A Study of the Turbulent Flows in Sloping and Adversely Sloping Rectangular Culverts

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ABSTRACT

In this paper, an experimental investigation was carried out to study the turbulent flows and flow characteristics through sloping and adversely sloping rectangular culverts in a rectangular channel of constant width using Laser Doppler Velocimetry (LDV). Also, experimental study was carried out to investigate the characteristics of the hydraulic jump occurring in a sloping and adversely sloping rectangular culvert with pressurized flow downstream from the jump and a submerged culvert outlet. Experiments were conducted on a culvert with relatively small slopes to study the variation of the relative tailwater depth with the main parameters affecting the jump in sloping and adversely sloping culverts. These parameters include the channel bottom slope, the initial Froude number and the ratio of the initial depth to culvert height. To study the turbulence characteristics, precise and accurate measurements of the mean fluctuating flow quantities such as streamwise and vertical mean velocity components, and streamwise and vertical turbulence intensity components and turbulence shear stress were carried out. Also, this paper presents the results of a Laser Doppler Velocimetry study of hydraulic jumps in a culvert with different relative tailwater depths and different initial Froude numbers. The characteristics of hydraulic jumps were discussed and analyzed. Non–dimensional design curves were provided to relate the jump characteristics. The maximum vertical velocity in the recirculating zone for all jumps is about 6% of the initial velocity. The results show that the maximum streamwise velocity near the center plane was smaller than that near the side wall. The turbulence shear stress near the center was about (35-45)% higher than that near the side wall. After the jump, the flow will recover into a two-dimensional flow.

KEYWORDS: Turbulent flow, Sloping, Adversely sloping, Rectangular culvert.

INTRODUCTION

The culvert is a covered channel of comparatively short length which is typically installed to drain water through an embankment. The culvert acts as an open channel, as long as the section is partly full, and is normally used in this condition. However, under flood conditions, the inlet or outlet may become submerged and a variety of flow patterns can exit. A culvert will run full, like a pipe, when the outlet is submerged or when the upstream level is sufficiently high. The hydraulic jump formed in closed conduits below control gates is a phenomenon which has been frequently observed (Rajaratnam, 1967). In open channels, the hydraulic jump provides a natural transition from initial supercritical flow to downstream subcritical free surface flow. In closed conduits, the initial free surface supercritical flow changes to a pressurized flow downstream from the jump and the conjugate depth is confined by the conduit height. The tailwater depth in that case provides the downstream subcritical free surface flow. The jump location in the

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conduit is very sensitive to any slight variation in the initial depth, conduit height, tailwater depth or conduit slope. Then, it is extremely important to investigate the interdependency of such variables. Earlier research carried out by Lane and Kindsvater (1938) for the case of horizontal conduits followed by Kalinske and Robertson (1943) for the case of sloping conduits concentrated on the air pumping capacity of the jump. The turbulent flow models in open channel flows were discussed by Garde (1993, 1994) and Rodi (1993). Measurements of turbulence characteristics in open channel flows using LDA have been pointed by Guoren and Xiaonan (1992), Nezu and Rodi (1986) and Song and Chinew (2001). The jump formation in closed conduits was studied by Haindi (1957) for horizontal conduits and by Rajaratnam (1965) for circular conduits. A practical case of the hydraulic jump formation in closed conduits includes the occurrence of the hydraulic jump in the barrel of a siphon inlet. Smith and Haid (1987) studied the jump characteristics for the case of circular pipes. Later, Smith and Chen (1989) investigated the relative height of the hydraulic jump formed in a steeply sloping square conduit without considering the tailwater depth conditions. They derived the theoretically momentum based equation for the relative height of the hydraulic jump formed in sloping square conduits, but they could not solve it because it contained too many unknowns. Hence, they provided a set of empirical equations of the form ($Hj/D = a F_1^4 + b$) (Hj being the height of jump, D is the conduit height, F_1 is the initial Froude number and a & b are coefficients that depend upon the values of the conduit slope and the ratio of the initial depth to conduit height). Hydraulic jumps were studied extensively because of their importance as energy dissipators for hydraulic structures. Experimental investigations have been carried out on both the macroscopic structure and internal structure of the hydraulic jumps, but most of these studies were directed to the macroscopic features. Major contributions of this subject were reviewed by Rajaratnam (1967) and more recently by Corquodale (1986). The hot-wire study on the turbulence characteristics in the hydraulic jump in an air model by Rouse and Siao (1958) was the first attempt to obtain information of turbulence field in free hydraulic jumps. More than a decade later, in 1972, Resch and Leutheusser used the hot film technique to make some limited observations on the turbulence in free hydraulic jumps in the actual water model. Both of these observations have been very valuable for the understanding and prediction of the internal structure of hydraulic jumps.

In the present paper, the experiments described are concerned with turbulence and flow characteristics on sloping and adversely sloping culverts in a rectangular channel of constant width. The Laser Doppler Velocimetry (LDV) study was conducted to provide detailed measurements of the streamwise and vertical mean velocity components, streamwise and vertical turbulence intensity components and turbulence shear stress, which could be used as a basis to improve the prediction methods. Also, in the present research, an experimental study is carried out, and the hydraulic jump is allowed to be formed in sloping and adversely sloping culverts of different heights. The relevant parameters were measured and non-dimensional design curves were prepared to determine the variation in the tail water depth with the change in slopes, initial Froude numbers and ratios of initial depth to conduit height.

EXPERIMENTAL SET-UP AND PROCEDURE

The experiments were conducted in a tilting glass sided flume 4m long, 10 cm wide and 30 cm deep as shown in Fig.1. The discharge was measured using a pre-calibrated orifice meter. An in-line valve fitted into the main supplying pipeline was used to regulate the flow rate. Depth measurements were taken using a needle point gauge with a reading accuracy of ± 0.1 mm. Uniform flow conditions were reached using a carefully designed inlet tank. The slope was adjusted using a screw jack located at the upstream end of the

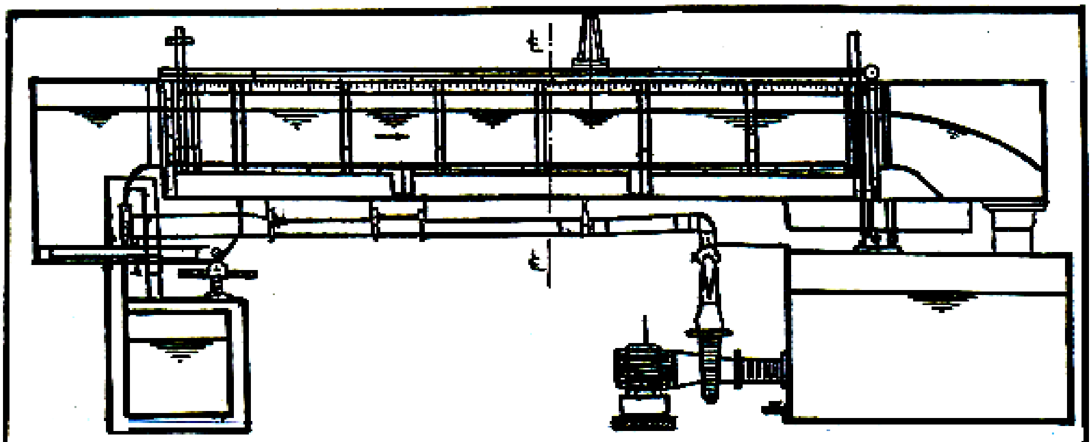

Fig. 1 Schematic sketch of test facility.

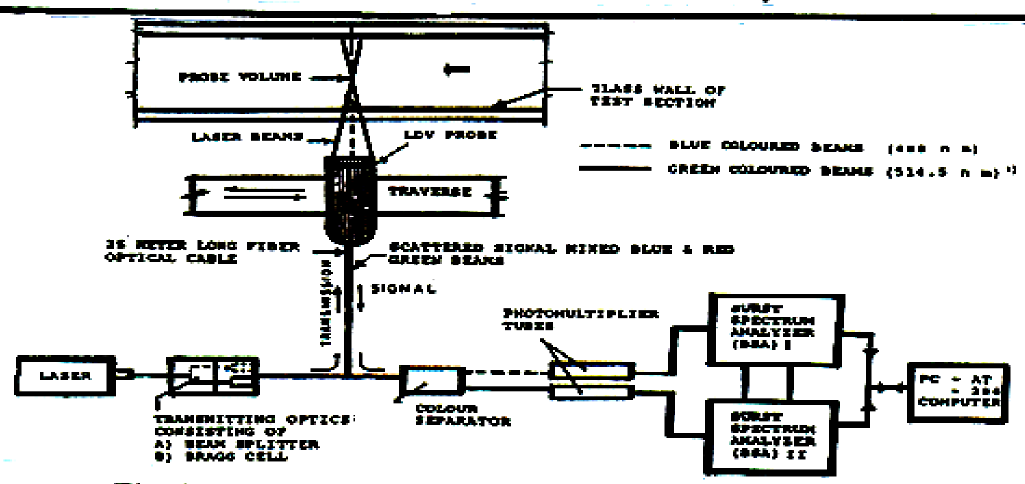

Fig. 2 Block diagram of the Laser Doppler Velocimetry.

