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Flow Characteristics Through Conduit Using Laser Technique

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Abstract: - In this paper, an experimental investigation was carried out to study the turbulent structure and flow characteristics; and to investigate the characteristics of the hydraulic jump occurring in a sloping and adversely sloping rectangular conduit (culvert) with pressurized flow downstream from the jump and a submerged culvert outlet using Laser technique. Experiments were conducted to study the variation of the relative tailwater depth with the main parameters affecting the jump. These parameters include the initial Froude number, bottom slope, and ratio of the initial depth to conduit height. To study the turbulence structure, measurements were carried out of the turbulence intensities and turbulence shear stress. Non-dimensional design curves are provided to relate the jump characteristics. The maximum vertical velocity in the recirculating zone for all jumps is about 7% of initial velocity. Also, 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 about (30-42)% higher than that near the side wall. After the jump, the flow will recover into a two dimensional flow.

Keywords: - *Turbulence structure- Turbulence shear stress-Flow characteristics-Laser technique-Sloping culvert -Adversely sloping culvert -Hydraulic jump-Initial Froude number.*

I. INTRODUCTION

The conduit is a covered channel of comparatively short length which is typically installed to drain water through an embankment. The culvert acts as on 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 conduit 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 [1]. 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 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 [10] for the case of horizontal conduits followed by Kalinske and Robertson [9] 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 [3,4], Rodi [15]. Measurements of turbulence characteristics in open channel flows using LDA have been pointed by Guoren [7], Nezu [11,12]; Song [18]. The jump formation in closed conduits was studied by Haindi [8] for horizontal conduits and by Rajaratnam [13] 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 [20] studied the jump characteristics for the case of circular pipes. Later, Smith and Chen[19] investigated the relative height of the hydraulic jump formed in a steeply sloping 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 conduits, but they could not solve it because it contained too many unknowns. Hence, they provided a set of empirical equations of the form ($H_j/D = a F_1^4 + b$) (H_j being the height of jump, D is the culvert 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 culvert 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 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 [1] and more recently by Corquodale [2]. The hot-wire study on the turbulence characteristics in the hydraulic jump in an air model by Rouse, Siao Nagaratnam [16] was the first attempt to obtain information of turbulence field in free Hydraulic jumps. More than a decade later in 1972, Resch and Leutheusser [17] 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 internal structure of hydraulic jumps.

In the present paper, the experiments described are concerned with turbulence and flow characteristics on sloping and adversely sloping culvert 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 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 culvert 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 culvert heights.

II. 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 flume while at the downstream end, the flume is allowed to rotate freely about a hinged pivot. The slope was directly determined using slope indicator. A downstream adjustable gate was used to regulate the tail water surface elevation. The experiments were carried out using five different conduit 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. Also, six different conduit 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 sloping adversely culvert. The slopes and adverse slope 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.

III. 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 a point from one side of the channel glass wall through an optical lens. The number of sample taken at every point was 3000 bursts. This curves point 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 correspond to a particle passing through the measuring volume. The measuring 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.

IV. THEORETICAL ANALYSIS

Figure.3 shows a definition sketch for the hydraulic jump formed in sloping rectangular culvert. Although the momentum equation along with the energy equation can be writhen 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 [7]. 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 conduit 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 conduit slope S_o as:

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

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 conduit adverse slope, and F_i is the initial Froude number ($F_i = Q/ b\, d_i \sqrt{g\, d_i}$) where Q being the discharge, b is the conduit width, and g is the gravitational acceleration. Eq. (1) could be defined and evaluated using the experimental data. The experimental data can be plotted 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.

V. 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 depth d_i/h of 0.20, 0.25, 0.30 and 0.35. The resulting curves indicate that, if 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 increases as the conduit slope increases. Also, Fig. 4 presents the effect of the initial Froude number F_i at fixed d_i/h and different conduit slops. It is observed that the effect of F_i on d_t/d_i is significant. The d_t/d_i increases non-linearly with the increase of F_i. Also, the higher the slope, the 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 conduit slope S_o for different F_i 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. Also, 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. Also, confirmed 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 at different culvert slope 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 a approximately linear trend. Also, at a particular d_i/h, d_t/d_i increases as the F_i increases. Also, Fig.6 shows the typical effect of d_i/h at different F_i of 3.5, 4, 4.5, 5 and 5.5 at different conduit 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 increase.

Figure.7 depicts the variation of culvert adverse slope S_o with relative tailwater depth d_t/d_i for different F_i 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. Also, 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. Also, confirmed 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 are 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 presents 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 ratio d_t/d_i is, 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 of 3.5, 4, 4.5, 5 and 5.5 at different culvert adverse slope S_o = 0.0, 0.01, 0.015, and 0.025. It is clear that for the investigated range of the 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.

Measurements were made for various flow conditions. However, only representative results are presented here. For each experimental condition, detailed measurements along the centerline along the plane z/b=0.5, were carried out to obtain vertical profiles of the mean and fluctuating flow quantities such as steamwise 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 turbulence at a very location from the wall of the order of 3mm as observed in Laser Doppler (LDV) experimentation, and not at the wall itself peruse. 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 varies considerably according to the cross section location x/b and the flow conditions. In the hydraulic jump location in the culvert, reversal flow could be observed as shown in Fig. 10 at x/b = 0 up to x/b = 12, as could be seen by the sharp of the velocity profiles, and as was observed by dye injection. Fig.11 presents 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 the zero value at some intermediate locations. This nature of variation, viz., change from positive to negative magnitude and vice versa occurred 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 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 point to the three dimensional interaction between the entrance flow to the hydraulic jump almost with negative vertical velocity component. The influence of jump itself along with the bed impeding the downward component of velocity. This complex interaction would influence the flow pattern giving rise to multiplicity null point.

