SYNOPSIS

An experimental investigation of incipient motion criteria for non-uniform gravel and coal bed mixtures at flow near to critical and at low relative depths has been carried out in an experimental flume with the object of developing suitable predictive relationships, in terms of Shields' parameter and mean velocity.

The non-uniform gravel and coal bed mixtures have been generated by varying the standard deviation and effective grain size of the mixtures considering normal distribution of the sediment grain size. For non-uniform grain size Christensens' relationship for evaluating effective diameter for incipient motion criteria has been adopted in the present investigation.

A total of forty eight test runs covering the two bed materials i.e. gravel and coal, with varying effective diameters and non-uniformity coefficients, designated as ratio of standard deviation to effective diameter, have been made in the present study.

Detailed measurements of the velocity, water surface profile, dynamic pressure drop recorded by a Preston tube and discharge have been made at flow conditions corresponding to incipient motion which is in accordance with the definition of weak movement by Kramer. For each run, detailed measurement

of the velocity distribution at several locations within the test section has been made with a view to studying the effect of varying roughness, non-uniformity coefficient and non-uniform nature of flow on the distribution of boundary shear.

To determine the distribution of boundary shear by energy gradient approach, the test section has been divided into several small segments. For each small segmental element, the specific energy gradient has been estimated separately. Using these values of energy gradient, the distribution of bed shear stress has been obtained and this is then compared with the mean shear stress estimated from average energy gradient of the test section as a whole.

The distribution of shear stress has also been obtained from the dynamic pressure drop recorded by a Preston tube. To convert dynamic pressure drop to boundary shear it is necessary to adopt a suitable velocity distribution law. The velocity distribution law in the present study has been obtained through the best fit curve of the measured velocity expressed in conventional form, i.e. ratio of local velocity to shear velocity versus ratio of flow depth to equivalent sand roughness height 'K_s' after Nikuradse with respect to a suitable datum.

The estimation of 'K_s' for various runs has been made based on the friction factor versus Reynolds number diagram after Taylor, the overall friction factor and bulk Reynolds number of flow having been determined from the processed experimental data. Using the velocity distribution law, the pressure shear relationship has been obtained following the approach suggested by Hwang et al. The computed pressure shear ratios are then adopted for conversion of dynamic pressure drop to shear stress. These shear stress values are then compared with those evaluated from energy gradient approach and it has been observed that the nature of distribution is similar and is of non-uniform in character.

The incipient motion criteria of the bed particles have been formulated in terms of critical shear stress after Shields', mean velocity criteria after Yang and Garde as well as with the criteria developed after Muller et al., which takes into account the effect of hydrodynamical lift on the bed particle.

Significant variation of the Shields' parameter designated as τ_* has been observed when the entrainment function has been evaluated at various locations in the test section for a particular experimental run, compared to Shields' accepted value of 0.06 in the rough turbulent zone. The experimental points have been observed to lie on a slope of -2 on the Shields' diagram. This, however, does not prove that the Shields' criterion is invalid since this can as well be attributed to spurious correlation as shear stress occurs both as dependent and independent variable, viz. Shields' parameter τ_* or $\tau_o/(\rho_s-\rho)g\, d_e$ and boundary particle Reynolds number $u_* d_e/\nu$ or $\sqrt{\tau_o/\rho}\, d_e/\nu$, where τ_o is the bed shear stress, ρ and ρ_s being the densities of the fluid and the sediment particles respectively, g is the acceleration due to gravity, d_e the effective diameter after Christensen, u_* the shear velocity and ν the kinematic viscosity of fluid. To eliminate the possible effect of spurious correlation, the Shields' diagrams have been replotted considering different experimental runs for identical relative depth $\bar{h}/10d_e$, where $\bar{h}$ is the average depth of flow between two consecutive cross sections. The plot shows that the scatter lies on a curved line. On the same plot the results of Bogardi and Rakoczi have also been shown at comparable relative depths. From the figure it has been observed that the relative roughness has a profound effect on τ_* i.e. the Shields' parameter.