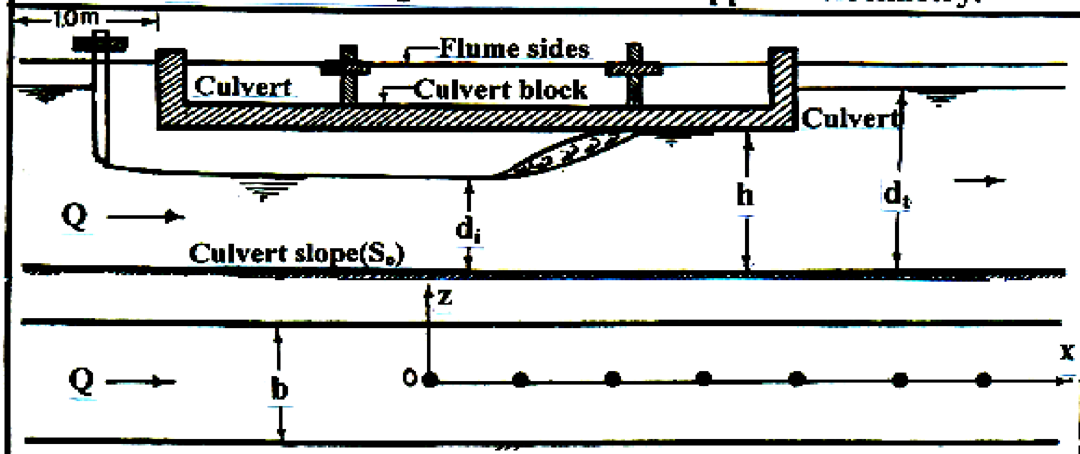

Fig.(3)Definition sketch showing the variables of the culvert

flume while at the downstream end, the flume is allowed to rotate freely about a hinged pivot. The slope was directly determined using a slope indicator. A downstream adjustable gate was used to regulate the tail water surface elevation. The experiments were carried out using five different culvert heights, h of 12, 14, 16, 18 and 20 cm. Six different culvert slopes, S_o, of 0.0 0.005, 0.01, 0.015, 0.02 and 0.025 were used. Also, six different culvert adverse slopes, S_o, of 0.0, 0.005, 0.01, 0.015, 0.02, and 0.025 were used to illustrate flows and jump formed in sloping and adversely sloping culverts. The slopes and adverse slopes were selected based on the flume facilities. For each combination of culvert slope and culvert adverse slope, and height, five different flow rates ranging from 400 L/min to 250 L/min were used. The initial Froude number ranges from 3.5 to 6 for each culvert height. The upstream control gate was so adjusted to produce supercritical depth, d_i. The downstream adjustable gate was adjusted to control the tailwater depth, d_t, that enabled the jump to be formed at a certain location in the culvert. The jump location was kept fixed throughout the course of experiments. For each combination of slope and adverse slope, and culvert height, the flow rate and the tailwater depth just downstream the culvert outlet were measured.

LASER MEASURING TECHNIQUE

The experimental data were collected using a DANTEC two-color back-scatter mode, two Burst Spectrum Analyzers [BSA] were used to evaluate the Doppler frequencies, and subsequent computer analysis consisted of velocity bias averaging and rejection. Figure 2 shows a block diagram of the two-component LDV set-up used for the measurements. On a traverse bench, the measuring probe [laser beams or measuring volume] was focused on a measuring point from one side of the channel glass wall through an optical lens. The number of samples taken at every point was 3000 bursts. This points to a simple averaging time of about 100 seconds. The data rate was about 10-20 Hz. Before acquiring the data, the LDV signal was checked for its regular Doppler burst that corresponds to a particle passing through the measuring volume. The measurements were taken at different positions along the centerline within and downstream of the culvert. Fig.3 shows the location of measuring sections [x/b]. For hydraulic jumps with high inlet Froude number, more air is entrained into the flow. When air bubbles are present, the data acquisition rate is low. So, for a region with relatively high concentration of bubbles, the sampling time is up to 300 seconds.

THEORETICAL ANALYSIS

Figure 3 shows a definition sketch for the hydraulic jump formed in a sloping culvert. Although the momentum equation along with the energy equation can be written to theoretically express the relationship among the different variables describing the phenomenon, the direct solution for each equation will be somewhat difficult as there are too many unknowns (Guoren and Xiaonan, 1992). These unknowns include the weight component of the jump in the direction of flow, the boundary frictional resistance, the exit losses and the air water ratio at the end of the jump. Therefore, the theoretical solution for the jump in sloping culverts is avoided in the present study. The relative tailwater depth d_t/d_i can be expressed in non-dimensional form to be a function of the initial Froude number F_i, the ratio of the initial depth to culvert height d_i/h and the culvert slope S_o as:

$$d_t/d_i = f\,(F_i\,,\, d_i/h\,,\, S_o); \qquad (1)$$

where d_t is the depth just downstream the outlet of the culvert and is termed in this paper as the tailwater depth, d_i is the initial depth of the jump, S_o is the culvert slope or culvert adverse slope and F_i is the initial Froude number ($F_i = Q/\ b\ d_i\ \sqrt{g\, d_i}$) where Q is the discharge, b is the culvert width and g is the gravitational acceleration. Eq. (1) could be defined and evaluated using the experimental data. The experimental data can be plotted

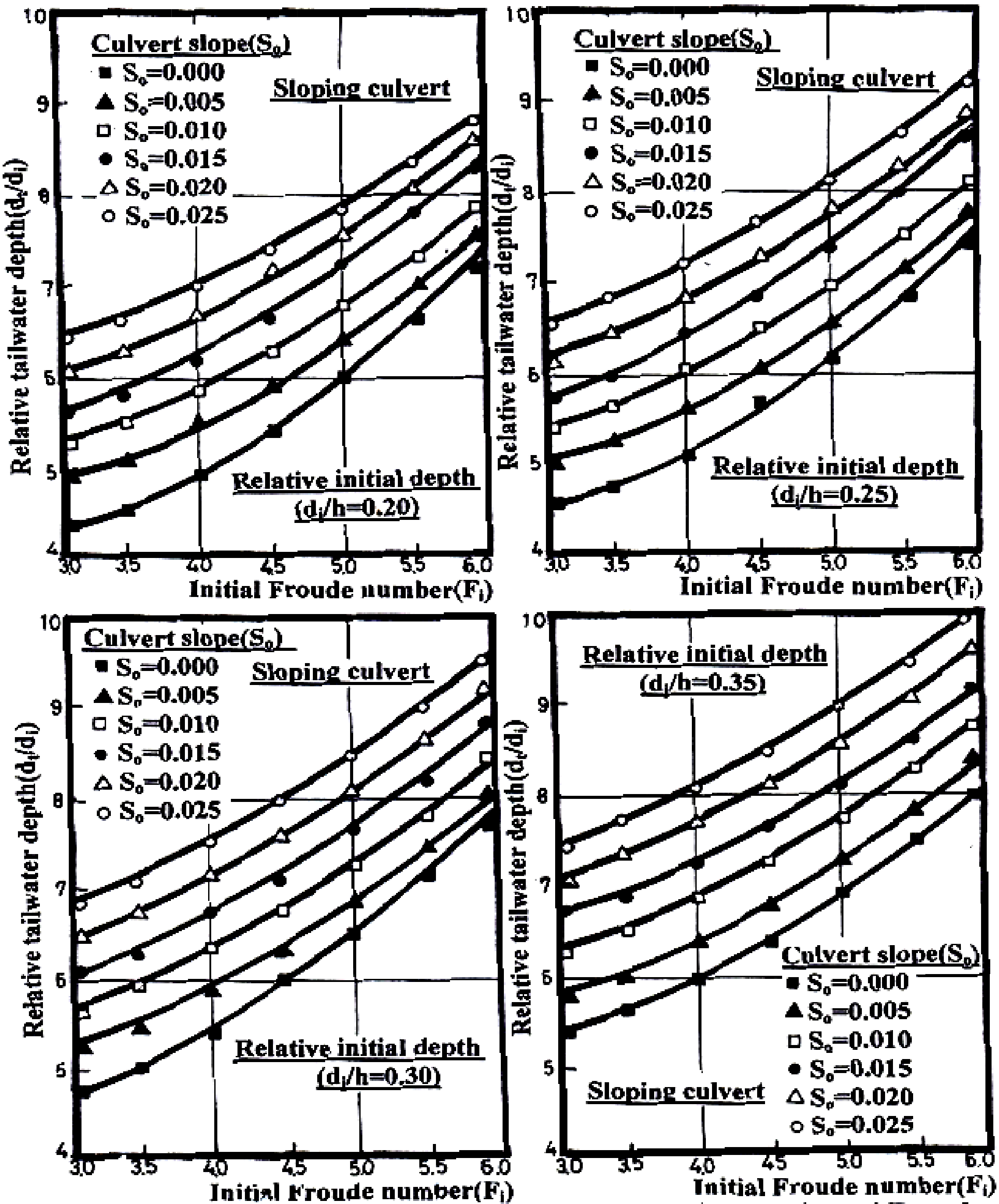

Fig.(4)Variation of relative tailwater depth d_t/d_i with initial Froude number F_i for different slope S_o at different relative initial depth d_i/h for sloping culvert.

on several planes to completely understand the phenomenon. Such planes may include [d_t/d_i, F_i], [d_t/d_i, S_o], and [d_t/d_i, d_i/h]. In each plane, for a constant value of one of the two remaining parameters, a family of curves is drawn for different values of the other one.