Root mean square (RMS) values of steamwise ad vertical components of turbulence intensity $\acute{u}/U_i$ and $\acute{v}$/Ui. Fig.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 location 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 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 steamwise and vertical turbulence intensities $\acute{u}/U_i$ and $\acute{v}/U_i$ grows rapidly after the inlet of the jump and is spreading in the all directions. An increase of the conduit slope S_o from 0.005 to 0.025 does increase 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 magnitude closer to the wall. With increasing the distance from the boundary, the turbulence intensities $\acute{u}/U_o$ and $\acute{v}/U_o$ increases in wall region tending a maximum in the intermediate region (core region) defined by $0.2 < d/d_o < 0.6$, where the location of the maximum value of the turbulence $\acute{u}/U_i$ and $\acute{v}/U_i$, 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, the surface waves play an important role in the turbulent production. As a comprehensive observation, it was noted that, the streamwise turbulence $\acute{u}/U_i$ was always greater than that for vertical turbulence $\acute{v}/U_i$. In farthest downstream, x/b > 12 the maximum turbulence intensities $\acute{u}/U_i$ and $\acute{v}/U_o$ were reduced almost to the same level of the streamwise free stream turbulence intensity. Fig. 14 shows the variation of turbulence shear stress profiles $-uv/Ui^2$ as a function of dimensionless water depth d/d_o along the depth at different location 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 conduit slope S_o does increase the turbulence shear stress $- uv/Ui^2$. Fig.15 depicts the variation of streamwise mean velocity $\bar{u}/U_i$ 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 to indicate spanwise variation was taken for each section at the plane of $d/d_o = 0.4$. The original erosion for these extra measurements was to validate the dimensionality of the flow as it was previously treated. Fig.16. Shows the variation of streamwise mean velocity $\bar{u}$/Ui 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 $\bar{u}_{max}$ near the center plane of the conduit is about 22 % smaller than near the side wall. Further downstream at x/b = 40, in which , it is near the end of the fully developed region, the difference between the maximum $\bar{u}_{max}$ near the side wall and minimum $\bar{u}_{min}$ near the center plane is up to 30 % as shown in Fig.16 at x/b = 40. Another effect is that the length scale for $\bar{u}/U_i$ near the side wall is higher than that near the center plane. This phenomena is called climb of a wall jet near the side wall by George [12] and Rajaratnarm [13]. This climbing effect is believed due to the influence of the vortex motion. The flow close to the bed is two dimensional shortly after the inlet of the inlet of the jump, but on top of this region there is vortex motion. This motion causes reversing flow near the center plane and forward flow near the side wall. The shear stress near the center is about 33 % higher than that the side wall. Therefore this vortex motion causes faster diffusion near the center plane than near the side wall at locations further downstream. The results are of course that $\bar{u}_{max}$ near the center plane is smaller than that near the side wall.

VI. CONCLUSIONS

A study of the turbulent flows in sloping and adversely sloping culvert 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. 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 side wall is due to the vortex motion. The maximum vertical mean velocity in the recirculating zone for all the jumps is only about of U_i . Also, the results show that the maximum steamwise 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 two dimensional flow. In the hydraulic jump region, the turbulence intensities $\acute{u}/U_i$ and $\acute{v}/U_i$ grow rapidly and spreading in all directions. In the wall region defined by $d/d_o < 0.2$, the turbulence intensities have substantially small magnitude closer to the wall. With increasing distance from the boundary, the turbulence intensities increases in wall region tending towards a maximum in the intermediate region (core region) defined by $0.2 < d/d_o < 0.6$, where the location of the maximum value of turbulence, reaching a lower value in the free surface region defined by $d/d_o > 0.6$ subsequently. As a comprehensive observation, the streamwise turbulence intensity $\acute{u}/U_i$ always greater than vertical turbulence intensity. Also, it is concluded that the relative tailwater depth d_t/d_i is a function of initial Froude number F_i, the conduit 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 conduit slope S_o have major effect on the jump characteristics while the ratio of the initial depth to the conduit height d_i/h is 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 conduit adverse slope. But, sloping conduit has a major effect on d_t/d_i which is comparable with the effect of F_i. On d_t/d_i which d_t/d_i increases non-linearly with the increase of conduit slope. Also, in sloping conduit, 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 adverse sloping conduit, 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 adverse sloping conduit , 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 increase of d_i/h.

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,
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),
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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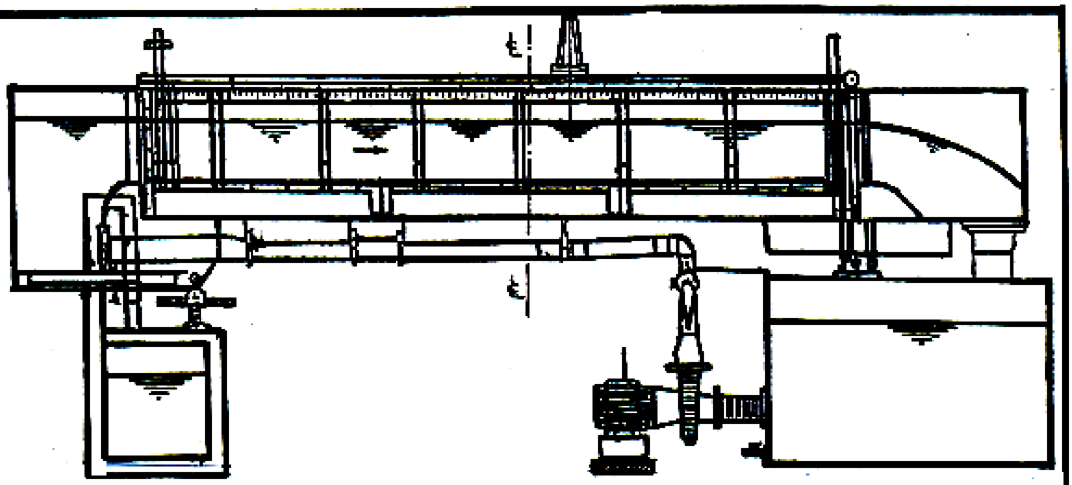

Fig. 1 Schematic sketch of test facility.

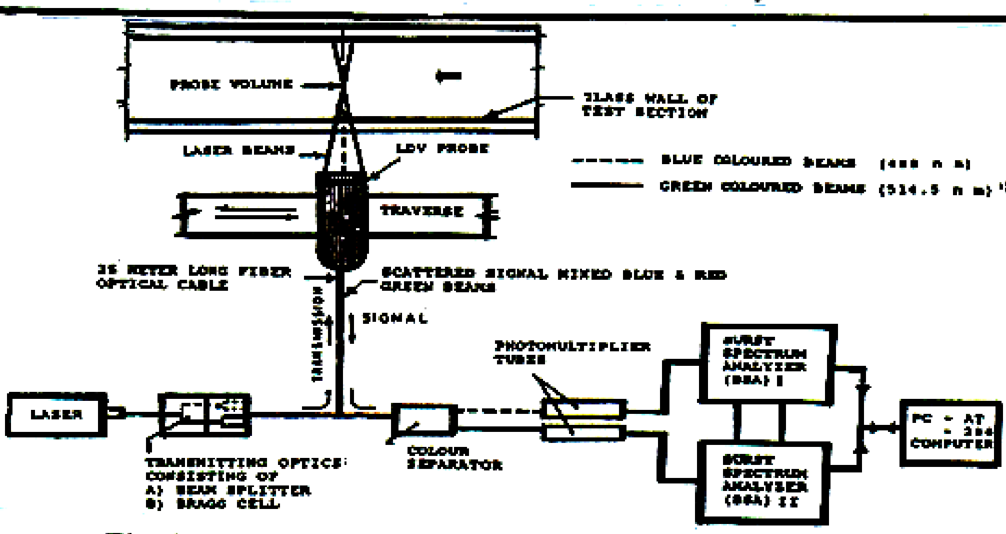

Fig. 2 Block diagram of the Laser Doppler Velocimetry.

