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SCOUR DOWNSTREAM OF HYDRAULIC JUMP

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SUMMARY

This paper reports on the scour of loose bed of sand downstream of hydraulic jump formed over a rigid apron. Different kinematic conditions are produced to investigate the scourholes and their development. The experimental data are used to study the relationship between the scour depth and the apron lenght. Some photographic investigations and LDA measurements are made to show the influence of the flow structure in the roller zone of the jump and the turbulence features at the end of the jump on the scouring process.

1.0 INTRODUCTION

Scour of loose beds located near the hydraulic structures is a problem of considerable importance in the flied of hydraulic engineering. Scour downstream of hydraulic jump, used as energy dissipator, has received considerate attention by many researchers. Most of these investigations forcused on studying the development of scourhole over time (Colaric et al. 1967), the similarity of scour profiles (Farhoudi et al. 1985), and proposing some formulas to calculate the scour depth for particular flow conditions (Valentin 1967, Razavan 1967, Gunko et al. 1971 and Catakli et al. 1973).

When dealing with the jump as a kinetic energy dissipator, it is usually assumed that the energy of the incoming supercritical flow, there is actually, within the flow, some supplementary kinetic energy, as turbulence energy, which may be called macroturbulent energy (Hartung et al. 1967), This residual macroturbulent energy has its maximum magnitude just downstream of the roller, and decays in the flow direction. It has been a common practice to express the turbulence features of the flow downstream of the jump by K_V, called turbulence intensity. This parameter has been investigated by many researchers. Rouse et al. (1959) and Razavan (1967, 1971) found that, starting from the jump, K_V decreased in the flow direction until it reached a constant value. Reach et al. (1971, 1976) showed the dependence of K_V on the inflow condition. Ortiz (1982) emphasized the great influence of the basin shape on the K_V values.

According to Shields, the incipient motion condition of the sand particles will take place when the mean bed shear stress τ_0, exerted by the flow downstream of the jump, reaches the critical value $(\tau_0)_{cr}$ defined by the following relationship:

$$(\tau_\star)_{cr} = \frac{(\tau_0)_{cr}}{(\gamma_s - \gamma) d_{50}} = f\left(\frac{d_{50} U_\star}{\nu}\right). \qquad (1)$$

In the problem studied a considerable movement of the sand particles was observed downstream of the jump at a lower mean shear stress value than the critical one defined by eq. (1). Such movement is thought to be caused by the residual macroturbulent energy downstream of the jump. In order to define the mean flow condition downstream of the jump and the incipient motion condition, a flow parameter T_r was used as the ratio of critical shear stress $(\tau_0)_{cr}$ to the actual mean value τ_0:

$$T_r = \frac{(\tau_0)_{cr}}{\tau_0} = \frac{(\tau_0)_{cr}}{\tau_0}. \qquad (2)$$

The influence of the mean flow condition and the turbulence characteristics of the stream at the end of the jump on the shape and dimensions of the scourholes are investigates are investigated in the present study. The relation between the scour depth (e) and the apron lenght (L) on which the jump is formed, was also studied (Fig. (1)).

2.0 EXPERIMENTAL SET-UP AND TRIALS

The experimental investigations were conducted in the laboratory of the International Centre for Advanced Mediterranean Agronomic Studies of Bari (Italy) in channel 7.72 *m* long having a rectangular section 0.3 *m* wide by 0.4 *m* deep. Two movable gates were constructed at the upstream and dowmstream ends of the channel to control the position of hydraulic jumps. A wooden plate and removable rows of concrete blocks were placed afted the upstream gate to obtain various apron lenghts (Fig. (2)).

The channel bottom was covered with erodible material consisting of guite uniform sand particles with a diameter d_{50} of 2 *mm* and a specific weight of 2.56 g/cm^3. The thickness of the sand layer was 5 *cm* and extended for the residual lenght of the channel with a longitudinal slope of 0.033%. Eight main series of experiments have been conducted. In each series, a defined jump was formed and a certain number of runs were performed with different apron lenghts. The total number of test runs was 44. The data collected in each run were the discharge Q, the jump parameners (y_1, y_2, L_j), the rigid apron lenght L, and the longitudinal scour profiles. These parameters are reported in the table below with the minimum (L_{min}) and maximum (L_{max}) lenghts of the used aprons.

For some runs, the growth of the maximum scour depth (e_m) over time was measured. It was found that for a time duration of eight hours, the rate of increase of e_m tended to be relatively slow and an equilibrium state was almost reached.