DISCUSSION AND RESULTS

Figure 4 shows the variation of initial Froude number F_i with relative tailwater depth d_t/d_i for different culvert slopes S_o = 0.0, 0.005, 0.01, 0.015, 0.02 and 0.025 for different relative initial depths d_i/h of 0.20, 0.25, 0.30 and 0.35. The resulting curves indicate that for a fixed d_i/h, the trend of variation between d_t/d_i and F_i is increasing with a nonlinear trend. Also, at a particular F_i, d_t/d_i increases as the culvert slope increases. Fig. 4 shows the effect of the initial Froude number F_i at fixed d_i/h and different culvert slopes. It is observed that the effect of F_i on d_t/d_i is significant. d_t/d_i increases non-linearly with the increase of F_i. Also, the higher the slope, the greater the ratio d_t/d_i which proves that the slope has an increasing effect on d_t/d_i. Similarly, the variation of d_t/d_i with culvert slope S_o for different F_i values is shown in Fig. 5 for d_i/h = 0.2, 0.25, 0.3 and 0.35. From Fig. 5, it can be observed that for a fixed d_i/h, the trend of variation between d_t/d_i and S_o is increasing with a nonlinear trend. Also, at a particular S_o, d_t/d_i increases as F_i increases. Fig.5 depicts that the slope has a major effect on d_t/d_i which is comparable with the effect of F_i on d_t/d_i where d_t/d_i increases non-linearly with the increase of culvert slope. This also confirms the increase of d_t/d_i with the increase of F_i at fixed d_i/h. Fig.6 depicts the variation of relative initial depth d_i/h with relative tailwater depth d_t/d_i for different F_i values at different culvert slopes S_o= 0.0, 0.010, 0.02 and 0.025. From this figure, it can be observed that for a fixed S_o, the trend of variation between d_i/h and d_t/d_i is increasing with an approximately linear trend. Also, at a particular d_i/h, d_t/d_i increases as F_i increases. Also, Fig.6 shows the typical effect of d_i/h at different F_i values of 3.5, 4, 4.5, 5 and 5.5 at different culvert slopes. It is clear that for the investigated range of slopes, the ratio of the initial depth to culvert height has insignificant effect on d_t/d_i as d_t/d_i is increasing very slightly with the increase of d_i/h. The figure indicates also that d_t/d_i increases as F_i increases.

Figure 7 depicts the variation of culvert adverse slope S_o with relative tailwater depth d_t/d_i for different F_i values of 3.5, 4, 4.5, 5 and 5.5 for different d_i/h of 0.2, 0.25, 0.3 and 0.35. From this figure, it can be observed that for a fixed d_i/h, the trend of variation between d_t/d_i and S_o is decreasing with nonlinear trend. Also, at a particular S_o, d_t/d_i increases as F_i increases. Fig.7 shows that the adverse slope has a major effect on d_t/d_i which is comparable with the effect of F_i on d_t/d_i where d_t/d_i decreases non-linearly with the increase of the culvert adverse slope. This also confirms the increase of F_i at a fixed d_i/h. Similarly, the variation of d_t/d_i with F_i for different tested adverse slopes S_o = 0.0, 0.005, 0.01, 0.015, 0.02 and 0.25 is presented in Fig.8 for d_i/h = 0.2, 0.25 , 0.3 and 0.35. From this figure, it can be observed that for a fixed d_i/h, the trend of variation between d_t/d_i and F_i is increasing with a nonlinear trend. Also, at a particular F_i, d_t/d_i decreases as the adverse slope of the culvert increases. Also, this figure shows the effect of the initial Froude number F_i at fixed d_i/h and different culvert slopes. It is observed that the effect of F_i on d_t/d_i is significant. The relative tailwater depth, d_t/d_i, increases non-linearly with the increase of F_i. Also, the higher the adverse slope, the less the ratio d_t/d_i, which proves that the adverse slope has a decreasing effect on d_t/d_i. Fig.9 shows the variation of relative tailwater depth d_t/d_i with relative initial depth d_i/h for different F_i values of 3.5, 4, 4.5, 5 and 5.5 at different culvert adverse slopes S_o = 0.0, 0.01, 0.015 and 0.025. It is clear that for the investigated range of adverse slopes, the ratio of the initial depth to culvert height d_i/h has insignificant effect on d_t/d_i as d_t/d_i is increasing very slightly with the increase of d_i/h. The figure indicates also that d_t/d_i increases as F_i increases.

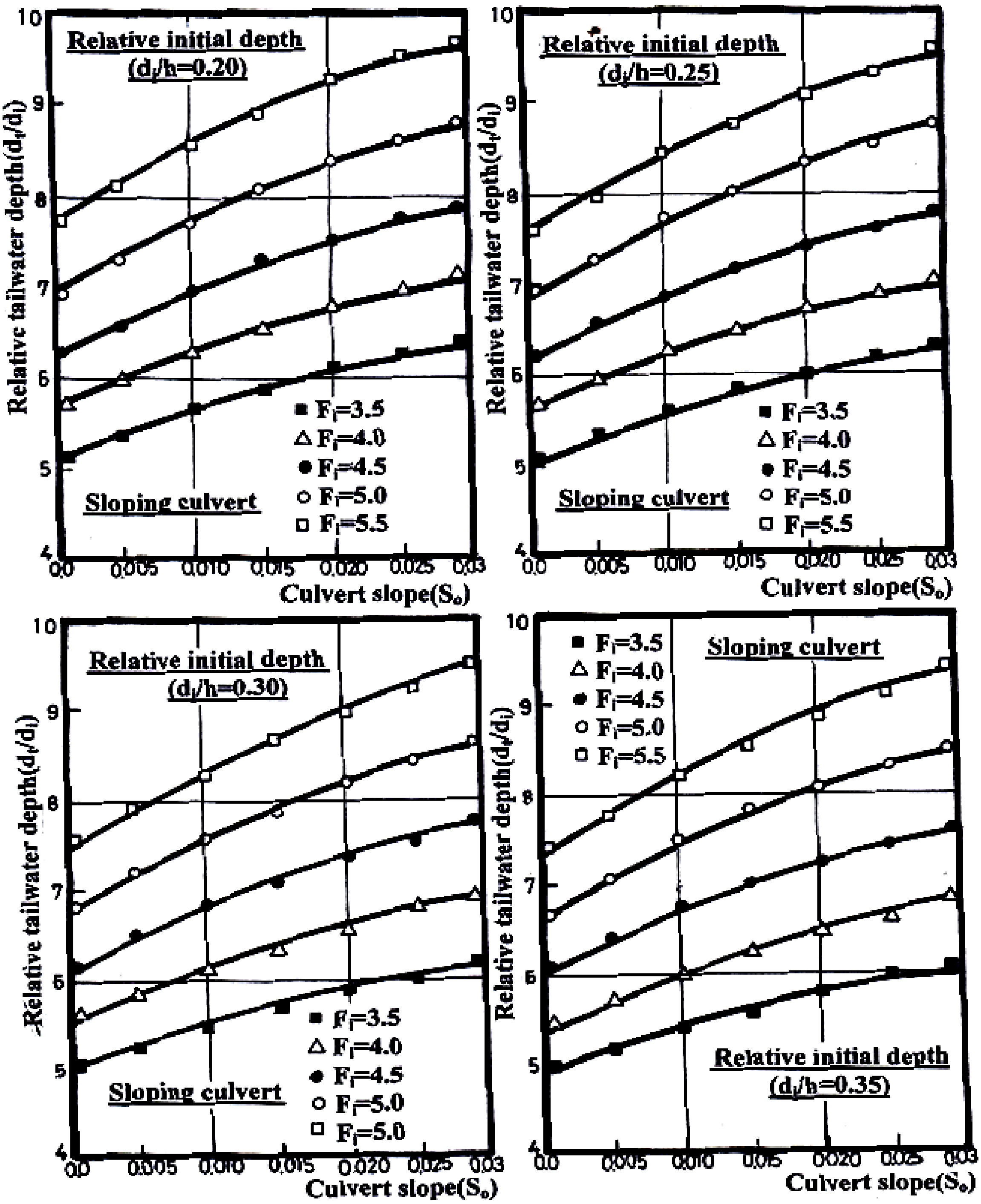

Fig.(5)Variation of relative tailwater depth d_t/d_i with slope S_o for different initial Froude number F_i at different relative initial depth d_i/h for sloping culvert.