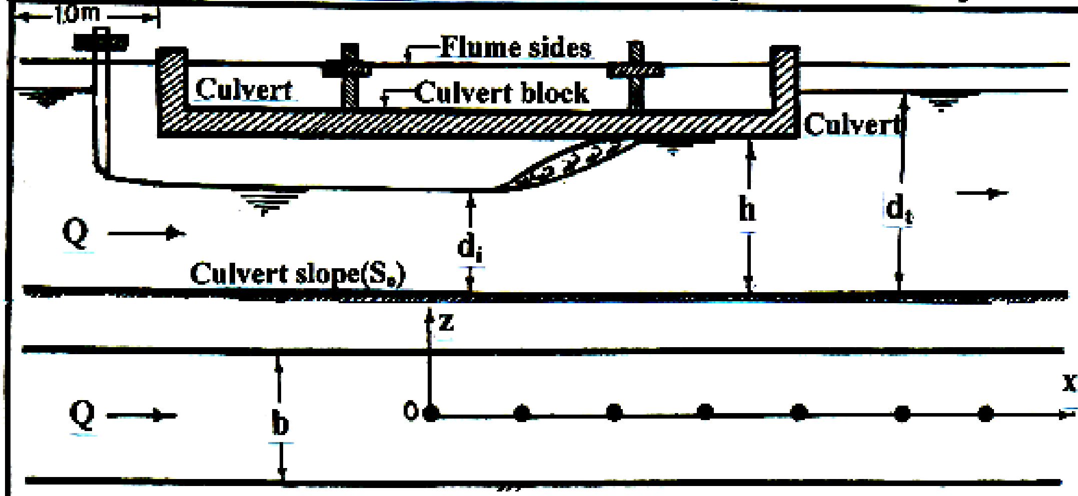

Fig.(3)Definition sketch showing the variables of the culvert

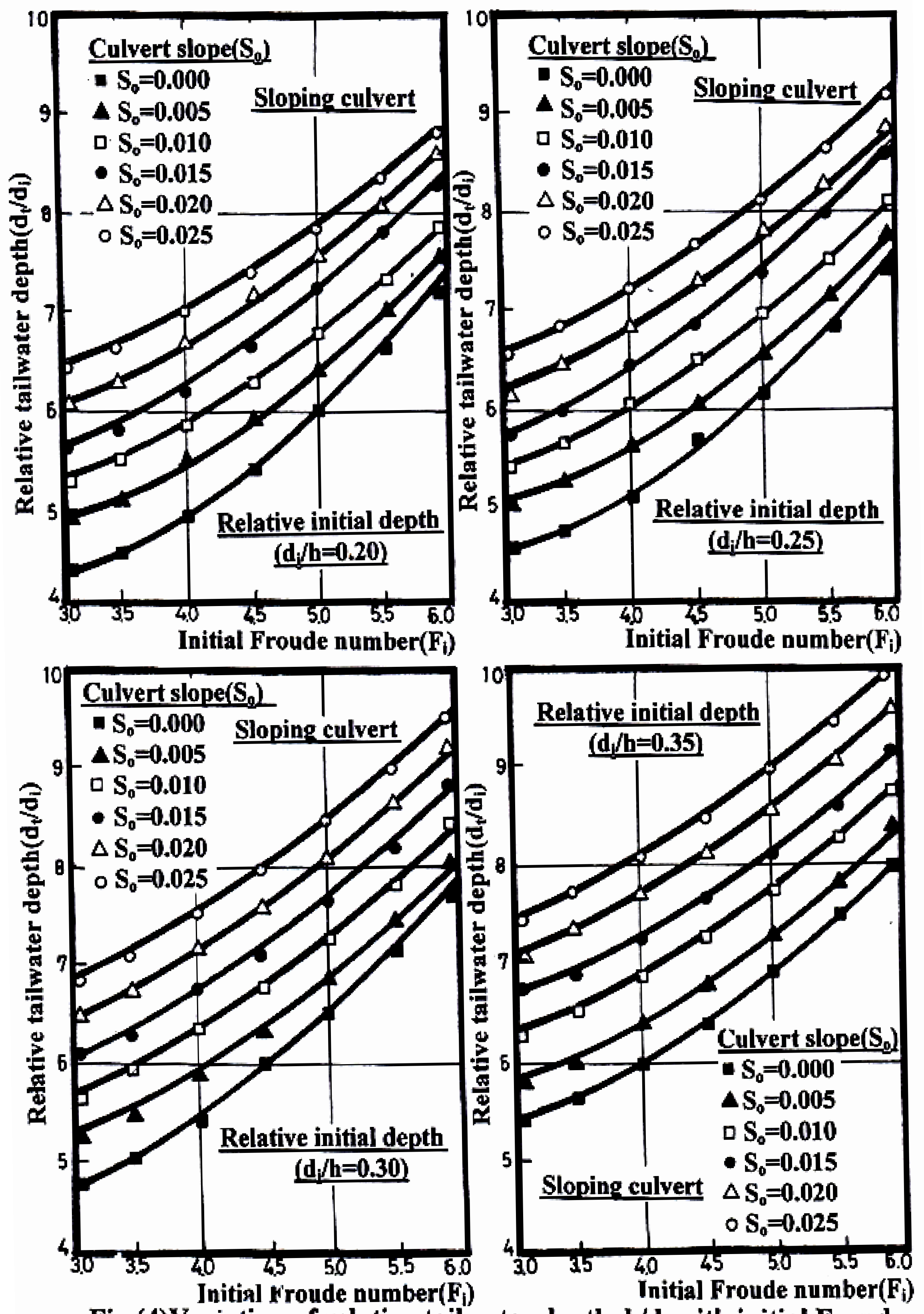

Fig.(4)Variation of relative tailwater depth d_t/d_i with initial Froude number F_i for different slope S_o at different relative initial depth d_i/h for sloping culvert.

