. The equilibrium scour depth increases with a decrease in gravel size and an increase in pier width. The scour depth also increases with an increase in flow depth for lower flow depths. However, the scour depth becomes independent of flow depth at higher flow depths. The nonuniform gravels reduce the scour depth due to formation of an armor-layer. The influence of the aforestated parameters on the magnitude of scour depth in gravel-beds is substantially different as compared with sand-beds. Consequently, new sediment size factors are developed for scour at piers. The time scales to represent the time-variation of scour depth in uniform and nonuniform gravels are obtained. For uniform gravels, the nondimensional time scale increases with increase in pier Froude number and gravel size; whereas for nonuniform gravels, the nondimensional time scale decreases with an increase in geometric standard deviation of particle size distribution of gravels. In general, the scour depth in gravel-beds is greater than that in sand-beds. Using the experimental data, an empirical equation for the maximum nondimensional equilibrium scour depth (scour depth - pier width ratio) is developed, which depends on excess pier Froude number, approaching flow depth - pier width ratio, and pier width - gravel size ratio.

The experimental findings of clear-water scour at piers, embedded in a sand-bed with a thin armor-layer of gravels are used to classify three cases of scour holes at piers in armored beds, which depend on the pier width, flow depth, armor-gravel and bed-sand sizes. The scour depth at a pier with an armor-layer is greater than that without armor-layer for the same bed sediments, if the secondary armoring formed within the scour hole is scattered. On the other hand, the scour depth with an armor-layer is less than that without armor-layer for the same bed sediments, when the scour hole is shielded by the secondary armor-layer. The design method is developed for the estimation of maximum equilibrium scour depth based on the empirical relationships of K-factors, which account for the effects of flow depth, pier shape, flow intensity, bed sediment and armor-gravel size on scour depth for individual cases of scour holes.

In addition, the sediment size factors for scour at abutments in gravel-beds are obtained. Combining pier and abutment scour data, an integrated approach for the evaluation of the equilibrium scour depth at a bridge foundation is proposed.

Keywords: Open channel flow; steady flow; turbulent flow; channel contraction, piers; gravel-beds, scour; sediment transport; hydraulics.