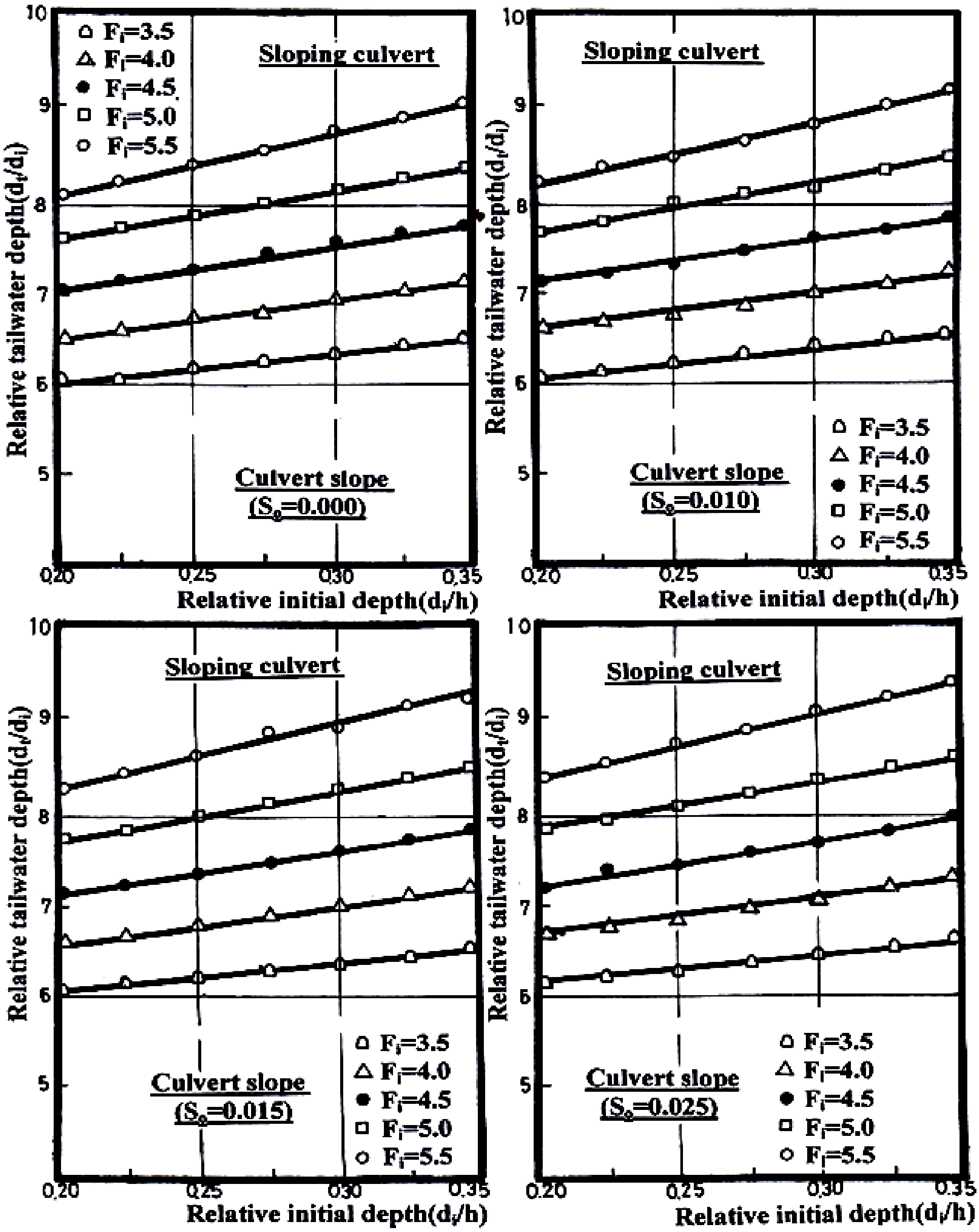

Fig.(6)Variation of relative tailwater depth d_t/d_i with relative initial depth d_i/h for different initial Froude number F_i at different slope S_o for sloping culvert.

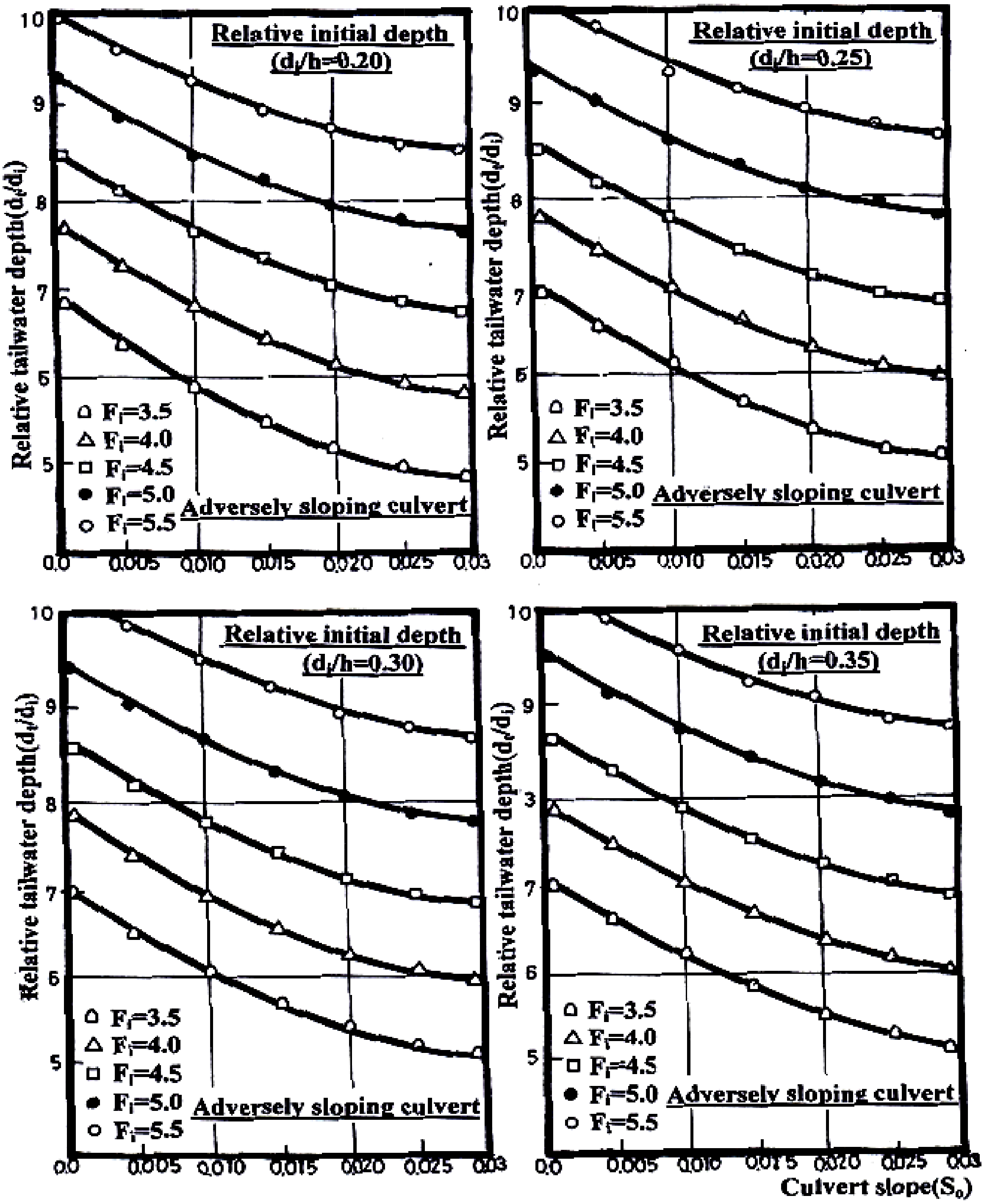

Fig.(7)Variation of slope S_o with relative tailwater depth d_t/d_i for different initial Froude number F_i at different relative initial depth d_i/h for adversely sloping culvert.