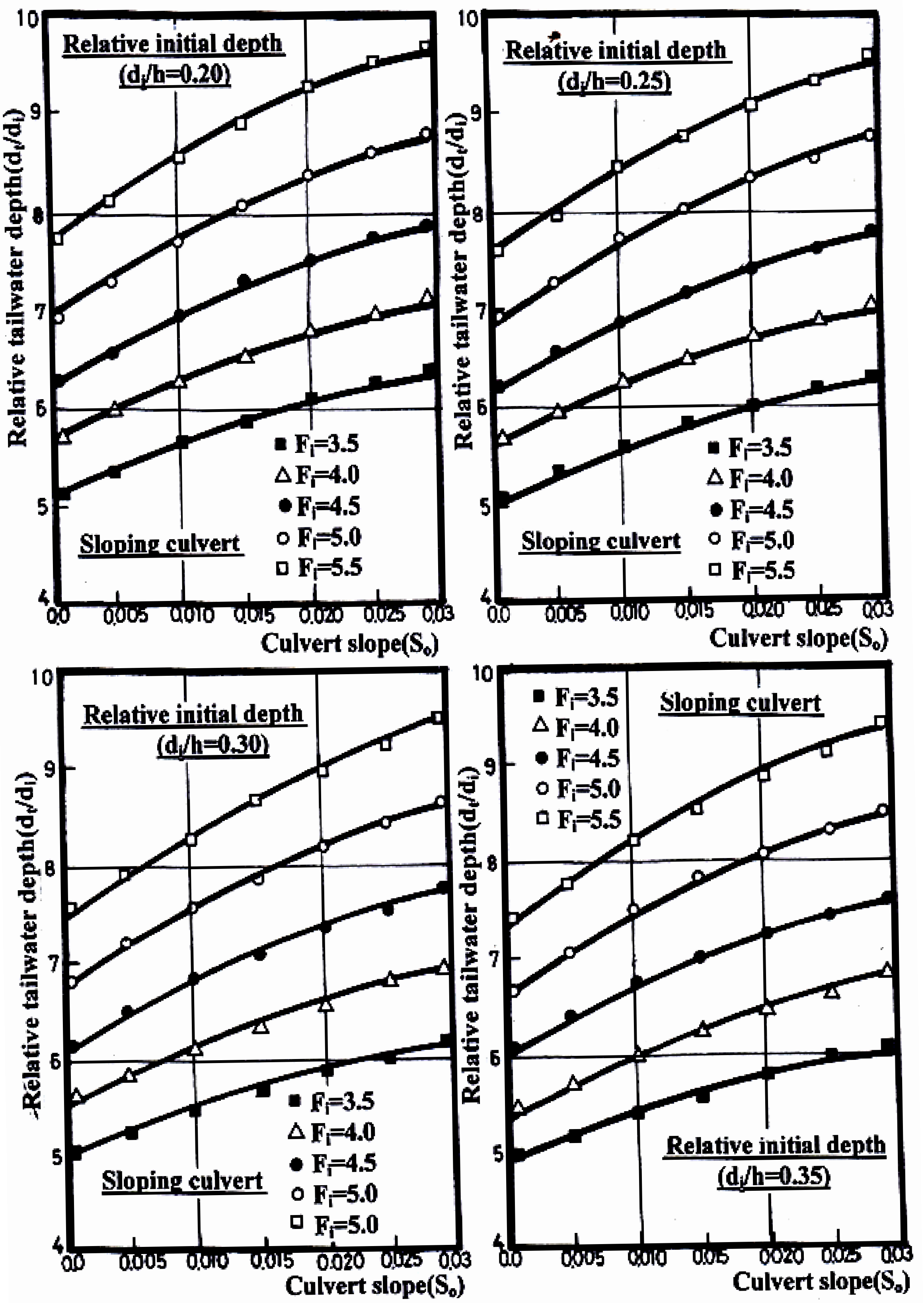

Fig.(5)Variation of relative tailwater depth d_t/d_i with slope S_o for different initial Froude number F_i at different relative initial depth d_i/h for sloping culvert.

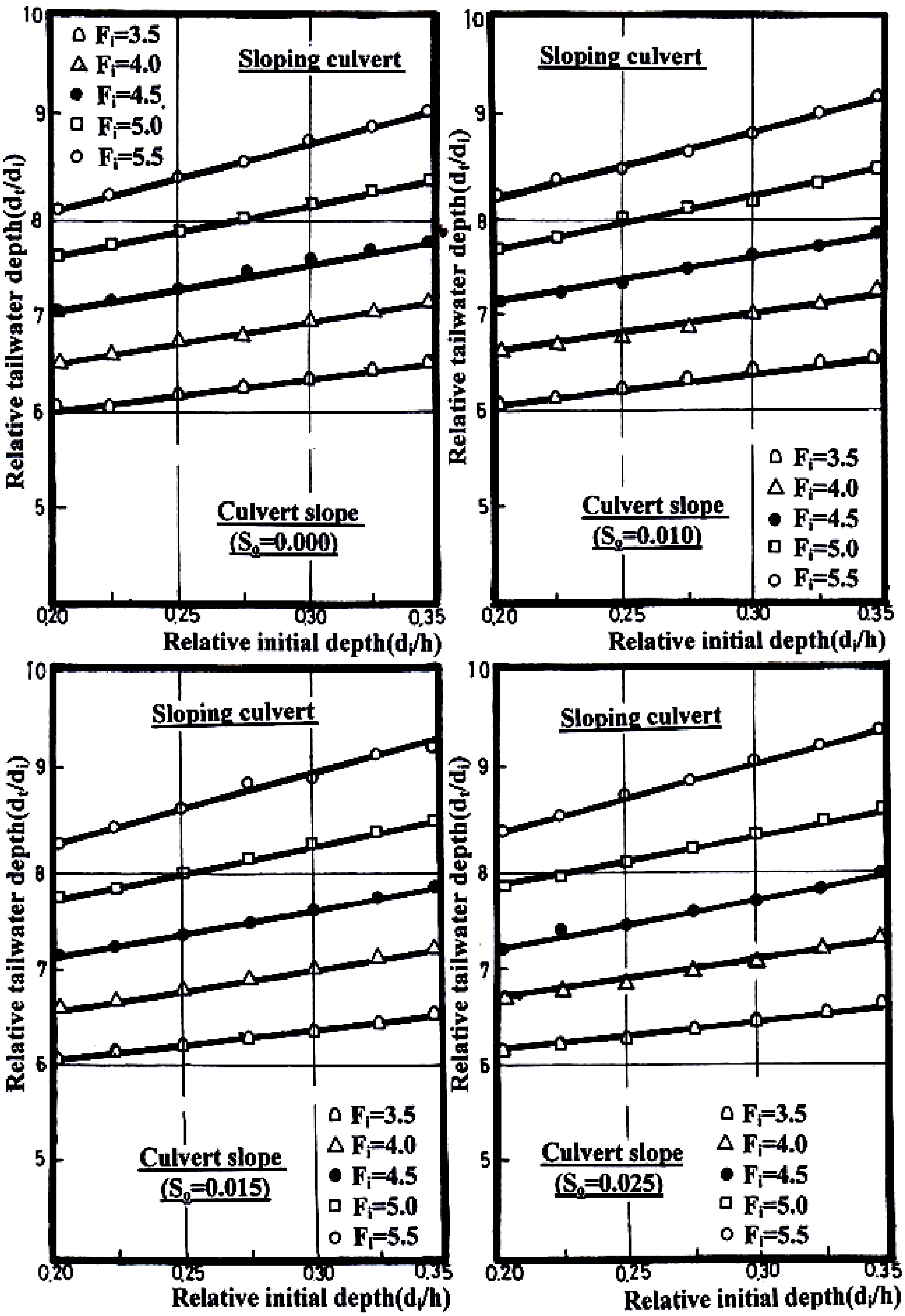

Fig.(6)Variation of relative tailwater depth d_t/d_i with relative initial depth d_i/h for different initial Froude number F_i at different slope S_o for sloping culvert.