3. ANALISTICS OF EXPERIMENTAL RESULTS

For each experimental series, T_r values were obtained using eq. (2). In fig. (3) the maximum scour depth e_m for each run was plotted against the corresponding apron lenght L. The downstream depth y_2 was used to normalise the data. From the figure it is clear that e_m depends on the K_V parameter (that is function of L) and the T_r parameter. The analysis of the scourholes shows that the profiles, reported in dimensionless form (e/e_m versus X/X_0), were similar.

No	y_1 (m)	y_2 (m)	q (m^2/s)	L_{min} (m)	L_{max} (m)
1	0.013	0.129	0.0353	0.50	1.40
2	0.025	0.093	0.0360	0.45	1.35
3	0.015	0.155	0.0448	0.84	1.68
4	0.019	0.162	0.0520	1.10	1.82
5	0.021	0.172	0.0588	1.30	1.84
6	0.012	0.136	0.0355	0.80	1.58
7	0.021	0.103	0.0363	0.62	1.46
8	0.027	0.114	0.0457	0.96	1.56

The experimental data were compared with the results of the some proposed formulas for the calculation of the maximum scour depth.

Catakli et al. (1973) proposed a formula for the case of a basing ending just at the jump downstream end. Futhermore, this formula was developed empirically for spetial experimental arrangements to which its application should be confined.

Taking into account the effect of the macroturbulent energy on the scouring process, using K_V, Rasavan (1971) developed the following formula:

$$e_c + y_2 = \frac{y_a}{1+2.5K_V}. \qquad (3)$$

To calculate the K_V parameter, Koumine (Ortiz 1982) suggested the following empirical formula:

$$K_V = \frac{1.8}{\frac{x}{y_2} - 1.69\sqrt{\left(\frac{y_2}{y_1}-4\right)+0.195\left(\frac{y_2}{y_1}-4\right)}}. \qquad (4)$$

This formula is valid for inflow Froude number $F_{r1} > 3.2$. In this study eq. (4) was used except for the series 2, for which Klais' formula (valid for $2.2 < F_{r1} < 6.3$) was applied.

A comparison of the calculated scour depth (e_c) using eq. (3) with the measured values is reported in fig. (4). The figure shows that Rasavan's formula has a satisfactory agreement except for low values of L/y_2 for which the erodible bed was located in the vicinity of the roller zone. The agreement between the measured and calculated data for L/y_2 values greated than 8 was due to a good evaluation of K_V (which varies along the longitidinal direction) obtained by eq. (4). On the contrary, for low values of L/y_2, the K_V parameters are scattered and not well fitted by the formulas proposed in literature.

4. LARGE-SCALE EDDY FEATURES IN THE JUMP AND TURBULENCE INTENSITY INVESTIGATION

The importance of the nacroturbulence, downstream of hydraulic jump, and the results obtained in the photographic study conducted by Long et al. (1991) induced us to investigate into the relation which might exist among these different phenomena and into the features of the scouring process downstream of the jump.

This was made possible by the use of a video camera (100 pictures per second) to study a jump with an in flow Froude number Fr_1 equal to 6.45, in the laboratory of the Water Engineering Department of Bari Polytechnic (Italy). The video images were taken at rate of 100 pictures/sec and the video tape could then be played at slower speeds, so that one picture every 0.04 *sec* could be studied individually. The fluctuations of the toe of the jump were shown to have a period of about 1.55 *sec.*

The fluctuations of the jump influence the turbulent components of velocity within the downstream reach of the roller zone.

Therefore, a Laser Doppler Anemometer (LDA) type 55x Disa was used to a measure the instantaneous velocity and the turbulence intencity of the flow downstream of the samé jump.

The measurements were taken in terms of velocity profiles at downstream sections located at $L/y_2 = 7.47$, 10.23 and 11.87.

A Fourier analysis was also performed for fluctuating velocities, and frecuencies ,below 5 Hz were found to be dominant. Fig. (5) shows the amplitude spectrum of the turbulent components of velocity at a point of a section downstream of the jump. Moreover, it may be observed that the spectrum shows higher values in the $0.1 - 1$ Hz range, which includes the pulsation frecuency of the jump ($f = 1/1.55 = 0.5$ Hz) observed in the photographic investigations. The fluctuations of the jump are to influence the turbulence components of velocity within the downstream reach of the roller zone. These processes are to be main cuase of the incipient motion of the sand particles of the erodible bed located downstream of the jump. This conclusion has been emphasized when some video images (not enclosed) concerning the movement of the sand particles located downstream of the apron on which the jump was formed, were studied. The analysis of such images suggested that a steady particle movement did not exist but the particles appeared to move under the effect of periodical flow pulsations caused by the previously observed periods of immigration vortex downstreamwards.