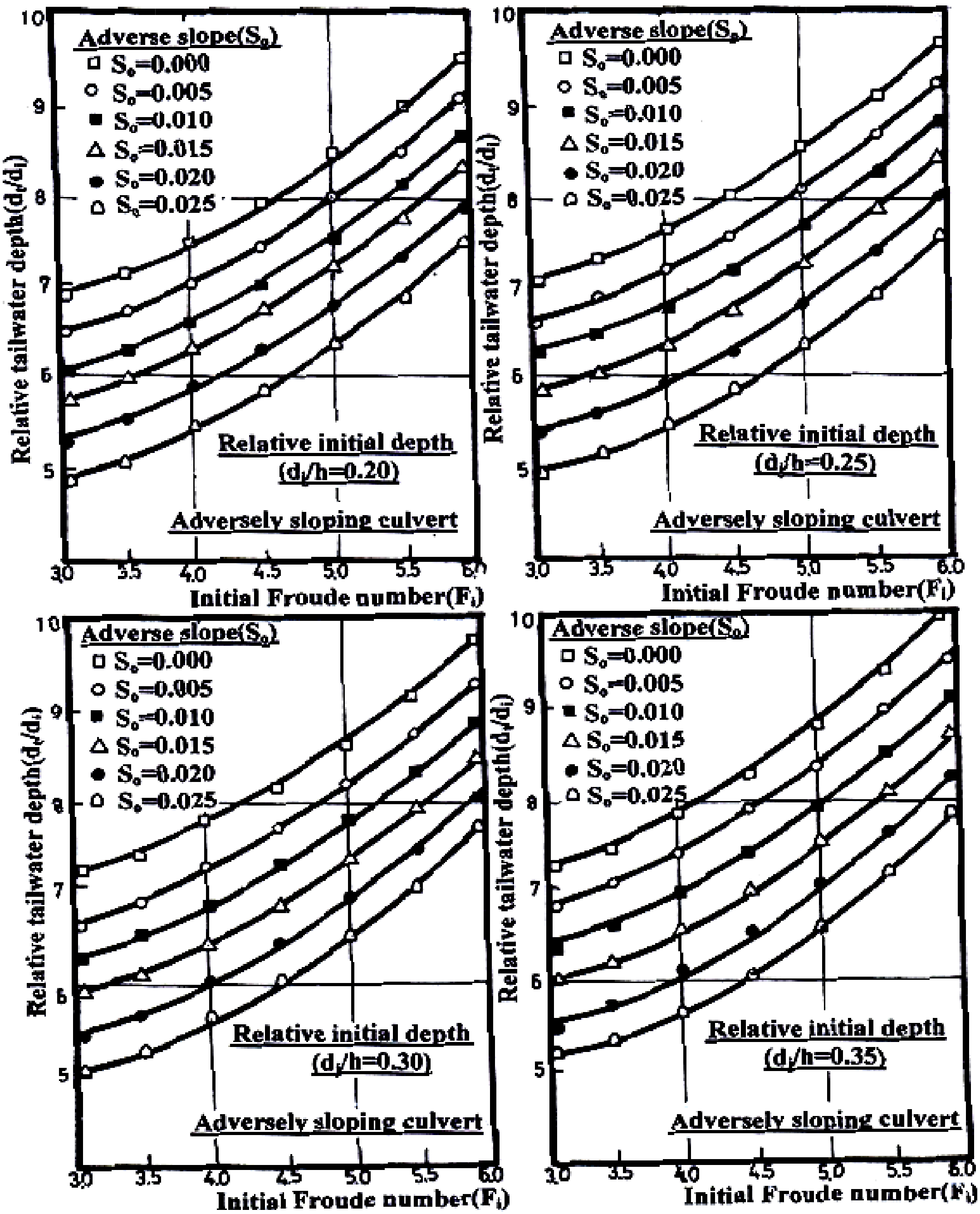

Fig.(8)Variation of initial Froude number F_i with relative tailwater depth d_t/d_i for different slope S_o at different relative initial depth d_i/h for adversely sloping culvert.

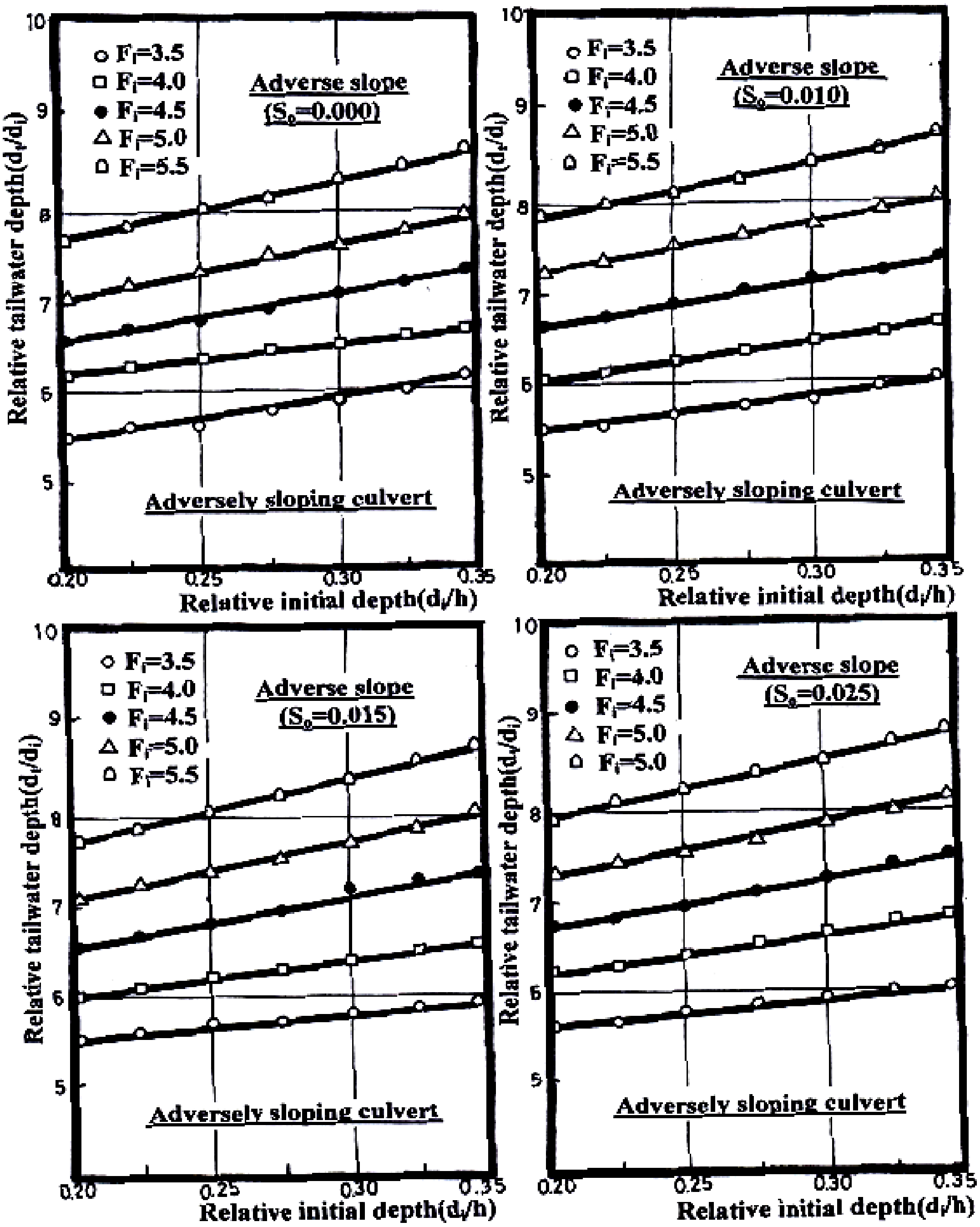

Fig.(9)Variation of relative initial depth d_i/h with relative tailwater depth d_t/d_i for different initial Froude number F_i at different slope S_o for adversely sloping culvert.