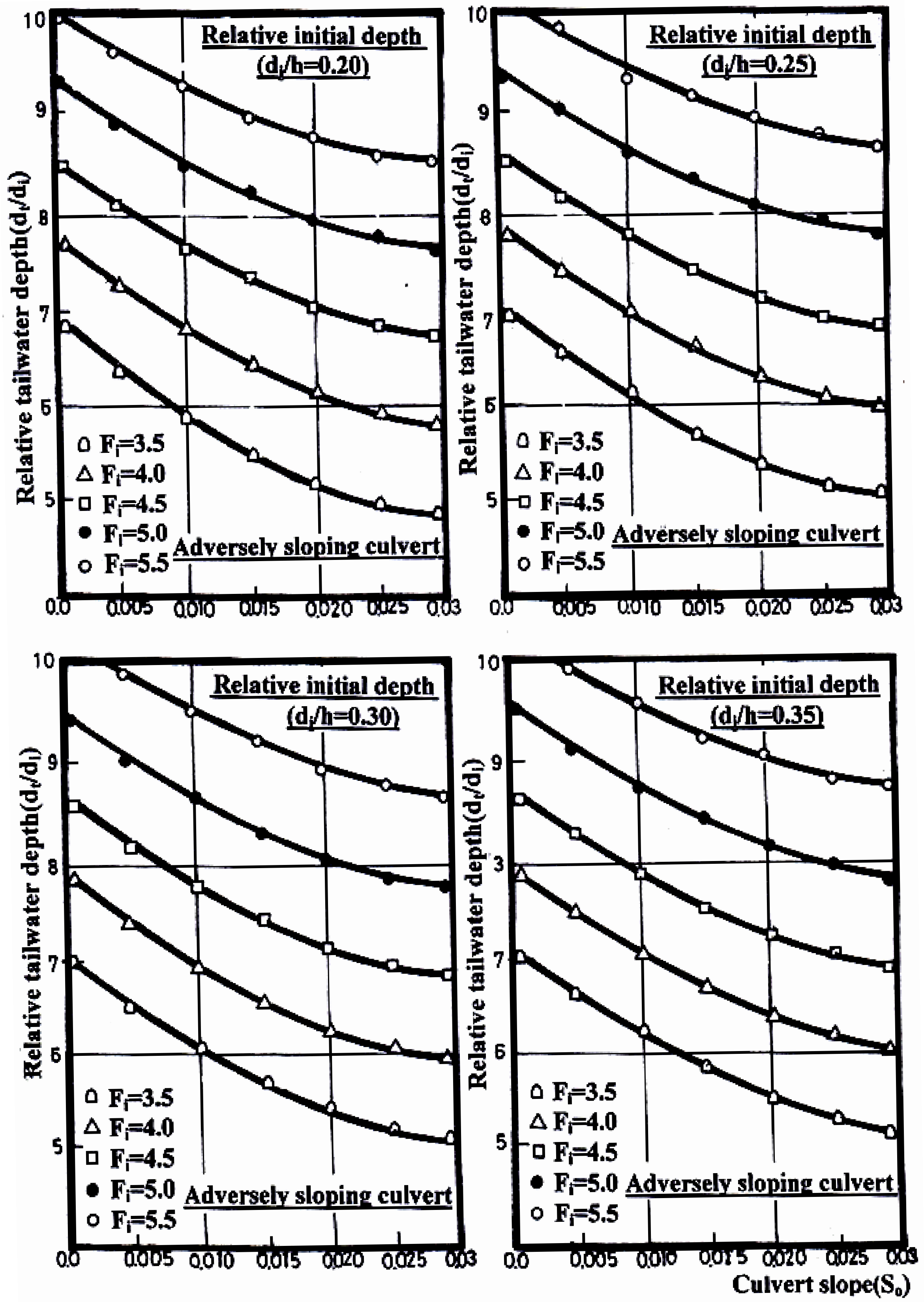

Fig.(7)Variation of slope S_o with relative tailwater depth d_t/d_i for different initial Froude number F_i at different relative initial depth d_i/h for adversely sloping culvert.

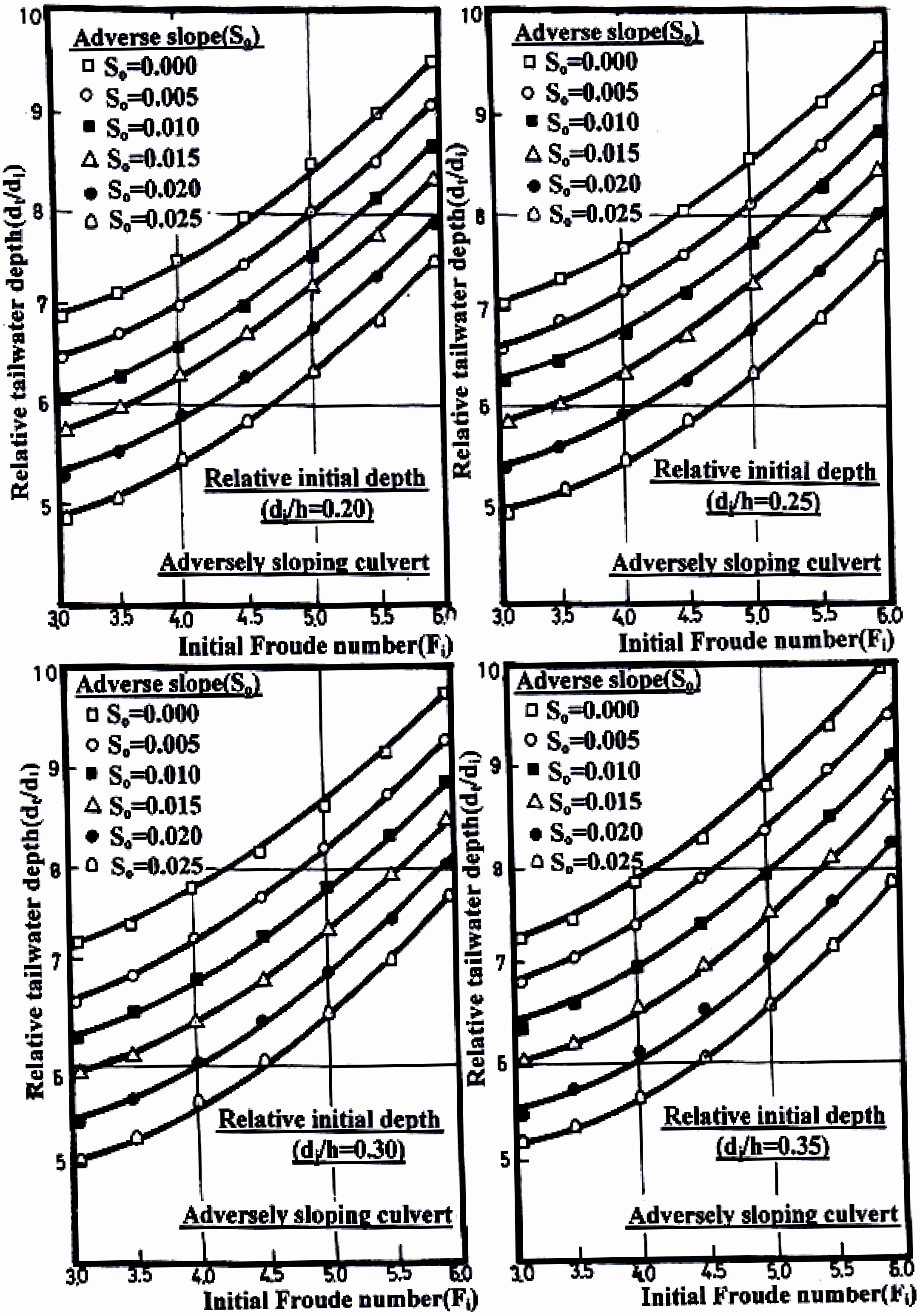

Fig.(8)Variation of initial Froude number F_i with relative tailwater depth d_t/d_i for different slope S_o at different relative initial depth d_i/h for adversely sloping culvert.