The turbulence intensity K_V values were calculated for the three considered profiles and plotted versus the flow depth y, as shown in fig. (6). The figure shows that K_V decreased along the longitudinal direction with its highest values near to the channel bottom.

The average values of the measured K_V, in the single section, were compared with the values obtained by eq. (4). A good agreement was found only for L/y_2 greater than 8. This fact and the results of fig (4) indicate that the use of eq. (3) and (4) values greater than 8.

CONCLUSIONS

1. Regarding the features of the scouring process, the shape and dimensions of the measured scourholes were seen to be dependent upon the kinematic and dynamic condition of the stream at the end of the jump. This was quantified by introducting the turbulence intensity parameter K_V and a flow parameter called shear stress ratio T_r, defined as the ratio of the critical shear stress obtained from Shields' diagram to the corresponding actual value.

2. The scour depth decreased with the increase of the rigid apron length (i.e. with the decrease of the K_V parameter) and with the increase of T_r.

3. Razavan's formula, in which the turbulence intensity of the flow downstream of the jump appears, was found to be satisfactory for estimating the maximum scour depth for L/y_2 values greater than 8. For low values of L/y_2, there is a disagreement between the calculated and measured maximum scour depth due to the difficulty of evaluating the K_V parameter by the formulas proposed in literature. An LDA system was used to measure the instantaneous velocity downstream of the jump. The average values of the measured K_V parameters in the single section were compared with the ones calculated by Koumine's empirical formula. A good

agreement was found only for L/y_2 values greater than 8.

4. Some photographic investigations were made using a video camera (100 images per second) to study the large-scale eddy features of the roller zone. Periods of vortex pairing and immigration were observed which caused oscilation of the location of the toe of the jump with a remarkable travel of broken vortices into the tailwater. These processes are seen to be the main cause of the instability of the sand particles located downstream of the jump.

SYMBOLS:

d_{50}:	mean particle diameter;
e:	scour depth below original level;
e_m:	maximum measured scour depth below original level;
e_c:	maximum calculated scour depth below original level;
f:	pulsation frecuency of the jump;
K_V:	turbulence intensity parameter;
L:	length of rigid apron from the upstream jump section;
L_{min}:	minimum value of L;
L_{max}:	maximum value of L;
L_j:	length of hydraulic jump;
Q:	discharge;
q:	unit discharge (discharge divided by the width of the channel);
T_r:	shear stress ratio $((\tau_0)_{cr}/\tau_0$;
U_2:	downstream mean velocity;
U_a:	critical velocity of incipient motion condition;
$U_\star$:	friction velocity;
x:	longitudinal distance from the toe of the jump;
X:	longitudinal distance from the end of rigid apron;
X_0:	width of scourhole;
X_m:	longitudinal distance from the end of rigid apron where the scour depth is maximum;
y:	flow depth (y_1 and y_2 upstream and downstream of the hydraulic jump;
γ:	specific weight of the fluid;
γ_s:	specific weigth of the particle;
ν:	kinematic viscosity;
τ_0:	bed shear stress;
$(\tau_0)_{cr}$:	critical bed stress obtained from Shields' diagram;
$\tau_\star$:	dimensionless bed shear stress;
$(\tau_\star)_{cr}$:	dimensionless critical bed shear stress obtained from Shields' diagram;