Measurements were made for various flow conditions. However, only representative results are presented here. For each experimental condition, detailed measurements along the centerline at the plane z/b=0.5 were carried out to obtain vertical profiles of the mean and fluctuating flow quantities such as streamwise and vertical mean velocity components $\bar{u}/U_i$ and $\bar{v}/U_i$, streamwise and vertical turbulence intensity components $\acute{u}/U_i$ and $\acute{v}/U_i$. The turbulence intensity components and velocity components are non-dimensionalized by the streamwise initial velocity in x-direction U_i. The water depth is non-dimensionalized by the free stream water depth y_o. Turbulence at the wall was construed to be a turbulence at a very near location from the wall of the order of 3mm as observed in Laser Doppler Velocimetry (LDV) experimentation, and not at the wall itself. At the boundary, velocity and turbulence are zero. Fig.10 depicts the streamwise mean velocity profiles $\bar{u}/U_i$ along the depth at different cross-sections along the centerline at the plane z/b=0.5 at F_i=4.5, S_o=0.01, d_t/d_i=7 and d_i/h=0.3. The streamwise mean velocity $\bar{u}/U_i$ profiles vary considerably according to the cross-section location x/b and the flow conditions. In the hydraulic jump location in the culvert, reverse flow could be observed as shown in Fig. 10 at x/b=0 up to x/b=12, as could be seen in the velocity profiles, and as was observed by dye injection. Fig.11 shows the profiles of vertical mean velocity distribution $\bar{v}/U_i$ along the depth at various locations x/b at the plane z/b=0.5 along the centerline at F_i =4.5 , S_o=0.01, d_t/d_i=7 and d_i/h=0.3. The profile of $\bar{v}/U_i$ assumes both positive and negative values at the same section and hence zero value at some intermediate locations. This nature of variation changes from positive to negative magnitude and *vice versa* almost at all the sections. The zero magnitude of vertical velocity component $\bar{v}/U_i$, occurs at more than one point at several locations. The magnitude of $\bar{v}/U_i$ increases steadily from the entrance section of the jump, the magnitude gradually decreases reaching a small value at the farthest downstream. This observation may be attributed to the expanding velocity field and diversion of flow in the jump region. The observation of the multiplicity of null points indicates the three-dimensional interaction between the entrance flow to the hydraulic jump almost with a negative vertical velocity component. The influence of the jump itself along with the bed impede the downward component of velocity. This complex interaction would influence the flow pattern giving rise to multiplicity of null points.

Root mean square (RMS) values of streamwise and vertical components of turbulence intensity $\acute{u}/U_i$ and $\acute{v}/U_i$ are shown. Figs.12 and 13 depict turbulence intensity profiles $\acute{u}/U_i$ and $\acute{v}/U_i$ as a function of dimensionless water depth d/d_o along the depth at different locations x/b along the centerline at z/b=0.5 at F_i=4.5, S_o= 0.01, d_t/d_i=7 and d_i/h=0.3, which are a measure of fluctuations about the respective streamwise and vertical mean velocity as shown in Figs.10 and 11. Also, Fig.17 depicts the variation of streamwise turbulence intensity $\acute{u}/U_i$ as a function of relative water depth d/d_o at different cross-sections x/b=10, 20 and 40 at different spanwise locations z/b = 0.1, 0.2, 0.3, 0.4 and 0.5 along the depth at F_i=4.5, S_o=0.01, d_t/d_i=7 and d_i/h=0.3. The conditions of the flow at the inlet of the hydraulic jump cause unidirectional distortion of the fluid elements which may be expected to produce nonhomogeneous and anisotropic turbulence. Under the action of dynamic process, the turbulence was produced some degree all over the field. The streamwise and vertical turbulence intensities $\acute{u}/U_i$ and $\acute{v}/U_i$ grow rapidly after the inlet of the jump spreading in the all directions. An increase of the culvert slope S_o from 0.005 to 0.025 increases enormously the turbulence intensities $\acute{u}/U_i$ and $\acute{v}/U_i$ after the entrance of the jump. In the wall region defined by d/d_o <0.2, the turbulence intensities $\acute{u}/U_i$ and $\acute{v}/U_i$ have substantially small magnitudes closer to the wall. With increasing the distance from the boundary, the turbulence intensities $\acute{u}/U_o$ and $\acute{v}/U_o$ increase in the wall region tending to a maximum in the intermediate region (core region) defined by $0.2<d/d_o<0.6$, at the

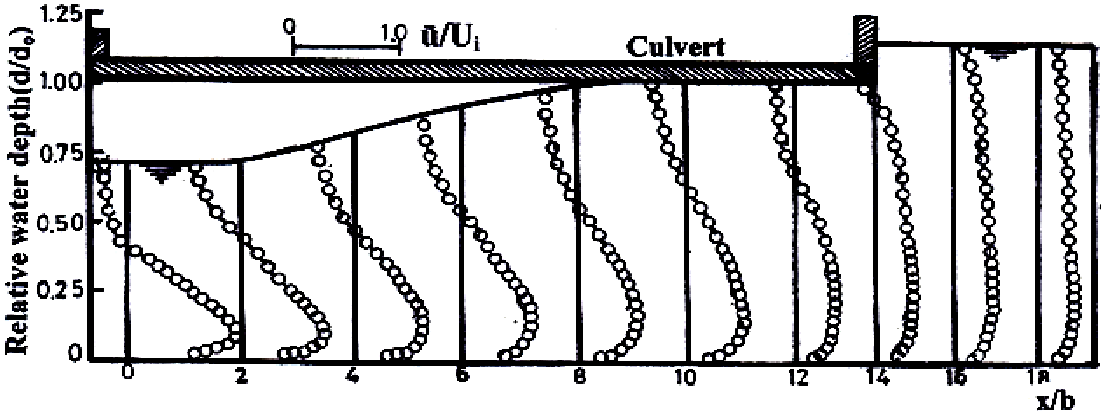

Fig.(10)Variation of streamwise mean velocity $\bar{u}/U_i$ along the depth at different cross sections(F_i=4.5, S_o=0.01,d_t/d_i=7 and d_i/h=0.3).

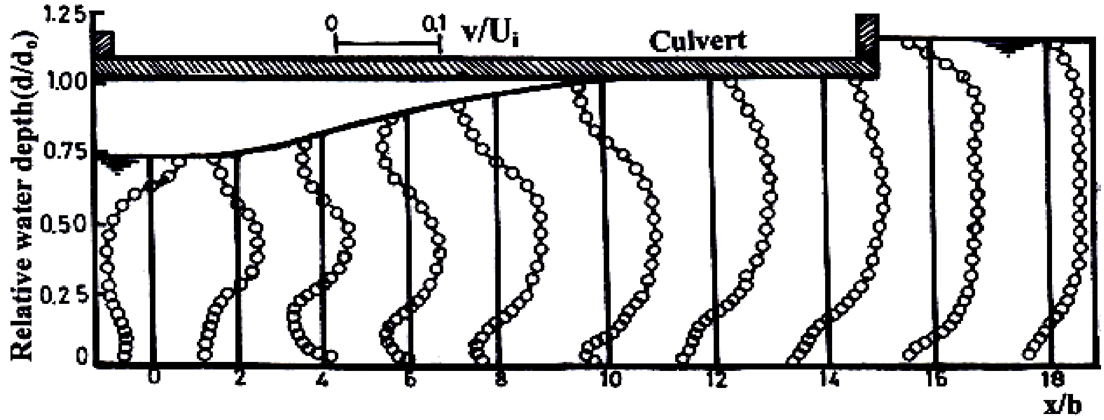

Fig.(11)Variation of vertical mean velocity $\bar{v}/U_i$ along the depth at different cross sections(F_i=4.5, S_o=0.01,d_t/d_i=7 and d_i/h=0.3).

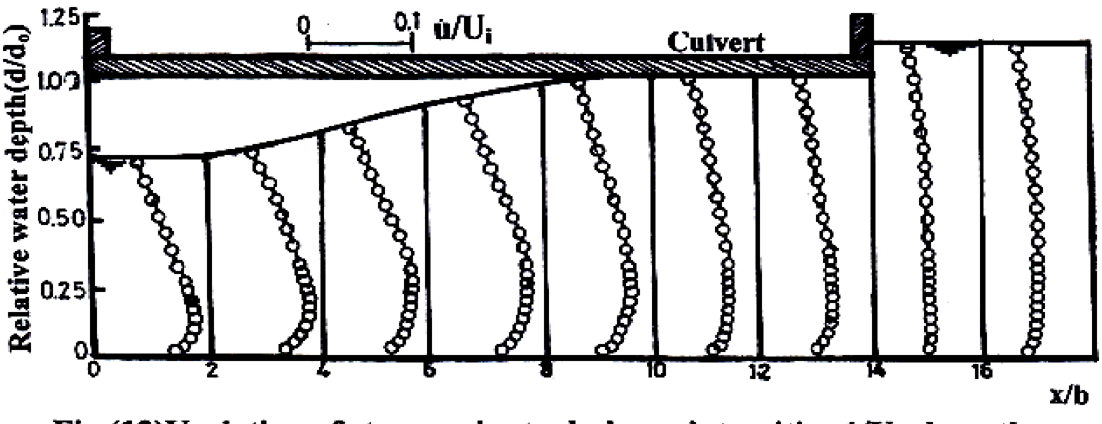

Fig.(12)Variation of streamwise turbulence intensities $\acute{u}/U_i$ along the depth at different cross sections(F_i=4.5, S_o=0.01,d_t/d_i =7 and d_i/h=0.3).