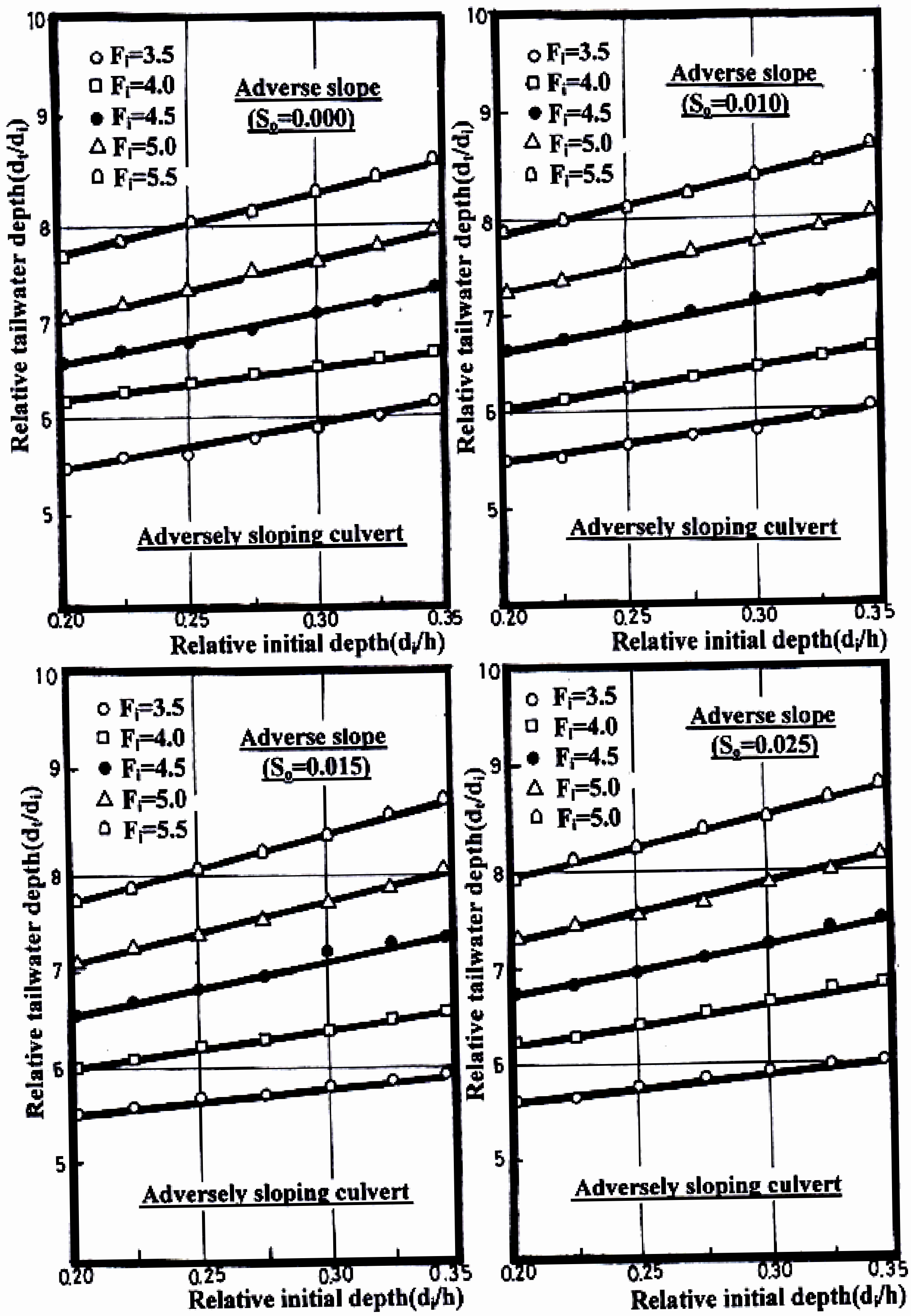

Fig.(9)Variation of relative initial depth d_i/h with relative tailwater depth d_t/d_i for different initial Froude number F_i at different slope S_o for adversely sloping culvert.

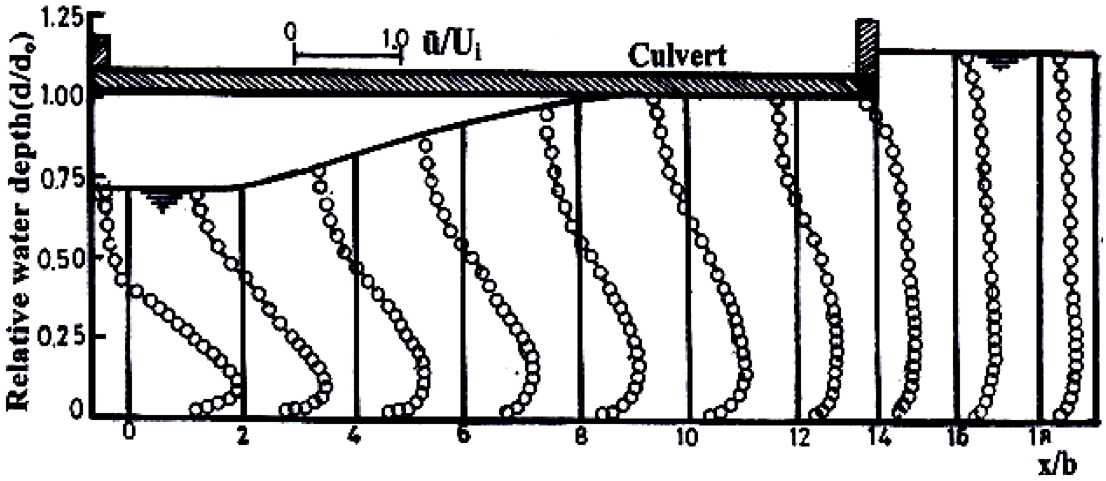

Fig.(10)Variation of streamwise mean velocity $\bar{u}/U_i$ along the depth at different cross sections(F_i=4.5, S_o=0.01,d_t/d_i=7 and d_i/h=0.3).