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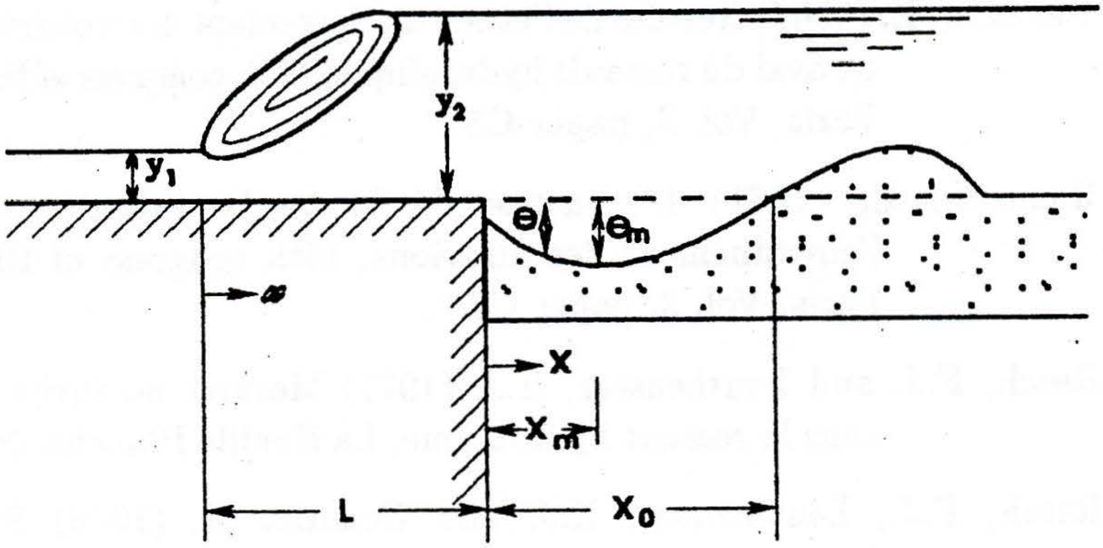

Fig. (1). Detailed sketch.