Apart from above, the entrainment criterion has been formulated in terms of average shear stress estimated from overall energy gradient considering incipient motion for the test section as a whole. The plot shows a scatter of variation of Shields' parameter from 0.022 to 0.078 , with boundary particle Reynolds number varying from 228 to 1991 and the scatter lies more or less on a horizontal band.

In order to formulate a new predictive relationship for the Shields' parameter τ_* a dimensional analysis of the variables has been carried out. The analysis indicates the dependence of Shields' parameter on relative depth, non-uniformity coefficient, discharge and slope. Regression analysis of the experimental data has furnished the coefficient of the functional relationship. The new predicted values of Shields' parameter have been found to be in good agreement with the measured values, the coefficient of correlation being of the order of 0.98.

The incipient motion criteria has also been looked upon from the angle of armouring effect following Odgaard. It is assumed that the exposed particles of the armour layer are at incipient motion and their size is related to the bed shear after Shields', which means that the size of the exposed bed particle is expected to show a statistical variation similar to that of critical shear stress i.e. τ_{oc}. The dimensionless grain size, according to Gessler, is expected to follow the normal distribution of $\left[\tau_{oc}/\tau_o\right]$ with standard deviation of 0.57. Accordingly, the initial grain size distribution and the predicted armour layer grain size distribution of the present experimental runs have been made and the result is compared with those of other investigators and the discrepancies explained.

Shen et al, have proposed a modified criterion for prediction of armoured layer distribution. The approach is based on the concept of sheltering of bigger particles as well as an increase in turbulence with decrease in relative particle size. In the present study hiding factor has been considered based on the approach suggested by Einstein and considering the probability of stay as a function of relative shear stress and hiding factor. Based on above and considering the variation of critical shear stress having a Gaussian normal distribution with standard deviation of 0.57, the measured and the predicted armour coats distribution for few typical runs have been made and these are then compared with the original distribution and found to be satisfactory.

The other approach of expressing incipient motion criteria is in terms of mean velocity and of the various relationships existing, the relationships proposed by Yang and Brownlie appear to be most promising. The results of the present investigation have therefore been analysed and plotted in accordance with Yang's parameter. It has been observed that the experimental data show some scatter and the best fit relationship shows a value of 1.816, which is slightly lower than the value 2.05, indicated in Yang's relationship for flow conditions in the rough turbulent region.

The results of the present investigation have been analysed and plotted in accordance with criteria suggested by Garde for incipient motion based on relative roughness, mean velocity of flow, and the properties of the sediment and the flowing liquid. The plot shows a scatter of experimental points and based on regression analysis the best fit curve through the experimental points has been determined and found to be satisfactory.

Brownlie, based on the dimensional analysis of the variables involved has shown that the mean velocity in non-dimensional form expressed as grain Froude number

$$F_g = \frac{V_c}{\sqrt{\left(\frac{\rho_s - \rho}{\rho}\right) g \, d_{50}}} ,$$

(where V_c is the critical mean flow velocity at incipient motion and d_{50} is the grain size for which 50% by weight of bed material is finer) is a function of transformed Shields' parameter, (which is again a function of fluid and sediment properties) discharge, relative depth, non-uniformity coefficient and energy slope. Following similar procedure, the test results of the present study have also been analysed and a suitable functional relationship has been proposed after regression analysis. The coefficient of correlation has been found to be of the order of 0.44 , which means that the correlation is not up to the expectation.

Looking at the incipient motion criteria as that corresponding to that when moment due to hydrodynamic forces is equal to that of restoring forces, a relationship correlating ratio of average velocity at the top of the grain to fall velocity with angle of dislodgement of the particles and coefficient of lift and drag has been formulated on the lines proposed by Muller et al. In the present investigation the lift coefficient has been evaluated indirectly based on Einstein and El Samni relationship, the other parameters, i.e. coefficient of drag and dislodgement angle having been determined experimentally. The predicted and the measured values of average velocity at the top of the grain have then been compared and the results have been found to be satisfactory.