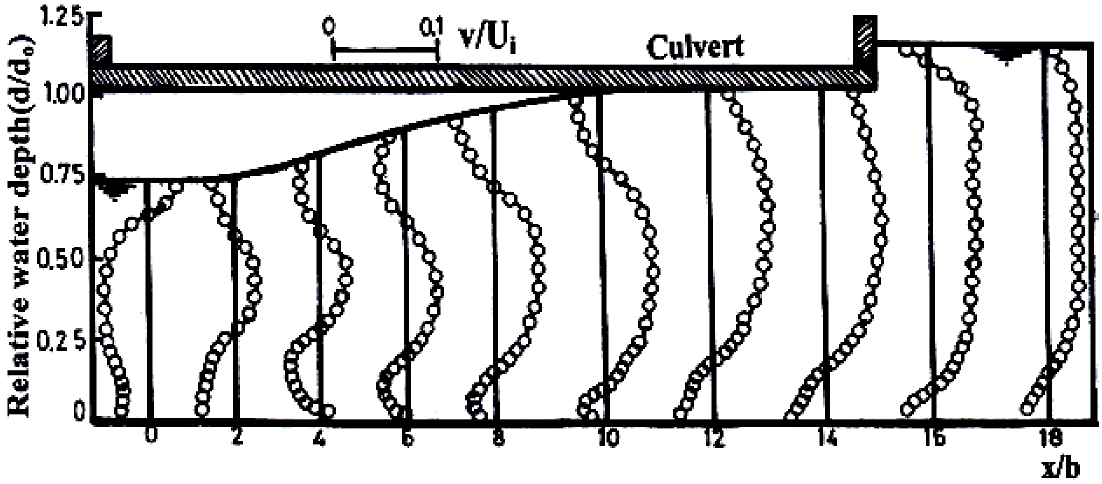

Fig.(11)Variation of vertical mean velocity $\bar{v}/U_i$ along the depth at different cross sections(F_i=4.5, S_o=0.01,d_t/d_i=7 and d_i/h=0.3).

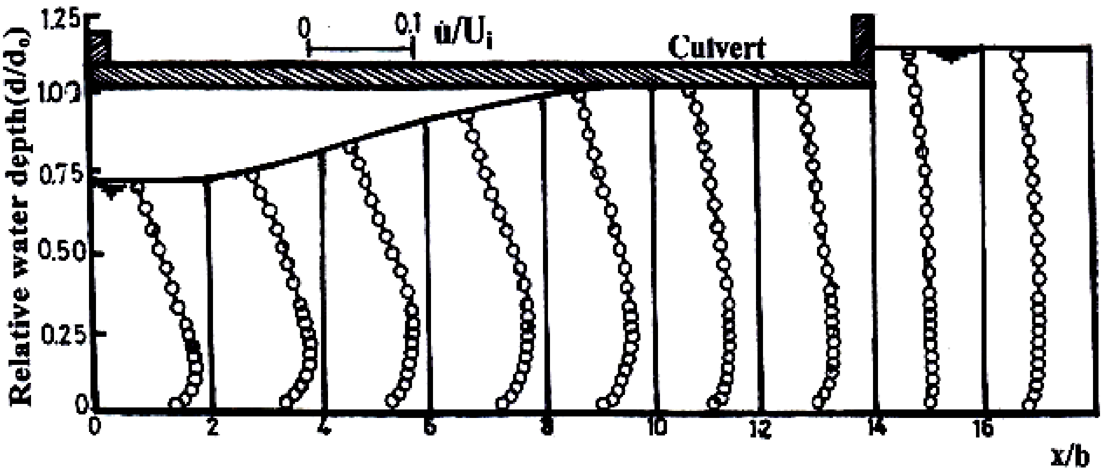

Fig.(12)Variation of streamwise turbulence intensities $\acute{u}/U_i$ along the depth at different cross sections(F_i=4.5, S_o=0.01,d_t/d_i =7 and d_i/h=0.3).

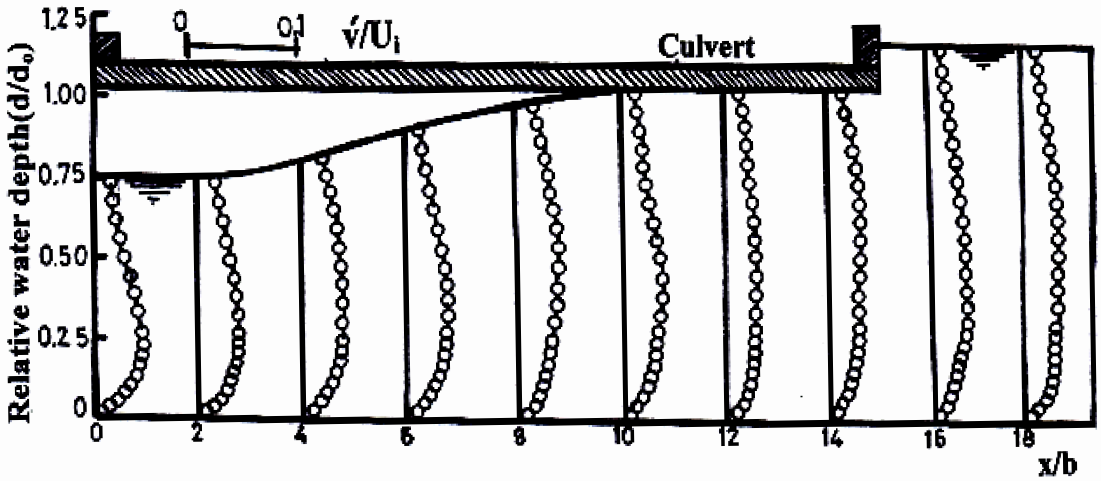

Fig.(13)Variation of vertical turbulence intensities $\acute{v}/U_i$ along the depth at different cross sections(F_i=4.5, S_o=0.01, d_t/d_i =7 and d_i/h=0.3).

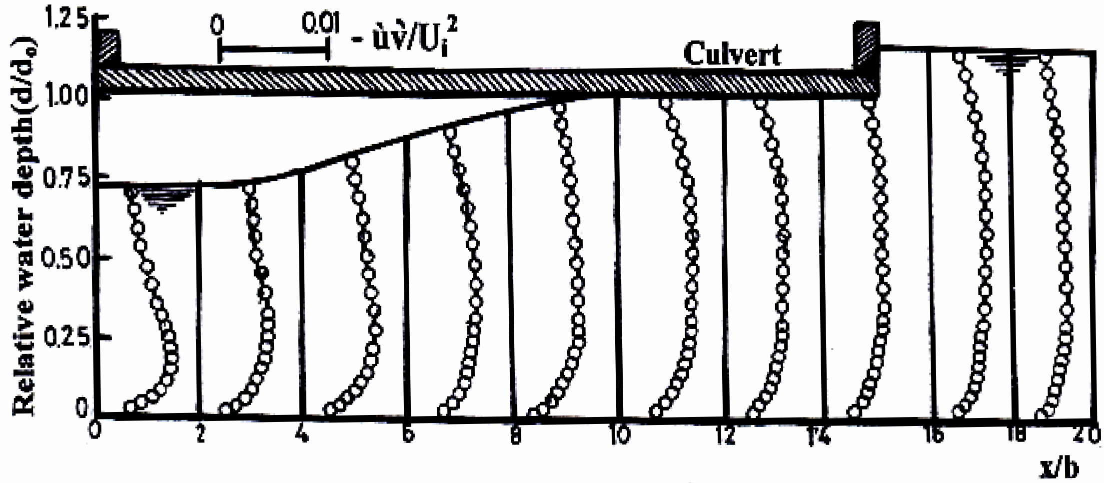

Fig.(14)Variation of turbulence shear stress $-\grave{u}\grave{v}/U_i^2$ along the depth at different cross sections(F_i=4.5, S_o=0.01, d_t/d_i =7 and d_i/h=0.3).