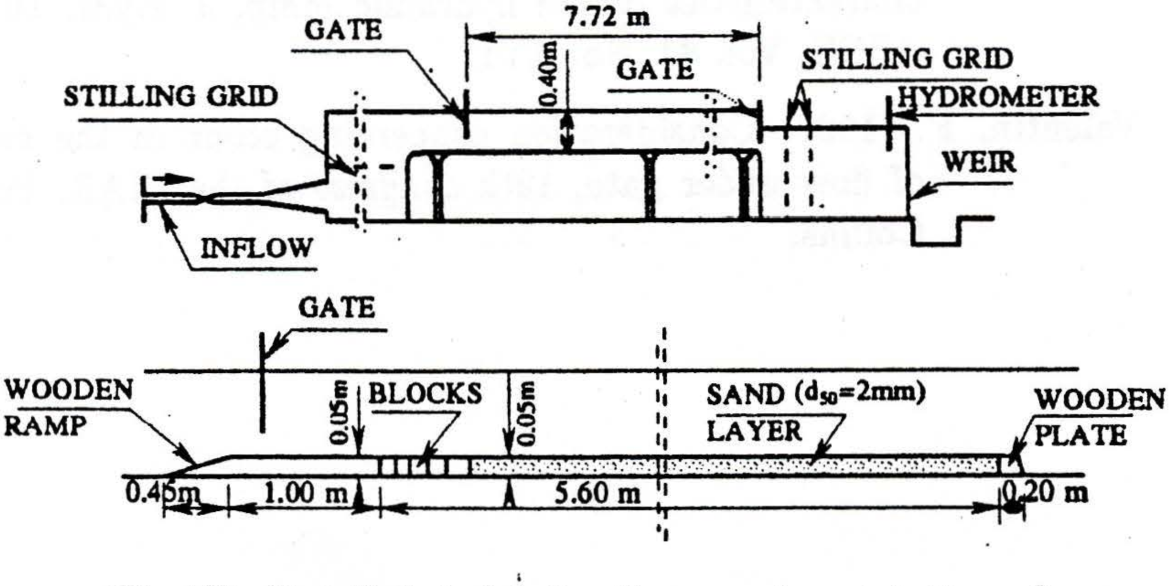

Fig. (2). Detailed sketch for the experimental channel

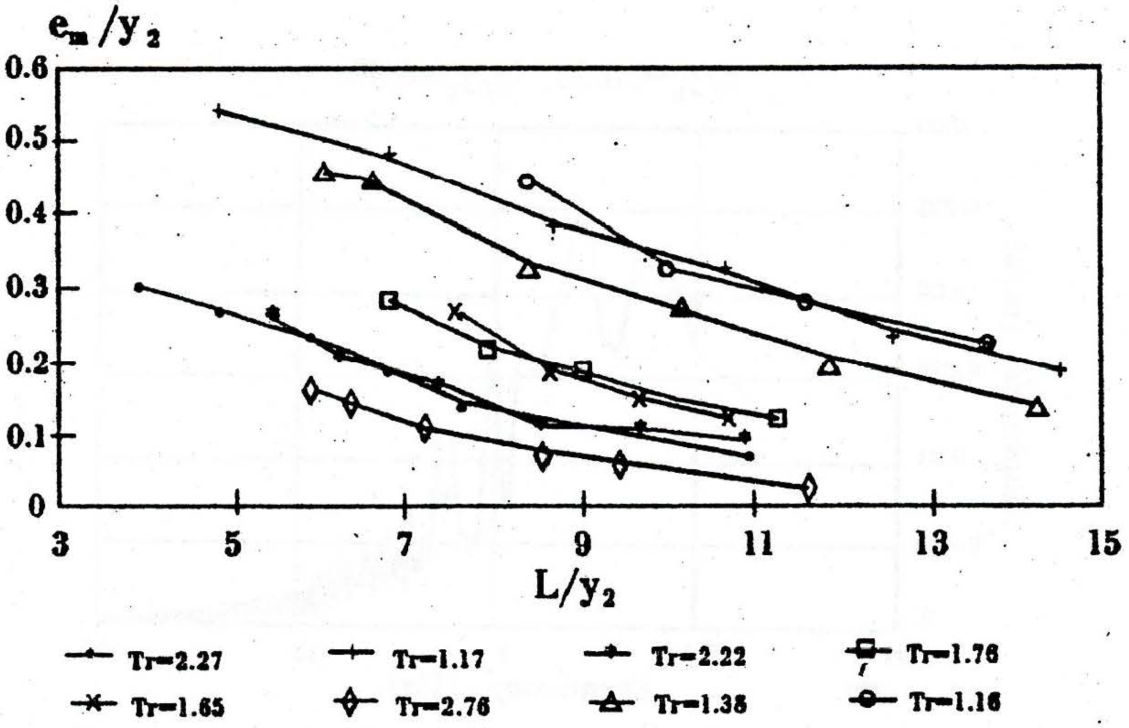

Fig. (3). Variation of the maximum scour depth with apron length (i. e. K_y) and T_r .

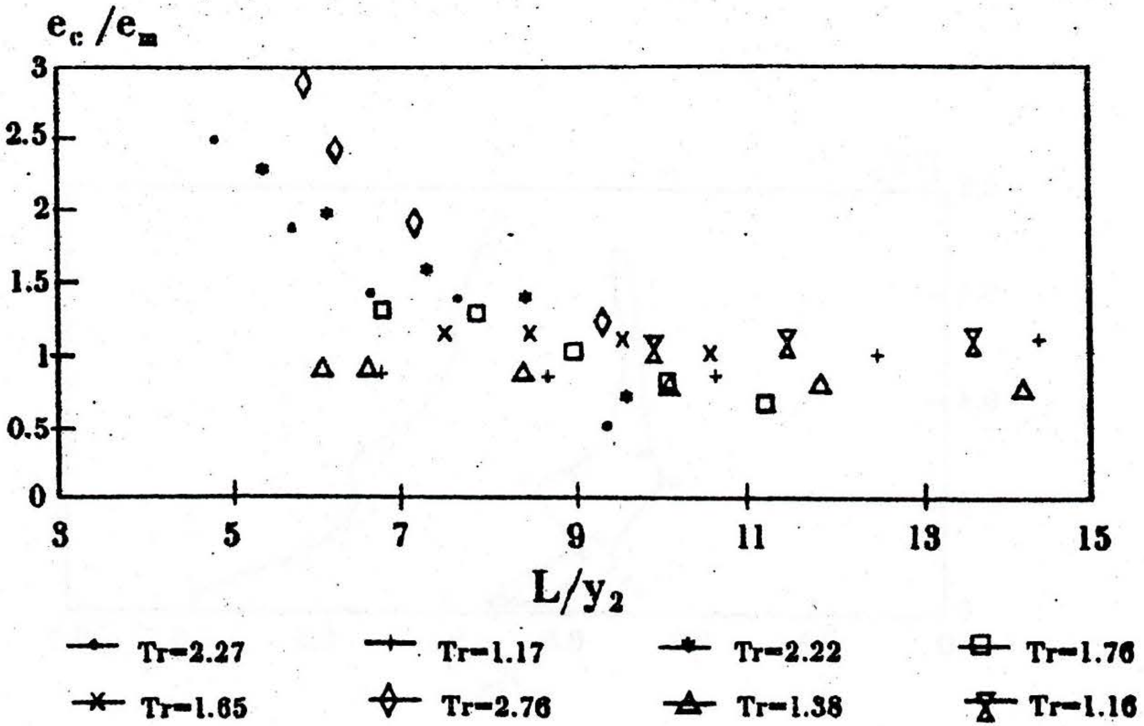

Fig. (4). Comparison of the calculated scour depth (e_c) using Razavan's equation and the measured ones (e_m).