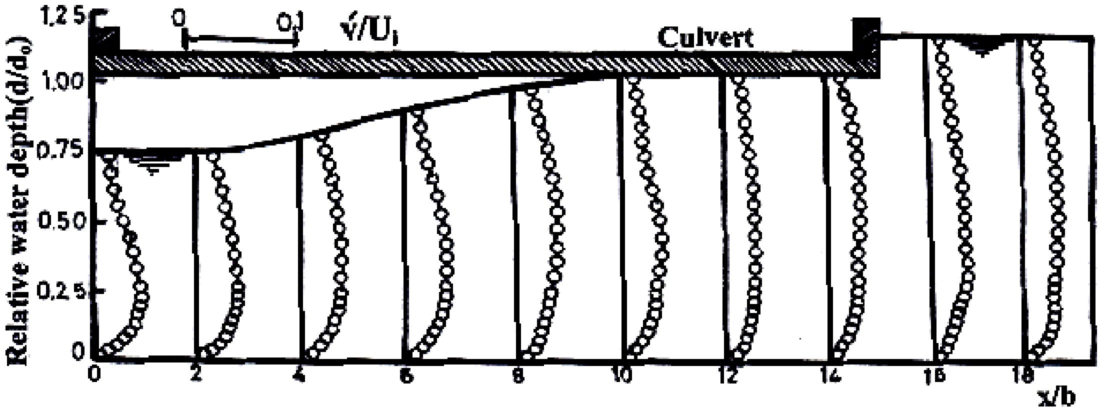

Fig.(13)Variation of vertical turbulence intensities $\acute{v}/U_i$ along the depth at different cross sections(F_i=4.5, S_o=0.01, d_t/d_i =7 and d_i/h=0.3).

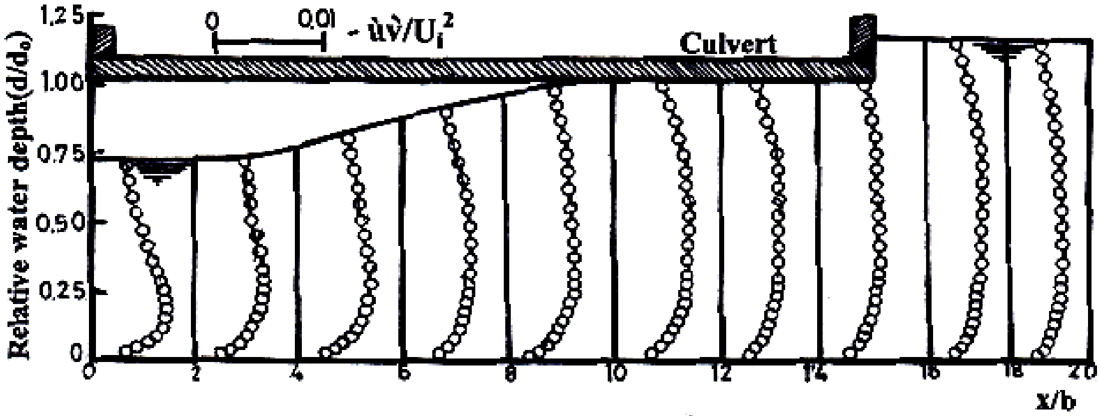

Fig.(14)Variation of turbulence shear stress - $\grave{u}\grave{v}/U_i^2$ along the depth at different cross sections(F_i=4.5, S_o=0.01, d_t/d_i =7 and d_i/h=0.3).

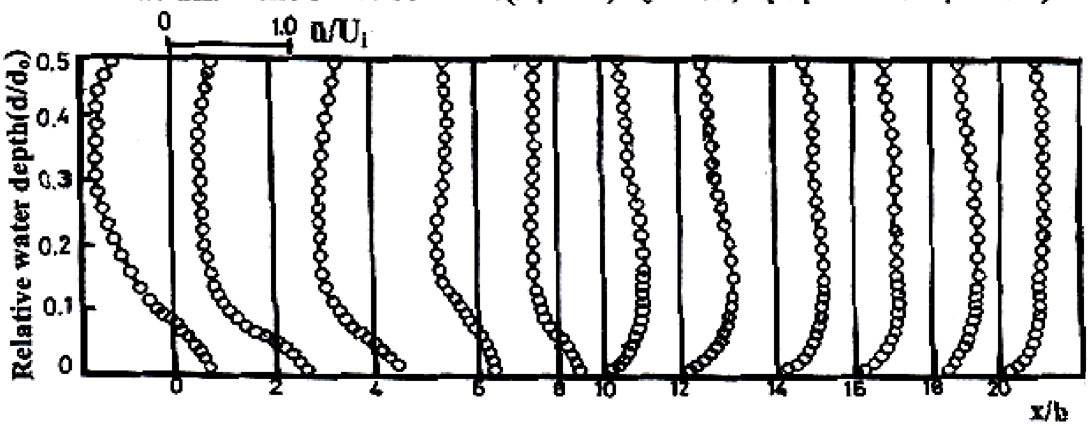

Fig.(15)Variation of streamwise mean velocity $\bar{u}/U_i$ at the plane of d/d_o=0.4(F_i=4.5, S_o=0.01, d_t/d_i =7 and d_i/h=0.3).

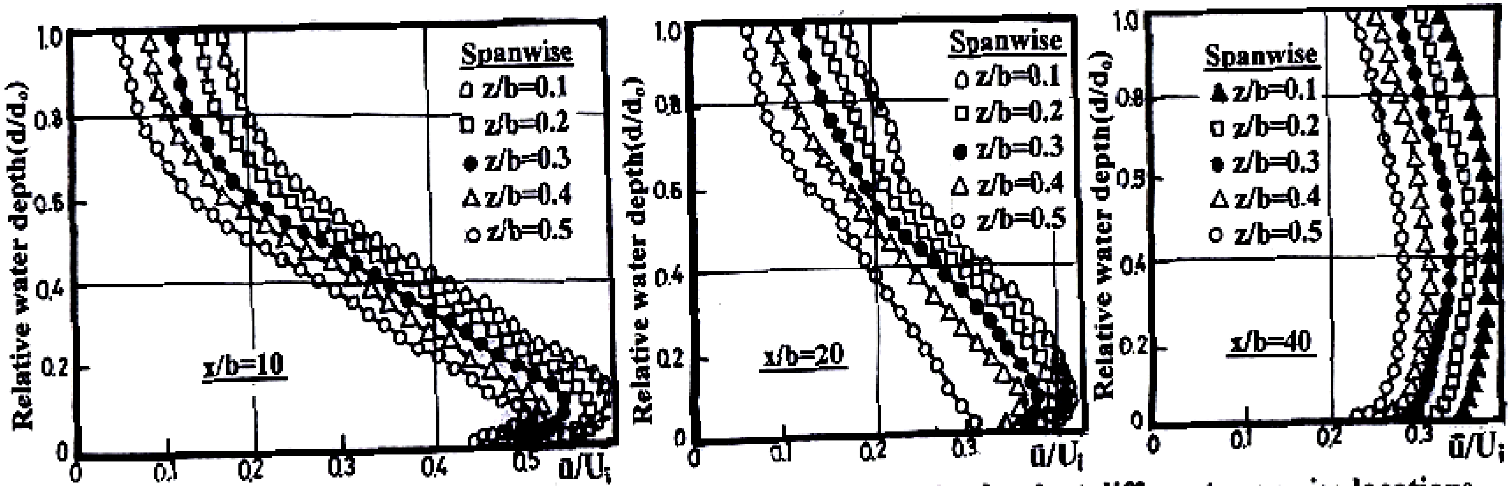

Fig.(16)Variation of streamwise mean velocity $\bar{u}/U_o$ along the depth at different spanwise locations z/b=0.1,0.2,0.3,0.4 and0.5 for different x/b=10,20 and 40(F_i=4.5, S_o=0.01, d_t/d_i =7 and d_i/h=0.3).