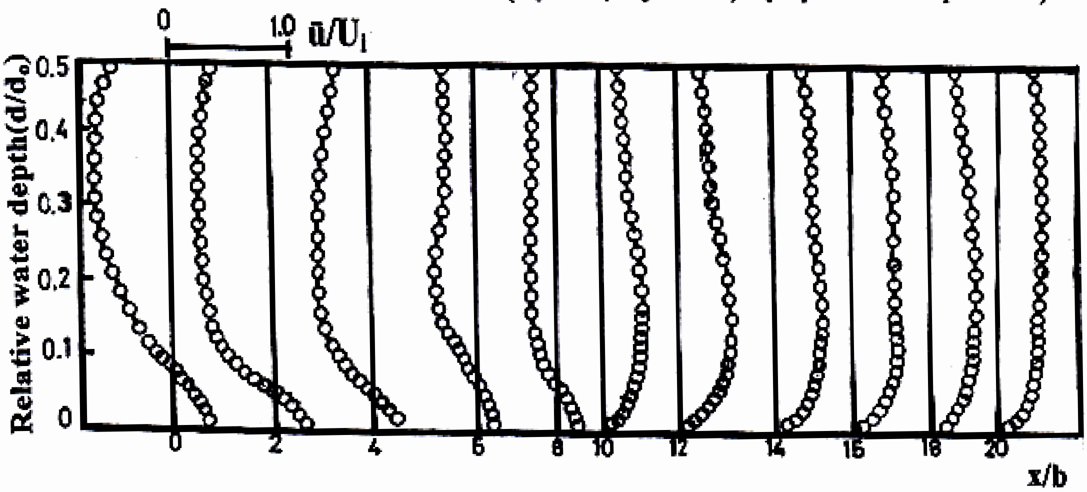

Fig.(15)Variation of streamwise mean velocity $\bar{u}/U_i$ at the plane of d/d_o=0.4(F_i=4.5, S_o=0.01, d_t/d_i =7 and d_i/h=0.3).

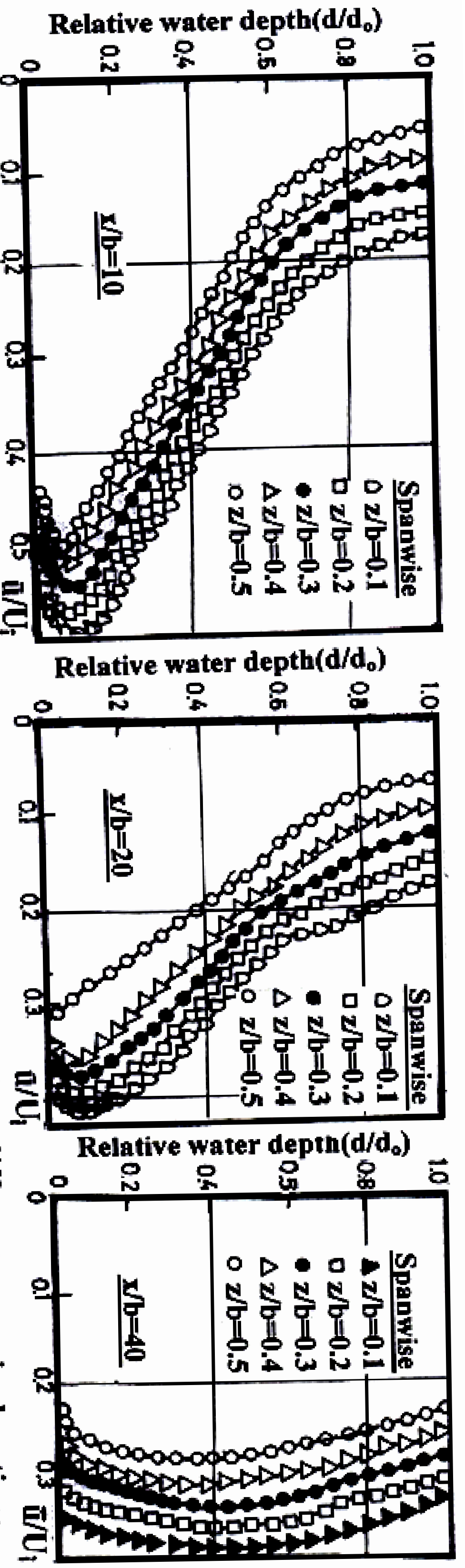

Fig.(16)Variation of streamwise mean velocity $\bar{u}/U_o$ along the depth at different spanwise locations z/b=0.1,0.2,0.3,0.4 and0.5 for different x/b=10,20 and 40(F_j=4.5, S_o=0.01, d_t/d_j =7 and d_t/h=0.3).

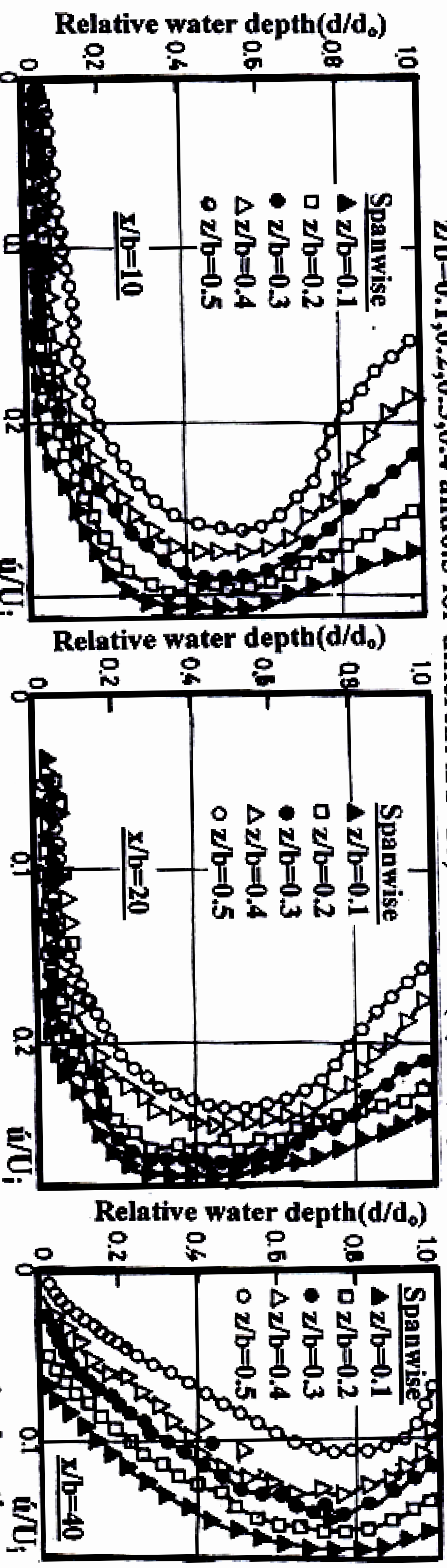

Fig.(17)Variation of streamwise turbulence intensity ú/U_o along the depth at different spanwise locations z/b=0.1,0.2,0.3,0.4 and0.5 for different x/b=10,20 and 40(F_j=4.5, S_o=0.01, d_t/d_j =7 and d_t/h=0.3).