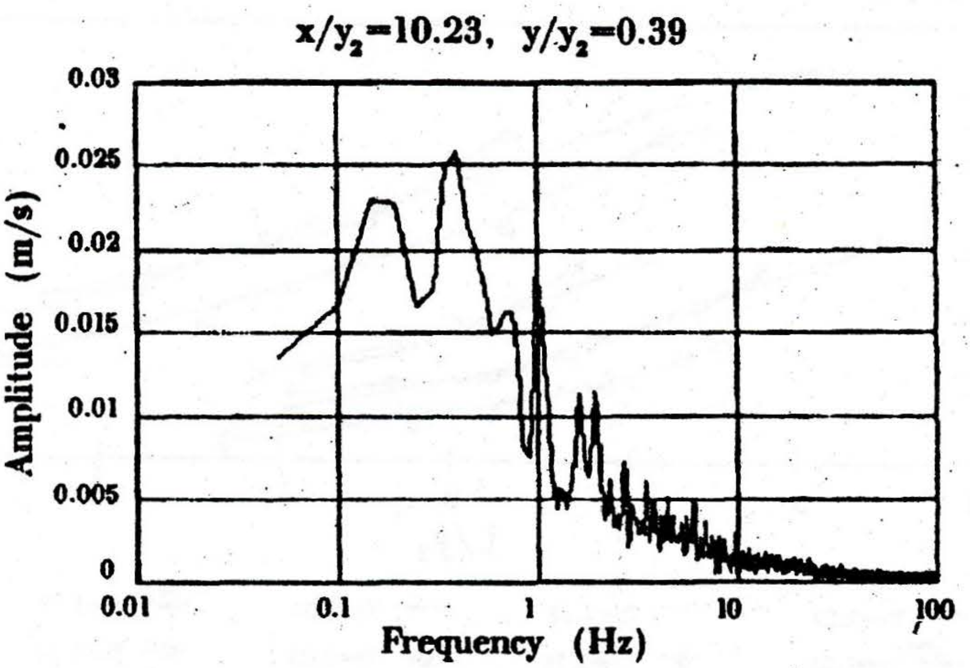

Fig. (5). Amplitude spectrum of the fluctuating velocities.

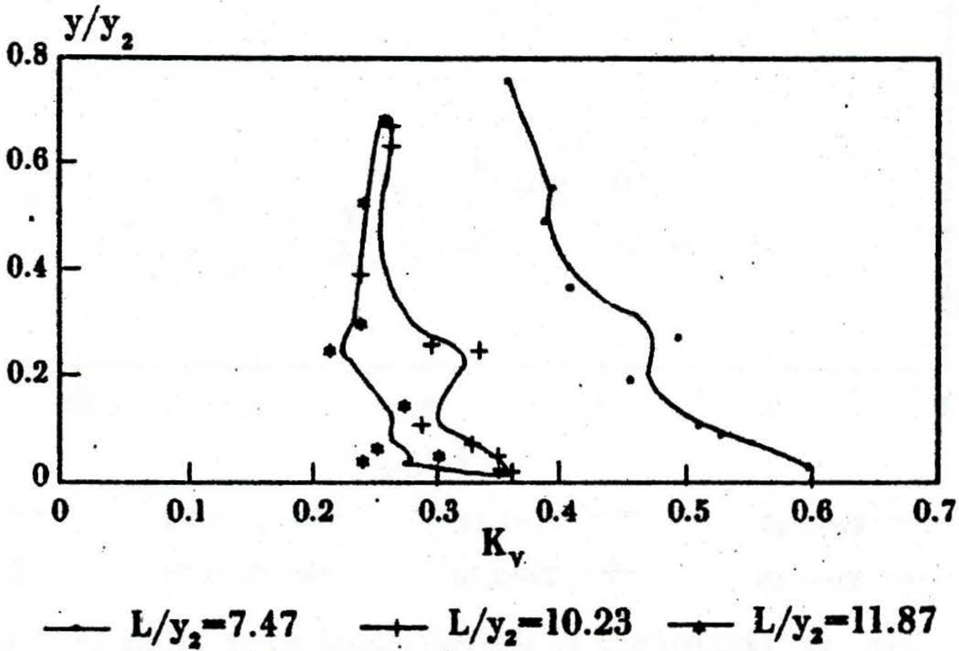

Fig. (6). Profiles of K_V values (using LDA system).