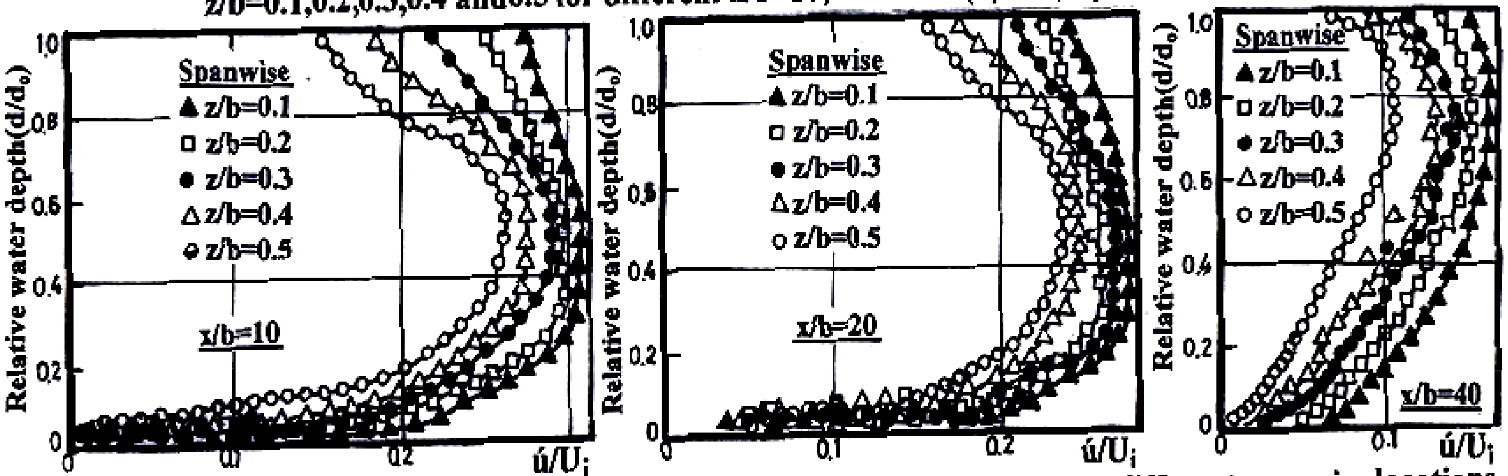

Fig.(17)Variation of streamwise turbulence intensity $\acute{u}/U_o$ along the depth at different spanwise locations z/b=0.1,0.2,0.3,0.4 and0.5 for different x/b=10,20 and 40(F_i=4.5, S_o=0.01, d_t/d_i =7 and d_i/h=0.3).

location of the maximum value of the turbulence $ú/U_i$ and $ύ/U_i$, reaching a lower value (minimum value) in the free surface region defined by $d/d_o>0.6$ subsequently. It has been observed during this experimentation that the surface waves play an important role in turbulence production. As a comprehensive observation, it was noted that the streamwise turbulence $ú/U_i$ was always greater than vertical turbulence $ύ/U_i$. In farthest downstream, x/b>12, the maximum turbulence intensities $ú/U_i$ and $ύ/U_o$ reduced almost to the same level of the streamwise free stream turbulence intensity. Fig. 14 shows the variation of turbulence shear stress profiles $–uv/U_i^2$ as a function of dimensionless water depth d/d_o along the depth at different locations z/b along the centerline at z/b = 0.5 at F_i=4.5, S_o=0.01, d_t/d_i=7 and d_i/h=0.3. The turbulence shear stress, as shown in Fig.14, grows after the entrance of the hydraulic jump and is spreading in the jump region. Also, an increase of the culvert slope S_o increases the turbulence shear stress – uv/U_i^2. Fig.15 depicts the variation of streamwise mean velocity $ū/U_i$ as a function of relative spanwise z/b at the plane d/d_o=0.4 at different locations x/b along the centerline at F_i =4.5, S_o=0.01, d_t/di=7 and d_i/h=0.3. To check the spanwise variation of the flow, besides these measurements, another set was taken to indicate spanwise variation for each section at the plane d/d_o = 0.4. The original erosion for these extra measurements was to validate the dimensionality of the flow as was previously treated. Fig.16. shows the variation of streamwise mean velocity $ū/U_i$ as a function of relative water depth d/d_o at different cross-sections x/b =10, 20 and 40 at different spanwise locations z/b= 0.1, 0.2, 0.3, 0.4 and 0.5 along the depth at F_i=4.5, S_o=0.01, d_t/d_i=7 and d_i/h=0.3. As shown in Fig.16, at x/b=10 , the maximum velocity $ū_{max}$ near the center plane of the culvert is about 22% smaller than that near the side wall. Further downstream at x/b=40, near the end of the fully developed region, the difference between the maximum $ū_{max}$ near the side wall and the minimum $ū_{min}$ near the center plane is up to 35% as shown in Fig.16 at x/b=40. Another effect is that the length scale for $ū/U_i$ near the side wall is higher than that near the center plane. This phenomenon is called "climb of a wall jet near the side wall" by George (1959) and Rajaratnam (1965). This climbing effect is believed to be due to the influence of the vortex motion. The flow close to the bed is two-dimensional shortly after the inlet of the jump, but on the top of this region there is a vortex motion. This motion causes reverse flow near the center plane and forward flow near the side wall. The shear stress near the center is about 35% higher than that at the side wall. Therefore, this vortex motion causes faster diffusion near the center plane than near the side wall at locations further downstream. The result is of course that $ū_{max}$ near the center plane is smaller than that near the side wall.

CONCLUSIONS

Turbulent flows in sloping and adversely sloping culverts considering the tailwater depth at the outlet and initial Froude number are analyzed with the aid of experimentally collected data by using a Laser Doppler Velocimeter. It is concluded that the relative tailwater depth d_t/d_i is a function of the initial Froude number F_i, the culvert slope S_o and the ratio of the initial depth to culvert height d_i/h. Both of the initial Froude number F_i and the culvert slope S_o have a major effect on the jump characteristics, while the ratio of the initial depth to the culvert height d_i/h has a minor effect when the slope is relatively small. In all cases, the relative tailwater depth increases nonlinearly with the increase of initial Froude number F_i and/or the increase of the conduit slope. It is also concluded that, the adverse slope has a major effect on relative tailwater depth d_t/d_i which is comparable with the effect of F_i on d_t/d_i where d_t/d_i decreases non-linearly with the increase of culvert adverse slope. But, sloping culvert has a major effect on d_t/d_i which is comparable with the effect of F_i on d_t/d_i where d_t/d_i increases non-linearly with the increase of the culvert slope. Also, in a sloping culvert, the higher the slope, the greater the relative tailwater depth

d_t/d_i which proves that the slope has an increasing effect on d_t/d_i. But, in an adversely sloping culvert, the higher the adverse slope, the less the relative tailwater depth d_i/d_i is, which proves that the adverse slope has a decreasing effect on d_t/d_i. Also, it is concluded that in sloping and adversely sloping culverts, the relative initial depth d_i/h has insignificant effect on relative tailwater depth d_t/d_i as d_t/d_i is increasing very slightly with the increase of d_i/h.

The conditions of the flow in the hydraulic jump cause unidirectional distortion of the fluid elements which may be expected to produce nonhomogeneous and anisotropic turbulence. Under the action of dynamic process, the turbulence was produced to some degree all over the field. The climbing effect of streamwise mean velocity near the side wall is due to the vortex motion. The maximum vertical mean velocity in the recirculating zone for all the jumps is only about U_i. Also, the results show that the maximum streamwise mean velocity $\bar{u}_{max}$ near the center plane is smaller than that near the side wall. The turbulence shear stress near the center is about 30% higher than that near the side wall. After the hydraulic jump, the flow will recover into a two-dimensional flow. In the hydraulic jump region, the turbulence intensities $ú/U_i$ and $\acute{v}/U_i$ grow rapidly spreading in all directions. In the wall region defined by $d/d_o<0.2$, the turbulence intensities have substantially small magnitudes closer to the wall. With increasing distance from the boundary, the turbulence intensities increase in the wall region tending towards a maximum in the intermediate region (core region) defined by $0.2< d/d_o<0.6$, at the location of the maximum value of turbulence, reaching a lower value in the free surface region defined by $d/d_o>0.6$. As a comprehensive observation, the streamwise turbulence intensity $ú/U_i$ is always greater than the vertical turbulence intensity.

NOMECLATURE

b: Channel width,
d_i: Initial depth of supercritical flow,
d_t: Tailwater depth,
d_o: Free stream water depth,
h: Culvert height,
F_i: Initial Froude number,
d_t/d_i: Relative tailwater depth,
d_i/h: Relative initial depth,
S_o: Culvert slope,
$\bar{u}$: Streamwise mean velocity in X-direction,
U_i: Initial streamwise mean velocity in X-direction,
u: Streamwise component of turbulence intensity in X-direction (RMS),
$\bar{v}$: Vertical mean velocity in Y-direction,
v: Vertical component of turbulence intensity in Y-direction (RMS),
x: Longitudinal axis along channel length,
y: Transverse axis along channel height,
z: Transverse axis along channel width.

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